F 809 – Instrumentação para o Ensino

Calorímetro de Smith

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1 - Sumário:

2 - Introdução:

A caracterização de materiais motiva a ciência a desenvolver ou aprimorar métodos existentes. São três as principais formas de se analisar as características inerentes a uma certa amostra. A caracterização por resistividade, por magnetização e por calor específico. Existem equipamentos que fazem todas essas medidas, como o PPMS (Physical Properties Measurements System) da Quantum Design, mas, no entanto, esses são demasiadamente caros e, devido a isso, não são utilizado em laboratórios de ensino.

No caso da medida de Calor Específico, geralmente, ela é realizada utilizando o método do duplo-tau (duplo - τ), que para alguns casos pode não ser o ideal. Para o caso de materiais que apresentam efeito magneto calórico gigante (EMCG) acompanhado de transição cristalográfica, como é o caso do $Gd_5Ge_2Si_2$, encontra-se um pico finito para a transição de primeira ordem [1]. No entanto, deveria ser encontrada uma descontinuidade, pois durante a transição cristalográfica não há como passar da estrutura monoclínica para ortorrômbica de maneira contínua. Isto ocorreu devido ao método utilizado para a medida de calor que é o de pulsos de calor [2]. Por este método, espera-se a estabilização térmica da amostra então se aplica um pulso de calor durante um tempo pré-determinado, medindo-se a variação de temperatura do conjunto suporte-amostra. Como este pulso de calor faz variar a temperatura da amostra ele é usado para a determinar variação de temperatura da mesma. Este método não detecta a descontinuidade de Cp porque, ao se aproximar da transição, os pulsos de calor fazem variar a temperatura de todo o conjunto amostra - adenda, e, como o aquecedor e o termômetro estão colados à adenda, o termômetro sempre detecta uma variação de temperatura para qualquer pulso de calor. O método, por isso, não permite a obtenção direta do calor latente da transformação, nem revela a esperada descontinuidade no calor específico. As mesmas observações aplicam-se ao método de medida do calor específico denominado relaxação térmica, ou método do duplo-tau (duplo - τ), em que o calor específico é determinado por ajuste das curvas de aquecimento e resfriamento durante e após um pulso de calor, após a estabilização da temperatura da amostra. Novamente, neste método, tanto o aquecedor quanto o termômetro estão colados ao suporte de amostra, o que leva ao termômetro ver sempre uma variação de temperatura para qualquer pico de calor.

O estudo dos materiais apresentando efeito magnetocalórico gigante vai requerer um novo sistema de medida de calor específico, uma vez que os métodos baseados em pulsos de calor não conseguem detectar com nitidez as transições de primeira ordem que em geral caracterizam os materiais de interesse. Por isso, um calorímetro baseado na abordagem de Smith [3,4] parece ser muito conveniente, não só porque, ao usar o fluxo de calor como parâmetro de controle do forno ele é capaz de determinar com precisão as transições de primeira ordem e, obviamente, quando a transição é de segunda ordem, mas também porque é um método dinâmico que pode permitir medidas com maior rapidez que os métodos baseados em pulsos de calor.

A importância de medidas de calor específico em função da temperatura é fundamental devido à possibilidade de obter a entropia do sistema quando submetido ou não a um campo magnético, isto é, Cp(T,H). As medidas a campo zero da entropia nestes sistemas podem ser relevantes para a interpretação dos processos quânticos durante a transição de fase estrutural durante o aquecimento (ou resfriamento). Nestes casos, o ideal é utilizar um calorímetro de fluxo de calor contínuo para determinar com maior detalhe o seu comportamento durante as transições de primeira ordem.

3 - Teoria:

3.1 – Condução Térmica

A termodinâmica clássica vista no ensino médio é a área da física mais simples de ser aplicada no cotidiano. O primeiro conceito que é intuitivamente demonstrado é a chamada lei Zero da Termodinâmica, que indica que o calor sempre flui da parte quente para a parte fria de qualquer material. Existem, no entanto, três métodos possíveis para o calor realizar este percurso.

1. Condução: No qual o calor passa pelo material;

2. Convecção: Na qual o calor é transferido por movimento relativo de partes do corpo esquecido;
3. Radiação: Calor é transferido a partes distantes de um corpo por radiação eletromagnética;

Nos líquidos e gases a convecção e radiação têm grande importância, já em sólidos não há convecção e a radiação é geralmente desprezível [5].

Para um calorímetro ideal devemos isolar o sistema de tal maneira que somente tenha troca de calor entre a amostra, cadinho e resistência, pois deste modo à energia cedida pela resistência vai aquecer a amostra em taxa constante.

Todas essas características foram primeiramente determinadas classicamente e somente com o advento da mecânica quântica é se iniciou o estudo do que ocorre no interior de um material que faça seu exterior reagir da maneira como pode ser medida, ou melhor, detectada, no entanto esse não é o intuito deste projeto fazer uma análise teórica dos fenômenos que explicam esses eventos.

3.2 - Análise Térmica de Smith

A análise térmica proposta por Smith é de grande sensibilidade, eficiente para medir o calor de reações, desde que sejam lentas. Este método também permite se obter também o calor específico dos materiais com boa precisão. Como será mostrada a seguir, uma característica única deste método é sua simplicidade. Com materiais e métodos relativamente simples a técnica proposta por Smith é capaz de determinar medidas quantitativas de calor.

O aparelho é constituído basicamente de um recipiente refratário de baixa condutividade térmica, inserido dentro uma fonte de calor. Neste recipiente coloca-se a amostra e um sensor de temperatura, normalmente utilizado um termopar. O método proposto por Smith consiste em realizar-se um aquecimento (ou resfriamento) lento no qual o fluxo de calor absorvido (ou emitido) pela amostra é constante. Para que esta situação seja estabelecida, deve-se manter uma diferença de temperatura constante entre a parede externa e a parede interna do recipiente.

Sabe-se que o fluxo de calor através do recipiente é igual ao produto de sua condutividade térmica, vezes uma constante que depende das suas características, vezes a diferença de temperatura entre a parede interna e externa. Para um mesmo recipiente, os dois primeiros fatores são constantes em um intervalo de tempo não muito grande. Deste modo, mantendo-se uma diferença de temperatura constante garante-se que o fluxo de calor através do recipiente é também constante.

Um problema que se pode verificar neste método é o fato de que a condutividade térmica do material do qual é feito o recipiente varia com a temperatura e conseqüentemente o fluxo de calor através do recipiente também. Mas isto é eliminado calibrando-se o recipiente para o intervalo de temperatura de interesse utilizando uma amostra padrão [6].

3.2.1 Equacionamento do Método

Denomina-se de $Q^{'}$ ao fluxo de calor, de ΔT à variação de temperatura do intervalo de tempo Δt, de c ao calor específico e de l ao calor latente de transformação de fase neste intervalo de tempo. Em um regime de aquecimento o fluxo de calor positivo está relacionado com o aumento de temperatura da amostra, o aumento de temperatura de parte indeterminada do cadinho e para realizar uma possível mudança de fase. As equações eq. 1a, eq. 1b, eq. 1c, expressam o calor ΔQ que passa através do cadinho durante o intervalo de tempo Δt nas situações a seguir: cadinho com amostra, cadinho com referência, e cadinho vazio. Os subíndices usados são a, r, e v respectivamente. O subíndice c refere-se ao cadinho.

$$\begin{aligned}
\Delta Q_a &= Q^{'} \times \Delta t_a = c_c m_c \Delta T_a + c_a m_a \Delta T_a + l_a m_a \\
\Delta Q_r &= Q^{'} \times \Delta t_r = c_c m_c \Delta T_r + c_r m_r \Delta T_r \\
\Delta Q_v &= Q^{'} \times \Delta t_v = c_c m_c \Delta T_v
\end{aligned}$$

Equação 1: a) Variação de calor da amostra, b) Variação de calor da referência, c) Variação do calor do cadinho vazio.

É importante que o material escolhido como referência seja termicamente inerte no intervalo de temperatura de trabalho. Este fato justifica o não aparecimento do calor latente na equação eq. 1b. Se no intervalo ΔT_a a amostra não está passando por nenhuma reação de transformação de fase o termo $l_a m_a$ da equação eq. 1a pode ser desprezado. Dividindo cada equação por sua respectiva variação de temperatura tem-se:

$$
\begin{aligned}
c_a m_a + c_c m_c &= Q' \times \frac{\Delta t_a}{\Delta T_a} \qquad \text{a)}\\
c_r m_r + c_c m_c &= Q' \times \frac{\Delta t_r}{\Delta T_r} \qquad \text{b)}\\
c_c m_c &= Q' \times \frac{\Delta t_v}{\Delta T_v} \qquad \text{c)}
\end{aligned}
$$

Equação 2 - Equação 1 dividida pelas respectivas temperaturas

Substituindo a eq. 2c nas equações 2a e 2b, obtém-se:

$$
\begin{aligned}
c_a m_a &= Q' \times \left[\frac{t_a}{T_a} - \frac{\Delta t_v}{\Delta T_v}\right] \qquad \text{a)}\\
c_r m_r &= Q' \times \left[\frac{t_r}{T_r} - \frac{\Delta t_v}{\Delta T_v}\right] \qquad \text{b)}
\end{aligned}
$$

Equação 3 - a) Calor específico da amostra, b) Calor específico da referência.

O fluxo de calor $\Delta Q'$ é o mesmo em cada temperatura para ambas as equações. Assim, dividindo eq. 3a por eq. 3b, obtém-se a seguinte relação:

$$
\frac{c_a}{c_r} = \frac{m_r}{m_a}\left[\frac{\frac{\Delta t_a}{\Delta T_a} - \frac{\Delta t_v}{\Delta T_v}}{\frac{\Delta t_r}{\Delta T_r} - \frac{\Delta t_v}{\Delta T_v}}\right] = \frac{m_r}{m_a}\left[\frac{\frac{1}{\Delta T_a'} - \frac{1}{\Delta T_v'}}{\frac{1}{\Delta T_r'} - \frac{1}{\Delta T_v'}}\right]
$$

Equação 4 - Razão entre c_a e c_r

O termo $\frac{\Delta t}{\Delta T} = \frac{1}{T'}$ é o inverso da derivada temporal de T, que corresponde ao tempo necessário para a temperatura variar de $1^o C$. A eq. 4 mostra qual razão do calor específico da amostra com o calor específico da referência é proporcional a razão dos tempos requeridos para mudar a temperatura de $1^o C$, após serem corrigidos pela subtração do termo $\frac{\Delta t_v}{\Delta T_v}$, uma espécie de sinal ou leitura em branco obtida da ATS com o recipiente vazio [6].

3.3 - A Física dos Termopares

Na física existem vários fenômenos que inter-relacionam energia térmica e elétrica. Tem-se o efeito joule e termoiônico e outros três intimamente relacionados e denominados termoelétricos. Esses efeitos são: Seeback, Peltier e Thomson.

3.3.1 – Efeito Seeback

O circuito da Figura 1, constitui uma malha constituída por fios condutores de materiais diferentes, X e Y. Se mantiverem as junções de X e Y à temperaturas diferentes T_1 e T_2 distintas, o circuito será percorrido por uma corrente elétrica. A força eletromotriz associada a esta corrente elétrica denomina-se de força termoeletromotriz (f_{tem}) de Seeback [7].

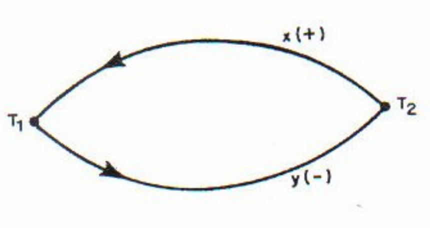

Figura 1 - Efeito Seeback. Têm-se indicados as polaridas dos condutores e o sentido da corrente de Seeback para $T_1<T_2$

3.3.2 - Efeito Peltier

A Figura 2 mostra o esquema de uma corrente elétrica percorrendo uma junção de dois metais diferentes X e Y. Haverá produção ou absorção de calor na junção dependendo do sentido da corrente que circula por ela, tal efeito denomina-se Peltier. A quantidade de calor absorvida ou cedida pela junção, no efeito, deverá ser proporcional à intensidade da corrente[7].

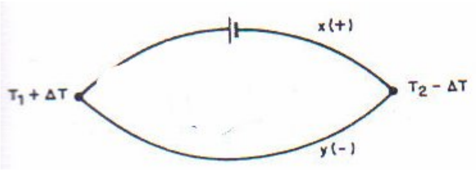

Figura 2 - Efeito Peltier

3.3.3 –Termopares

Denominam-se termopares aos dispositivos constituídos de dois materiais X e Y distintos. Geralmente fios condutores metálicos unidos por um dos lados. Esta união constitui a junta ou junção de medida (p). O circuito Seebeck é formado ligando-se as outras duas pontas aos terminais de um instrumento destinados a ler a fem; estes últimos terminais constituem, neste caso, a denominada junta fria, q_1 e q_2 na Figura 3.

A fem que o instrumento mede, é a ftem de Seebeck correspondente à diferença de temperatura entre as duas juntas.

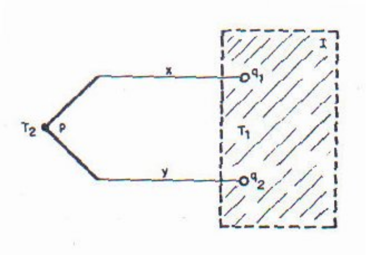

Figura 3 - Circuito de um termopar ou circuito Seeback. X e Y são os fios condutores de natureza diferente; p é a junta de medida e q1 e q2 ligadas ao terminais do instrumento I , que lê fem, constituem a junta de referência.

A relação entre E r T é empírica e é do tipo:

$$E = A + BT + CT^2 + DT^3 + \ldots$$

Onde A, B, C etc., são constantes a serem determinadas experimentalmente.

Denomina-se de potência termoelétrica de um termopar a derivada da ftem com relação a T,

$$P = \frac{dE}{dT}$$

A potência termoelétrica é uma grandeza útil na caracterização de um dado termopar; assim, se a relação entre E e T for rigorosamente parabólica, como ocorre para o termopar de platina-platina 10% rhodio, da faixa de temperatura entre 400 ºC e 1100 ºC, tem-se que a potência termoelétrica varia linearmente com T [7].

3.3.4 - Efeito Thomson

Seja um termopar de ferro-cobre em que a junta fria é mantida à temperatura do gelo fundente e a quente a uma temperatura variável que cresça gradualmente. Observa-se que a ftem desenvolvida cresce de início rapidamente e depois mais lentamente; passa por um máximo e inicia a decrescer passando por zero e revertendo o sinal. Este comportamento da ftem em função da temperatura não deveria ser esperado se os únicos efeitos reversíveis fossem, os de Peltier nas junções minimizadas, as perdas por condução e por efeito joule, posto que, as ftem desenvolvidas deveriam ser diretamente proporcionais à variação da temperatura da junta quente, mantida constante a da junta fria. A explicação desta aparente anomalia deve-se a Sir Hilliam Thomson (Lord Kelvin).

Thomson verificou a existência de um efeito reversível, em condutores homogéneos, entre gradiente de temperatura da barra condutora e corrente elétrica que circula na mesma. Num condutor de cobre, homogêneo, submetido a um gradiente de temperatura há uma corrente elétrica de origem térmica. Sempre que houver uma corrente elétrica externa de mesmo sentido que a corrente de origem térmica haverá liberação de calor num ponto P qualquer da mesma. A absorção de calor ocorrerá quando o sentido da corrente externa é invertido.

Praticamente verifica-se que o efeito Thomson tem menos influência sobre a temperatura do condutor do que o tem o efeito Peltier sobre a da junção. A detecção do efeito Thomson envolve correntes elevadas e detectores sensíveis.

Decorrentes dos trabalhos de Thomson, a ftem de Seebeck é considerada atualmente como a soma algébrica das ftem nas junções, devidas ao efeito Peltier, e das devidas ao efeito Thomson e que ocorrem nos condutores distintos. Despreza-se os efeitos irreversíveis: perdas por condução e efeito joule, pois podem ser minimizados [7].

4 – Experimental

A construção do calorímetro foi realizada em duas etapas: A primeira consistiu em desenvolver e construir uma interface para capturar a intensidade da ftem gerada pelo termopar e enviá-la para o computador utilizando alguma interface de entrada disponível, como a de joystick, a paralela, a serial ou a usb. A segunda consistiu em construir um cadinho no qual foi colocado em seu interior uma amostra e foi envolto por uma resistência. Esse sistema foi resfriado a 77 K e depois de encontrado o equilíbrio térmico foi aquecido homogeneamente e lentamente (2K por minuto) até 300 K. No entanto faltou um aspecto para que a proposta de Smith fosse atingida, o sistema ser adiabático.

4.1 - Aquisição de Dados

Foi feito um estudo inicial das características dessas portas. Dentre as quatro a única que contém conversores analógico/digital em seu interior é a de joystick. Para as outras portas o desenvolvimento do circuito seria mais complexo demandaria mais dinheiro, pois seria necessário circuitos integrados específicos para a conversão de sinal analógico e comunicação com a devida porta. A mais complexa delas é a porta usb então foi descartada. Isto é justificável, pelo fato de que não teria tempo suficiente para aprender a eletrônica e a física envolvidas no processo de comunicação e conversão do sinal. A porta serial a paralela tem interfaces semelhantes, no entanto, encontra-se maior material disponível sobre a interface paralela, isto fez a escolhermos como segunda opção, caso a porta de joystick falhasse.

4.1.1 – A porta de Joystick

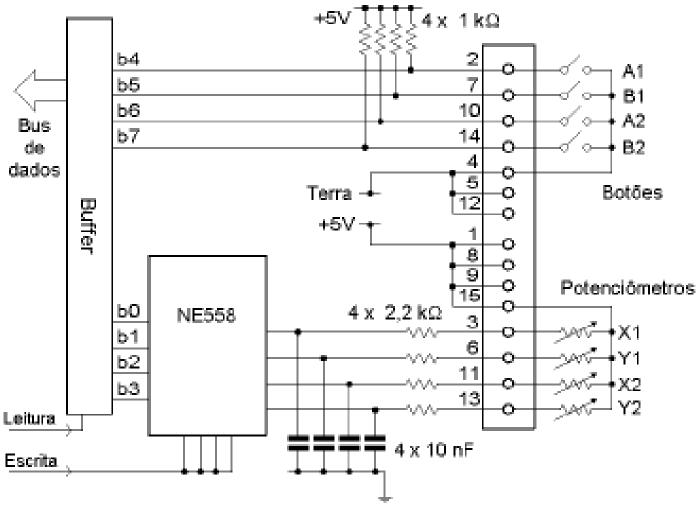

Figura 4 - Esquema da porta de Joystick

A Figura 4 apresenta as características de uma porta de joystick. X1 e Y1 são detectores de resistência elétrica e funcionam como conversores analógico digital, pois captam o valor da resistência acoplada a eles e depois emitem o valor para o computador de maneia digital. O que ocorre é que quando a resistência é ligada nos pinos 1 e 3 da Figura 4 existe uma corrente que passa por essa resistência ($i = \frac{U}{R}$, U = +5V – pino 1). É medido então o tempo que esta corrente demora para carregar um circuito RC. Isto implica que este tempo é proporcional ao valor da resistência colocada. Uma limitação grave desse sistema é que capacitores carregam e descarregam exponencialmente. Deste modo só há precisão para correntes muito baixas, da ordem de μA. Esta intensidade de corrente é muito pequena e grande parte dos circuitos integrados comumente utilizados não trabalham com essa faixa de valores. Outra limitação é a impedância de entrada do circuito que é da ordem de kOhms. Esta alta impedância elimina o sinal do termopar que tem apenas alguns Ohms de impedância. Foi desenvolvido então um circuito para aumentar a impedância de saída do termopar, com o intuito de não perder o sinal. Não se conseguiu eliminar o ruído e nem igualar as impedâncias, pois a impedância de saída do circuito era da ordem de MOhms, como pode ser verificado pela Figura 5.

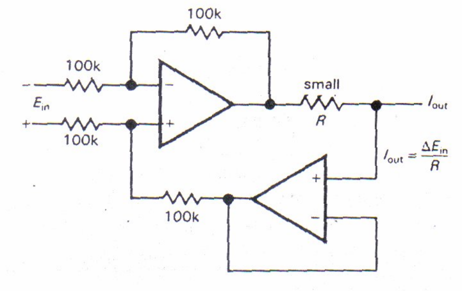

Figura 5 - Fonte de corrente de precisão de tensão diferencial

Esta configuração ocasionou uma leitura de dados ruidosa e, deste modo, a utilização desta porta foi eliminada.

4.1.2 – Segunda Alternativa: Porta Paralela

A aquisição de dados então foi completamente alterada (em relação à aquisição via joystick), pois para a comunicação com a porta paralela o sinal que está sendo enviado, já deve estar sendo emitido em bits, não sendo possível enviar o sinal analógico diretamente. No entanto, o sinal gerado pelo termopar é relativamente baixo, pra o utilizado (tipo K) a -100 K a potencia termoelétrica é da ordem de $30\frac{\mu V}{^{o}C}$ e um circuito integrado que faz a conversão de tensão em sinal digital para porta paralela (ADC0804) tem uma precisão de 8 bits com o sinal variando de 0 a 5 volts, como pode ser verificado pela Figura 6.

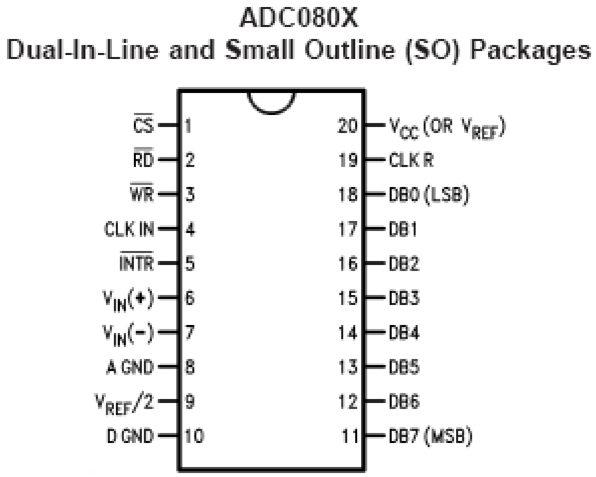

Figura 6 - Esquema do ADC0804

Para a captura de vários termopares ao mesmo tempo deve-se utilizar os termopares conectados a um multiplexador como pode ser verificado pela Figura 7.

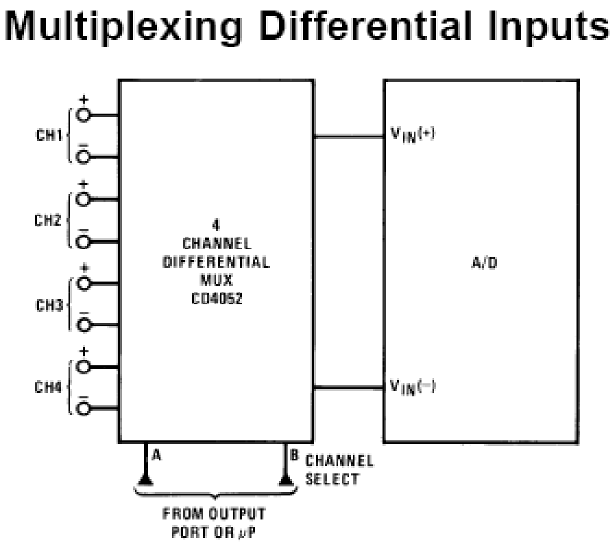

Figura 7 - Multiplexador para conectar 4 termopares a uma porta paralela

O sinal que deve ser conectado nos canais de entrada, porém o sinal do termopar é da ordem de mVolts e sua variação da ordem de µV. Dessa maneira, foi necessário utilizar um sistema de amplificação que pudesse eliminar o ruído e que fosse estável, ou seja, funcionaria por longos períodos de tempo sem alteração.

Utilizando como junção fria a temperatura do nitrogênio (77K), a variação do sinal até 300K é da ordem de 10mV. Para que este sinal possa ser capturado pelo conversor deve ser amplificado de modo que o sinal de 10 mV seja amplificado para 5V. Para isso seria necessário uma amplificação de 500 vezes. Foi necessário então verificar características dos amplificadores operacionais disponíveis no mercado capazes de fornecer o que é necessário.

4.1.2.1 - LM124/LM224/LM324

Esse conjunto de amplificadores apresenta as características:

- Baixa tensão de alimentação única: +3V até 32V;
- Quatro amplificadores em um circuito integrado;
- Offset de entrada: de 1mV a 9mV;

4.1.2.2 – OP07

Amplificador muito estável recomendado para se utilizado com circuitos de instrumentação, de sensores de temperatura, de filtros de precisão e rede sem fio.

- Tensão de alimentação: ± 3V até ± 18V;
- Offset de entrada, com alimentação de ± 15V: de 30 μ V a 75 μ V;

4.1.2.3 – Circuito Amplificador

O grande problema da série LM apresentada é o offset de tensão que é muito elevado, pois a variação do sinal do termopar é da ordem de micro volts. Esse offset é muito maior (podendo chegar a 1000 vezes) que a variação sinal de entrada por Kelvin, fazendo com que o sinal de saída não seja o sinal do termopar, mas sim uma soma dos dois sinais e como o seu sinal interno é elevado alterará muito a saída do sinal. Já o OP07 apresenta um offset da ordem da variação do sinal de entrada (micro Volts). Isso faz a incerteza aumentar um pouco uns 2ºC aproximadamente, mas certamente menor do que a incerteza da série LM. Isto levou a escolha do OP07.

O circuito escolhido para a amplificação foi o circuito não inversor utilizando malha fechada que pode ser conferido pela Figura 8.

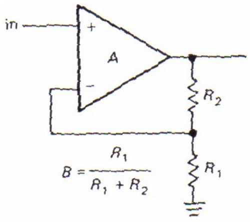

Figura 8 - Circuito Amplificador não inversor - malha fechada.

Uma vantagem desse circuito é aumentar a impedância de entrada para que tentar eliminar ruídos do sinal, no entanto isso é difícil, então foi colocado em paralelo com a entrada um capacitor com o intuito de criar um filtro passa baixa, pois deste modo o freqüências mais altas (ruídos) serão retidos e um sinal mais estável será enviado ao amplificador.

Para dar estabilidade a amplificação, deve-se utilizar uma fonte de tensão que seja a mais estável possível. Isso levou a descartar os modelos que utilizam a série de circuitos integrados LM317 e LM337, o motivo é que estes precisam de bons dissipadores de calor pois estes dispositivos esquentam demasiadamente. Quando estão em temperaturas próximas as dos limites de trabalho ocorre uma sensível variação na tensão emitida e há uma variação na amplificação do circuito. Isto ocorre devido a amplificação ser dependente da tensão de alimentação do CI (circuito integrado).

Uma fonte estável e que elimina CI´s e somente utiliza componentes primários pode ser verificada pela Figura 9.

Primeiramente a fonte é montada por uma ponde de diodos, pois estes têm a função de retificar o sinal em duas partes, uma negativa e outra positiva, porém o sinal ainda tem forma de uma senoide cortada ao meio. Os capacitores são utilizados de modo a diminuir a tensão de riple do circuito e os diodos zener tem a característica de limitar a tensão a qual é submetido de acordo com suas características internas. Isto é importante, pois deixa o circuito muito versátil, pois se pode obter várias tensões na saída dependendo das características do zener utilizado. Esta fonte é mais estável, pois somente utiliza componentes primários que apresentam grande estabilidade, do que a contendo Circuitos Integrados e quando o sistema é conectado a um terra limpo tem-se uma alimentação pouco ruidosa (tensão estável, não oscilante) e isso é necessário quando existe o tratamento de sinais baixos.

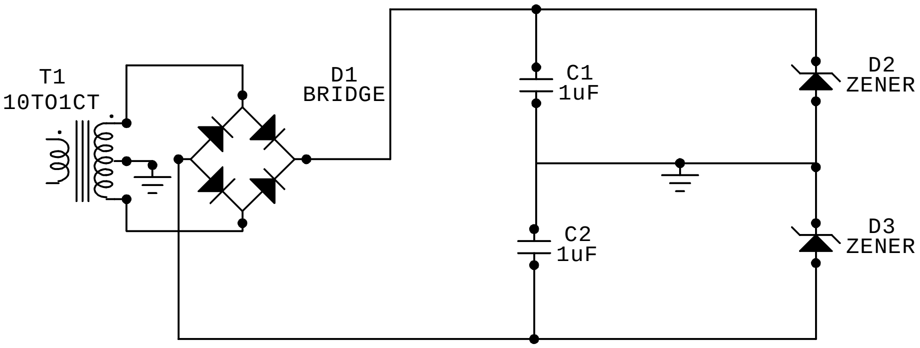

Figura 9 - Circuito representativo da fonte de tensão

4.1.2.4 – A Comunicação com o Computador

Para a comunicação entre o computador e o conversor pela porta paralela existem duas possibilidades: Programação direta em C++, ou pascal e uma interface de interpretação chamada Microsoft Windows Logo. Não é o objetivo entrar em detalhes técnicos de cada um desses métodos, no entanto, abaixo está um código em C++ para a comunicação com porta paralela.

A primeira opção é utilizar a interface Logo, por ser simples e não precisar utilizar módulos alternativos (dll) como é o caso de C++ ou pascal.

Outra vantagem é que a interface Logo já tem, em tempos reais, um gráfico sendo formado a partir do valor lido no eixo y e do tempo que se passou até aquele valor no eixo x. O arquivo de saída é no formado adequado para ser utilizado por vários programas de análise de dados. O que será utilizado é o Gnuplot que foi escolhido pela interface rápida, amigável e por ter licença GNU.

4.2 – Calorímetro

Para a construção do calorímetro foram escolhidos materiais que fossem de fácil obtenção. Como é mais interessante deixar o aparato compacto, foi utilizado, como parte externa, isopor de guardar cerveja. Foi colocado então nitrogênio líquido até a metade do recipiente, tentando-se manter este nível constante durante o procedimento para que a distância entre a fonte fria e a amostra fique aproximadamente a mesma para que a troca de calor seja homogênea em todo o processo. Foi então feito um suporte para amostra que foi colocado no interior de uma resistência elétrica de modo que a amostra tenha um aquecimento homogêneo. Foi utilizado um material metálico, pois se tentou utilizar um material cerâmico, pois não conduz bem calor e, deste modo, o calor que por contado for até a amostra não seria reabsorvido pelo suporte, no entanto não se conseguiu encontrar o material no tamanho adequado. Para minimizar os efeitos de troca de calor entre a amostra e o cadinho metálico será utilizando uma amostra com massa relativamente maior do que a utilizada nos sistemas de calorimetria. Como o cadinho era metálico, foi envolto com fita isolante para que haja um maior isolamento e não faça contato metálico com a resistência. Estas características não afetarão a medida de calor específico das amostras, devido ao fato de que será realizada uma medida do cadinho vazio para que se tenha um sinal base, de modo que possa ser subtraído do gráfico geral.

Contudo, mesmo com esses cuidados não foi conseguido deixar o sistema adiabático e isto acaba por invalidar as equações propostas por Smith. Isto implica que o calorímetro construído não pode ser considerado um Calorímetro de Smith.

5 – Resultados e Discussão

Na Figura 10 encontra-se todo o equipamento que foi montado, tem-se a fonte a esquerda, o calorímetro composto pelo isopor com um suporte para resistência e cadinho serem colocados em seu interior. Pela direita está o sistema de amplificação e comunicação com o computador.

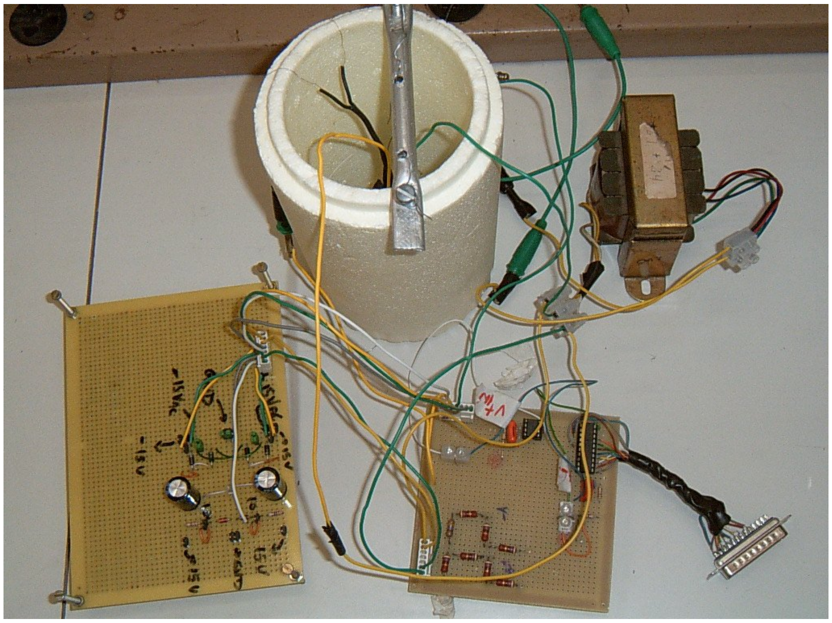

Figura 10 - Esquema do Calorímetro com o equipamento de captura e conversão do sinal para porta paralela

Já na Figura 11 encontra-se o circuito da fonte em detalhes, verifica-se os componentes primários utilizados que garantem uma estabilidade de alimentação de $(12,00 \pm ,05)V$ muito melhor que as de circuito integrado na qual os chips apresentam incerteza maior.

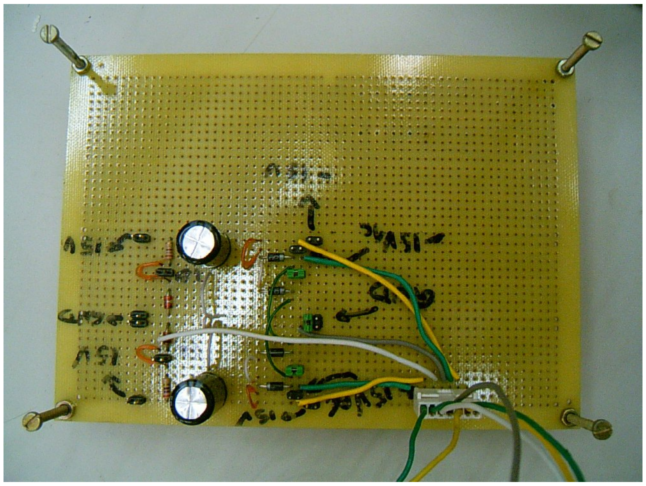

Figura 11 - Circuito da fonte em detalhes

Na Figura 12 tem-se o circuito de amplificação, e de conversão do sinal analógico digital (A/D). A amplificação experimental é por volta de 457 vezes, valor muito próximo do esperado (500vezes). Isso se deve a imprecisão dos resistores escolhidos que eram de 5% alterando, dessa maneira um pouco o ganho. O conversor A/D é de 8 bits e como a tensão que de entrada deve estar entre 0 a 5 V, então a precisão do bit lido é dada por $\frac{5}{2^8} \approx 0{,}02\,\mathrm{V}$, ou 20 mVolts.

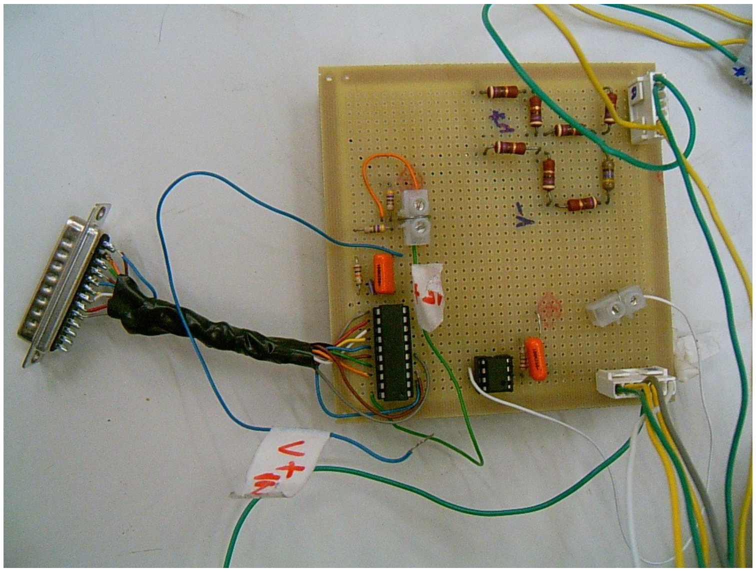

Figura 12 - Amplificador e Conversor analógico digital

Figura 14 - Cadinho envolto pela resistência elétrica

Figura 15 - Cadinho depois das medidas de calibração

As Figuras 14 e 15 mostram o cadinho antes e depois da sua utilização. Ele foi envolto em fita isolante para isolar eletricamente da resistência. Ocorreu que a fita isolante não consegue agüentar a variação de temperatura e o que ocorre é ela rachou em varias partes. O aquecimento foi mais rápido que o previsto, pois o cadinho estava em contato com a resistência e, como é metálica, a condução de calor foi bem rápida, se fosse utilizado cadinho de cerâmica, por exemplo, o aquecimento seria mais lento.

Depois de realizada a montagem do equipamento como demonstrado pela Figura 10, foi realizada a primeira medida utilizando o cadinho vazio, para verificar a resposta do sistema. O computador utilizado apresentou problemas na porta paralela, então os dados obtidos se referem ao valor analógico do sinal amplificado, como pode ser verificado pelo gráfico da Figura 13.

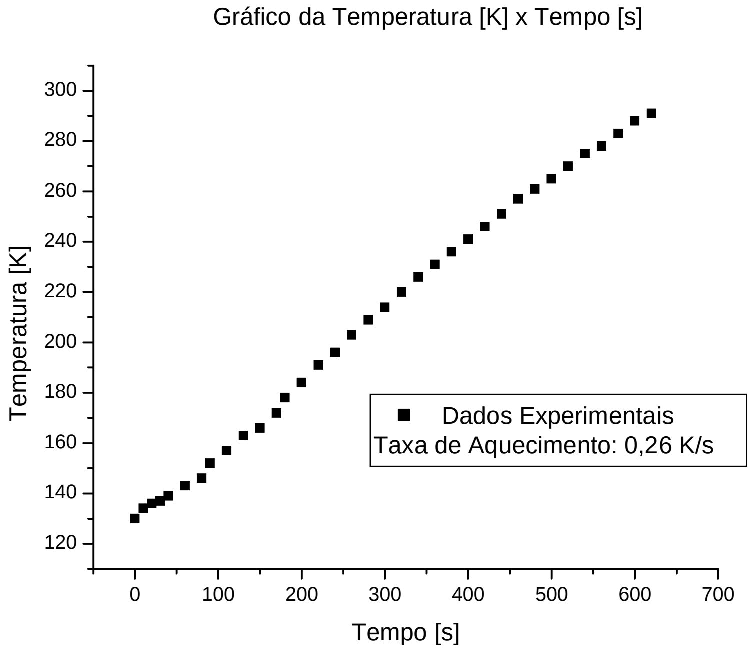

Figura 13 - Gráfico de Temperatura (K) x Tempo (s) durante o aquecimento do cadinho vazio

Verifica-se pelo gráfico acima que a variação da temperatura com o tempo é aproximadamente constante, a uma taxa de 0,26 K/s, é uma taxa um pouco rápida comparada com a de 2K /min verificada sem o cadinho. Isso se deve ao fato de que com a presença do cadinho o calor emitido pela resistência tem um meio sólido para de propagar de maneira mais eficiente, fazendo com que o aquecimento ocorresse a uma taxa muito maior, uma solução para ser aplicada seria diminuir a diferença de potencial que é aplicada à resistência de modo que diminua a potência elétrica dissipada.

A interface com o computador funcionou com LED´s, mas o computador disponibilizado para o uso do laboratório apresentou problemas na porta paralela e a conexão final não pode ser realizada até o presente momento. Foi utilizado para teste o programa LPTVolt, código em C++ pode ser encontrado no Anexo 1.

Nota: A porta paralela deve aceitar comunicação bidirecional para que o circuito funcione (EPP ou ECP), caso contrário a aquisição de dados não funciona!

6 – Conclusão

A idéia do projeto começou com uma necessidade de um aprendizado de maneira prática dos conceitos teóricos de termodinâmica e calorimetria. Estas compõem uma área da física que, ainda hoje, tem-se muito a estudar. Foi escolhido então a construção de um calorímetro, pois pode ser uma ferramenta útil para qualquer físico experimental. Por ser baseado em conceitos simples da termodinâmica pode também ser utilizado em ensino didático de física. Então foram escolhidos materiais simples, podendo ser adquirido em lojas comerciais, como mostrado na Figura 10.

Para entender e construir o calorímetro, foi necessário estudar a física dos componentes utilizados, entre eles, termopar, diodo, amplificadores operacionais, conversores analógico digital, tratamento de sinais baixos (eliminação de ruídos e amplificação), interfaceamento com o computador e a termodinâmica clássica usada no Calorímetro de Smith.

Conseguiu-se então caracterizar o aumento de temperatura no interior do cadinho. Sendo o razoável o resultado obtido Figura 13, considerando os materiais utilizados e o tempo em que o projeto foi desenvolvido.

Essa caracterização mostrou que a taxa de aquecimento é aproximadamente constante, justamente o que a proposta de Smith contempla, no entanto o sistema não seja adiabático. Este problema pode ser resolvido inserindo o sistema dentro de um criostato.

Tenho como intuito aprimorar mais o sistema montado para que seja viável o seu uso em laboratórios de pesquisa, devido ao seu baixo custo (100 reais, contra 2200 reais, sistema de aquisição de dados. Preço que pesquisei para comparar com o projeto que estava desenvolvendo) e sua portabilidade. Estas características fazem o equipamento viável também para ser utilizado em ensino. Finalmente, vejo que o projeto foi desenvolvido de maneira satisfatória e o mais importante foi o aprendizado constante.

7 – Bibliografia

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8 – Anexos

8.1 – Código Fonte do programa LPT Volt que foi utilizado para teste da comunicação com o computador

Obervação: Esse código somente funciona em windows 95/98/Me para uma versão compatível com todos os sitemas um código de exemplo já foi explicitado anteriormente no relatorio.

```
//---------------------------------------------------------------------------
// Objetivo: Medir tensão elétrica entre 0 à 5v através da porta EPP.
// Autor: Antonio Rogério Messias
// Data Criação: 12/11/2001
// E-Mail: rogercom@rogercom.com
// Todos os Direitos Reservados
//---------------------------------------------------------------------------
#include  "vcl.h"
#include  "stdio.h"
#pragma hdrstop
#include "UnitPrincipal.h"
#include "Porta.h"
#include "ClassBinario.h"
#define B0 0x01
#define B1 0x02
#define B2 0x04
#define B3 0x08
#define B4 0x10
#define B5 0x20
#define B6 0x40
#define B7 0x80
#define S3 B3
#define S4 B4
#define S5 B5
#define S6 B6
#define S7 B7
#define BASE     0x378
#define DADOS    BASE + 0
#define STATUS   BASE + 1
#define CONTROLE BASE + 2
#define EPPDATA  BASE + 4
//---------------------------------------------------------------------------
#pragma package(smart_init)
#pragma resource "*.dfm"
TformPrincipal *formPrincipal;
TPorta *Porta;      //Declara objeto para controle da porta paralela.
TBinario *Binario;  //Declara objeto p/ converter um int numa string binária.
unsigned char ByteADC; //Variável para armazenar o byte recebido através da
porta.
int TimeOut;           //Váriável para armazenar o tempo de resposta do circuito.
//---------------------------------------------------------------------------
__fastcall TformPrincipal::TformPrincipal(TComponent* Owner)
        : TForm(Owner)
{
}
//---------------------------------------------------------------------------
```

```
void __fastcall TformPrincipal::TimerAquisicaoTimer(TObject *Sender)
{
  char buf[7]; //Vriável para armazenar uma string de números.
  //IMPORTANTE: Para ativar um pino no ADC envia um 0 (zero) e para desativar 1
(um).

  //Inicializa a conversão do ADC enviando um pulso Baixo(0) no pino 14 C1,
  //momentaneamente.

  Porta->Envia(CONTROLE,34);   //34 0010-0010 aguarda mais ou menos 100 micro
segundos.
  Porta->Envia(CONTROLE,32);   //32 0010-0000 habilita a conversão.
  TimeOut=0;

  do{     //Loop para verificar o Sinal INTR do ADC0804.
     TimeOut++;
  }while(((Porta->Recebe(STATUS) & S3) == S3) && (TimeOut != 256)); //0000-1000.
  if(TimeOut == 256)
  {
    formPrincipal->Caption = "Erro!";
  }else
  {                               //35 0010-0011
     Porta->Envia(CONTROLE,35);   //Pino 1 C0 Baixo(0),Habilita a saída(leitura)
do ADC.
     ByteADC =  Porta->Recebe(DADOS); //34 0010-0010
     Porta->Envia(CONTROLE,34); //Pino 1 C0 Alto(1),Desabilita a saída(leitura)
do ADC.
     sprintf(buf,"%0.2f",ByteADC*0.0196); //Calcula: Byte recebido x 0.0196v.
     labeVisor->Caption = buf;  //Exibe valor.
  }
}
//---------------------------------------------------------------------------

void __fastcall TformPrincipal::SpeedButtonSairClick(TObject *Sender)
{
  Porta->Envia(CONTROLE,0); //Desabilita a leitura EPP.
  Close();
}
//---------------------------------------------------------------------------

void __fastcall TformPrincipal::SpeedButtonMiniClick(TObject *Sender)
{
    WindowState = wsMinimized;
}
//---------------------------------------------------------------------------
```

```
//Classe TPorta com seus métodos: Envia e Recebe
//Objetivo: Enviar e receber bytes através da Porta Paralela
//Copyright(c) 1999-2004, ROGERCOM
//www.rogercom.com
//rogercom@rogercom.com

class TPorta
{
  private:
  public:
    void Envia(short int iEndPorta,unsigned char iByte);
    unsigned char Recebe(short int iEndPorta);
};
```

```
//---------------------------------------------------------------
//Envia um byte para a Porta Paralela
void TPorta::Envia(short int iEndPorta,unsigned char iByte)
{
  _DX = iEndPorta;
  _AL = iByte;
  __emit__ (0xEE);//Instrução da CPU
}

//---------------------------------------------------------------
//Recebe um byte pela Porta Paralela
unsigned char TPorta::Recebe(short int iEndPorta)
{
  _DX = iEndPorta;
  __emit__ (0xEC);//Instrução da CPU
     return(_AL);//Retorna um byte
}

// Objetivo: Converter um Byte em uma string binária de caracteres.
//www.rogercom.com
//rogercom@rogercom.com
//-------------------------------------------------------------------------
#include "vcl\vcl.h"
#include "string.h"
#pragma hdrstop
//-------------------------------------------------------------------------
class TBinario {

  public:
      char * __fastcall IntToStrBin(unsigned short int num);
};
//-------------------------------------------------------------------------
char * __fastcall TBinario::IntToStrBin(unsigned short int num)
{
   unsigned short int BYTE[8] = {
      0x01,0x02,0x04,0x08,
      0x10,0x20,0x40,0x80
   };

   unsigned short int cont,bit=7;
   static char buf[10];  //para armazenar a string de números binários.
   for( cont = 0; cont <= 7; cont++ )
   {
      if( (num & BYTE[cont]) == BYTE[cont] )
          buf[bit] = '1';
      else
          buf[bit] = '0';
          bit--;
   }
   buf[8] = NULL;
   return(buf);
}
```

8.2 – Código fonte de um programa, em C++, capaz de comunicar com windows XP

```
/*************************************************/
```

```
/***                                           ***/
/*** TEST.c  -- test interface to inpout32.dll  ***/
/***  ( http://www.logix4u.net/inpout32.htm )   ***/
/***                                           ***/
/*** Copyright (C) 2003, Douglas Beattie Jr.    ***/
/***                                           ***/
/***    <beattidp@ieee.org>                     ***/
/***    http://www.hytherion.com/beattidp/      ***/
/***                                           ***/
/**************************************************/
/*************************************************/
/*                                                    */
/*  Builds with Borland's Command-line C Compiler     */
/*    (free for public download from Borland.com, at  */
/*  http://www.borland.com/bcppbuilder/freecompiler ) */
/*                                                    */
/*   Compile with:                                    */
/*                                                    */
/*   BCC32 -IC:\BORLAND\BCC55\INCLUDE  TEST.C         */
/*                                                    */
/*                                                    */
/*  Be sure to change the Port addresses              */
/*  accordingly if your LPT port is addressed         */
/*  elsewhere.                                        */
/*                                                    */
/*************************************************/
#include <stdio.h>
#include <conio.h>
#include <windows.h>

/* Definitions in the build of inpout32.dll are:            */
/*   short _stdcall Inp32(short PortAddress);               */
/*   void _stdcall Out32(short PortAddress, short data);    */
/* prototype (function typedef) for DLL function Inp32: */
     typedef short _stdcall (*inpfuncPtr)(short portaddr);
     typedef void _stdcall (*oupfuncPtr)(short portaddr, short datum);
int main(void)
{
     HINSTANCE hLib;
     inpfuncPtr inp32;
     oupfuncPtr oup32;
     short x;
     int i;
     /* Load the library */
     hLib = LoadLibrary("inpout32.dll");
     if (hLib == NULL) {
```

```
          printf("LoadLibrary Failed.\n");
          return -1;
     }
     /* get the address of the function */
     inp32 = (inpfuncPtr) GetProcAddress(hLib, "Inp32");
     if (inp32 == NULL) {
          printf("GetProcAddress for Inp32 Failed.\n");
          return -1;
     }
     oup32 = (oupfuncPtr) GetProcAddress(hLib, "Out32");
     if (oup32 == NULL) {
          printf("GetProcAddress for Oup32 Failed.\n");
          return -1;
     }
/*************************************************/
/* now test the functions */
/* Try to read 0x378..0x37F, LPT1:  */
     for (i=0x378; (i<0x380); i++) {
          x = (inp32)(i);
    printf("port read (%04X)= %04X\n",i,x);
  }
/*****  Write the data register */
  i=0x378;
  x=0x77;
  (oup32)(i,x);
  printf("port write to 0x%X, datum=0x%2X\n" ,i ,x);
  /***** And read back to verify  */
  x = (inp32)(i);
  printf("port read (%04X)= %04X\n",i,x);
  /*****  One more time, different value */
  i=0x378;
  x=0xAA;
  (oup32)(i,x);
  printf("port write to 0x%X, datum=0x%2X\n" ,i ,x);
  /***** And read back to verify  */
  x = (inp32)(i);
  printf("port read (%04X)= %04X\n",i,x);
  FreeLibrary(hLib);
  return 0;
}
```

8.3 Código fonte de um programa em C++ para Linux

```
/*
 * example.c: very simple example of port I/O
 *
```

```
 * This code does nothing useful, just a port write, a pause,
 * and a port read. Compile with `gcc -O2 -o example example.c',
 * and run as root with `./example'.
 */

#include <stdio.h>
#include <unistd.h>
#include <asm/io.h>

#define BASEPORT 0x378 /* lp1 */

int main()
{
  /* Get access to the ports */
  if (ioperm(BASEPORT, 3, 1)) {perror("ioperm"); exit(1);}

  /* Set the data signals (D0-7) of the port to all low (0) */
  outb(0, BASEPORT);

  /* Sleep for a while (100 ms) */
  usleep(100000);

  /* Read from the status port (BASE+1) and display the result */
  printf("status: %d\n", inb(BASEPORT + 1));

  /* We don't need the ports anymore */
  if (ioperm(BASEPORT, 3, 0)) {perror("ioperm"); exit(1);}

  exit(0);
}

/* end of example.c */
```

Porta Paralela

Aquisição de dados

Por: Antônio Rogério Messias

ÍNDICE DOS ARTIGOS

INTRODUÇÃO

A porta paralela é uma interface de comunicação entre o computador e um periférico. Quando a IBM criou seu primeiro PC (Personal Computer) ou Computador Pessoal, a idéia era conectar a essa Porta uma impressora, mas atualmente, são vários os periféricos que utilizam-se desta Porta para enviar e receber dados para o computador (exemplos: Scanners, Câmeras de vídeo, Unidade de disco removível e outros).

Se você conhece um pouco de eletrônica e domina uma linguagem de programação como: C/C++/C++Builder, Pascal/Delph ou mesmo o Visual Basic, poderá desenvolver um programa que controle um aparelho conectado à Porta paralela, ou um programa de transferência de arquivos entre dois computadores, utilizando um cabo paralelo como meio de transmissão. O seu conhecimento de Eletrônica servirá para você desenvolver sua própria placa Eletrônica, que será conectada ao *DB25* da porta paralela.

Está página lhe fornecerá conhecimentos sobre a porta paralela, que o fará compreender e utilizá-la, de uma maneira não convencional, isto é, não somente para ser utilizada com uma impressora, mas também como qualquer outro aparelho, que o usuário tenha conhecimento sobre seu funcionamento, desejando controlá-lo através de seu Personal Computer, como diz a IBM.

Atenção!

A Porta Paralela está ligada diretamente à placa mãe de seu computador. Muito cuidado ao conectar circuitos eletrônicos a essa porta, pois, uma descarga elétrica ou um componente com a polaridade invertida, poderá causar danos irreparáveis ao seu computador, seja coerente.

TERMO DE RESPONSABILIDADE

**Não me responsabilizo por nenhum dano causado tanto no equipamento,
como na montagem/instalação inadequada dos circuitos.**

***

Boa pesquisa...

MODELOS DE PORTA PARALELA

Transmissão unidirecional

**A porta paralela SPP (Standard Parallel Port) pode chegar a uma taxa de transmissão de dados a 150KB/s. Comunica-se com a CPU utilizando um BUS de dados de 8 bits.
Para a transmissão de dados entre periféricos são usado 4 bits por vez.**

Transmissão bidirecional

A porta avançada EPP (Enhanced Parallel Port) chega a atingir uma taxa de transferência de 2 MB/s. Para atingir essa velocidade, será necessário um cabo especial.
Comunica-se com a CPU utilizando um BUS de dados de 32 bits.
Para a transmissão de dados entre periféricos são usado 8 bits por vez.

A porta avançada ECP (Enhanced Capabilities Port) tem as mesmas características que a EPP, porém, utiliza DMA (acesso direto à memória), sem a necessidade do uso do processador, para a transferência de dados. Utiliza também um buffer FIFO de 16 bytes.

EXTENSÃO DO CABO PARALELO

A extensão do cabo para interligar um computador a um periférico, é de no máximo 8m. Na prática, utiliza-se um cabo com extensão menor. Quanto maior a extensão do cabo, maior é a interferência na transmissão dos dados.

ENDEREÇOS DA PORTA PARALELA

O seu computador nomeia as Portas Paralelas, chamando-as de LPT1, LPT2, LPT3 etc, mas, a Porta física padrão de seu computador é a LPT1, e seus endereços são: 378h (para enviar um byte de dados pela Porta), 378+1h (para receber um valor através da Porta) e, 378+2h (para enviar dados). Às vezes pode está disponível a LPT2, e seus endereços são: 278h, 278+1h e 278+2h, com as mesmas funções dos endereços da porta LPT1 respectivamente.

Nome da Porta	Endereço de memória	Endereço da Porta		Descrição
LPT1	0000:0408	378 hexadecimal	888 decimal	Endereço base
LPT2	0000:040A	278 hexadecimal	632 decimal	Endereço base

REGISTRADORES

Utilizando a Porta Paralela conectada a uma impressora, os endereços terão nomes sugestivos, como segue abaixo:

Nome	Endereços LPT1	Endereços LPT2	Descrição
Registro de Dados	378h	278h	Envia um byte para a impressora
Registro de Status	379h	279h	Ler o Status da impressora
Registro de Controle	37Ah	27Ah	Envia dados de controle para a impressora

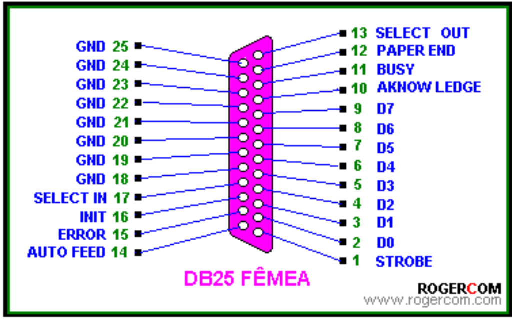
O CONECTOR DB25

O DB25 é um conector que fica na parte de trás do gabinete do computador, e é através deste, que o cabo paralelo se conecta ao computador para poder enviar e receber dados.

No DB25, um pino está em nível lógico 0 quando a tensão elétrica no mesmo está entre 0 à 0,4v. Um pino se encontra em nível lógico 1 quando a tensão elétrica no mesmo está acima de 3.1 e até 5v.

A figura abaixo mostra o conector padrão DB25, com 25 pinos, onde cada pino tem um nome que o identifica:

DB25 que fica atrás do Micro



Conector Macho do Cabo Paralelo

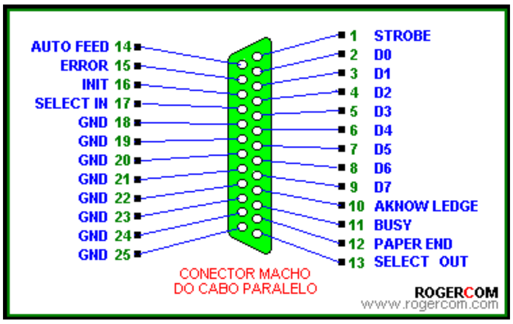
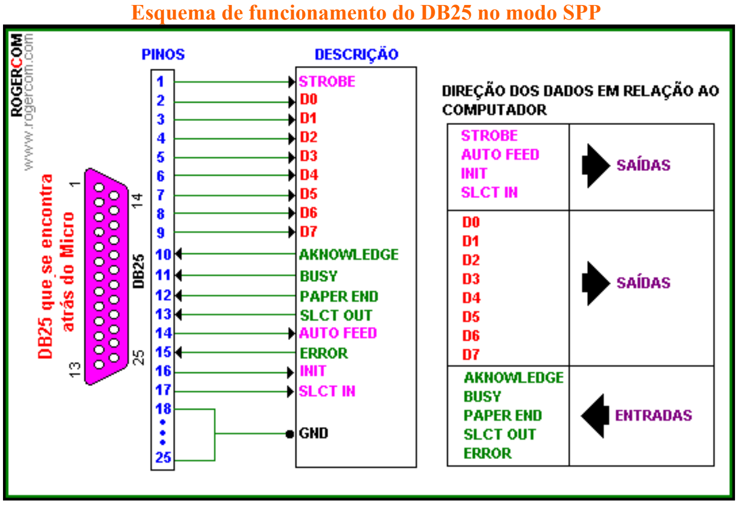


Foto do conector DB25 macho do cabo Paralelo

Esquema de funcionamento do DB25 no modo SPP

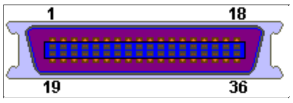


O CONECTOR MACHO CENTRONICS 36 PINOS

O conector macho Centronics 36 pinos faz parte do cabo da impressora, é através deste cabo que a impressora é conectada ao computador.

Quando desenvolvemos uma projeto que utilize uma interface para conectarmos ao computador, poderemos utilizar um conector centronics 36 pinos fêmea, isso faz com que nossa interface aproveite o cabo da impressora, onde poderemos conseguir com facilidade em lojas de Informática.

A figura abaixo mostra o conector Centronics 36 pinos e sua descrição:



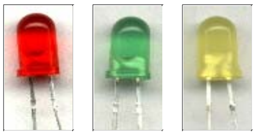
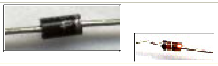
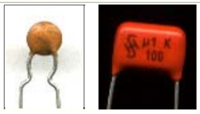
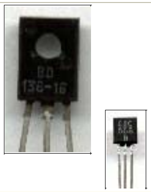
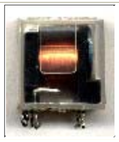
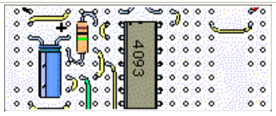
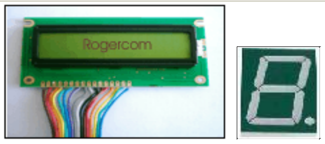
Significado de cada pino do conector Centronics 36 pinos

Número do Pino	Descrição
1	Strob
2 ao 9	Dados (D0...D7)
10	Ack
11	Busy
12	Paper End
13	Select Out
14	Auto Feed
15 ao 18	Não conectato
19 ao 30	GROUND
31	Init
32	Error
33	GROUND
34 a 35	Não conectato
36	Select In

LISTA DOS COMPONENTES UTILIZADOS PARA DESENVOLVER OS CIRCUITOS

Para desenvolver os circuitos, você precisará adquirir os componentes eletônicos, e poderá encontrar em lojas que vendam materiais de Eletrônica, componentes como: cabo Paralelo, resistores, transistores, diodos, LEDs etc.

Lista de alguns componentes utilizados para desenvolver os circuitos:

Descrição	Componentes
Cabo Paralelo (o mesmo utilizado pela impressora)	
LEDs	
Resistores	
Diodos	
Capacitores	
Circuitos Integrados	
Motor de passo	
Transistores	
Relê	
Foto-transistors e sensores	
Matriz de contato	
Distplay	

Fios para a interligação dos componentes	
Ferro de soldar componentes, fonte de alimentação de 0 a 12v, solda, multímetro etc.	 

CLASSES E FUNÇÕES EM C/C++, PARA IMPLEMENTAR SEUS PROGRAMAS

Utilize a classe em C++ abaixo, caso queira desenvolver programas para serem executados nos Sistemas Operacionais Windows.

Código fonte em C/C++

Listagem da classe TPorta para ser usada nos compiladores C++ da Borland

```
//Classe TPorta com seus métodos: Envia e Recebe
//Objetivo: Enviar e receber bytes através da Porta Paralela
//Copyright(c) 1999-2004, ROGERCOM
//www.rogercom.com
//rogercom@rogercom.com

class TPorta
{
  private:
  public:
    void Envia(short int iEndPorta,unsigned char iByte);
    unsigned char Recebe(short int iEndPorta);
};

//--------------------------------------------------------------------
//Envia um byte para a Porta Paralela
void TPorta::Envia(short int iEndPorta,unsigned char iByte)
{
  _DX = iEndPorta;
  _AL = iByte;
  __emit__ (0xEE);//Instrução da CPU
}

//--------------------------------------------------------------------
//Recebe um byte pela Porta Paralela
unsigned char TPorta::Recebe(short int iEndPorta)
{
  _DX = iEndPorta;
  __emit__ (0xEC);//Instrução da CPU
     return(_AL);//Retorna um byte
}
```

Código fonte em C/C++

Listagem da classe ClasseTBinario para ser usada em programas escritos em C++

```
// Objetivo: Converter um Byte em uma string binária de caracteres.
//www.rogercom.com
//rogercom@rogercom.com
//----------------------------------------------------------------------------
#include "vcl\vcl.h"
#include "string.h"
#pragma hdrstop
//---------------------------------------------------------------------------
class TBinario {

  public:
     char * __fastcall IntToStrBin(unsigned short int num);
};
//---------------------------------------------------------------------------
char * __fastcall TBinario::IntToStrBin(unsigned short int num)
{
   unsigned short int BYTE[8] = {
       0x01,0x02,0x04,0x08,
       0x10,0x20,0x40,0x80
   };

   unsigned short int cont,bit=7;
   static char buf[10];  //para armazenar a string de números binários.
   for( cont = 0; cont <= 7; cont++ )
   {
       if( (num & BYTE[cont]) == BYTE[cont] )
           buf[bit] = '1';
       else
           buf[bit] = '0';
           bit--;
   }
   buf[8] = NULL;
```

```
    return(buf);
}
```

Já para desenvolver programas no Sistema Operacional MS-DOS, utilize as funções descritas abaixo, encontradas nos compiladores da Borland com: Turbo C e o Borland C++.

Funções para serem compiladas em 16 bits

Funções dos compiladores Turbo C ou C++Borland(R)

Ler um byte de uma Porta do computador:
unsigned char **inportb**(int **portid**);
Onde: **portid** é o endereço da porta que se quer receber um byte.
Retorno: O byte lido da porta é capturado assim:
unsigned char RetByte = **inportb**(**número_da_porta_que_se_quer_ler**);

Envia um byte para uma Porta do computador:
void **outportb**(int **portid**, unsigned char **value**);
Onde: **portid** é o endereço da porta que se quer enviar um byte.
value é um byte a ser enviado para a porta.

ACESSANDO A IMPRESSORA ATRAVÉS DO BIOS

Você pode acessar a impressora através da interrupção de número 17h, fornecida pelo BIOS (Basic Input Output System), ou Sistema Básico de Entrada e Saída, que executa as funções elementares de funcionamento de seu computador.

O BIOS fornece três serviços através desta interrupção: o serviço 00, que tem como objetivo enviar um byte à impressora; 01, inicializa a impressora, limpando seu buffer e o 02, retorna ao computador o Status da impressora (um byte codificado em bits), informando seu estado atual, ou seja, se tem papel ou não na bandeja, se está pronta para receber dados do computador e outras informações de controle.

Código fonte em C/C++.

O exemplo abaixo mostra duas funções escritas em linguagem C++, utilizando o BIOS para interagir com uma impressora. A primeira função tem o objetivo de enviar um byte à impressora, e a outra, de ler seu status.

```
//Funções: PrintValor() e StatusPrint()
//Objetivo: Acessar a impressora através do BIOS
//Copyright(c) 1999-2004, ROGERCOM
//Todos os Direitos Reservados
//------------------------------------------------------------
//Envia um byte para a impressora
void PrintValor(unsigned char Valor);
{
 union REGS regs;
 regs.h.ah = 0; //Servico de impressão
 regs.h.al = Valor;
 regs.x.dx = 0; //0 é a porta LPT1, 1,a LPT2
 int86(0x17,& regs,& regs); //Interrupção da impressora
}

//Ler o status da impressora
unsigned char StatusPrint(void)
{
  union REGS regs;
  regs.h.ah = 2; //Serviço 2 ler o status
  regs.x.dx = 0; //0 é a porta LPT1
  int86(0x17,& regs,& regs);//Interrupção da impressora
  return( regs.h.ah ); //Retorna um byte de status
}
```

LIGANDO E DESLIGANDO APARELHOS EXTERNOS ATRAVÉS DA PORTA PARALELA

Como já comentado, a Porta Paralela não é usada somente com uma impressora, você pode desenvolver um circuito eletrônico e acoplá-lo a essa porta e, através de um programa específico, enviar-lhe sinais digitais para controlá-lo.

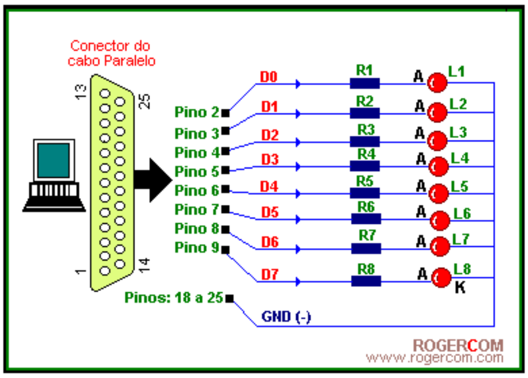
Abaixo temos três circuitos: o circuito-1, o circuito-2 e o circuito-3 que podem ser acoplados à Porta Paralela através de um cabo Paralelo e, controlados por um programa.

CIRCUITO-1

A princípio o objetivo do circuito-1 é de ligar e desligar oito LEDs, conectados através de uma cabo à Porta Paralela.

No esboço abaixo, observe que o terminal do catodo (K) dos LEDs estão ligados aos terminais dos resistores, que estes por si, estão ligados através do cabo aos pinos do DB25. Se invertidos, o circuito não funcionará. Observe a enumeração da pinagem do conector DB25.

Circuito-1



Lista de componentes:

1 (um) Cabo Paralelo - o mesmo utilizado pela impressora;
8 (oito) Resistores (R1 a R8) todos de 470 ohm (amarelo, violeta e marrom);
8 (oito) LEDs (L1 a L8) comuns de qualquer cor.
Geral: fios, fero de soldar, solda etc.

Código fonte em C/C++

O programa abaixo pode ser compilado e executado para acender e apagar os LEDs do circuito-1.

```
//www.rogercom.com
//rogercom@rogercom.com
//-------------------------------------------------------------------------------------------------------------
#include <stdio.h>
#include <conio.h>
#include <dos.h>
#define LPT1 0x378
int main(void)
{
   unsigned char Valor=128; //Em binário: 10000000
   while( Valor > 0 )
  {
           outportb(LPT1, Valor); // Envia para a Porta LPT1
           printf("\nPressione uma tecla para ascender o próximo LED...");
           getch( );
           Valor = Valor >> 1; //A cada passagem, o bit 1 é movido para a direita
   }
}
```

Este programa, envia à Porta Paralela oito bytes, um a cada vez que o usuário pressionar uma tecla. A sequência de bytes geradas é vista na tabela abaixo:

Decimal	Hexadecimal	Binário	Pino/Fio ativo (5V)	Comentário
128	**80**	**1**0000000	**9** - D7	Cada bit do byte enviado à Porta Paralela está relacionado com um pino do DB5, e um fio do cabo paralelo, fisicamente. Ao enviar um byte, que o(s) bit(s) esteja(m) ligado(s) ou desligado(s), os LEDs acende(rão) ou apaga(rão) conforme os estados dos bits.
64	**40**	0**1**000000	**8** - D6	
32	**20**	00**1**00000	**7** - D5	
16	**10**	000**1**0000	**6** - D4	
8	**8**	0000**1**000	**5** - D3	
4	**4**	00000**1**00	**4** - D2	
2	**2**	000000**1**0	**3** - D1	
1	**1**	0000000**1**	**2** - D0	

Para saber como o computador agrupa os bits num byte, observe o esquema abaixo:

BYTE

No esquema acima observe que cada nibble equivale a 4 bits; e a contagem dos bits é feita da direita para a esquerda (0,1,2,3...).

CIRCUITO-2

Com o circuito-2, você pode controlar através da Porta Paralela mais quatro aparelhos eletro/eletrônico, enviando sinais para o registrador 37Ah. Ao enviar um byte para este registrador, mantenha os 4 últimos bits (nibble alto) inalterados, para não interferir no registrador 378h.

Quando for trabalhar com o endereço do registrador 37Ah, tenha sempre em mente que para ativar os sinais Slct In, AutoFeed e Strob, será necessário colocar os bits em 0 (zero), porque eles trabalham de forma invetida, 0 (zero) ativa, 1 (um) desativa. Somente o Init trabalha na sua forma normal.

Os bits do byte de CONTROLE também são conhecidos como; C3 (Slct In), C2 (Init), C1 (Auto Feed) e C0 (Strob). A letra C significa registrador de CONTROLE, e o número significa a posição do bit no byte; juntos, formam um nome sugestivo para os sinais.

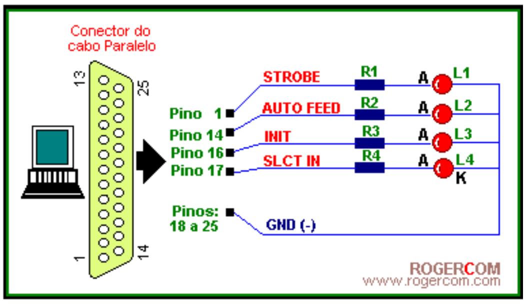
OBS.: Quando o nome de um bit de Controle estiver com uma linha em cima, indica que o sinal será ativo com 0 (zero).

Ex.: $\overline{C3}$ (Slct In), $\overline{C1}$ (Auto Feed) e $\overline{C0}$ (Strob).

Tabela descritiva dos sinais de CONTROLE

					$\overline{C3}$	C2	$\overline{C1}$	$\overline{C0}$
Descrição/número dos pinos:	nenhum pino relacionado				Slct In 17	Init 16	Auto Feed 14	Strob 1
Posição dos bits:	7	6	5	4	3	2	1	0
Byte em binário:	0	0	0	0	1	1	1	1
Byte em Decimal:	15							

Circuito-2



Lista de componentes:

1 (um) Cabo Paralelo - o mesmo utilizado pela impressora;
4 (quatro) Resistores (R1 a R4) todos de 470 ohm (amarelo, violeta e marrom);
4 (quatro) LEDs (L1 a L4) comuns de qualquer cor.
Geral: fios, fero de soldar, solda etc.

Código fonte em C/C++.

O programa abaixo testa o circuito-2. O seu funcionamento é simples. Ao executá-lo, em primeiro lugar será enviado um byte à Porta Paralela que ligará todos os LEDs. Em seguida você pressionará uma tecla para enviar mais outro byte, agora este ligará somente o LED 1 e assim sucessivamente, até seja enviado o último byte, que apagará todos os LEDs.

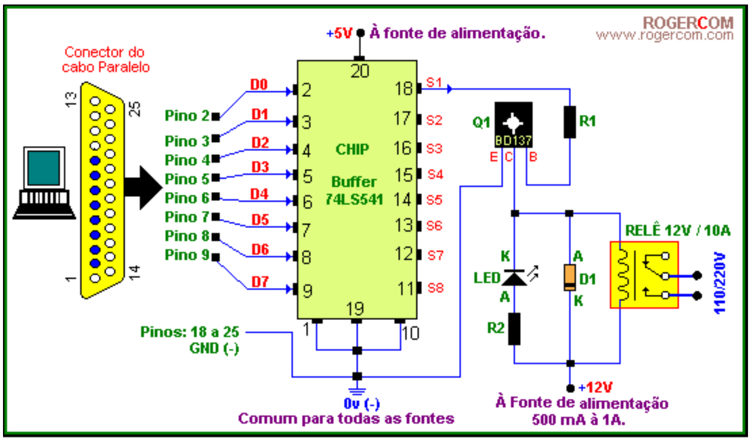
```
//www.rogercom.com
//rogercom@rogercom.com
//----------------------------------------------------------------------------------------------------------------
#include <stdio.h>
#include <conio.h>
#include <dos.h>
#define BIT0LIGALED1    3    // 0000 1010
#define BIT1LIGALED2  15    // 0000 1001
#define BIT2LIGALED3    9    // 0000 1111
#define BIT3LIGALED4  10    // 0000 0011
#define LIGATODOS        4   // 0000 0100
#define DESLIGATODOS   11   // 0000 1011

int main(void)
{
   outportb(0x37A,LIGATODOS);  //Liga todos os LEDs
   getch();
   outportb(0x37A,BIT0LIGALED1); //Liga LED 1
   getch();
   outportb(0x37A,BIT1LIGALED2);
   getch();
   outportb(0x37A,BIT2LIGALED3);
   getch();
   outportb(0x37A,BIT3LIGALED4);
   getch();
```

```
    outportb(0x37A,DESLIGATODOS);    //Desliga todos os LEDs
}
```

CIRCUITO-3

A princípio, o objetivo do circuito-3, é de ligar e desligar aparelhos eletro/eletrônicos como: motores, portas e portões elétricos, fechaduras elétricas, rádios, televisões, etc. Mas você pode muito bem através de um programa de computador controlar braços de robôs, temporizadores, controles automáticos e muito mais.

Circuito-3



No circuito acima, o chip 74LS541 é usado para proteger a Porta Paralela de altas correntes. Ele é alimentado com 5v, diferente da outra parte do circuito que controla o relê, que precisa de 12v para ser acionado. Os contatos do relê devem suportar 220v/10A, para que você possa acionar aparelhos de potência.

Neste circuito você pode controlar até oito aparelhos simultaneamente, a partir das saídas S1 a S8.

Se você desejar controlar mais que um aparelho, adicione mais circuitos, idênticos ao da saída S1, às demais saídas (S2 a S8).

Atenção!

O circuito acima trabalha ligado a Rede elétrica 110/220v. Tome muito cuidado ao conectar os componentes, um fio ligado na posição errada é fatal, tanto para você como para seu computador. Seja coerente, se você não conhece o suficiente de eletro/eletrônica, solicite a ajuda de um profissional.

Lista de componentes:
1 (um) Cabo Paralelo - o mesmo utilizado pela impressora;
1 (um) LED verde;
1 (um) diodo 1N4148;
1 (um) Resistor R1: 2,2K ohm (vermelho, vermelho e vermelho);
1 (um) Resistor R2: 470 ohm (amarelo, violeta e marrom);
1 (um) Transístor BD 137;
1 (um) Circuito integrado buffer 74LS541;
1 (um) Relê 12 volts na bobina - cargas até 220v/10A
1 (uma) fonte de alimentação estabilizada de 5 a 12volts;
Geral: fios, fero de soldar, solda etc.

RECEBENDO SINAIS EXTERNOS ATRAVÉS DA PORTA PARALELA

A Porta Paralela, no modo padrão, têm cinco entradas. Isso é útil quando você precisa capturar sinais do mundo externo para dentro do computador. Como por exemplo, saber se um sensor esta ativo ou não; se um alarme foi disparado, etc.

As cinco entradas através do conector DB25 são: Ack no pino 10, Busy no pino 11, Paper end no pino 12, Slct out no pino 13 e Error no pino 15. Portanto você poderá enviar para o computador cinco bits de uma só vez.

Os bits do byte de STATUS também são conhecidos como; S7 (Busy), S6 (Ack), S5 (Paper end), S4 (Slct out), e S3 (Error). A letra S significa registrador de STATUS, e o número significa a posição do bit no byte; juntos, formam um nome sugestivo para os sinais.
OBS.: Quando o nome de um bit de Status estiver com uma linha em cima, indica que o sinal será ativo com 0 (zero).

Ex.: $\overline{\text{S7}}$ (Busy).

Usando as funções *inportb()* ou *Recebe()* da classe TPorta, já comentadas nesta página, você poderá ler o registrador de Status da Porta Paralela, e saber se o sinal em um determinado pino está alto ou baixo (0-zero ou 1-um) no sistema binário.

As funções *inportb()* e *Recebe()* lêem um byte através da Porta Paralela. Se você quiser saber se um determinado pino está com o sinal alto ou baixo, terá de converter este byte em binário para saber o estado do mesmo.

Nem todos os bits do byte recebido através das funções *inportb()* ou *Recebe()* são válidos, como eu já mencionei, são somente cinco as entradas no registrador de Status da Porta Paralela, e cada entrada está relacionada com um bit.

Ao ler o registrador de Status, os bits nas posições 0, 1 e 2 não devem ser levados em conta, porque não estão relacionados com nenhum pino do DB25, mesmo assim fará parte do byte recebido.

A tabela abaixo mostra o significado de cada bit do byte recebido, através das funções *inportb( )* ou *Recebe( )*, usando o *Circuito 4* conectado à Porta Paralela. Observe que os bits, *Ack*, *Paper end*, *Slct out* e *Error*, trabalham de maneira normal, diferente de *Busy*, que só é ativado quando tiver um sinal 0 (zero) no pino 11:

Tabela descritiva dos sinais de STATUS

Descrição/número dos pinos:	$\overline{S7}$	S6	S5	S4	S3	Nenhum pino relacionado nestas posições do byte		
	busy 11	Ack 10	Paper end 12	Slct out 13	Error 15			
Byte lido em binário:	0	1	1	1	1	1	1	0
Byte lido em Decimal:	126							

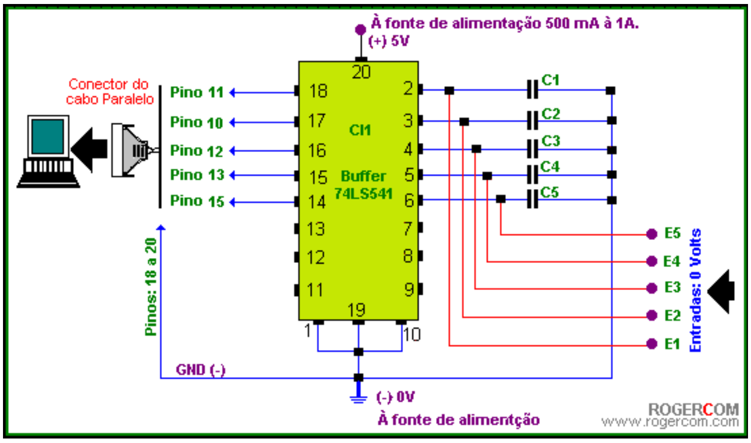
CIRCUITO-4

Com o circuito-4 conectado à Porta Paralela você poderá enviar sinais para dentro de seu computador através das entradas E1 a E 5.

Para enviar um bit através da entrada E1, ligue-a direto ao negativo da fonte de alimentação (0v), ou instale um interruptor para ficar mais prático.

Como o circuito abaixo utiliza um Circuito Integrado buffer, que tem o poder de amplificar o sinal recebido, você poderá estender os cabos conectados as entradas (E1 a E5) a mais ou menos 20m de distância. Faça testes.

Circuito-4



Atenção!

Para enviar dados para dentro de seu computador através do circuito acima, use as entradas E1 a E5, com tensão elétrica negativa (0V) da fonte de alimentação em uso.

Para enviar um bit com valor (1), ligue a respectiva entrada ao negativo.

Para enviar um bit com valor (0), desligue a respectiva entrada do negativo.

Lista de componentes:
1 (um) Cabo Paralelo - o mesmo utilizado pela impressora;
5 (cinco) Capacitores cerâmicos de (C1 a C5) todos de 100nF;
1 (um) Circuito Integrado 74LS541 (buffer);
1 (uma) fonte de alimentação estabilizada de 5 volts;
Geral: fios, fero de soldar, solda etc.

Código fonte em C/C++.

O programa abaixo, lê a Porta Paralela LPT1 ininterruptamente enquanto nenhuma tecla seja pressionada, e exibe na tela do computador, o valor recebido em decimal.

```
//www.rogercom.com
//rogercom@rogercom.com
//--------------------------------------------------------------------------------------------------------
#include <stdio.h>
#include <conio.h>
#include <dos.h>
int main(void)
{
   unsigned char RetByte; //Para armazenar o valor recebido da Porta Paralela.
   while( ! kbhit( ) )         //Faz enquanto nenhuma tecla for pressionada.
   {
        RetByte = inportb(0x379);  //Ler um byte da Porta Paralela (0x379)LPT1.
           printf("%u\n",RetByte);
    }
}
```

Código fonte em C/C++.

O programa abaixo, foi escrito para o Sistema Operacional MS-DOS, mas pode ser adaptado para outros sistemas.

Ele lê a Porta Paralela LPT1 ininterruptamente enquanto nenhuma tecla for pressionada, e exibe na tela do computador o estado de cada bit do byte recebido a cada ciclo do laço *while()*.

```
//www.rogercom.com
//rogercom@rogercom.com
//-------------------------------------------------------------------------------------------------------------
#include <stdio.h>
#include <conio.h>
#include <dos.h>
#define BIT0  0x01  // Não usado
#define BIT1  0x02  // Não usado
#define BIT2  0x04  // Não usado
#define BIT3  0x08  // Error
#define BIT4  0x10  // Slct out
#define BIT5  0x20  // Paper End
#define BIT6  0x40  // Ack
#define BIT7  0x80  // Busy

int main(void)
{
    int x=10, y=5; //Coluna e Linha do vídeo
    unsigned char Byte; //Para armazenar o byte recebido da Porta Paralela
    clrscr();
    gotoxy(30,1);   printf("RECEBENDO SINAIS...");
    gotoxy(30,20); printf("Pressione uma tecla para sair...");
    gotoxy(x, y);    printf("Bit 3 - Error....:");
    gotoxy(x,y+1); printf("Bit 4 - Slct out.:");
    gotoxy(x,y+2); printf("Bit 5 - Paper End:");
    gotoxy(x,y+3); printf("Bit 6 - Ack:.....:");
    gotoxy(x,y+4); printf("Bit 7 - Busy.....:");
    while( ! kbhit() )  //Executa enquanto nenhuma tecla for pressionada.
    {
         Byte = inportb(0x379);    //Ler um byte da Porta Paralela
         if((Byte & BIT3) == 0){     // Error: 0000-1000
            gotoxy(x+20,y); printf("INATIVO");
         }else{
            gotoxy(x+20,y); printf("ATIVO      ");
         }
         if((Byte & BIT4) == 0){    // Slct out: 0001-0000
            gotoxy(x+20,y+1); printf("INATIVO");
         }else{
            gotoxy(x+20,y+1); printf("ATIVO   ");
         }
         if((Byte & BIT5) == 0){    // Paper end: 0010-0000
            gotoxy(x+20,y+2); printf("INATIVO");
         }else{
            gotoxy(x+20,y+2); printf("ATIVO   ");
         }
         if((Byte & BIT6) == 0){     // Ack: 0100-0000
            gotoxy(x+20,y+3); printf("INATIVO");
         }else{
            gotoxy(x+20,y+3); printf("ATIVO   ");
         }
         if((Byte & BIT7) == 0){     // Busy: 1000-0000
            gotoxy(x+20,y+4); printf("INATIVO");
         }else{
            gotoxy(x+20,y+4); printf("ATIVO   ");
         }
     }
     clrscr();
}
```

PRINCIPAL ÍNDICE

http://www.rogercom.com

Porta Paralela

para Controle de dispositivos

Por: Antônio Rogério Messias

AQUISIÇÃO DE DADOS BYTE-A-BYTE ATRAVÉS DA PORTA PARALELA.

O objetivo do circuito abaixo é enviar, para a Porta Paralela, 8 bits (1 byte) de cada vez usando o modo EPP.

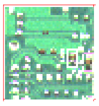
Para que esse projeto tenha uma boa utilidade usaremos o Conversor Analógico Digital ADC0804, com a intenção de criarmos um voltímetro digital.

O Conversor Analógico Digital ADC0804 converte uma tensão elétrica entre 0 a 5v, com passos de 0,0196v, em um número de 8 bits.

Criaremos um software para ler os 8 bits, através da Porta Paralela, no modo EPP convertendo-os em valores decimais, e exibindo-os no visor em escala de tensão elétrica.

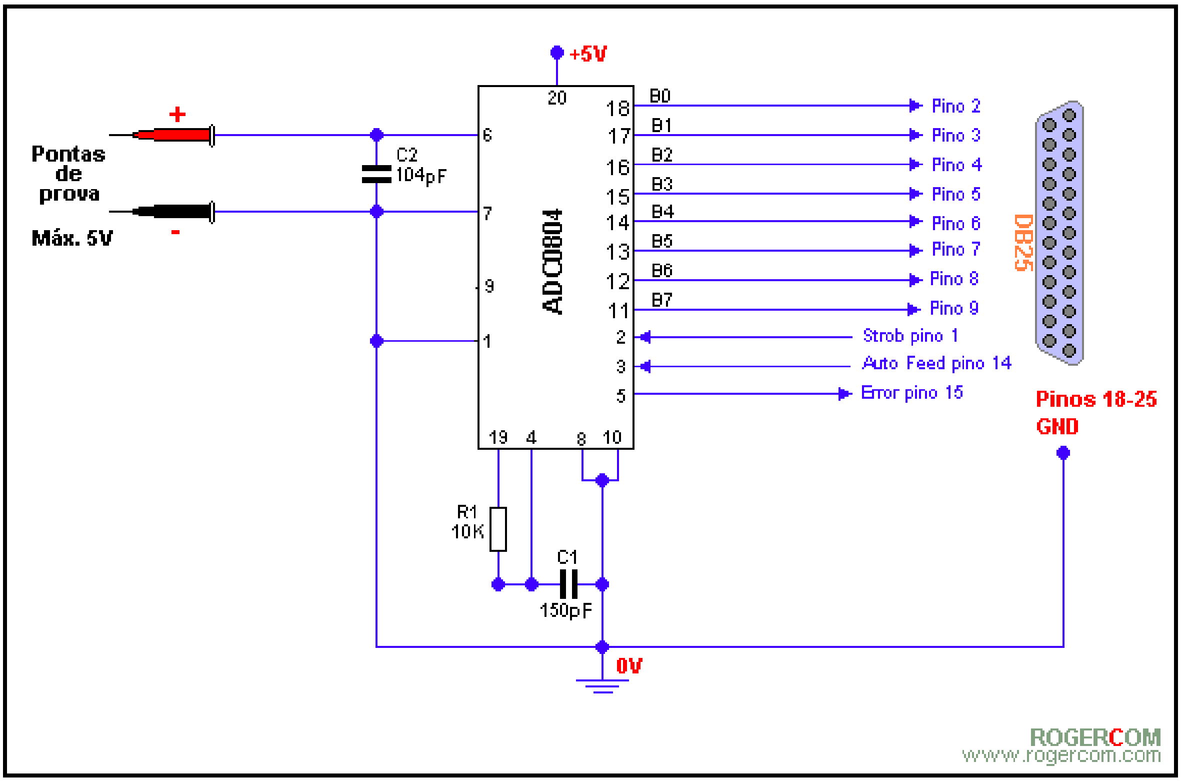
⚠ Atenção!

Este circuito é um dos mais críticos em termos de proteção à Porta Paralela.
O circuito abaixo só poderá ser usado para medir tensões elétricas contínuas entre 0 à 5v. Não tente, de forma alguma, ultrapassar esse limite, podendo danificar tanto o ADC0804 como a Porta Paralela.
Observe que no circuito abaixo não foi utilizado nenhum componente para proteger a Porta Paralela.
Utilize um Buffer ou acopladores óptico.
Também certifique-se de que a Porta Paralela esteja configurada para trabalhar no modo EPP.



Circuito ByteAByte

Esquema elétrico do circuito



Lista de materiais

1 - Circuito integrado - **ADC0804**;
1 - R1 - Resistor **10K** ohm;
1 - C1 - Capacitor **150** pF;
1 - C2 - Capacitor **104** pF;

Geral:
1 - Fonte de alimentação de 5v;
1 - Cabo Paralelo;
Pontas de prova e fios.

Código fonte em C/C++

Listagem do programa LPTVolt.cpp

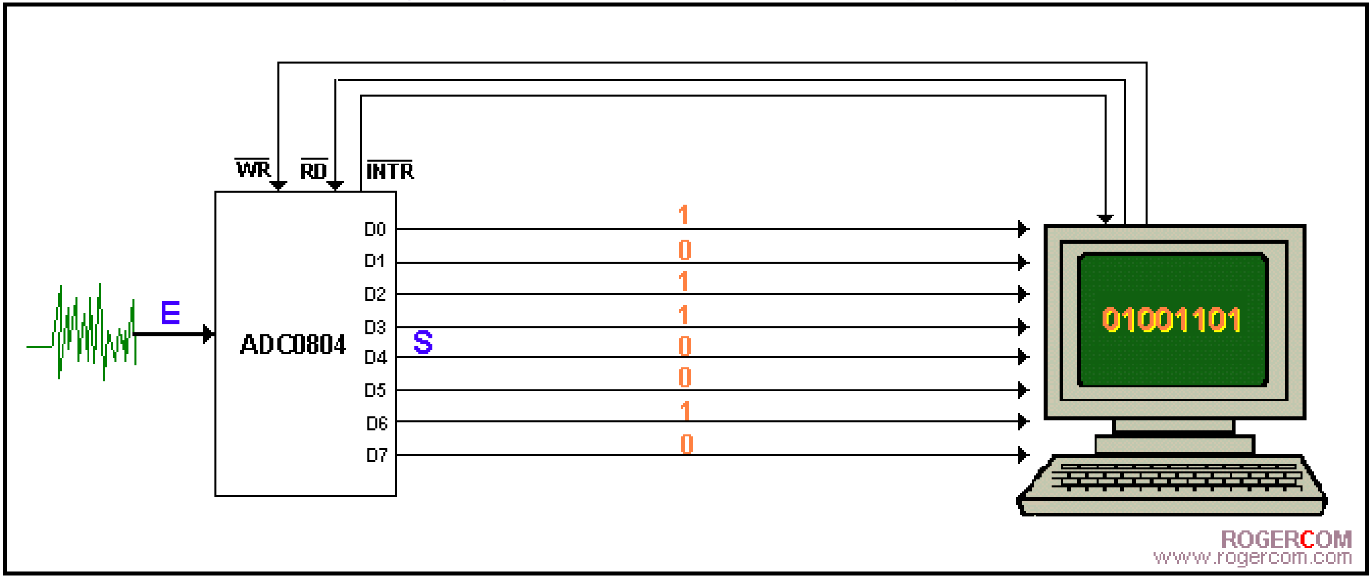
```
//---------------------------------------------------------------------------
// Objetivo: Medir tensão elétrica entre 0 à 5v através da porta EPP.
// Autor: Antonio Rogério Messias
// Data Criação: 12/11/2001
// E-Mail: rogercom@rogercom.com
// Todos os Direitos Reservados
//---------------------------------------------------------------------------
#include  "vcl.h"
#include  "stdio.h"
#pragma hdrstop
#include "UnitPrincipal.h"
#include "Porta.h"
#include "ClassBinario.h"
#define B0 0x01
#define B1 0x02
#define B2 0x04
#define B3 0x08
#define B4 0x10
#define B5 0x20
#define B6 0x40
#define B7 0x80
#define S3 B3
#define S4 B4
#define S5 B5
#define S6 B6
#define S7 B7
#define BASE     0x378
#define DADOS    BASE + 0
#define STATUS   BASE + 1
#define CONTROLE BASE + 2
#define EPPDATA  BASE + 4
//---------------------------------------------------------------------------
#pragma package(smart_init)
#pragma resource "*.dfm"
TformPrincipal *formPrincipal;
TPorta *Porta;      //Declara objeto para controle da porta paralela.
TBinario *Binario;  //Declara objeto p/ converter um int numa string binária.
unsigned char ByteADC; //Variável para armazenar o byte recebido através da porta.
int TimeOut;           //Váriável para armazenar o tempo de resposta do circuito.
//---------------------------------------------------------------------------
__fastcall TformPrincipal::TformPrincipal(TComponent* Owner)
        : TForm(Owner)
{
}
//---------------------------------------------------------------------------

void __fastcall TformPrincipal::TimerAquisicaoTimer(TObject *Sender)
{
  char buf[7]; //Vriável para armazenar uma string de números.
  //IMPORTANTE: Para ativar um pino no ADC envia um 0 (zero) e para desativar 1 (um).

  //Inicializa a conversão do ADC enviando um pulso Baixo(0) no pino 14 C1,
  //momentaneamente.

  Porta->Envia(CONTROLE,34);   //34 0010-0010 aguarda mais ou menos 100 micro segundos.
  Porta->Envia(CONTROLE,32);   //32 0010-0000 habilita a conversão.
  TimeOut=0;

  do{     //Loop para verificar o Sinal INTR do ADC0804.
     TimeOut++;
  }while(((Porta->Recebe(STATUS) & S3) == S3) && (TimeOut != 256)); //0000-1000.
  if(TimeOut == 256)
  {
    formPrincipal->Caption = "Erro!";
  }else
  {                              //35 0010-0011
     Porta->Envia(CONTROLE,35);  //Pino 1 C0 Baixo(0),Habilita a saída(leitura) do ADC.
     ByteADC =  Porta->Recebe(DADOS); //34 0010-0010
     Porta->Envia(CONTROLE,34); //Pino 1 C0 Alto(1),Desabilita a saída(leitura) do ADC.
     sprintf(buf,"%0.2f",ByteADC*0.0196); //Calcula: Byte recebido x 0.0196v.
     labeVisor->Caption = buf;  //Exibe valor.
  }
}
```

```
//---------------------------------------------------------------------------

void __fastcall TformPrincipal::SpeedButtonSairClick(TObject *Sender)
{
  Porta->Envia(CONTROLE,0); //Desabilita a leitura EPP.
  Close();
}
//---------------------------------------------------------------------------

void __fastcall TformPrincipal::SpeedButtonMiniClick(TObject *Sender)
{
    WindowState = wsMinimized;
}
//---------------------------------------------------------------------------
```

Para testar o circuito:

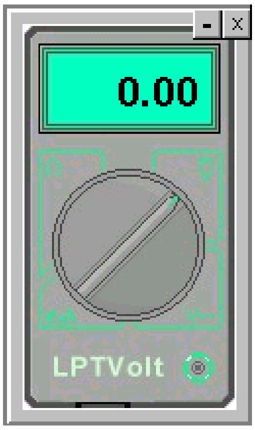
Com a interface ligada à Porta Paralela e o programa LPTVolt rodando, pegue uma pilha de 1,5 volt, posicione a ponta de prova de cor vermelha no pólo positivo e a ponta de prova preta no pólo negativo, verifique no visor se o valor medido está na faixa de +/- 1,5v. Se inverter as polaridades, o valor medido será sempre o limite de 5v.

Diagrama genérico de funcionamento do projeto.



No diagrama acima, WR, RD e INTR são controles de comunicação entre o computador e o ADC0804.
E, é a entrada analógica de 0 a 5v e S, é a saída transformada e convertida em binário.

Download: Download do programa LPTVOLT.EXE



PRINCIPAL ÍNDICE

http://www.rogercom.com

ANALOG DEVICES

Ultralow Offset Voltage Operational Amplifiers

OP07

FEATURES

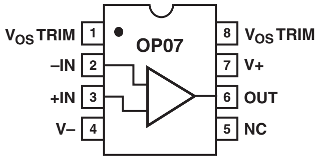
Low V_{OS}: 75 µV Max
Low V_{OS} Drift: 1.3 µV/°C Max
Ultra-Stable vs. Time: 1.5 µV/Month Max
Low Noise: 0.6 µV p-p Max
Wide Input Voltage Range: ±14 V
Wide Supply Voltage Range: 3 V to 18 V
Fits 725,108A/308A, 741, AD510 Sockets
125°C Temperature-Tested Dice

APPLICATIONS

Wireless Base Station Control Circuits
Optical Network Control Circuits
Instrumentation
Sensors and Controls
  Thermocouples
  RTDs
  Strain Bridges
  Shunt Current Measurements
Precision Filters

PIN CONNECTIONS

Epoxy Mini-Dip (P-Suffix)
8-Pin SO (S-Suffix)



NC = NO CONNECT

GENERAL DESCRIPTION

The OP07 has very low input offset voltage (75 µV max for OP07E) which is obtained by trimming at the wafer stage. These low offset voltages generally eliminate any need for external nulling. The OP07 also features low input bias current (±4 nA for OP07E) and high open-loop gain (200 V/mV for OP07E). The low offsets and high open-loop gain make the OP07 particularly useful for high-gain instrumentation applications.

The wide input voltage range of ±13 V minimum combined with high CMRR of 106 dB (OP07E) and high input impedace provides high accuracy in the noninverting circuit configuration. Excellent linearity and gain accuracy can be maintained even at high closed-loop gains. Stability of offsets and gain with time or variations in temperature is excellent. The accuracy and stability of the OP07, even at high gain, combined with the freedom from external nulling have made the OP07 an industry standard for instrumentation applications.

The OP07 is available in two standard performance grades. The OP07E is specified for operation over the 0°C to 70°C range, and OP07C over the –40°C to +85°C temperature range.

The OP07 is available in epoxy 8-lead Mini-DIP and 8-lead SOIC. It is a direct replacement for 725,108A, and OP05 amplifiers; 741-types may be directly replaced by removing the 741's nulling potentiometer. For improved specifications, see the OP177 or OP1177. For ceramic DIP and TO-99 packages and standard micro circuit (SMD) versions, see the OP77.

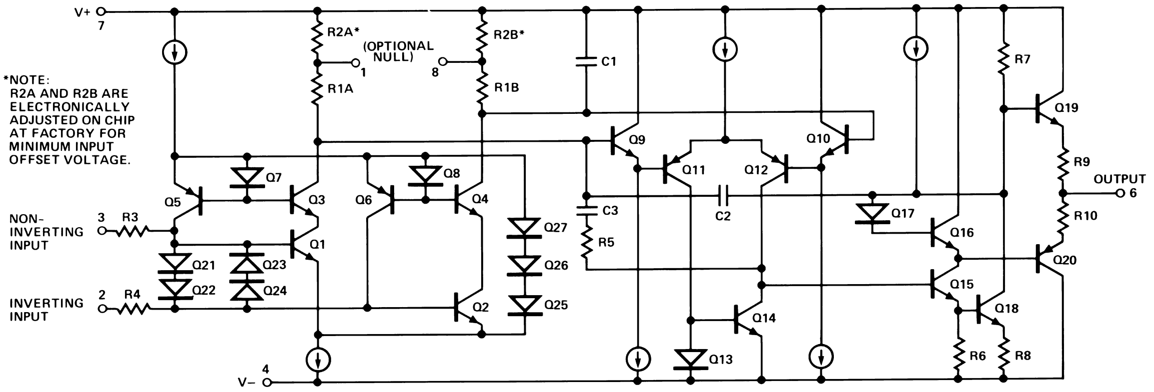


Figure 1. Simplified Schematic

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 www.analog.com
Fax: 781/326-8703

OP07–SPECIFICATIONS

OP07E ELECTRICAL CHARACTERISTICS (V_S = ±15 V, T_A = 25°C, unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
Input Offset Voltage[1]	V_{OS}			30	75	μV
Long-Term V_{OS} Stability[2]	V_{OS}/Time			0.3	1.5	μV/Mo
Input Offset Current	I_{OS}			0.5	3.8	nA
Input Bias Current	I_B			±1.2	±4.0	nA
Input Noise Voltage	e_n p-p	0.1 Hz to 10 Hz[3]		0.35	0.6	μV p-p
Input Noise Voltage Density	e_n	f_O = 10 Hz		10.3	18.0	nV√Hz
		f_O = 100 Hz[3]		10.0	13.0	nV√Hz
		f_O = 1 kHz		9.6	11.0	nV√Hz
Input Noise Current	I_n p-p			14	30	pA p-p
Input Noise Current Density	I_n	f_O = 10 Hz		0.32	0.80	pA√Hz
		f_O = 100 Hz[3]		0.14	0.23	pA√Hz
		f_O = 1 kHz		0.12	0.17	pA√Hz
Input Resistance—Differential Mode[4]	R_{IN}		15	50		mΩ
Input Resistance—Common-Mode	R_{INCM}			160		GΩ
Input Voltage Range	IVR		±13	±14		V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13 V	106	123		dB
Power Supply Rejection Ratio	PSRR	V_S = ±3 V to ±18 V		5	20	μV/V
Large-Signal Voltage Gain	A_{VO}	$R_L \geq$ 2 kΩ, V_O = ±10 V	200	500		V/mV
		$R_L \geq$ 500 Ω, V_O = ±0.5 V, V_S = ±3 V[4]	150	400		V/mV
OUTPUT CHARACTERISTICS						
Output Voltage Swing	V_O	$R_L \geq$ 10 kΩ	±12.5	±13.0		V
		$R_L \geq$ 2 kΩ	±12.0	±12.8		V
		$R_L \geq$ 1 kΩ	±10.5	±12.0		V
DYNAMIC PERFORMANCE						
Slew Rate	SR	$R_L \geq$ 2 kΩ[3]	0.1	0.3		V/μs
Closed-Loop Bandwidth	BW	A_{VOL} = 1[5]	0.4	0.6		MHz
Closed-Loop Output Resistance	R_O	V_O = 0, I_O = 0		60		Ω
Power Consumption	P_d	V_S = ±15 V, No Load		75	120	mW
		V_S = ±13 V, No Load		4	6	mW
Offset Adjustment Range		R_P = 20 kΩ		±4		mV

NOTES

[1] Input offset voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.

[2] Long-term input offset voltage stability refers to the averaged trend time of VOS vs. Time over extended periods after the first 30 days of operation. Excluding the initial hour of operation, changes in VOS during the first 30 operating days are typically 2.5 μV refer to the typical performance curves. Parameter is sample tested.

[3] Sample tested.

[4] Guaranteed by design.

[5] Guaranteed but not tested.

Specifications subject to change without notice.

OP07C ELECTRICAL CHARACTERISTICS (V_S = ±15 V, T_A = 25°C, unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
Input Offset Voltage[1]	V_{OS}			60	150	µV
Long-Term V_{OS} Stability[2]	V_{OS}/Time			0.4	2.0	µV/Mo
Input Offset Current	I_{OS}			0.8	6.0	nA
Input Bias Current	I_B			±1.8	±7.0	nA
Input Noise Voltage	e_n p-p	0.1 Hz to 10 Hz[3]		0.38	0.65	µV p-p
Input Noise Voltage Density	e_n	f_O = 10 Hz		10.5	20.0	nV$\sqrt{Hz}$
		f_O = 100 Hz[3]		10.2	13.5	nV$\sqrt{Hz}$
		f_O = 1 kHz		9.8	11.5	nV$\sqrt{Hz}$
Input Noise Current	I_n p-p			15	35	pA p-p
Input Noise Current Density	I_n	f_O = 10 Hz		0.35	0.90	pA$\sqrt{Hz}$
		f_O = 100 Hz[3]		0.15	0.27	pA$\sqrt{Hz}$
		f_O = 1 kHz		0.13	0.18	pA$\sqrt{Hz}$
Input Resistance- Differential Mode[4]	R_{IN}		8	33		mΩ
Input Resistance- Common-Mode	R_{INCM}			120		GΩ
Input Voltage Range	IVR		±13	±14		V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13 V	100	120		dB
Power Supply Rejection Ratio	PSRR	V_S = ±3 V to ±18 V		7	32	µV/V
Large-Signal Voltage Gain	A_{VO}	$R_L \geq 2$ kΩ, V_O = ±10 V	120	400		V/mV
		$R_L \geq 500$ Ω, V_O = ±0.5 V, V_S = ±3 V[4]	100	400		V/mV
OUTPUT CHARACTERISTICS						
Output Voltage Swing	V_O	$R_L \geq 10$ kΩ	±12.0	±13.0		V
		$R_L \geq 2$ kΩ	±11.5	±12.8		V
		$R_L \geq 1$ kΩ		±12.0		V
DYNAMIC PERFORMANCE						
Slew Rate	SR	$R_L \geq 2$ kΩ[3]	0.1	0.3		V/µs
Closed-Loop Bandwidth	BW	A_{VOL} = 1[5]	0.4	0.6		MHz
Closed-Loop Output Resistance	R_O	V_O = 0, I_O = 0		60		Ω
Power Consumption	P_d	V_S = ±15 V, No Load		80	150	mW
		V_S = ±13 V, No Load		4	8	mW
Offset Adjustment Range		R_P = 20 kΩ		±4		mV

NOTES

[1] Input offset voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.

[2] Long-term input offset voltage stability refers to the averaged trend time of VOS vs. Time over extended periods after the first 30 days of operation. Excluding the initial hour of operation, changes in VOS during the first 30 operating days are typically 2.5 µV refer to the typical performance curves. Parameter is sample tested.

[3] Sample tested.

[4] Guaranteed by design.

[5] Guaranteed but not tested.

Specifications subject to change without notice.

OP07–SPECIFICATIONS

OP07E ELECTRICAL CHARACTERISTICS (V_S = ±15 V, 0°C ≤ T_A ≤ 70°C, unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
Input Offset Voltage[1]	V_{OS}			45	130	μV
Voltage Drift without External Trim[2]	TCV_{OS}			0.3	1.3	μV/°C
Voltage Drift with External Trim[3]	TCV_{OSN}	R_P = 20 kΩ		0.3	1.3	μV/°C
Input Offset Current	I_{OS}			0.9	5.3	nA
Input Offset Current Drift	TCI_{OS}			8	35	pA/°C
Input Bias Current	I_B			±1.5	±5.5	nA
Input Bias Current Drift	TCI_B			13	35	pA/°C
Input Voltage Range	IVR		±13	±13.5		V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13 V	103	123		dB
Power Supply Rejection Ratio	PSRR	V_S = ±3 V to ±18 V		7	32	μV/V
Large-Signal Voltage Gain	A_{VO}	R_L ≥ 2 kΩ, V_O = ±10 V	180	450		V/mV
OUTPUT CHARACTERISTICS						
Output Voltage Swing	V_O	R_L ≥ 10 kΩ	±12	±12.6		V

NOTES

[1] Input offset voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.

[2] Guaranteed by design.

[3] Sample tested.

Specifications subject to change without notice.

OP07C ELECTRICAL CHARACTERISTICS (V_S = ±15 V, −40°C ≤ T_A ≤ +85°C, unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
Input Offset Voltage[1]	V_{OS}			85	250	μV
Voltage Drift without External Trim[2]	TCV_{OS}			0.5	1.8	μV/°C
Voltage Drift with External Trim[3]	TCV_{OSN}	R_P = 20 kΩ		0.4	1.8	μV/°C
Input Offset Current	I_{OS}			1.6	8.0	nA
Input Offset Current Drift	TCI_{OS}			12	50	pA/°C
Input Bias Current	I_B			±2.2	±9.0	nA
Input Bias Current Drift	TCI_B			18	50	pA/°C
Input Voltage Range	IVR		±13	±13.5		V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13 V	97	120		dB
Power Supply Rejection Ratio	PSRR	V_S = ±3 V to ±18 V		10	51	μV/V
Large-Signal Voltage Gain	A_{VO}	R_L ≥ 2 kΩ, V_O = ±10 V	100	400		V/mV
OUTPUT CHARACTERISTICS						
Output Voltage Swing	V_O	R_L ≥ 10 kΩ	±11	±12.6		V

NOTES

[1] Input offset voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.

[2] Guaranteed by design.

[3] Sample tested.

Specifications subject to change without notice.

ABSOLUTE MAXIMUM RATINGS*

Supply Voltage (V_S)	±22 V
Input Voltage*	±22 V
Differential Input Voltage	±30 V
Output Short-Circuit Duration	Indefinite
Storage Temperature Range	
S, P Packages	–65°C to +125°C
Operating Temperature Range	
OP07E	0°C to 70°C
OP07C	–40°C to +85°C
Junction Temperature Range	150°C
Lead Temperature Range (Soldering, 60 sec)	300°C

*For supply voltages less than ±22 V, the absolute maximum input voltage is equal to the supply voltage.

Package Type	θ_{JA}*	θ_{JC}	Units
8-Lead Plastic DIP (P)	103	43	°C/W
8-Lead SOIC (S)	158	43	°C/W

*θ_{JA} is specified for worst case conditions, i.e., θ_{JA} is specified for device in socket for P-DIP package, θ_{JA} is specified for device soldered to printed circuit board for SO package.

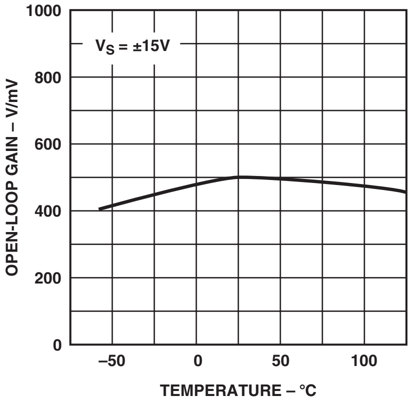
ORDERING GUIDE

Model	Temperature Range	Package Description	Package Option	Branding Information
OP07EP	0°C to 70°C	8-Lead Epoxy DIP	P-8	
OP07CP	–40°C to 85°C	8-Lead Epoxy DIP	P-8	
OP07CS	–40°C to 85°C	8-Lead SOIC	S-8	

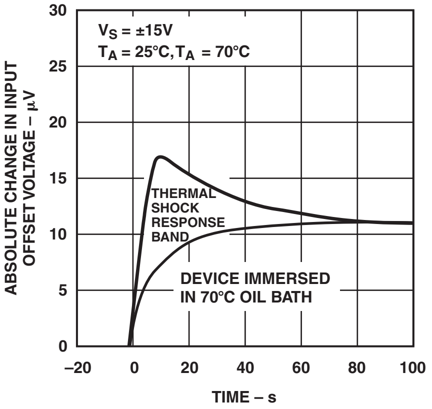
CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the OP07 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high-energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

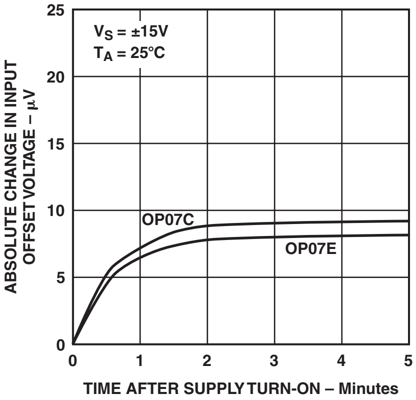
OP07 – Typical Performance Characteristics



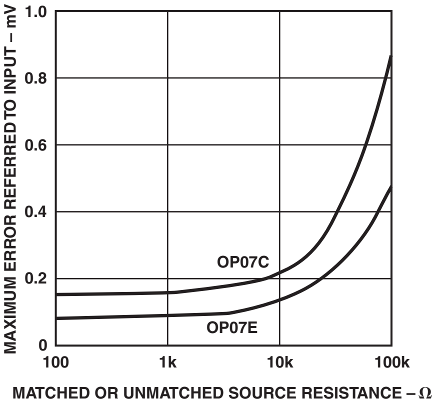
TPC 1. Open-Loop Gain vs. Temperature



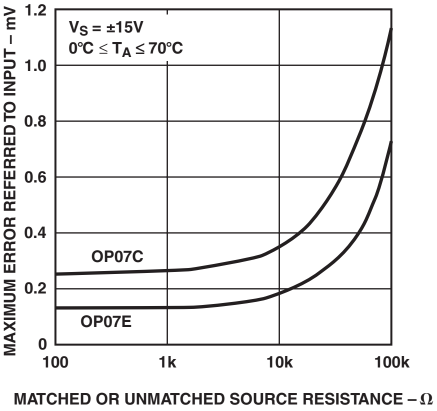
TPC 2. Offset Voltage Change Due to Thermal Shock



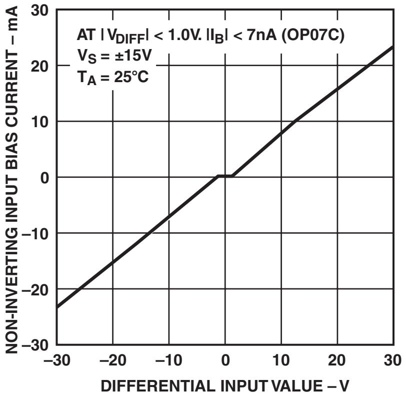
TPC 3. Warm-Up Drift



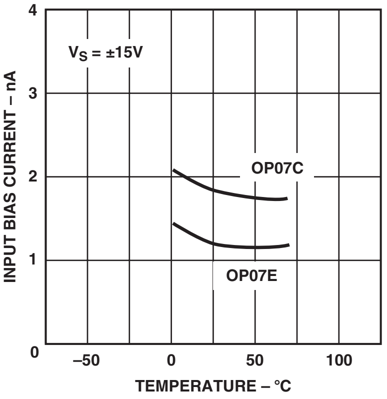
TPC 4. Maximum Error vs. Source Resistance



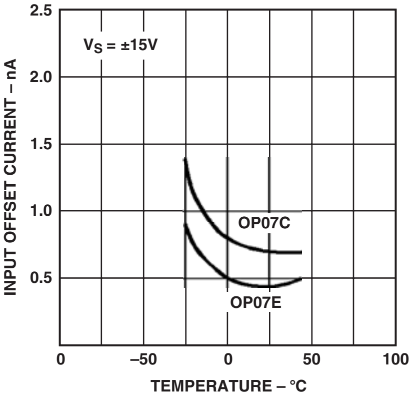
TPC 5. Maximum Error vs. Source Resistance



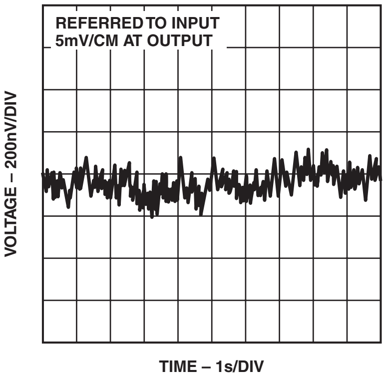
TPC 6. Input Bias Current vs. Differential Input Voltage



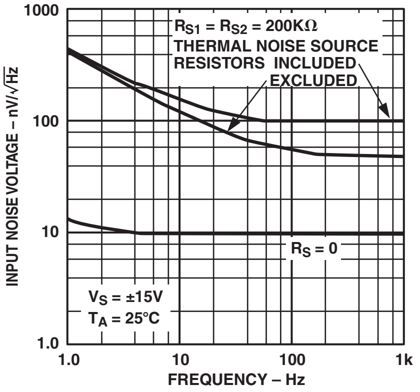
TPC 7. Input Bias Current vs. Temperature



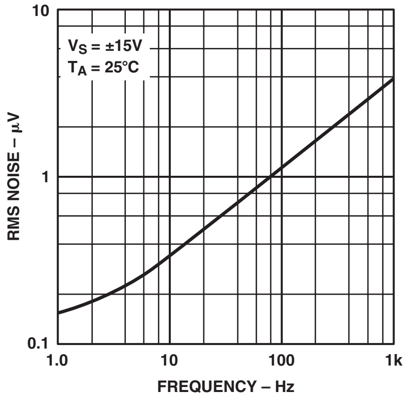
TPC 8. Input Offset Current vs. Temperature



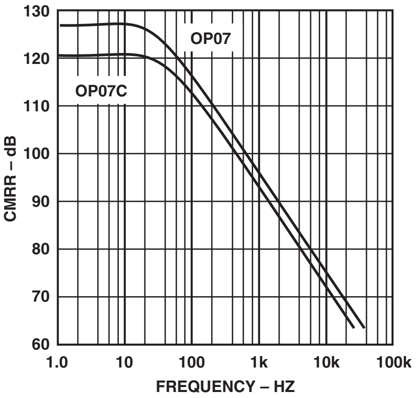
TPC 9. Low Frequency Noise



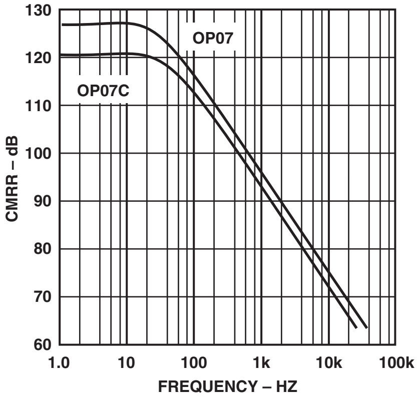
TPC 10. Total Input Noise Voltage vs. Frequency



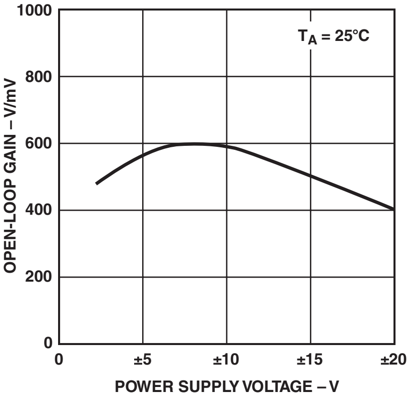
TPC 11. Input Wideband Noise vs Bandwidth (0.1 Hz to Frequency Indicated)



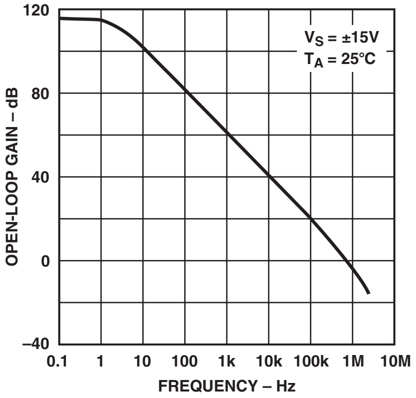
TPC 12. CMRR vs. Frequency



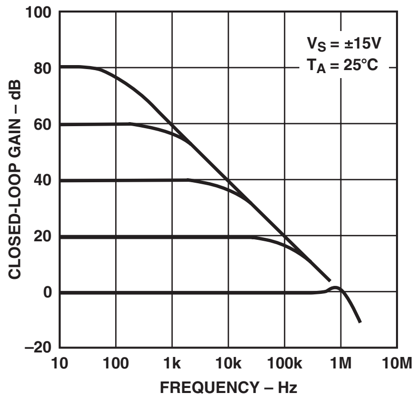
TPC 13. PSRR vs. Frequency



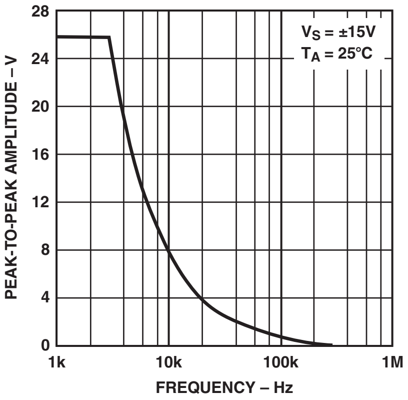
TPC 14. Open-Loop Gain vs Power Supply Voltage



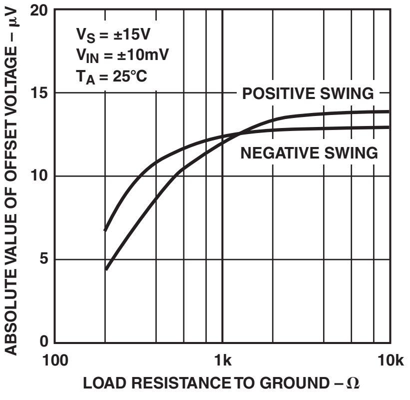
TPC 15. Open-Loop Frequency Response



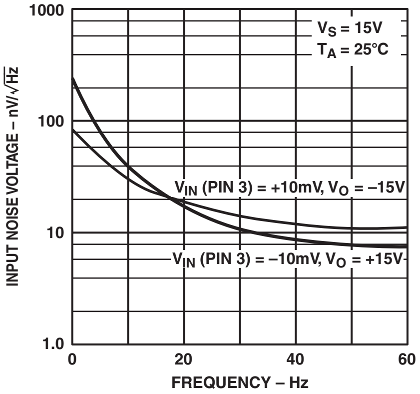
TPC 16. Closed-Loop Response for Various Gain Configurations



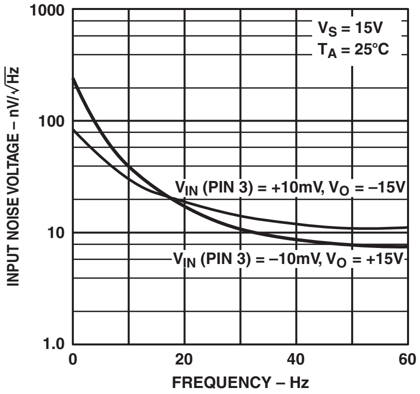
TPC 17. Maximum Output Swing vs. Frequency



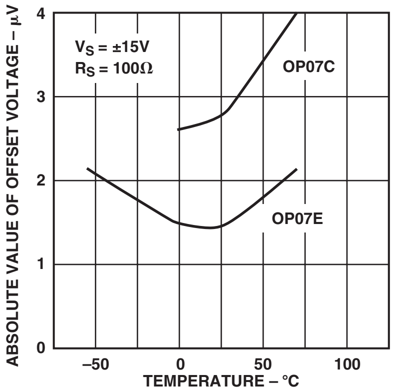
TPC 18. Maximum Output Voltage vs. Load Resistance



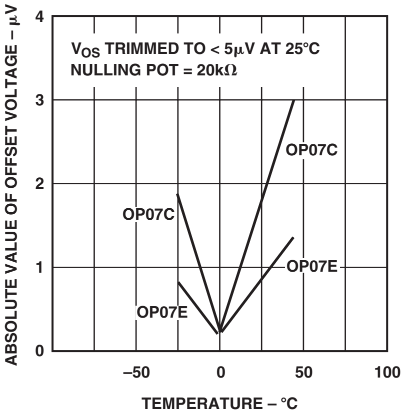
TPC 19. Power Consumption vs. Power Supply



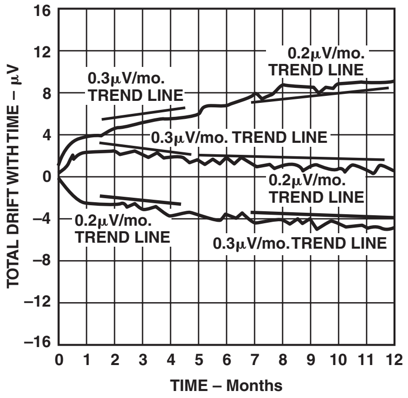
TPC 20. Output Short-Circuit Current vs. Time



TPC 21. Untrimmed Offset Voltage vs. Temperature



TPC 22. Trimmed Offset Voltage vs. Temperature



TPC 23. Offset Voltage Stability vs. Time

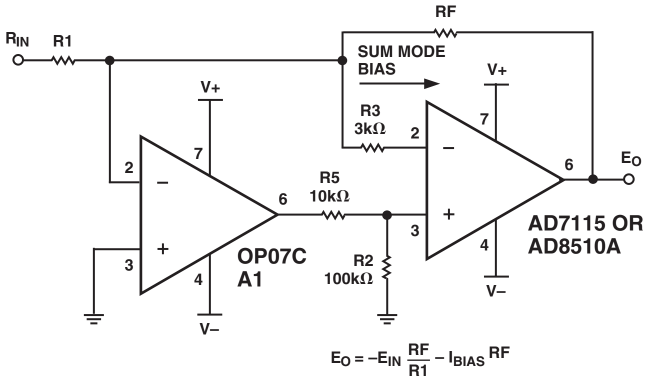


Figure 2. Typical Offset Voltage Test Circuit

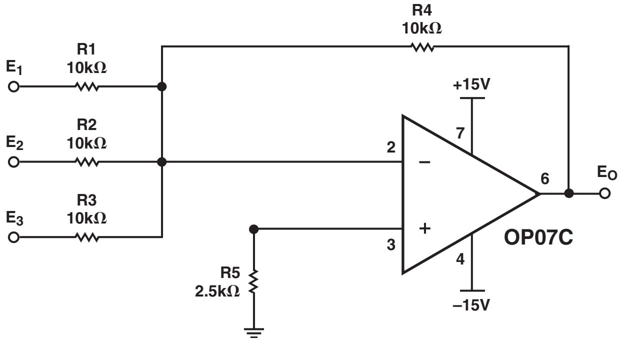


Figure 3. Typical Low-Frequency Noise Circuit

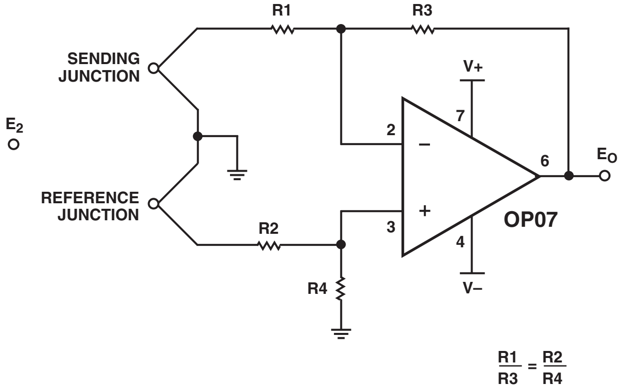


Figure 4. Optional Offset Nulling Circuit

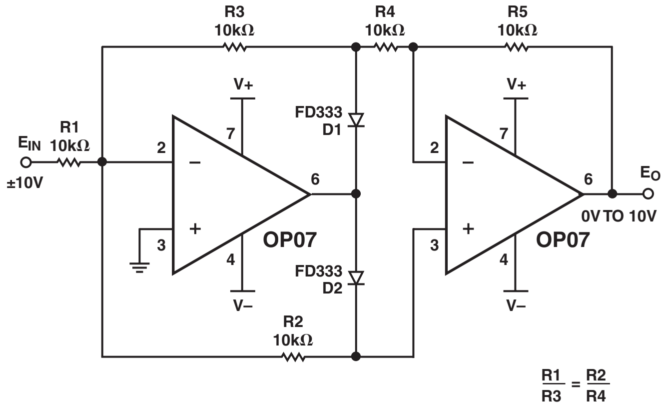
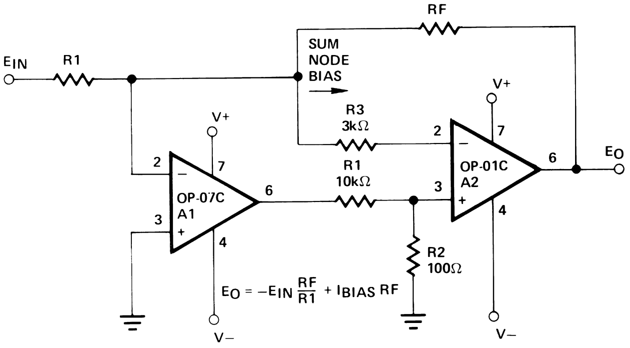
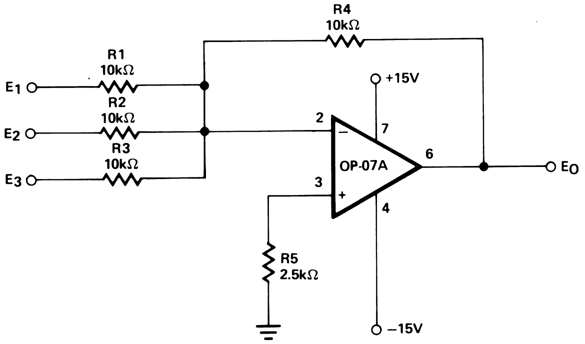


Figure 5. Burn-In circuit



PINOUTS SHOWN FOR J, P, AND Z PACKAGES

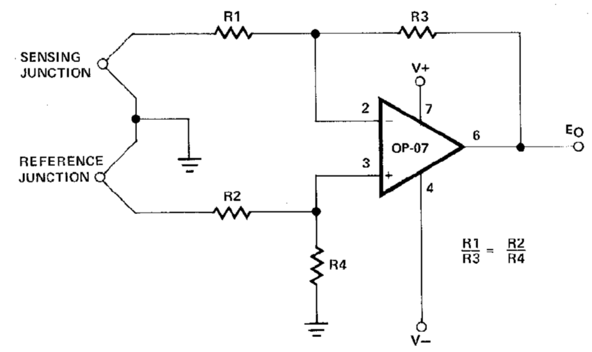
Figure 6. High-Speed, Low VOS Composite Amplifier



PINOUTS SHOWN FOR J, P, AND Z PACKAGES

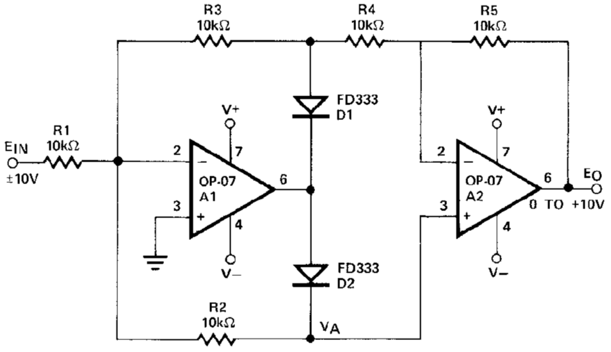
Figure 7. Adjustment-Free Precision Summing Amplifier

TYPICAL APPLICATIONS



PINOUTS SHOWN FOR J, P, AND Z PACKAGES

Figure 8. High-Stability Thermocouple Amplifier



PINOUTS SHOWN FOR J, P, AND Z PACKAGES

Figure 9. Precision Absolute-Value Circuit

APPLICATIONS INFORMATION

OP07 series units may be substituted directly into 725, 108A/308A* and OP05 sockets with or without removal of external compensation or nulling components. Additionally, the OP07 may be used in unnulled 741 type sockets. However, if conventional 741 nulling circuitry is in use, it should be modified or removed to enable proper OP07 operation. OP07 offset voltage may be nulled to zero through use of a potentiometer (see offset nulling circuit diagram).

PRECISION ABSOLUTE-VALUE CIRCUIT

The OP07 provides stable operation with load capacitance of up to 500 pF and ±10 V swings; larger capacitances should be decoupled with a 50 Q decoupling resistor.

Stray thermoelectric voltages generated by dissimilar metals at the contacts to the input terminals can degrade drift performance. Therefore, best operation will be obtained when both input contacts are maintained at the same temperature, preferably close to the package temperature.

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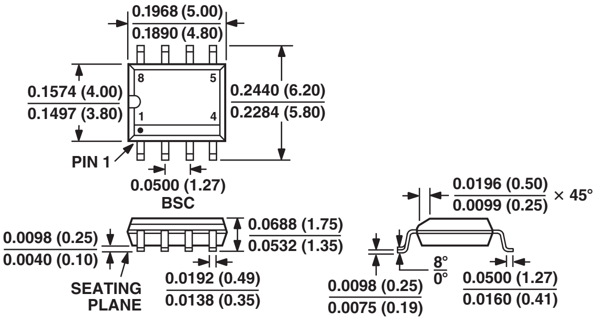
*TO-99 Package only

OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

8-Lead SO DIP
(S-Suffix)



Revision History

Location	Page
Data Sheet changed from REV. 0 to REV. A.	
Edits to FEATURES	1
Edits to ORDERING GUIDE	1
Edits to PIN CONNECTION drawings	1
Edits to ABSOLUTE MAXIMUM RATINGS	2
Deleted ELECTRICAL CHARACTERISTICS	2–3
Deleted OP07D Column from ELECTRICAL CHARACTERISTICS	4–5
Edits to TPCs	7–9
Edits to HIGH-SPEED, LOW V_{OS} COMPOSITE AMPLIFIER	9

C00316–0–2/02(A)

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TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
-270	-6.458											-270
-260	-6.411	-6.444	-6.446	-6.448	-6.450	-6.452	-6.453	-6.455	-6.456	-6.457	-6.458	-260
-250	-6.404	-6.408	-6.413	-6.417	-6.421	-6.425	-6.429	-6.432	-6.435	-6.438	-6.441	-250
-240	-6.344	-6.351	-6.358	-6.364	-6.370	-6.377	-6.382	-6.388	-6.393	-6.399	-6.404	-240
-230	-6.262	-6.271	-6.280	-6.289	-6.297	-6.306	-6.314	-6.322	-6.329	-6.337	-6.344	-230
-220	-6.158	-6.170	-6.181	-6.192	-6.202	-6.213	-6.223	-6.233	-6.243	-6.252	-6.262	-220
-210	-6.035	-6.048	-6.061	-6.074	-6.087	-6.099	-6.111	-6.123	-6.135	-6.147	-6.158	-210
-200	-5.891	-5.907	-5.922	-5.936	-5.951	-5.965	-5.980	-5.994	-6.007	-6.021	-6.035	-200
-190	-5.730	-5.747	-5.763	-5.780	-5.797	-5.813	-5.829	-5.845	-5.861	-5.876	-5.891	-190
-180	-5.550	-5.569	-5.588	-5.606	-5.624	-5.642	-5.660	-5.678	-5.695	-5.713	-5.730	-180
-170	-5.354	-5.374	-5.395	-5.415	-5.435	-5.454	-5.474	-5.493	-5.512	-5.531	-5.550	-170
-160	-5.141	-5.163	-5.185	-5.207	-5.228	-5.250	-5.271	-5.292	-5.313	-5.333	-5.354	-160
-150	-4.913	-4.936	-4.960	-4.983	-5.006	-5.029	-5.052	-5.074	-5.097	-5.119	-5.141	-150
-140	-4.669	-4.694	-4.719	-4.744	-4.768	-4.793	-4.817	-4.841	-4.865	-4.889	-4.913	-140
-130	-4.411	-4.437	-4.463	-4.490	-4.516	-4.542	-4.567	-4.593	-4.618	-4.644	-4.669	-130
-120	-4.138	-4.166	-4.194	-4.221	-4.249	-4.276	-4.303	-4.330	-4.357	-4.384	-4.411	-120
-110	-3.852	-3.882	-3.911	-3.939	-3.968	-3.997	-4.025	-4.054	-4.082	-4.110	-4.138	-110
-100	-3.554	-3.584	-3.614	-3.645	-3.675	-3.705	-3.734	-3.764	-3.794	-3.823	-3.852	-100
-90	-3.243	-3.274	-3.306	-3.337	-3.368	-3.400	-3.431	-3.462	-3.492	-3.523	-3.554	-90
-80	-2.920	-2.953	-2.986	-3.018	-3.050	-3.083	-3.115	-3.147	-3.179	-3.211	-3.243	-80
-70	-2.587	-2.620	-2.654	-2.688	-2.721	-2.755	-2.788	-2.821	-2.854	-2.887	-2.920	-70
-60	-2.243	-2.278	-2.312	-2.347	-2.382	-2.416	-2.450	-2.485	-2.519	-2.553	-2.587	-60
-50	-1.889	-1.925	-1.961	-1.996	-2.032	-2.067	-2.103	-2.138	-2.173	-2.208	-2.243	-50
-40	-1.527	-1.564	-1.600	-1.637	-1.673	-1.709	-1.745	-1.782	-1.818	-1.854	-1.889	-40
-30	-1.156	-1.194	-1.231	-1.268	-1.305	-1.343	-1.380	-1.417	-1.453	-1.490	-1.527	-30
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156	-20
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778	-10
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**°C**

TABLE 9 *Type K Thermocouple — thermoelectric voltage as a function of temperature (℃); reference junctions at 0 ℃*

K°C

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (℃); reference junctions at 0 ℃*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
800	33.275	33.316	33.357	33.398	33.439	33.480	33.521	33.562	33.603	33.644	33.685	800
810	33.685	33.726	33.767	33.808	33.848	33.889	33.930	33.971	34.012	34.053	34.093	810
820	34.093	34.134	34.175	34.216	34.257	34.297	34.338	34.379	34.420	34.460	34.501	820
830	34.501	34.542	34.582	34.623	34.664	34.704	34.745	34.786	34.826	34.867	34.908	830
840	34.908	34.948	34.989	35.029	35.070	35.110	35.151	35.192	35.232	35.273	35.313	840
850	35.313	35.354	35.394	35.435	35.475	35.516	35.556	35.596	35.637	35.677	35.718	850
860	35.718	35.758	35.798	35.839	35.879	35.920	35.960	36.000	36.041	36.081	36.121	860
870	36.121	36.162	36.202	36.242	36.282	36.323	36.363	36.403	36.443	36.484	36.524	870
880	36.524	36.564	36.604	36.644	36.685	36.725	36.765	36.805	36.845	36.885	36.925	880
890	36.925	36.965	37.006	37.046	37.086	37.126	37.166	37.206	37.246	37.286	37.326	890
900	37.326	37.366	37.406	37.446	37.486	37.526	37.566	37.606	37.646	37.686	37.725	900
910	37.725	37.765	37.805	37.845	37.885	37.925	37.965	38.005	38.044	38.084	38.124	910
920	38.124	38.164	38.204	38.243	38.283	38.323	38.363	38.402	38.442	38.482	38.522	920
930	38.522	38.561	38.601	38.641	38.680	38.720	38.760	38.799	38.839	38.878	38.918	930
940	38.918	38.958	38.997	39.037	39.076	39.116	39.155	39.195	39.235	39.274	39.314	940
950	39.314	39.353	39.393	39.432	39.471	39.511	39.550	39.590	39.629	39.669	39.708	950
960	39.708	39.747	39.787	39.826	39.866	39.905	39.944	39.984	40.023	40.062	40.101	960
970	40.101	40.141	40.180	40.219	40.259	40.298	40.337	40.376	40.415	40.455	40.494	970
980	40.494	40.533	40.572	40.611	40.651	40.690	40.729	40.768	40.807	40.846	40.885	980
990	40.885	40.924	40.963	41.002	41.042	41.081	41.120	41.159	41.198	41.237	41.276	990
1000	41.276	41.315	41.354	41.393	41.431	41.470	41.509	41.548	41.587	41.626	41.665	1000
1010	41.665	41.704	41.743	41.781	41.820	41.859	41.898	41.937	41.976	42.014	42.053	1010
1020	42.053	42.092	42.131	42.169	42.208	42.247	42.286	42.324	42.363	42.402	42.440	1020
1030	42.440	42.479	42.518	42.556	42.595	42.633	42.672	42.711	42.749	42.788	42.826	1030
1040	42.826	42.865	42.903	42.942	42.980	43.019	43.057	43.096	43.134	43.173	43.211	1040
1050	43.211	43.250	43.288	43.327	43.365	43.403	43.442	43.480	43.518	43.557	43.595	1050
1060	43.595	43.633	43.672	43.710	43.748	43.787	43.825	43.863	43.901	43.940	43.978	1060
1070	43.978	44.016	44.054	44.092	44.130	44.169	44.207	44.245	44.283	44.321	44.359	1070
1080	44.359	44.397	44.435	44.473	44.512	44.550	44.588	44.626	44.664	44.702	44.740	1080
1090	44.740	44.778	44.816	44.853	44.891	44.929	44.967	45.005	45.043	45.081	45.119	1090
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140
1150	46.995	47.033	47.070	47.107	47.144	47.181	47.218	47.256	47.293	47.330	47.367	1150
1160	47.367	47.404	47.441	47.478	47.515	47.552	47.589	47.626	47.663	47.700	47.737	1160
1170	47.737	47.774	47.811	47.848	47.884	47.921	47.958	47.995	48.032	48.069	48.105	1170
1180	48.105	48.142	48.179	48.216	48.252	48.289	48.326	48.363	48.399	48.436	48.473	1180
1190	48.473	48.509	48.546	48.582	48.619	48.656	48.692	48.729	48.765	48.802	48.838	1190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
1200	48.838	48.875	48.911	48.948	48.984	49.021	49.057	49.093	49.130	49.166	49.202	1200
1210	49.202	49.239	49.275	49.311	49.348	49.384	49.420	49.456	49.493	49.529	49.565	1210
1220	49.565	49.601	49.637	49.674	49.710	49.746	49.782	49.818	49.854	49.890	49.926	1220
1230	49.926	49.962	49.998	50.034	50.070	50.106	50.142	50.178	50.214	50.250	50.286	1230
1240	50.286	50.322	50.358	50.393	50.429	50.465	50.501	50.537	50.572	50.608	50.644	1240
1250	50.644	50.680	50.715	50.751	50.787	50.822	50.858	50.894	50.929	50.965	51.000	1250
1260	51.000	51.036	51.071	51.107	51.142	51.178	51.213	51.249	51.284	51.320	51.355	1260
1270	51.355	51.391	51.426	51.461	51.497	51.532	51.567	51.603	51.638	51.673	51.708	1270
1280	51.708	51.744	51.779	51.814	51.849	51.885	51.920	51.955	51.990	52.025	52.060	1280
1290	52.060	52.095	52.130	52.165	52.200	52.235	52.270	52.305	52.340	52.375	52.410	1290
1300	52.410	52.445	52.480	52.515	52.550	52.585	52.620	52.654	52.689	52.724	52.759	1300
1310	52.759	52.794	52.828	52.863	52.898	52.932	52.967	53.002	53.037	53.071	53.106	1310
1320	53.106	53.140	53.175	53.210	53.244	53.279	53.313	53.348	53.382	53.417	53.451	1320
1330	53.451	53.486	53.520	53.555	53.589	53.623	53.658	53.692	53.727	53.761	53.795	1330
1340	53.795	53.830	53.864	53.898	53.932	53.967	54.001	54.035	54.069	54.104	54.138	1340
1350	54.138	54.172	54.206	54.240	54.274	54.308	54.343	54.377	54.411	54.445	54.479	1350
1360	54.479	54.513	54.547	54.581	54.615	54.649	54.683	54.717	54.751	54.785	54.819	1360
1370	54.819	54.852	54.886									1370
°C	0	1	2	3	4	5	6	7	8	9	10	°C

AN929

Temperature Measurement Circuits for Embedded Applications

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INTRODUCTION

This application note shows how to select a temperature sensor and conditioning circuit to maximize the measurement accuracy and simplify the interface to the microcontroller. Practical circuits and interface techniques will be provided for embedded applications with thermocouples, Resistive Temperature Detectors (RTDs), thermistors and silicon integrated circuit temperature sensors. The attributes of each temperature sensor and the advantages of analog, frequency, ramp rate, duty cycle, serial and logic output solutions will be discussed. An analog output thermocouple circuit will be compared with a frequency output RTD oscillator circuit, along with design examples using serial and analog output silicon Integrated Circuit (IC) sensors. In addition, a Programmable Gain Amplifier (PGA) circuit will be shown that can increase the effectiveness of the Analog-to-Digital Converter (ADC) bit resolution of a non-linear thermistor sensor.

DEFINITIONS

The following terms are used in this application note:

- Accuracy is the difference between the true and measured temperature
- Common Mode Rejection Ratio (CMRR) is defined as the ability of the amplifier to reject a signal which is common to both inputs
- Input Offset Voltage (V_{OS}) is the voltage that must be applied to an amplifier to produce a zero volt output
- Local sensors are located on the same PCB as the microcontroller
- Precision is the ability to measure a small temperature gradient and determines the interchangeability of the sensor
- Remote sensors are located at a distance from the microcontroller's PCB
- Repeatability is the sensor's ability to reproduce previously measured values
- Stability is defined as the long-term drift of the sensor over a period of time

SENSOR-TO-MICROCONTROLLER INTERFACE OPTIONS

The sensor interface option is selected by evaluating the complexity of the sensor circuitry, in addition to the required hardware and software trade-offs of the microcontroller. The available sensor interface options that are proportional to temperature include:

- Analog
- Frequency
- Ramp Rate
- Duty Cycle
- Serial Output
- Logic Output

Analog Output

Thermocouples, RTDs and thermistors can be interfaced to an amplifier circuit to provide a voltage which is proportional to temperature. Analog output silicon sensors are available that integrate the sensor and the signal conditioning circuit. Figure 1 shows a block diagram of a typical analog interface circuit.

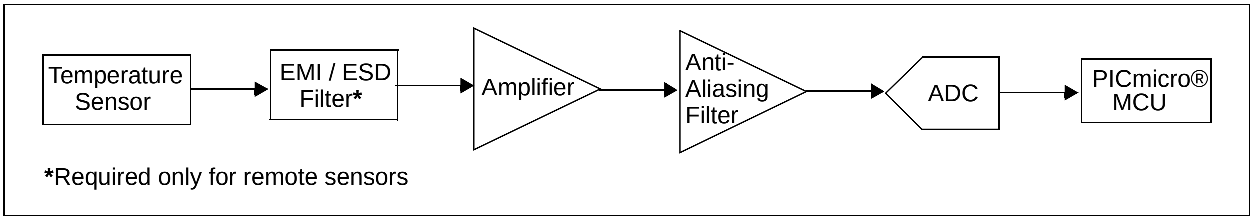


FIGURE 1: *Block Diagram of an Analog Output Sensor.*

Frequency Output

Oscillators provide a frequency output proportional to temperature that can be interfaced to a microcontroller, as shown in Figure 2. While a Resistor-Capacitor (RC) operational amplifier (op amp) oscillator can accurately measure the resistance of an RTD, this circuit is typically not used with a thermistor because of the large logarithmic change in the sensor's resistance over temperature. The main advantage of a frequency output is that an ADC is not required. A frequency output is also useful in applications where the sensor conditioning circuitry is combined with a remote sensor. A logic-level output signal is less sensitive to noise than an analog output signal that transmits information to the microcontroller.

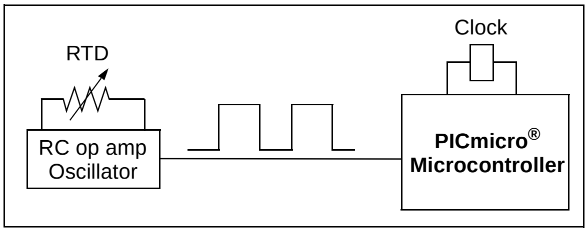


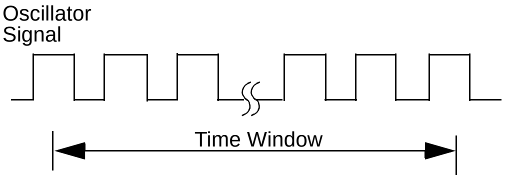
FIGURE 2: *Block Diagram of a Frequency Output Sensor.*

The accuracy of the frequency measurement is directly related to the quality of the microcontroller's clock signal. Precision high-frequency microcontroller clock oscillators are readily available. However, they are relatively expensive. The two options available to measure frequency are the fixed time or fixed cycle methods. The microcontroller resources required for determining frequency varies depending upon the processor bandwidth, available peripherals and desired measurement accuracy.

FIXED TIME METHOD

The fixed time method, shown in Figure 3, consists of counting the number of pulses within a specific time window, such as 100 ms. The frequency is then calculated by multiplying the count by the integer required to correlate the number of pulses in one second. This measurement approach inherently minimizes the effect of error sources (such as jitter) by averaging many oscillator pulses in the time window. The fixed time method utilizes a firmware delay or hardware delay routine. The firmware can poll for input edges, though this consumes processor bandwidth. A more common implementation uses a hardware timer/counter to count the input cycles during a firmware delay. If a second timer is available, the delay can be generated using this timer, thus requiring minimal processor bandwidth.

Algorithm:
Count the number of clock pulses in a time window.



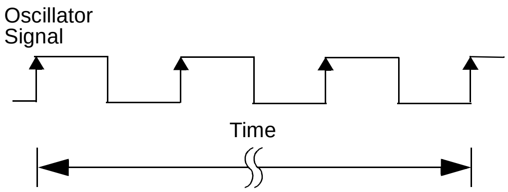
Example: Measure the number of oscillation pulses in a 100 msec. window and multiply by 10 to determine the frequency.

FIGURE 3: *Frequency Output - Fixed Time Method.*

FIXED CYCLE METHOD

In the fixed cycle method, shown in Figure 4, the number of cycles measured is fixed and the measurement time is variable. This approach measures the elapsed time for a fixed number of cycles. The number of cycles is chosen by the designer based on the desired accuracy, input frequency, measurement rate and the microcontroller clock frequency (F_{OSC}). F_{OSC} determines the minimum time an edge can be resolved. The measurement error will then be proportional to the total amount of time versus F_{OSC}. Increasing the number of cycles measured will increase the measurement time and reduce the error. Increasing F_{OSC} will also decrease the minimum time to resolve an edge, thereby reducing the error.

Algorithm:
Determine the time between a fixed number of oscillation pulses.



Example: Measure time between four rising edges of the oscillation signal.

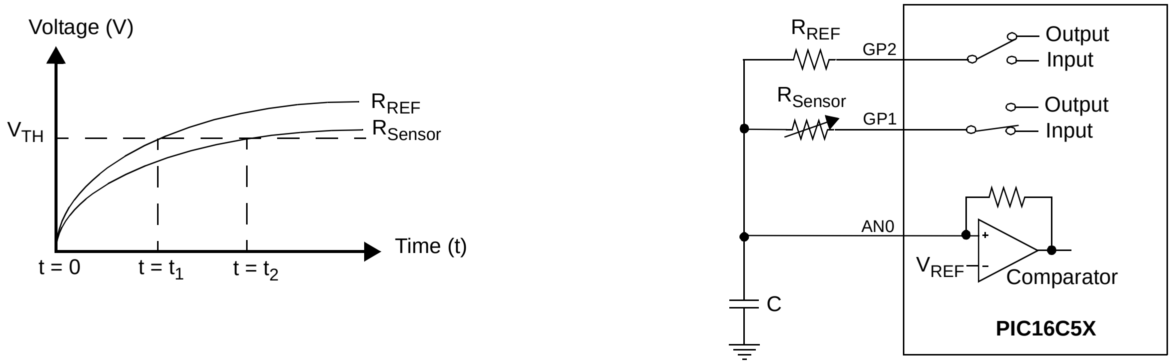
FIGURE 4: *Frequency Output - Fixed Cycle Method.*

The fixed cycle method can utilize firmware to both measure time and poll the input edges. This, however, is processor-intensive and has accuracy limitations. For example, a more common implementation is to utilize the Capture/Compare/PWM (CCP) module of a PICmicro® microcontroller configured in the Capture mode. This approach uses the 16-bit timer TMR1 peripheral and has excellent accuracy and range.

Ramp Rate Method

The resistor-capacitor (RC) ramp rate method shown in Figure 5 provides a simple solution for resistive sensors, such as thermistors. This method provides a low-cost solution with an accuracy of approximately ±1%. When voltage is applied to a RC combination, the capacitor's voltage will increase exponentially and the ramping time can be measured with a comparator. The accuracy of the RC timing method can be improved by comparing the ramp rates of a sensor resistor (R_{Sensor}) and a known resistance (R_{REF}) to reduce the effects of temperature and component tolerance.

The RC timing method can be implemented using the circuitry inside a microcontroller. The timing measurement begins by configuring the GP1 pin as a logic ‘`1`’ output and GP2 as an input. This connects R_{SENSOR} to a logic-high voltage ($V_{OH} \cong V_{DD}$), while R_{REF} is disconnected from the circuit via the high impedance of an input pin. The I/O pin AN0 is configured as an input and connects the capacitor to a comparator inside the microcontroller. The time required for the capacitor voltage to ramp-up to the reference voltage of the comparator ($V_{TH} \cong V_{REF}$) can be determined through either a hardware or software timer. Once the measurement is completed, the GP1 pin is toggled to a logic ‘`0`’ output to discharge the capacitor. The configuration procedure of GP1 and GP2 is then reversed in order to measure R_{REF}.



$$V_c(t) = V_{DD}\left(1 - e^{\frac{-t}{RC}}\right) \qquad t = -RC\, In\left(1 - \frac{V_{TH}}{V_{DD}}\right) \qquad R_{Sensor} = \left(\frac{t_2}{t_1}\right)R_{REF}$$

FIGURE 5: *Ramp Rate Method.*

Duty Cycle Output

Silicon IC sensors that provide an output proportional to the duty cycle of a digital signal are available, as shown in Figure 6. These sensors typically have a constant "on" time (t_1) and a variable "off" time (t_2). However, it is often necessary to calculate the t_1-to-t_2 ratio in order to achieve the specified sensor accuracy. It is possible to have a duty cycle output with a thermocouple, RTD or thermistor. However, the circuit is relatively complex when compared to other signal conditioning options.

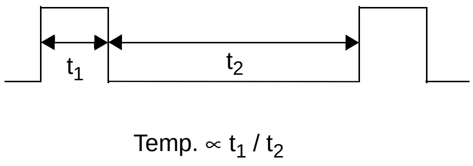


FIGURE 6: *Duty Cycle Output.*

Serial Output

Serial output sensors measure temperature and communicate with the processor via a standard serial data protocol, such as the SPI™, I^{2}C™ or SMBus protocols. Silicon IC sensors are available that integrate the temperature sensor, ADC and temperature detection logic on a single chip. Thermocouple and RTD ASICs are available that have an amplifier, ADC and linearization logic integrated into a single IC. Serial output sensors offer the advantage of reducing the system component count, as well as using digital logic to provide a linear output.

Figure 7 provides an example of the timing diagram of the SPI serial output of the TC77 silicon IC sensor where the temperature data is represented by a 13-bit two's complement digital word. The SPI serial interface consists of the Chip Select (CS), Serial Clock (SCK) and bidirectional Serial Data (SI/O) signals. Communication with the TC77 is initiated when the CS goes to a logic '`0`' and the SI/O then transmits the first bit of data. The Least Significant Bit (LSB) is equal to 0.0625°C. The SCK input is provided by the microcontroller and data is transferred on the rising edge of SCK. Once 13 bits of data have been transmitted, the SI/O line is then tri-stated.

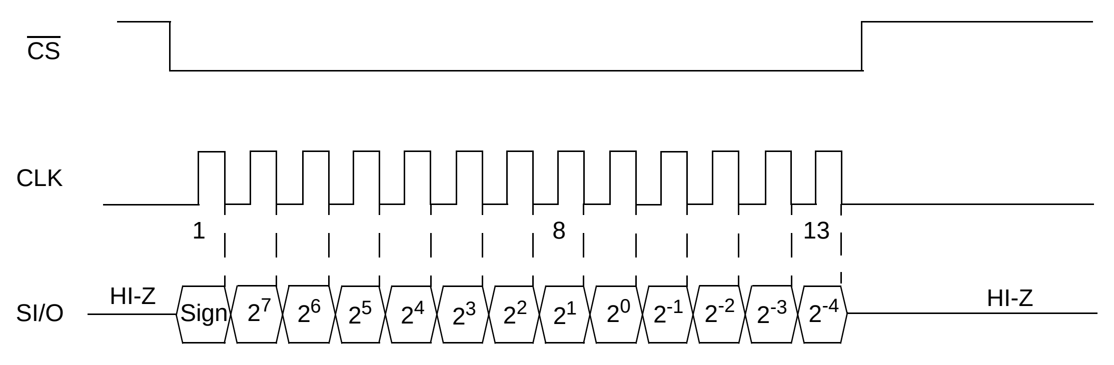


FIGURE 7: *TC77 SPI Serial Output Silicon IC Sensor.*

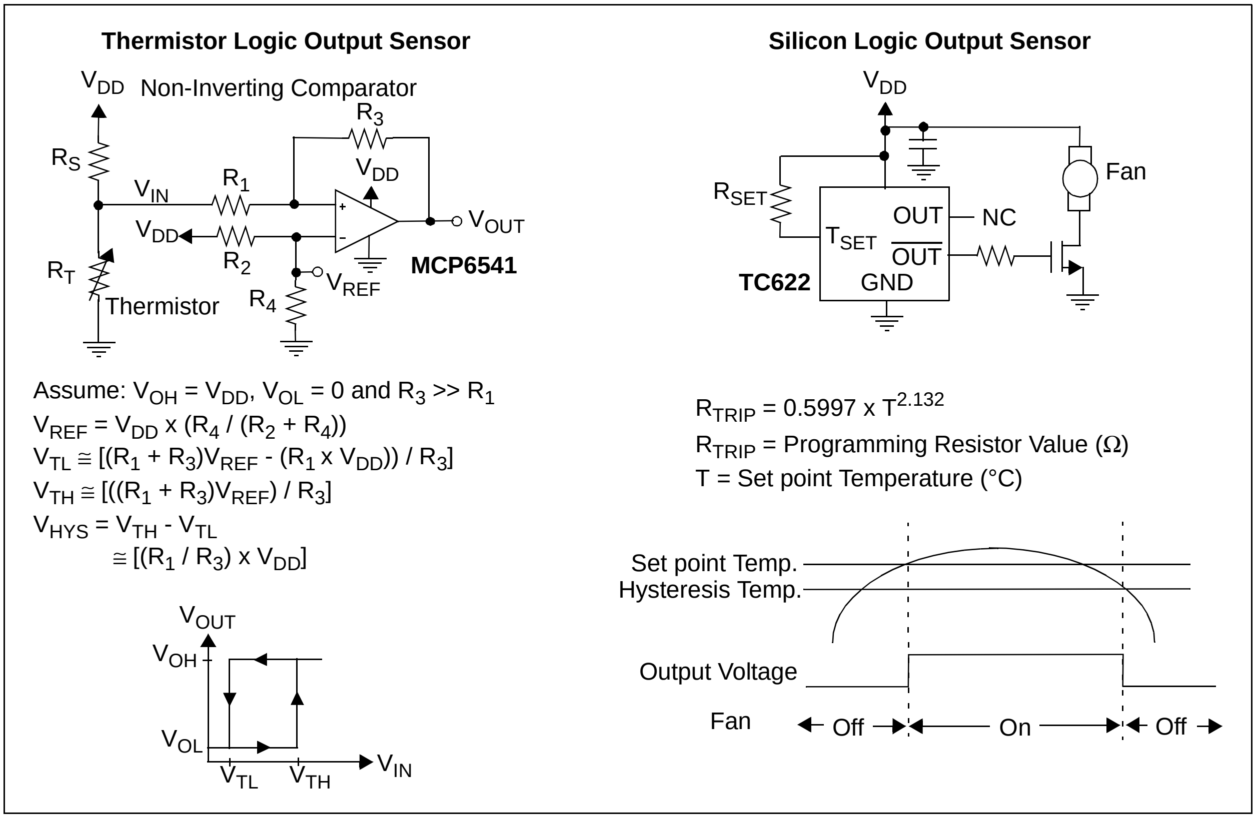
Logic Output Sensors

Logic output sensors are sometimes referred to as temperature switches because they typically function as a thermostat to notify the system that a maximum or minimum temperature limit has been detected. Figure 8 shows an example of a thermistor and silicon logic output sensor.

The features of logic output sensors include:

- Logic level output
- Output indicates that the temperature is above (or below) a preset value
- Available in both push-pull and open-drain configurations
- Output signal can be either active-low or high
- Either factory or user-programmable temperature settings

Logic level output sensors are similar to analog output sensors, except that the output amplifier of the sensor is a comparator. The comparator circuit sets the switch point of the sensor through either internal or external resistors. The output is typically not latched and, thus, the switch will turn-off when the temperature falls below the temperature set point. Note that it is necessary to have hysteresis so the switch does not "chatter" when crossing the temperature setpoint.



Assume: $V_{OH} = V_{DD}$, $V_{OL} = 0$ and $R_3 >> R_1$

$V_{REF} = V_{DD} \times (R_4 / (R_2 + R_4))$

$V_{TL} \cong [(R_1 + R_3)V_{REF} - (R_1 \times V_{DD})) / R_3]$

$V_{TH} \cong [((R_1 + R_3)V_{REF}) / R_3]$

$V_{HYS} = V_{TH} - V_{TL}$

$\cong [(R_1 / R_3) \times V_{DD}]$

$R_{TRIP} = 0.5997 \times T^{2.132}$

R_{TRIP} = Programming Resistor Value (Ω)

T = Set point Temperature (°C)

FIGURE 8: Logic Output Sensors.

Most logic output sensors are available in either a hot or cold option, as shown in Figure 9. The hot and cold options are used to allow the flexibility of using the switch in either hot (temperature increasing) or cold (temperature decreasing) sensing applications. The hot and cold options ensure that the hysteresis is in the appropriate position, either below or above the temperature set point.

For example, assume that the temperature switch is being used to turn on a cooling fan. The setpoint is 75°C and the hysteresis is 10°C. A sensor with the hot option will switch to the active logic level at 75°C. The sensor will remain in the on condition and the fan will run until the temperature drops to 65°C, or 10°C below the temperature setpoint.

In contrast, assume that a cold option switch is used in an application that requires a heater to turn on to prevent freezing. Assume that the temperature set point is 0°C and the hysteresis is 10°C. The cold option sensor will switch to the active logic level at 0°C and turn on the heater. The sensor will remain in the on condition until the temperature increases to 10°C, or 10°C above the temperature set point.

Hot Option

$T_{SET} > T_{HYS}$

"ON" if temperature > T_{SET}

"OFF" if temperature < T_{HYS}

Cold Option

$T_{SET} < T_{HYS}$

"ON" if temperature < T_{SET}

"OFF" if temperature > T_{HYS}

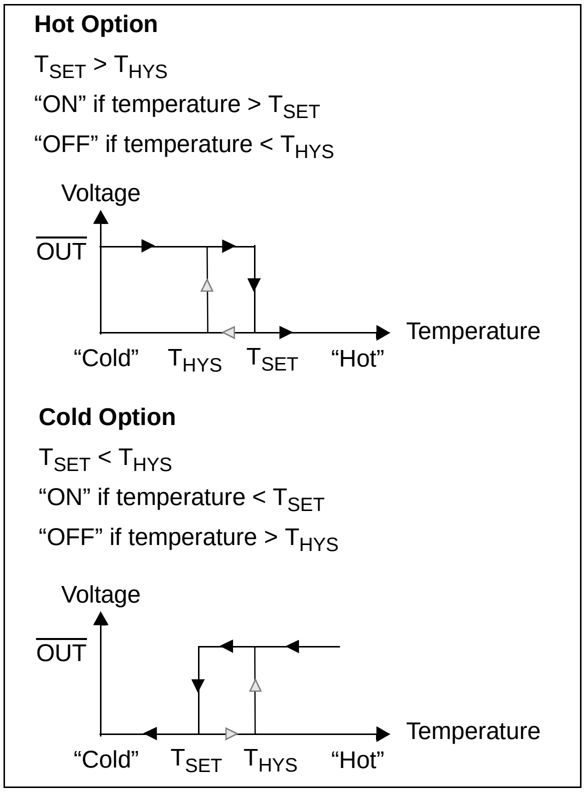


FIGURE 9: Logic Output Sensors - Hot and Cold Options.

SYSTEM INTEGRATION ISSUES

Local versus Remote Sensing

The location of the sensor relative to the conditioning circuit, as shown in Figure 10, plays a key role in selecting the appropriate interface and noise reduction circuit. Local sensors are located relatively close to their signal conditioning circuits. Therefore, the noise environment usually is not as severe as remote sensors. In contrast, remote sensors are connected to the amplifier via long wires that often introduce noise into the electronics. A non-inverting amplifier circuit is a good choice for a local sensor, while a remote sensor requires a differential measurement in order to cancel noise. All sensors should be considered as remote sensors in high-noise environments or precision applications to take advantage of the high CMRR and noise reduction of a differential amplifier.

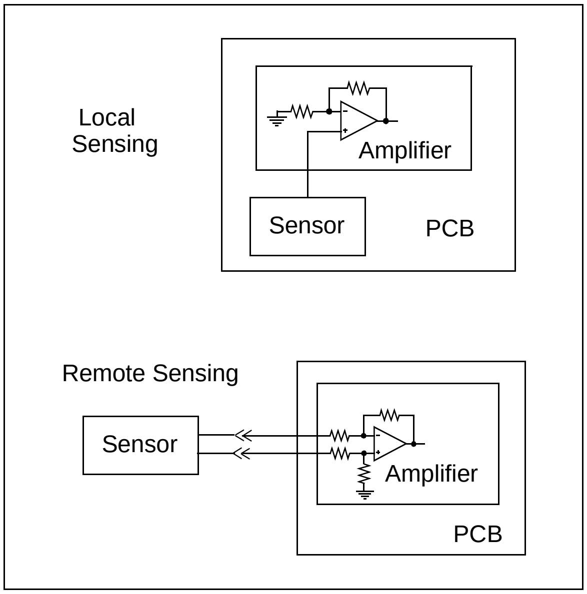


FIGURE 10: *Local versus Remote Sensing.*

Noise Reduction Techniques

Accurate temperature measurements require careful attention to noise reduction techniques. The high CMRR of the differential amplifier reduces noise. However, grounding, shielded cables and Electromagnetic Interference/Electro-Static Discharge (EMI/ESD) filters are also required to prevent noise from degrading the accuracy of the measurement.

Grounding

Figure 11 shows four basic methods of grounding a sensor. A grounded source has its negative terminal connected to ground at the sensor, often by virtue of the mechanical mounting of the sensor. In contrast, a floating source connects the sensor's negative terminal to ground at the amplifier.

The preferred grounding configuration for a remote sensor is shown in circuits B and D. These circuits provide for a two-wire differential measurement that can be implemented with either a differential or instrumentation amplifier. A differential measurement requires that the common mode voltage level of the signal source does not exceed the amplifier's maximum input voltage specification. As shown in circuit D, adding bias resistors to reference the input signal to a known voltage can solve this problem and the resistors will not affect the measurement, if they are relatively large.

The grounding methods of circuits A and C provide a single-ended input measurement that should only be used with a local sensor. The separate sensor and amplifier grounds of circuit A can produce an offset voltage due to the difference in the voltage potentials of the two grounds. In local sensor applications, the magnitude of ΔV_{GND} is small and either an inverting or non-inverting op amp can be used. The configuration of circuit C should be used with caution in low signal output sensors such as thermocouples. Noise can be induced into the measurement via the thermocouple wires and the magnitude of the sensor voltage will be affected by ground bounce or switching noise at the amplifier's ground.

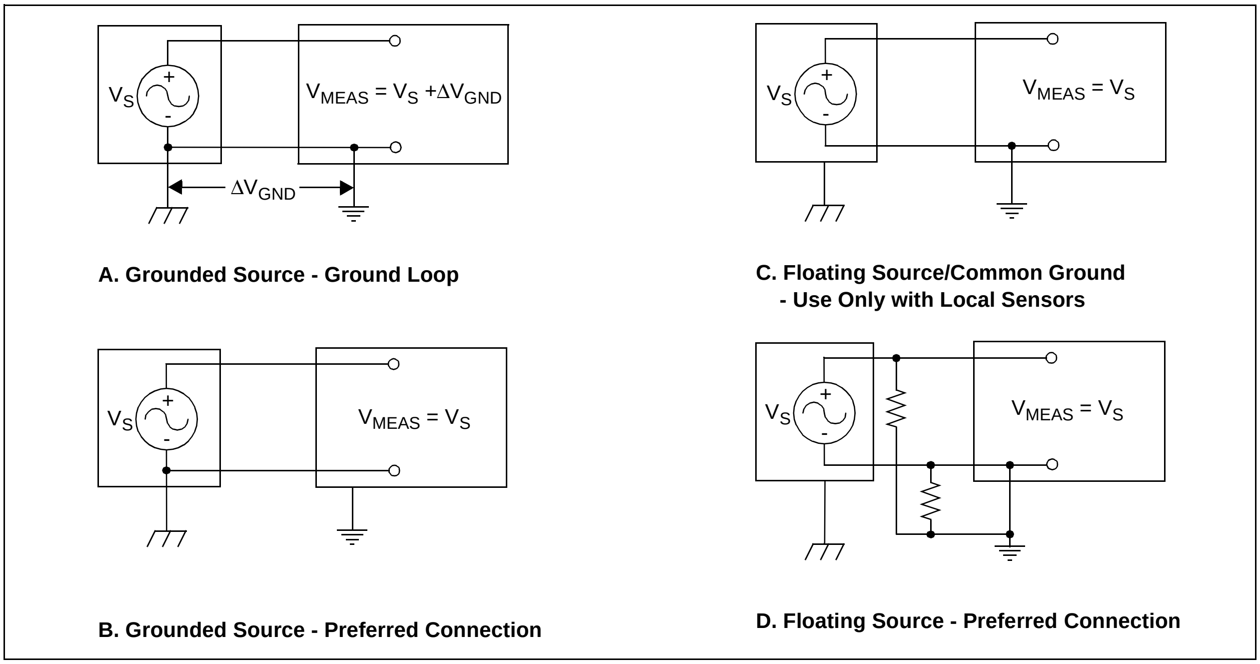


FIGURE 11: *Accurate Measurements Require Careful Grounding.*

Shielded Cables

A shielded cable is an effective tool to prevent radiated interference from introducing a noise voltage on the signal wires. Shielded twisted-pair cables reduce the loop area of the victim signal and minimize the voltage induced on the sensor signal lines. The noise signals on each wire in the cable will be essentially equal, which is the assumption needed for the high CMRR feature of a differential amplifier to cancel the interference. For most applications, it is recommended that the shield be connected to ground only at one point. In applications using a metal enclosure, the shield's connection to chassis ground can occur through the mechanical connection of the cable connector to the box. Figure 12 provides an example of a remote RTD measurement using a shielded cable.

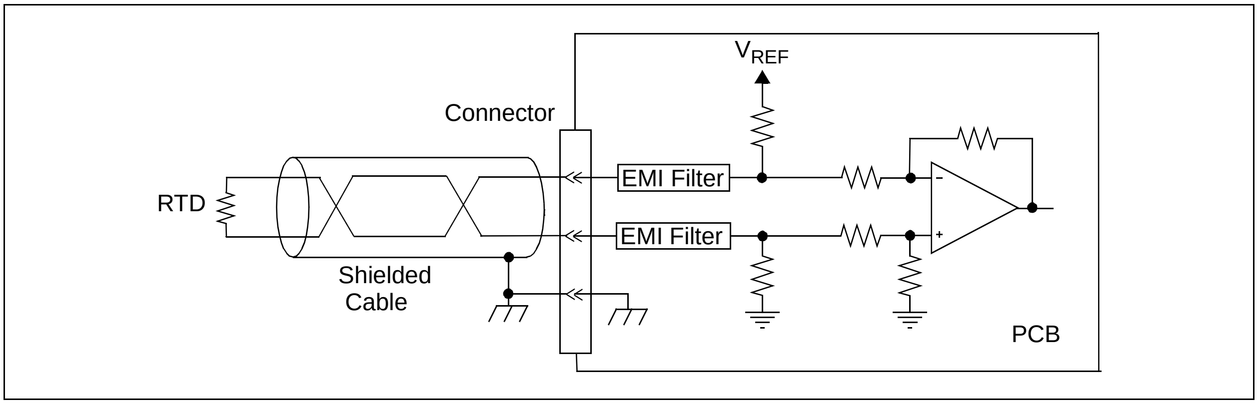


FIGURE 12: *Use Shielded Cables and EMI Filters for Remote Measurements.*

EMI/ESD Protection

EMI and ESD filters function as both a noise filter and a protective device to the circuit on the PCB. An IC input pin should never be connected directly to a remote sensor because EMI or ESD overvoltage failures will likely occur. Ferrite beads, capacitive feed-through filters, RC filters and transient-voltage-suppressor (TVS) zener diodes are popular devices that can be used to provide protection for the sensor circuit.

Ferrite beads, capacitive feed-through filters and RC filters function as filters and only limit the slew rate of a transient-input voltage. A voltage-clamping device (such as a TVS zener diode) is required to limit the input voltage to a safe value that will not damage the IC amplifier. Though a TVS device is similar to a standard zener diode, they are designed to turn on fast and dissipate a short duration, high-peak energy voltage transient. In contrast, a zener diode is designed to clamp a steady-state voltage for a long duration.

In many applications, a combination of different EMI/ESD filter devices are often used. One option is to use a capacitive feed-through filter that is located inside the connector, in addition to TVS and RC filters which are placed on the PCB board, as shown in Figure 13. Feed-through capacitors are typically mounted on a conductive chassis, with the mechanical mounting forming the ground connection. The noise signal is filtered at the connector before the signal reaches the PCB. The effectiveness of the filter is usually very good because the inductance associated with the ground connection is minimized. The TVS diodes on the PCB ensure that the transient voltage is limited to a safe value, while the RC filters provide additional filtering to the instrumentation amplifier.

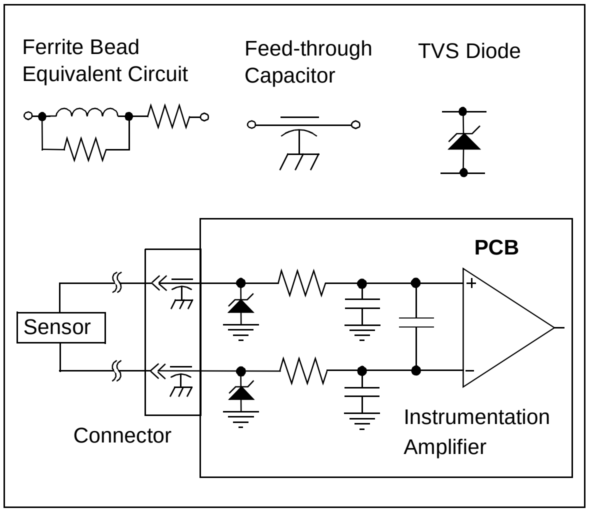
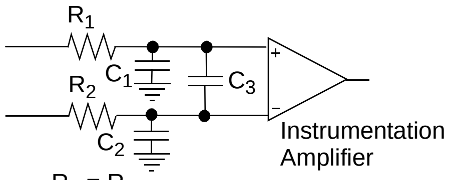


FIGURE 13: *Remote Sensors May Require Multiple EMI Filter Devices.*

Figure 14 provides the design equations for a RC filter which can be used with differential and instrumentation amplifiers. The RC combinations of R_1/C_1 and R_2/C_2 are used to form common mode filters and reduce the noise which is common to both input lines. The common-mode resistors and capacitors should be matched as close as possible and the resistors should have a tolerance of 1% or better, while the capacitors should be at least 5%. Capacitor C_3 forms a differential mode filter that attenuates the signal with respect to the difference in the voltage potentials of the two inputs. C_3 also compensates for any mismatch of R_1/C_1 and R_2/C_2, which is important because the difference in the R/C combinations degrades an amplifier's CMRR.



$R_1 = R_2$
$C_1 = C_2$
$C_3 >> C_1$ and C_2

Common Mode Filters
$f_{-3dB} = 1/(2\pi R_1C_1)$
$f_{-3dB} = 1/(2\pi R_2C_2)$

Differential Mode Filter

$$f_{-3db} = \frac{1}{2\pi(R_1 + R_2)\left[\left(\frac{C_1 \times C_2}{C_1 + C_2}\right) + C_3\right]}$$

FIGURE 14: *Providing EMI/ESD Overvoltage Protection with Resistors and Capacitors.*

Fault Detection Capability

It is often necessary to identify a failed sensor, especially in remote-sensing applications. Differential amplifiers can be used to implement a Built-In-Test (BIT) circuit that can determine an open or short failure at the sensor. Figure 15 shows circuits that can be used to detect a failed RTD and thermocouple. A logic inverter gate can be used to monitor the voltage divider network of a RTD. Another approach to provide BIT to a sensor is to add pull-up or pull-down resistors, or both, as shown in Figure 15.

The typical failure mode of RTDs and thermocouples is an open-circuit failure. Wire wound RTDs are constructed from a relatively small gauge wire and are prone to vibration failures. Thermocouple wires can also fail due to vibration because the wires get brittle over time when exposed to high temperatures. Also, the voltage at the amplifier inputs resulting from noise can be equal in magnitude to a functional thermocouple.

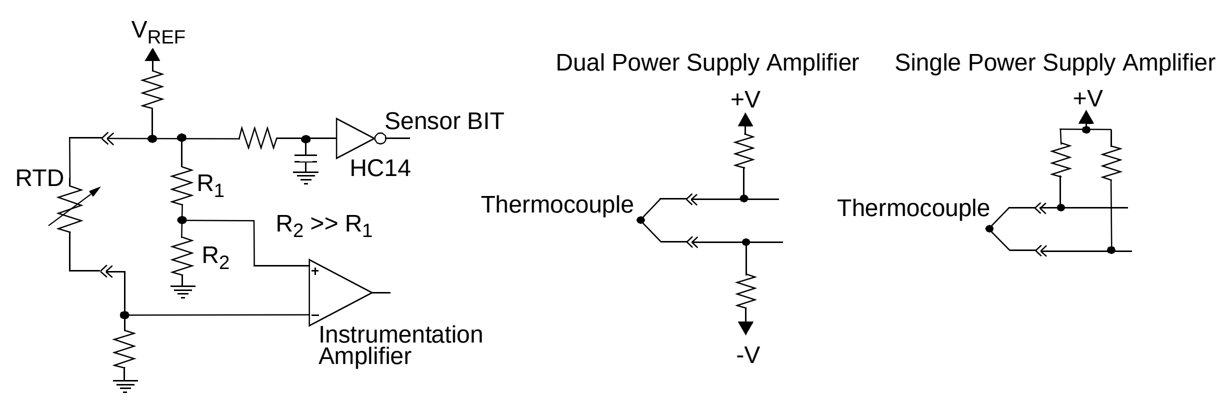


FIGURE 15: *Remote Sensor Fault Detection Circuits.*

Amplifier Selection Criteria

Two key op amp specifications in a sensor amplifier are V_{OS} and CMRR. V_{OS} is important in sensor applications when the input signal is of the same magnitude as V_{OS}, while the CMRR ratio is critical in reducing the noise signal induced on the long wires of a remote sensor. Other op amp specifications, such as the AC frequency characteristics are less important because the frequency content of a temperature sensor is typically less than 100 Hz. The op amps used in oscillators are relatively immune to DC specifications such as V_{OS}. The important parameters for oscillators are the amplifier's frequency response and the Gain Bandwidth Product (GBWP). The op amp's GBWP should be at least a factor of 100 times the maximum oscillation frequency.

SENSOR SELECTION CRITERIA

Table 1 provides a summary of the attributes of thermocouples, RTDs, thermistors and silicon IC sensors.

TABLE 1: ATTRIBUTES OF THERMOCOUPLES, RTDS, THERMISTORS AND SILICON IC SENSORS

Attribute	Thermocouple (type K)	RTD	Thermistor	Silicon IC
Range	-184°C to 1260°C	-200°C to 850°C	-55°C to 150°C	-55°C to 125°C
Temperature (t) Accuracy	Greater of ±2.2°C or ±0.75%	Class B = ± [0.012 + (0.0019 |t|) – 6 X $10^{-7}t^2$]	Various, ±0.5°C to 5°C	Various, ±0.5°C to 4°C
Output Signal	40 µV/°C	≈ 0.00385 Ω /Ω/°C	≈ 4% ΔR/°C for 0°C ≤ t ≤ 70°C	Analog, Serial, Logic, Duty Cycle
Linearity	Fair	Excellent	Poor	Good
Precision	Fair	Excellent	Poor	Fair
Durability	Good at lower temp., Poor at high temp, Open-circuit vibration failures	Good, Wire wound prone to open-circuit vibration failures	Good, Power derated with temperature	Excellent
Thermal Response Time	Fast (function of probe material)	Fast (function of probe material)	Moderate	Slow
Cost	Low	Wire wound – High, Thin-film – Moderate	Low	Moderate
Interface Issues	Cold junction compensation, Small ΔV	Small ΔR/°C	Non-linear resistance	Sensor located on PCB

Thermocouples

Thermocouples are the most common sensor used in high-temperature measurements. A thermoelectric electromagnetic-force (emf) or voltage results when two dissimilar metals are joined together that produce an output voltage that is proportional to temperature. Figure 16 shows a block diagram of a typical thermocouple system. The thermocouple probes are typically located remotely from the amplifier circuit and are connected to the amplifier via the thermocouple wires that enter the enclosure through a connector. The cold junction occurs at the point where the copper wires of the PCB meet the Alumel and Chromel connector pins. The cold junction will be formed at the inside wall of the enclosure if the connector uses Alumel and Chromel pins. The temperature of the cold junction or "isothermal block" is estimated by a sensor that is located as close as possible to the connector on the PCB.

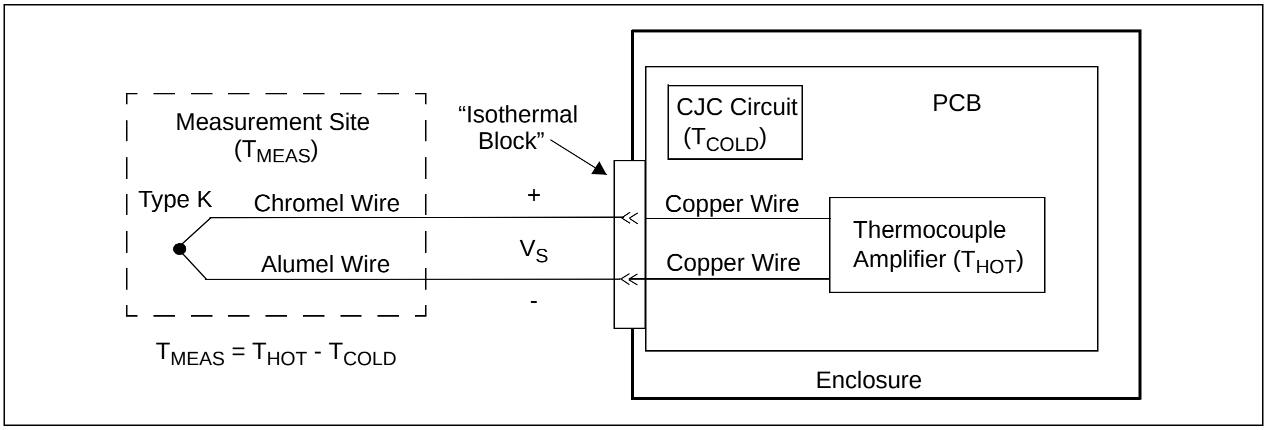


FIGURE 16: *Thermocouple Basics – Typical Measurement System.*

RTDs

RTDs are the standard sensor chosen for precision sensing applications because of their excellent repeatability and stability characteristics. RTDs are based on the principle that the resistance of a metal changes with temperature. A RTD can be characterized against temperature to obtain a table of temperature correction coefficients. The correction can be added to the measured temperature to obtain an accuracy greater than 0.05°C. RTDs are available in two basic designs: wire wound and thin film. Wire wound RTDs are built by winding the sensing wire around a core to form a coil, while thin film RTDs are manufactured by depositing a very thin layer of platinum on a ceramic substrate.

Thermistors

The main advantages of thermistors are that they are inexpensive and available in a wide variety of packages. Thermistors are built with semiconductor materials and can have either a positive (PTC) or a negative (NTC) temperature coefficient. However, the NTC devices are typically used for temperature sensing. The main negative feature of thermistors is that the change in resistance with temperature is very non-linear at temperatures less than 0°C and greater than 70°C.

Silicon Integrated Circuits

Silicon IC sensors provide an accurate temperature measurement for a steady-state or relatively constant temperature. However, their thermal response time to a rapid change in temperature is poor. Silicon sensors provide a non-contact temperature measurement. Thus, the location of the sensor is important. These sensors measure temperature by monitoring the voltage of a diode located on the IC die, as shown in Figure 17. The substrate of the die is typically grounded and connected to the PCB's ground plane via a bonding wire and the lead of the package. The ground pin of the IC provides a low-impedance thermal path between the die and the PCB, allowing the sensor to effectively monitor the temperature of the PCB board. The thermal path between the top of the package to the ambient air and between the bottom of the package and the PCB is not as efficient because the plastic IC housing package functions as a thermal insulator. Silicon sensors provide a measurement of the temperature of the PCB's ground plane and the ambient air temperature has only a small effect on the measurement.

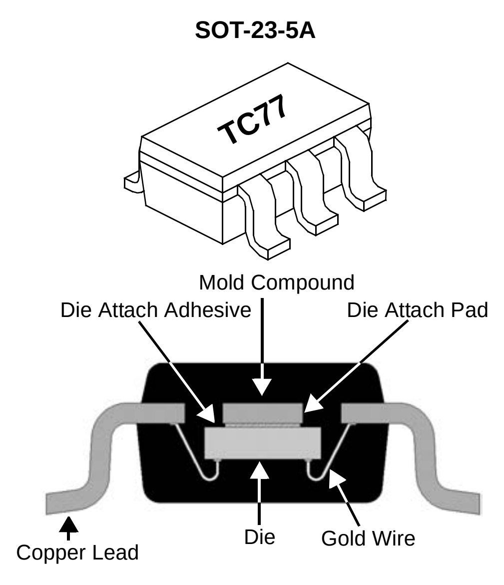


FIGURE 17: *Cross-section of the TC77 Silicon IC Sensor.*

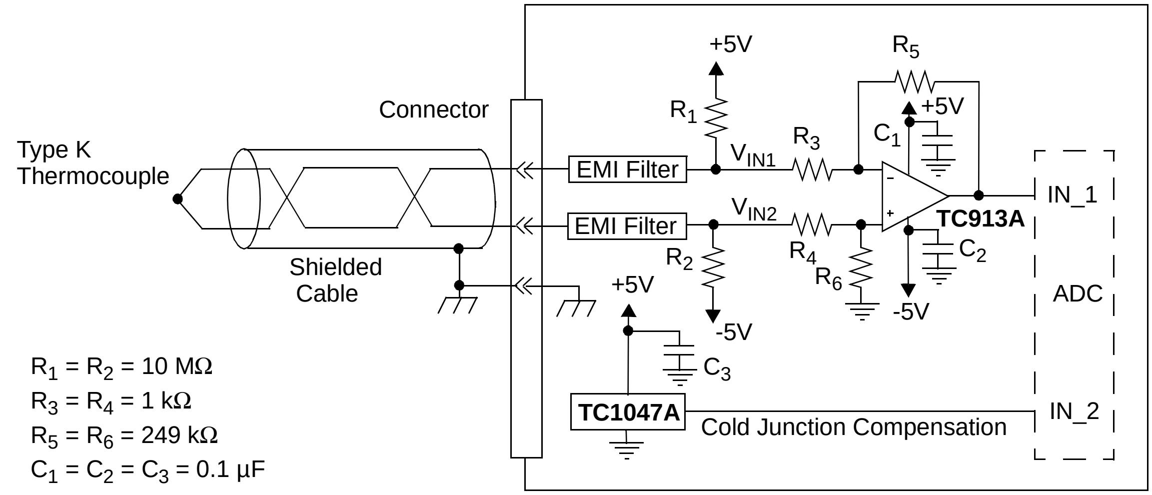
Noise immunity can be provided to silicon sensors by using a decoupling capacitor and a good PCB layout. A 0.1 µF to 1 µF decoupling capacitor should be inserted between the power supply and ground pins. The PCB should be designed with the standard layout guidelines used for a low-noise circuit. The temperature sensor's main thermal path to the PCB is through the ground connection. Thus, the size of the ground pad at the sensor should be as large as possible. A good PCB layout keeps high-frequency clock and switching power supply PCB traces away from the sensor pins.

DESIGN EXAMPLES

Thermocouple Circuits

DUAL POWER SUPPLY CIRCUIT

Figure 18 shows a circuit that can be used for a remote thermocouple-sensing application. A TC913A auto-zeroed op amp was selected as the amplifier because of its low V_{OS} of 15 mV (max.) and high CMRR of 116 dB (typ.). Auto-zero, chopper and instrumentation amplifiers are good thermocouple amplifiers because of their good V_{OS} and CMRR specifications. The thermocouple inputs are tied to a positive and negative supply through 10 MΩ resistors, so that the circuit can detect a failed open-circuit thermocouple. The gain of the amplifier was selected to be 249, which provides a temperature coefficient (TC) of 10 mV/°C.



$$V_{OUT} = (V_{IN2} - V_{IN1})\left(\frac{R_5}{R_3}\right) + V_{REF} = (\Delta V_{IN})\left(\frac{249k}{1k}\right)$$

$$\text{Temp. Coef.} = 249 \times 40\mu V/°C \cong 10mV/°C$$

FIGURE 18: *Schematic of Dual Supply Voltage Thermocouple Amplifier.*

The microcontroller computes the actual temperature by subtracting the cold junction temperature from the temperature determined from the thermocouple amplifier. The cold junction temperature is measured with a TC1047A silicon IC analog output sensor that is located on the PCB. The actual cold junction occurs where the thermocouple wires meet the copper wires, which is typically at a connector. Placing the TC1047A adjacent to the connector can minimize the cold junction error ($T_{CJC\_Location}$) that results by placing the temperature sensor on the PCB. The voltage output of the TC1047A is listed below.

$$V_{OUT} = [(\text{Temp. } (°C)) \times (10\text{ mV}/°C)] + 500\text{ mV}$$

The TC1047A provides an output voltage of 10 mV/°C with an offset of 500 mV.

The accuracy of the thermocouple amplifier and cold junction circuits were estimated to be ±5.4°C by using the root-squared-sum (RSS) equation. The common mode voltage noise signal entering the circuit from the thermocouple leads was assumed to be equal to 10V. It is important to use tight tolerance resistors for the differential amplifier in order to achieve a high CMRR. 0.1% resistors were chosen for R_3, R_4, R_5 and R_6. The analysis shows that the majority of the measurement error is due to the error of the cold junction compensation.

$$CMRR\ Resistors \approx \frac{1 + Amplifier\ Gain}{4 \times Tolerance} = \frac{1 + 249}{4 \times 0.001} = 62500 = 95.9db$$

$$Error\ CMRR\ Resistors = \frac{V_{CM-NOISE}}{CMRR\ Resistors} = \frac{10V}{62500} = 160\mu V \cong 4°C$$

$$CMRR\ Amplifier\ (TC913A) = 116db(typ.)$$

$$Noise\ Attenuation = \frac{1}{630{,}957}$$

$$Error\ CMRR\ Amplifier\ (TC913A) = \frac{V_{CM-NOISE}}{CMRR\ Amplifier\ (TC913A)} = \frac{10V}{630{,}957} = 15.8\mu V \cong 0.4°C$$

$$V_{OS}\ error = \frac{V_{OS}\ (TC913A)}{Temp.\ Coef.\ (type\ K)} = \frac{15\mu V}{40\mu V/°C} \cong 0.4°C$$

$$T_{CJC\_Sensor}\ (TC1047A)\ error = 3°C\ (max.) \qquad T_{CJC\_Location} error = 2°C\ (est.)$$

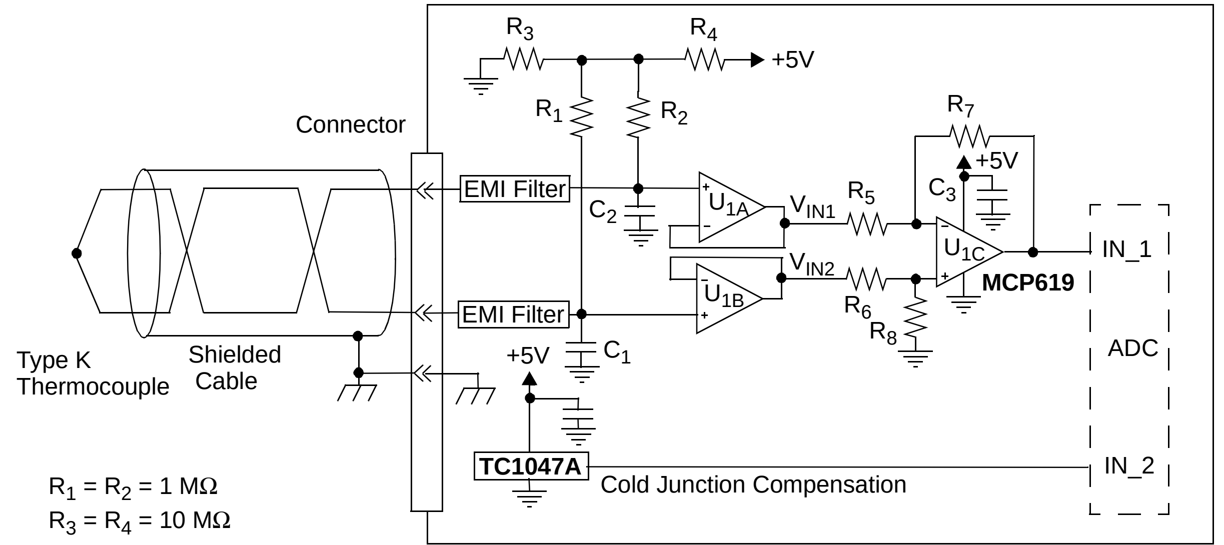
$$Total\ error_{Worst\ Case} = CMRR_{RESISTORS} + CMRR_{AMPLIFIER\ (TC913A)} + V_{OS} + T_{CJC\_Sensor} + T_{CJC\_Location}$$

$$= 4 + 0.4 + 0.4 + 3 + 2 = 9.8°C$$

$$Total\ error_{RSS} = \sqrt{(4)^2 + (0.4)^2 + (0.4)^2 + (3)^2 + (2)^2} = 5.4°C$$

SINGLE POWER SUPPLY CIRCUIT

Figure 19 provides a low-cost, single power supply thermocouple amplifier circuit using a quad op amp. The buffered input differential amplifier topology is similar to an instrumentation amplifier and offers the feature of equal and high input impedance at the amplifier inputs. An instrumentation amplifier with integrated gain resistors can also be used to implement this circuit. The gain of the amplifier was selected to be 249, providing a temperature coefficient of 10 mV/°C. The thermocouple inputs are biased to $V_{DD}/2$ through 10 MΩ resistors, providing the ability to detect a failed open-circuit thermocouple.



$R_1 = R_2 = 1\ \text{M}\Omega$
$R_3 = R_4 = 10\ \text{M}\Omega$
$R_5 = R_6 = 1\ \text{k}\Omega$
$R_7 = R_8 = 249\ \text{k}\Omega$
$C_1 = C_2 = 1\ \text{nF}$
$C_3 = 0.1\ \mu\text{F}$

$$V_{OUT} = (V_{IN2} - V_{IN1})\left(\frac{R_7}{R_5}\right) + V_{REF} = (\Delta V_{IN})\left(\frac{249k}{1k}\right)$$

$$Temp.\ Coef. = 249 \times 40 \mu V/°C \cong 10 mV/°C$$

FIGURE 19: *Schematic of Single Supply Voltage Thermocouple Amplifier.*

RTD Oscillator Circuits

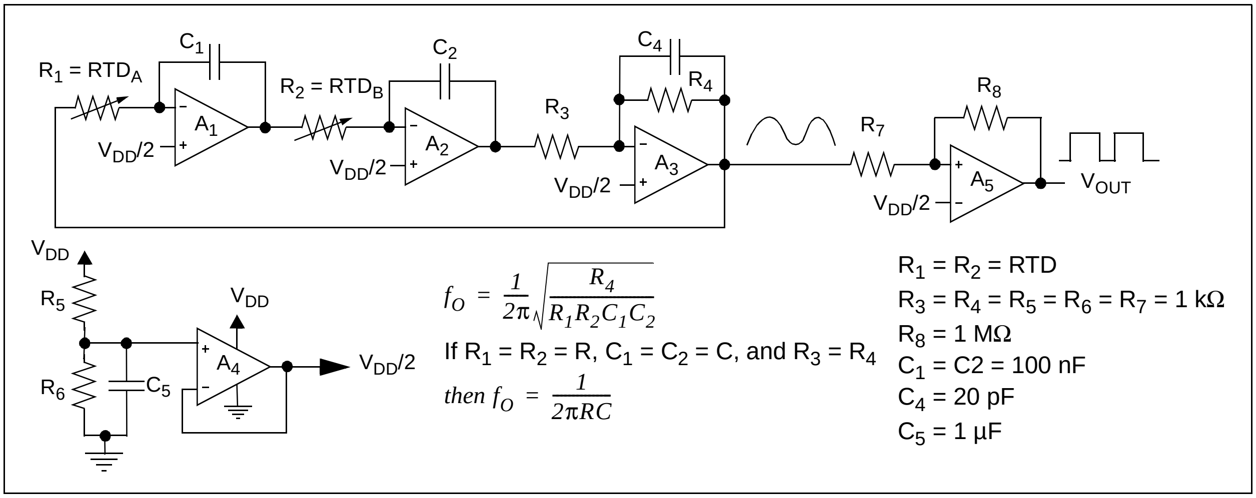
Oscillator circuits can be used to provide an accurate temperature measurement with an RTD sensor. The state variable oscillator provides an output frequency that is proportional to the square root of the product of two temperature-sensing resistors and is a good circuit for precision applications. The astable multi-vibrator or relaxation oscillator provides a square wave output with a single amplifier and is a good alternative for cost-sensitive applications.

The components must be chosen carefully so that the change in the oscillation frequency results primarily from the RTD and not from variation due to the component tolerance, temperature coefficient and drift rate. Metal film resistors, metal foil resistors and NPO porcelain capacitors are recommended to minimize the component error. Capacitors are relatively poor in performance when compared to resistors. Typically, the capacitor limits the accuracy of the oscillator. Furthermore, precision capacitors are only available in relatively small values. The state variable oscillator requires two 100 nF capacitors, while the relaxation oscillator uses a 0.68 µF capacitor to produce a nominal oscillation of 1 kHz. The state variable and relaxation circuits have an uncalibrated measurement accuracy of approximately 1°C and 3°C, respectively. The difference is primarily due to the capacitor error.

An application that requires an accuracy of better than ±1°C may require a temperature calibration and burn-in procedure. A temperature compensation algorithm can easily be implemented using the E^2 non-volatile memory of a microcontroller to store temperature correction data in a look-up table. The temperature coefficients are obtained by calibrating the circuit over temperature and comparing the measured temperature against the actual temperature. A burn-in or temperature-cycling procedure can significantly reduce the drift of the resistors and capacitors. Burn-in procedures are useful because the majority of the change in magnitude of resistors and capacitors occurs within the 500 hours of a life test.

STATE VARIABLE OSCILLATOR

The state variable oscillator shown in Figure 20 consists of integrators A_1, A_2 and inverter circuit A_3. Each integrator provides a phase shift of 90°, while the inverter adds an additional 180° phase shift. The total phase shift of the three amplifiers is equal to 360° and an oscillation is produced when the output of the third amplifier is fed back to the first amplifier. The addition of capacitor C_4 helps ensure oscillation start-up. The dual element RTD represented by R_1 and R_2 is used to increase the difference in the oscillation frequency from the minimum to the maximum sensed temperature.



$$f_O = \frac{1}{2\pi}\sqrt{\frac{R_4}{R_1R_2C_1C_2}}$$

If $R_1 = R_2 = R$, $C_1 = C_2 = C$, and $R_3 = R_4$

$$\text{then } f_O = \frac{1}{2\pi RC}$$

$R_1 = R_2 = RTD$
$R_3 = R_4 = R_5 = R_6 = R_7 = 1\ k\Omega$
$R_8 = 1\ M\Omega$
$C_1 = C2 = 100\ nF$
$C_4 = 20\ pF$
$C_5 = 1\ \mu F$

FIGURE 20: *State Variable RTD Oscillator.*

The state variable circuit offers the advantage that a limit circuit is not required if rail-to-rail input/output (RRIO) amplifiers are used and the gain of the inverter stage A_3 is equal to one (i.e., $R_3 = R_4$). In contrast, most oscillators require a limit or clamping circuit to prevent the amplifiers from saturating. Amplifier A_4 is used to provide the mid-supply reference voltage ($V_{DD}/2$) required for the single-supply voltage circuit. Resistors R_5 and R_6 form a voltage divider, while capacitor C_5 is used to provide additional noise filtering. A comparator circuit A_5 is used to convert the sinewave output to a square wave digital signal. The comparator functions as a zero-crossing detector with a switching threshold that is equal to $V_{DD}/2$. Resistor R_8 is used to provide additional hysteresis (V_{HYS}) to the comparator.

Design Procedure:

Set $R_1 = R_2 = R$, $C_1 = C_2 = C$, $R_3 = R_4$ and R_O is the RTD resistance at 0°C.

1. Select a desired nominal oscillation frequency.
2. $C = 1 / (2\pi R_o f_o)$.

   where: R_o = RTD resistance @ 0°C.
3. Select an op amp with a GBWP $\geq$ 100 x f_{max}

   where: $f_{max} = 1 / (2\pi R_{min}C)$ and R_{min} = RTD resistance at coldest sensing temperature.
4. Select $R_3 = R_4$ equal to 1 to 10 times R_o.
5. Select C_4 using the following equations:
   $f_{-3dB} = 1 / (2\pi R_4 C_4)$
   $C_4 \approx 1 / (2\pi R_4 f_{-3dB})$
   where: $f_{-3dB} \cong$ op amp's GBWP

RELAXATION OSCILLATOR

The relaxation oscillator shown in Figure 21 provides a simple circuit to interface a RTD to a microcontroller. This circuit requires only a comparator, capacitor and a few resistors to generate a frequency output that is proportional to the RTD resistance. The accuracy of this circuit is limited by the poor tolerance and large temperature coefficient available with the required, relatively large, capacitor C_1.

The relaxation oscillator functions as a comparator. Resistors R_2, R_3 and R_4 form a voltage divider that sets the hysteresis and voltage trip levels. Resistor R_1 and capacitor C_1 form the RC time constant that determines the charge and discharge rate or oscillation frequency. If V_{OUT} equals V_{DD}, C_1 charges from the comparator's low threshold (V_{TL}) to the high threshold (V_{TH}), causing V_{OUT} to toggle to V_{SS}. If V_{OUT} equals V_{SS}, C_1 discharges from V_{TH} to V_{TL} and V_{OUT} switches to V_{DD}. The voltage-switching process then repeats, which generates the oscillation.

The accuracy of the relaxation oscillator can be improved by using a comparator rather than an op amp for the amplifier. A comparator offers several advantages over an op amp in a non-linear switching circuit, such as a square wave oscillator. An op amp is intended to operate as a linear amplifier, while the comparator is designed to function as a fast switch. The switching specifications (such as propagation delay and rise/fall time) of a comparator are typically much better than an op amp's specifications. Also, the switching characteristics of an op amp typically consist of only a slew rate specification. The accuracy of the relaxation oscillator can be improved by using a higher resistance RTD and a higher performance comparator. The trade-off, however, will be that the comparator's current consumption will be much higher.

Design Procedure:

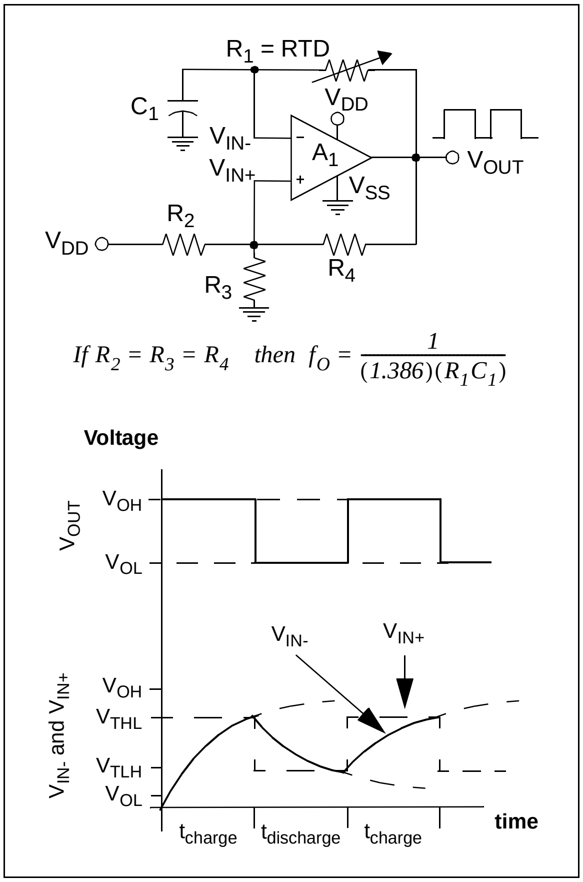
Set R_1 = RTD sensor, $R_2 = R_3 = R_4 = R$ and $R \cong 10 \times R_o$, where: R_o = RTD resistance at 0°C.

1. Select a desired nominal oscillation frequency.
2. $C_1 = 1/(1.386\ R_o\ f_o)$
3. Select a comparator with an Output Short Circuit Current (I_{SC}), which is at least five times greater than the maximum output current, to ensure start-up at cold and a relatively good accuracy.

   $I_{OUT\_MAX} = V_{DD}/R_{1\_MIN}$

   $I_{SC} = I_{OUT\_MAX} * 5$

   where: R_{1_MIN} = RTD resistance at coldest sensing temperature and V_{DD} is equal to the supply voltage.



$$\text{If } R_2 = R_3 = R_4 \quad \text{then } f_O = \frac{1}{(1.386)(R_1 C_1)}$$

FIGURE 21: *Relaxation RTD Oscillator.*

Thermistor Circuits

VOLTAGE DIVIDER CIRCUIT

Thermistors offer the advantages of a high sensitivity (ΔR vs. temperature) and a linear change in resistance between approximately 0°C and 70°C. Figure 22 shows the conventional circuit used with thermistors. The circuit consists of a voltage divider and a voltage-follower op amp with a gain of one. The voltage divider network consists of reference voltage V_{REF} and series resistor R_S. A low-pass, noise-reduction filter is formed by R_2 and C_1. The equation listed below can be used to select R_S.

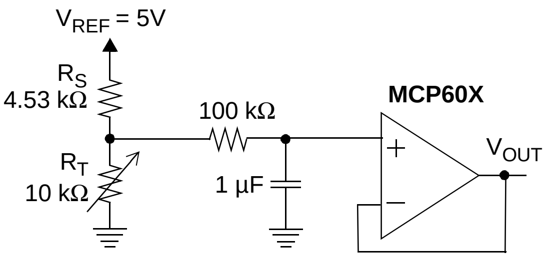
$$R_s = \frac{R_{T1}R_{T2} + R_{T2}R_{T3} - 2R_{T1}R_{T3}}{R_{T1} + R_{T3} - 2R_{T2}}$$

Where:

R_{T1} = thermistor resistance at the low temperature.

R_{T2} = thermistor resistance at the mid-point temperature.

R_{T3} = thermistor resistance at the high temperature.



$$V_{OUT} = \left(\frac{R_T}{R_S + R_T}\right) V_{REF}$$

FIGURE 22: *Voltage Divider Circuit.*

A plot of the output of the divider circuit is shown in Figure 23. While a microcontroller can use a software routine to improve the linearization, a high-bit ADC is required to resolve the small change in the output voltage at temperatures less than 0°C and greater than 70°C. Figure 24 shows the change in voltage or slope of the output voltage. The ADC must be able to resolve a voltage of approximately 50 mV at 35°C and a voltage of less than 20 mV at temperatures less than -5°C and greater than 90°C. Table 2 provides the resolution of an ADC, assuming that the ADC's Effective Number of Bits (ENOB) is equal to one bit less than the maximum available resolution. If this aggressive ENOB assumption is made, an 8-bit ADC is required to measure temperatures between 10°C and 60°C, with an 11-bit ADC being required to measure temperatures at the cold and hot end points.

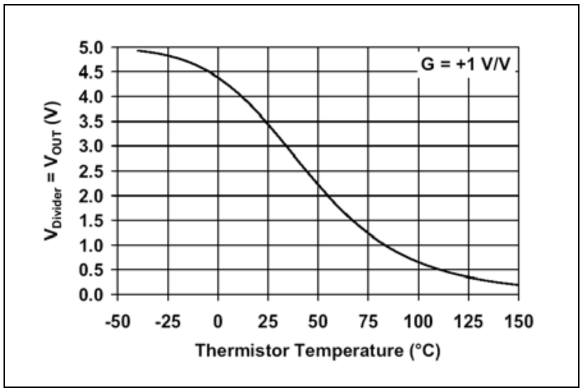


FIGURE 23: V_{OUT} vs. Temperature.

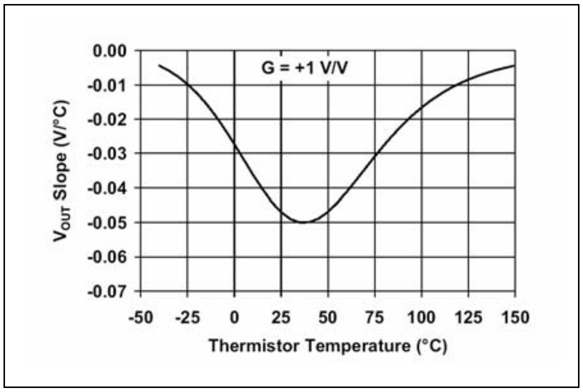


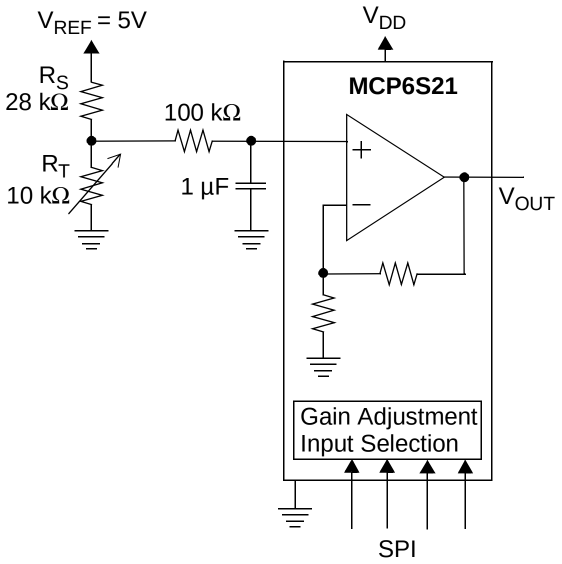
FIGURE 24: ΔV_{OUT} vs. Temperature.

TABLE 2: ADC RESOLUTION

ADC (N-bits)	2^N	Ideal ADC Volts/bit (V_{FS} = 5V)	ENOB (N - 1)	ENOB Volts/bit (V_{FS} = 5V)
8 bits	256	19.5 mV	7-bits	39.0 mV
9 bits	512	9.77 mV	8-bits	19.5 mV
10 bits	1024	4.88 mV	9-bits	9.77 mV
11 bits	2048	2.44 mV	10-bits	4.88 mV
12 bits	4096	1.22 mV	11-bits	2.44 mV

PROGRAMMABLE GAIN AMPLIFIER (PGA) CIRCUIT

A PGA circuit can be used to increase the gain of the amplifier at the temperatures where a small change in the output voltage is difficult to detect. Increasing the output voltage as a function of temperature allows a lower bit ADC to accurately resolve the relative small differences in the thermistor's resistance at cold and hot temperatures. The circuit shown in Figure 25 uses the MCP6S21, which uses a SPI interface to select a gain of 1, 2, 4, 8, 16 or 32 V/V.



$$V_{OUT} = \left(\frac{R_T}{R_S + R_T}\right)(V_{REF})\ (Amplifier\ Gain)$$

FIGURE 25: PGA Thermistor Circuit.

TABLE 3: GAIN CHANGE POINTS WITH HYSTERESIS

Gain Change (V/V)	Temperature (°C)	V_{OUT} (V)
1 → 2	37.0	0.885
2 → 4	57.0	0.451
4 → 8	77.0	0.236
8 → 16	97.0	0.1288
16 → 32	118.5	0.0708
16 ← 32	114.5	0.0789
8 ← 16	93.0	0.1448
4 ← 8	73.0	0.268
2 ← 4	53.0	0.516
1 ← 2	33.0	1.012

The output voltage of the PGA circuit is shown in Figure 26. The gain of the amplifier is adjusted as a function of temperature with the values shown in Table 3. The advantage of the PGA circuit is shown by comparing the V_{OUT} slope plots of Figure 24 and Figure 27. The V_{OUT} slope for the PGA circuit has a minimum value of 30 mV for temperatures greater than 35°C, which means that only a 9-bit ADC is required. In contrast, a voltage divider with a gain of one will require an 11-bit or higher ADC to provide an equivalent temperature resolution. The resolution of a thermistor circuit is important in applications such as overtemperature shutdown circuits.

An accurate thermistor is required for the PGA circuit to provide an advantage with the variable gain. A BC Components™ #2322 640 5103 thermistor was chosen that has a resistance tolerance of 1% at 25°C and a ΔR accuracy of 0.75%, which corresponds to a temperature accuracy of approximately 0.2°C at 25°C and 1°C at 100°C. The accuracy of a standard thermistor is typically ±2°C to ±5°C and the magnitude of the sensor error is too large to achieve the improved resolution benefit of an adjustable gain circuit.

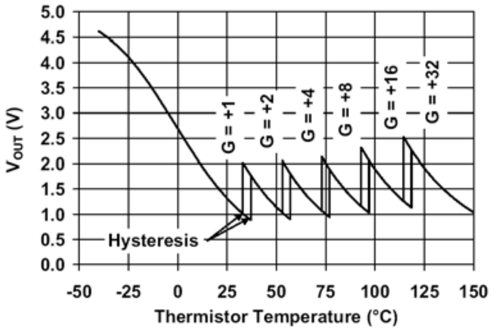


FIGURE 26: *PGA V_{OUT} vs. Temperature.*

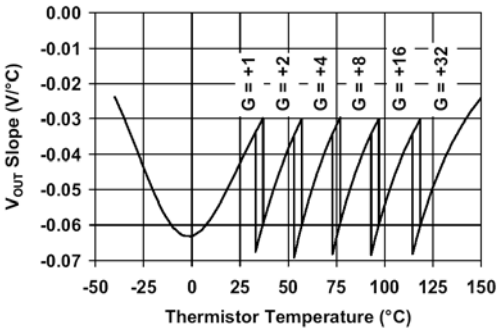


FIGURE 27: PGA ΔV_{OUT} *vs. Temperature.*

Silicon IC Sensors

SERIAL OUTPUT

Figure 28 shows a schematic of the TC77 serial-output sensor which integrates the temperature sensor, ADC and digital registers on a single chip that is connected to the processor through the SPI serial bus. The SPI bus uses SCK, SI/O and CS pins to transmit and receive data. Temperature is measured by monitoring the voltage of a diode with a 13-bit ADC. The temperature data is stored in the Temperature register. If a Temperature register read operation occurs while an ADC conversion is in progress, the previous completed conversion will be outputted. The Configuration register is used to select either the continuous temperature conversion or shut-down operating modes. The Shutdown mode disables the temperature-conversion circuitry to minimize the power consumption. However, the serial I/O communication port remains active. The test registers are used for offset and gain calibration by the vendor and are not available to the user.

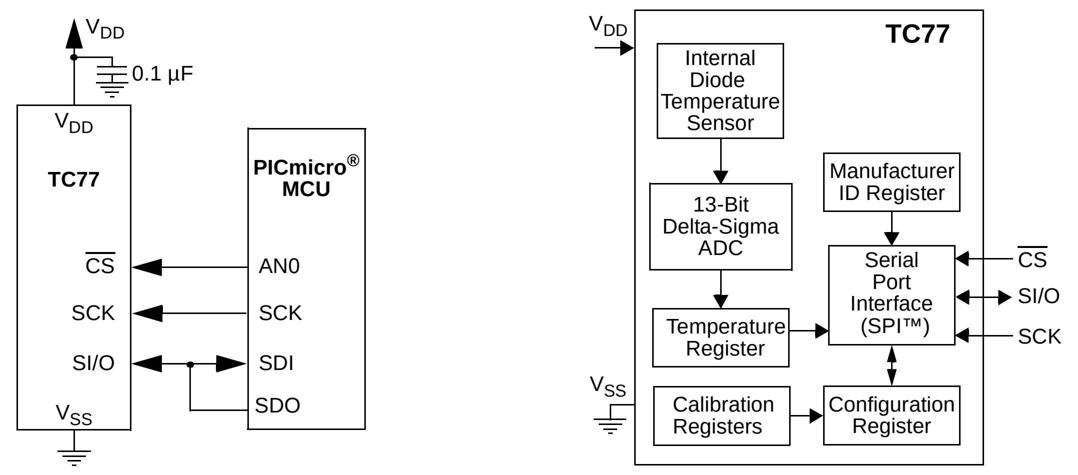


FIGURE 28: *Interfacing a TC77 Silicon IC Sensor to a Microcontroller.*

Serial I/O sensors can be used to monitor multiple temperatures on the same PCB and minimize the number of microcontroller interface pins. Most silicon sensors available today are designed using the SPI, the two-wire SMBus or I^2C protocols. Also, a number of temperature sensors are available that use a single I/O pin to transmit information using a pulse-width coding scheme.

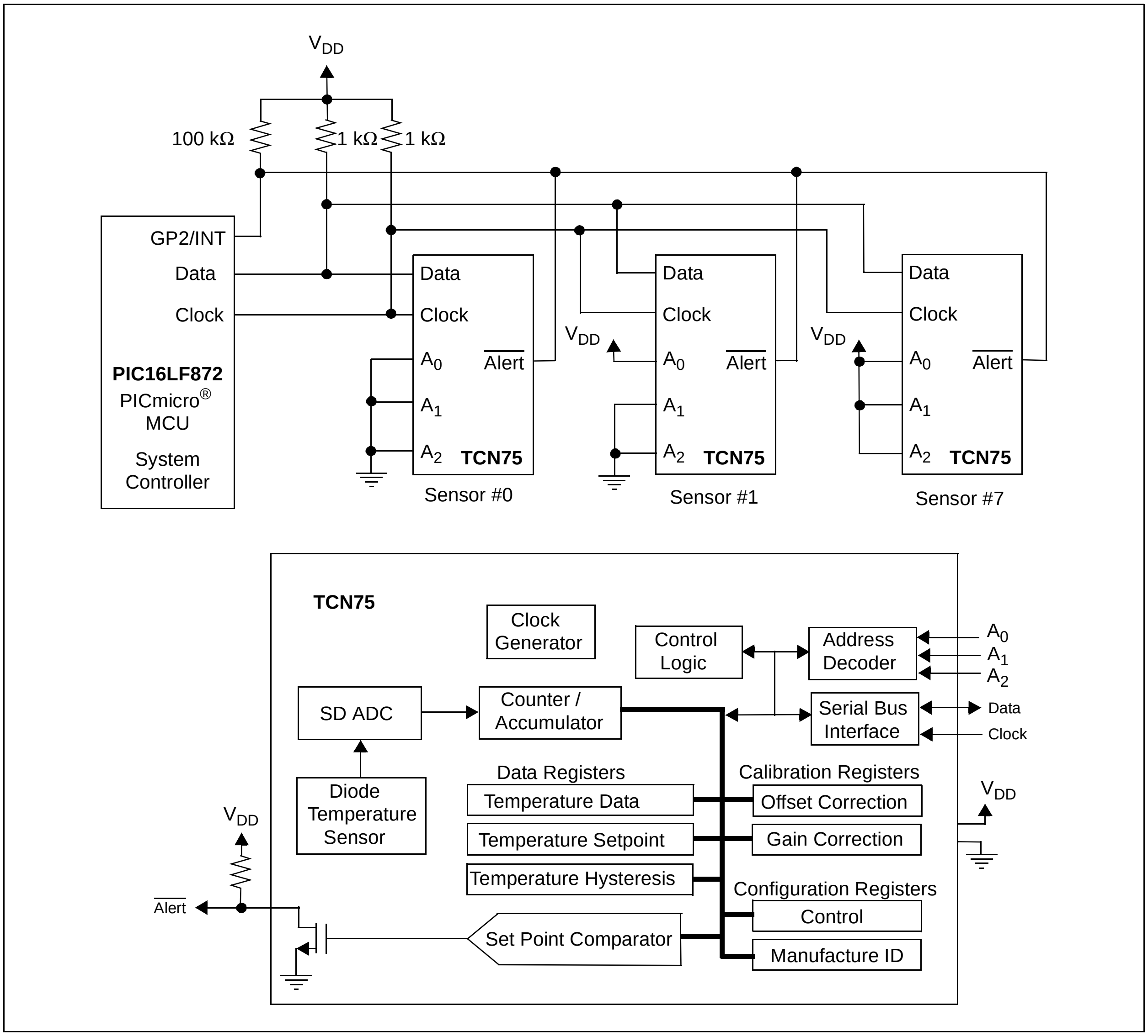
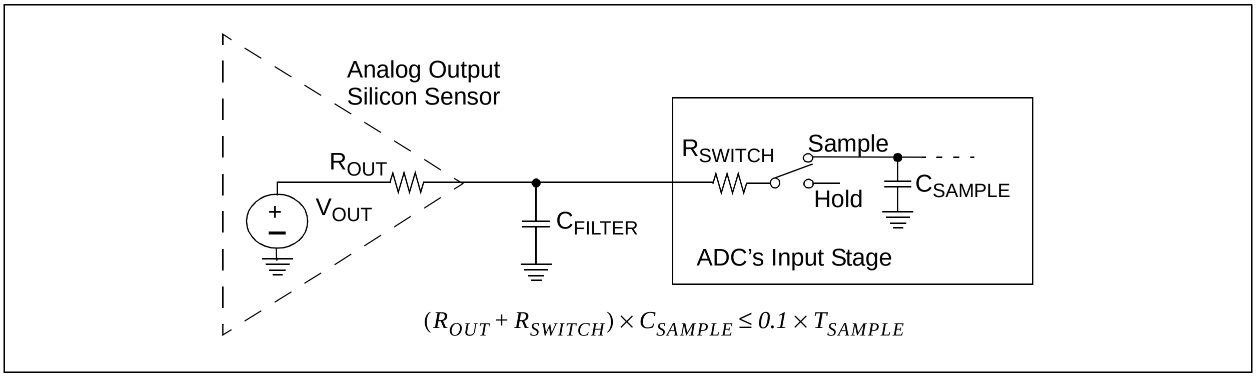


FIGURE 29: *Multi-Zone Temperature Monitoring with the TCN75 Thermal Sensor.*

Figure 29 provides a multi-zone temperature monitor that uses the TCN75 sensor to notify the host controller when the ambient temperature exceeds a user-programmed set point. Communication with the TCN75 sensor is accomplished via a two-wire serial bus. The microcontroller can monitor the temperature of each sensor by reading the Temperature Data register or the sensor can function as a stand-alone thermostat. The temperature threshold trip point is programmed by writing to the Set Point register. The INT pin is an open-drain output that can be connected to the microcontroller's interrupt pin to monitor up to eight sensors. Three address pins are used to identify each sensor.

ANALOG OUTPUT

Analog output silicon sensors have an output voltage in the form of the equation of a straight line. The slope of the output is equal to a constant temperature coefficient (mV/°C), while the y-intercept point typically is the sensor's output voltage at 0°C. A simplified schematic of an analog sensor and ADC system is shown in Figure 30.



$$(R_{OUT} + R_{SWITCH}) \times C_{SAMPLE} \leq 0.1 \times T_{SAMPLE}$$

FIGURE 30: *Interfacing an Analog Output Silicon Sensor to an ADC.*

The sensor's output impedance can affect the ADC. The temperature sensor's output pin is typically driven by a buffer op amp, while the input of a typical ADC consists of a sample and hold circuit with a switch that connects V_{OUT} to C_{SAMPLE}. R_{OUT}, R_{SWITCH} and C_{SAMPLE} form a time constant which must be less than the sampling rate (T_{SAMPLE}) of the ADC, as illustrated by the equation in Figure 30. An external capacitor C_{FILTER} can be added to the output pin to provide additional filtering. However, this may impact the time response of the sensor. Enough time must be provided to allow C_{FILTER} to charge sufficiently between ADC conversions.

The magnitude of the C_{FILTER} capacitor should be in the range of 1 nF to 100 nF to prevent the sensor amplifier from oscillating. A small resistor of approximately 10Ω to 100Ω can be added between the output pin of the sensor and C_{FILTER} to isolate the sensor's amplifier from the capacitive load. The output impedance of the sensor R_{OUT} varies as a function of frequency. Thus, a series resistor should be added to the effective R_{OUT} resistance, if C_{FILTER} is intended to serve as the ADC's anti-aliasing filter.

CONCLUSION

Temperature sensors are used in embedded systems for both thermal monitoring and management applications. A designer must evaluate the trade-offs of the sensor, conditioning circuitry and sensor output in order to maximize the measurement accuracy while easing the interface to the microcontroller. In addition, the designer must consider system integration issues such as the location of the sensor, grounding, EMI/ESD protection and shielding in order to provide a robust temperature measurement. A sample of practical circuits and interface techniques has been provided along with design equations.

The following sensor guidelines can be used as a starting point to select a temperature sensor. If your application requires a high-temperature measurement, thermocouples are a good choice because of their wide temperature operating range. Thermocouples are typically used as remote sensors and, therefore, the circuit must provide noise immunity by using good grounding and shielding methods. If your application requires precision, RTDs set the standard with their superior repeatability and stability characteristics. For applications such as the temperature measurement on a PCB, either thermistors or silicon IC sensors should be considered. Thermistors are available in more packages, are lower in cost and have a faster thermal response time than silicon sensors. However, thermistors require additional signal-conditioning circuitry, while silicon sensors provide both the sensor and circuitry on a single IC that can be interfaced directly to the microcontroller.

The output of the sensor is selected by the available microcontroller hardware and software resources, in addition to the complexity of the sensor circuit. The sensor output can consist of an analog, frequency, ramp rate, duty cycle, serial or logic format that is proportional to temperature. Temperature measurement is a popular topic and the designer should review the literature to evaluate the many sensor and circuit options available.

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02/17/04

National
Semiconductor

August 2000

LM741
Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

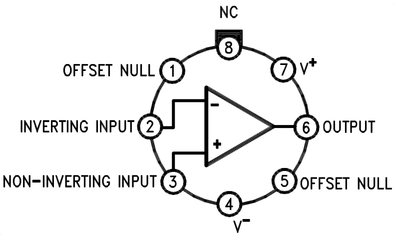
The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0˚C to +70˚C temperature range, instead of −55˚C to +125˚C.

Features

Connection Diagrams

Metal Can Package



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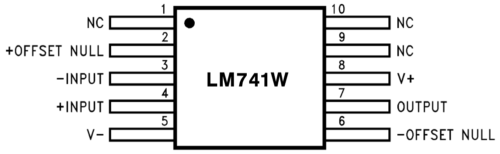
Note 1: LM741H is available per JM38510/10101

Order Number LM741H, LM741H/883 (Note 1),
LM741AH/883 or LM741CH
See NS Package Number H08C

Ceramic Flatpak



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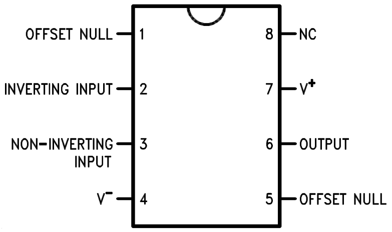
Order Number LM741W/883
See NS Package Number W10A

Dual-In-Line or S.O. Package

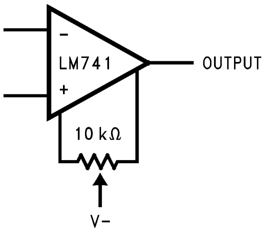


00934103

Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

Typical Application

Offset Nulling Circuit



00934107

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	**LM741**	**LM741C**
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55°C to +125°C	−55°C to +125°C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Junction Temperature	150°C	150°C	100°C
Soldering Information			
N-Package (10 seconds)	260°C	260°C	260°C
J- or H-Package (10 seconds)	300°C	300°C	300°C
M-Package			
Vapor Phase (60 seconds)	215°C	215°C	215°C
Infrared (15 seconds)	215°C	215°C	215°C

See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering

surface mount devices.

ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$										
	$R_S \le 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \le 50\Omega$		0.8	3.0							mV
	$T_{AMIN} \le T_A \le T_{AMAX}$										
	$R_S \le 50\Omega$			4.0							mV
	$R_S \le 10\ k\Omega$						6.0			7.5	mV
Average Input Offset Voltage Drift				15							μV/°C
Input Offset Voltage Adjustment Range	$T_A = 25°C$, $V_S = \pm 20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25°C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	$T_A = 25°C$		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	$T_A = 25°C$, $V_S = \pm 20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = \pm 20V$	0.5									MΩ
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25^\circ C$, $R_L \geq 2\ k\Omega$										
	$V_S = \pm 20V$, $V_O = \pm 15V$	50									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2\ k\Omega$,										
	$V_S = \pm 20V$, $V_O = \pm 15V$	32									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				25			15			V/mV
	$V_S = \pm 5V$, $V_O = \pm 2V$	10									V/mV
Output Voltage Swing	$V_S = \pm 20V$										
	$R_L \geq 10\ k\Omega$	±16									V
	$R_L \geq 2\ k\Omega$	±15									V
	$V_S = \pm 15V$										
	$R_L \geq 10\ k\Omega$				±12	±14		±12	±14		V
	$R_L \geq 2\ k\Omega$				±10	±13		±10	±13		V
Output Short Circuit Current	$T_A = 25^\circ C$	10	25	35		25			25		mA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 10\ k\Omega$, $V_{CM} = \pm 12V$				70	90		70	90		dB
	$R_S \leq 50\Omega$, $V_{CM} = \pm 12V$	80	95								dB
Supply Voltage Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$V_S = \pm 20V$ to $V_S = \pm 5V$										
	$R_S \leq 50\Omega$	86	96								dB
	$R_S \leq 10\ k\Omega$				77	96		77	96		dB
Transient Response	$T_A = 25^\circ C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		µs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25^\circ C$	0.437	1.5								MHz
Slew Rate	$T_A = 25^\circ C$, Unity Gain	0.3	0.7			0.5			0.5		V/µs
Supply Current	$T_A = 25^\circ C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25^\circ C$										
	$V_S = \pm 20V$		80	150							mW
	$V_S = \pm 15V$					50	85		50	85	mW
LM741A	$V_S = \pm 20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = \pm 15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100˚C/W	100˚C/W	170˚C/W	195˚C/W
θ_{jC} (Junction to Case)	N/A	N/A	25˚C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

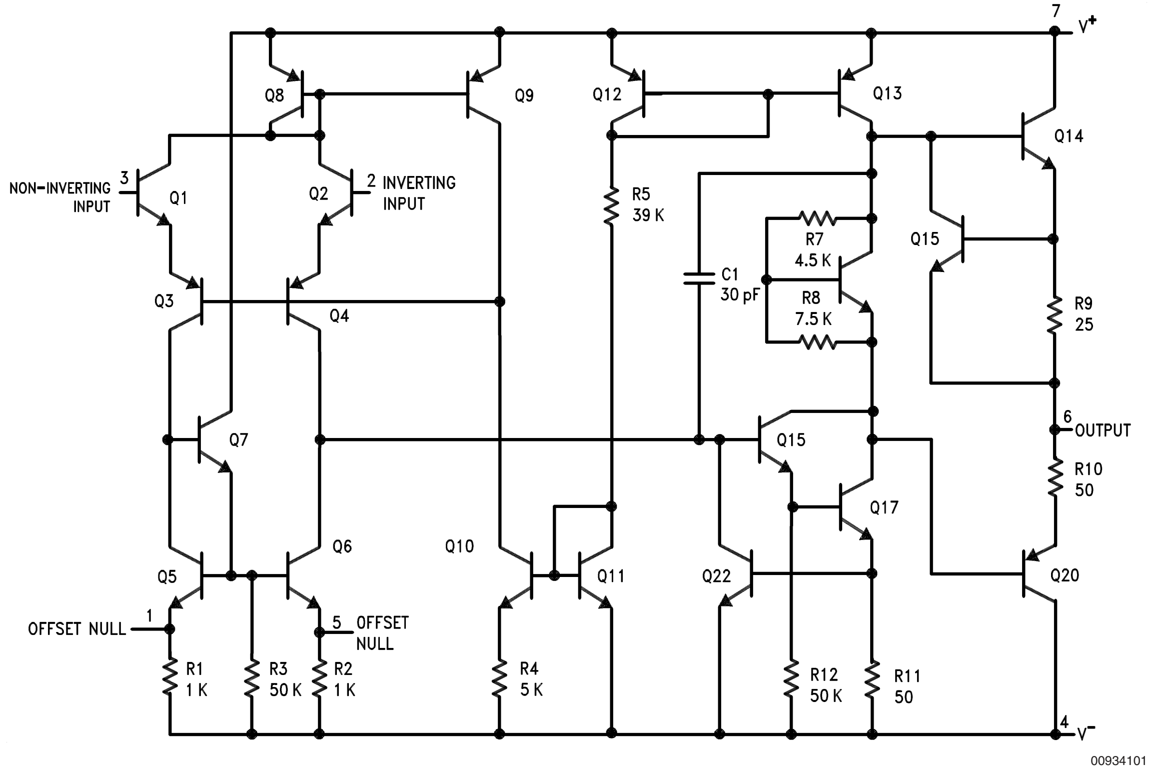
Note 5: Unless otherwise specified, these specifications apply for $V_S = \pm 15V$, $-55˚C \le T_A \le +125˚C$ (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to $0˚C \le T_A \le +70˚C$.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(μs).

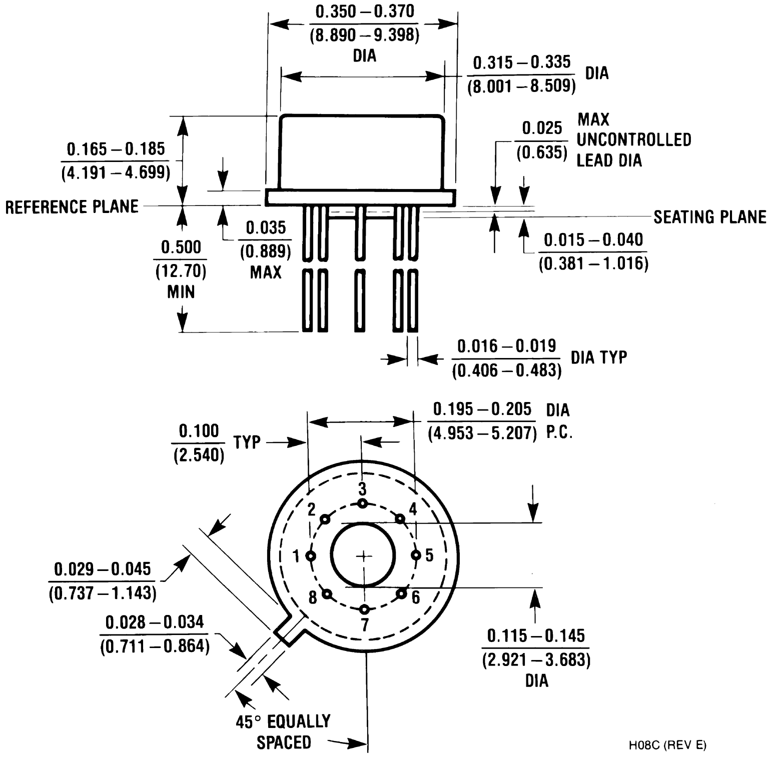
Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram

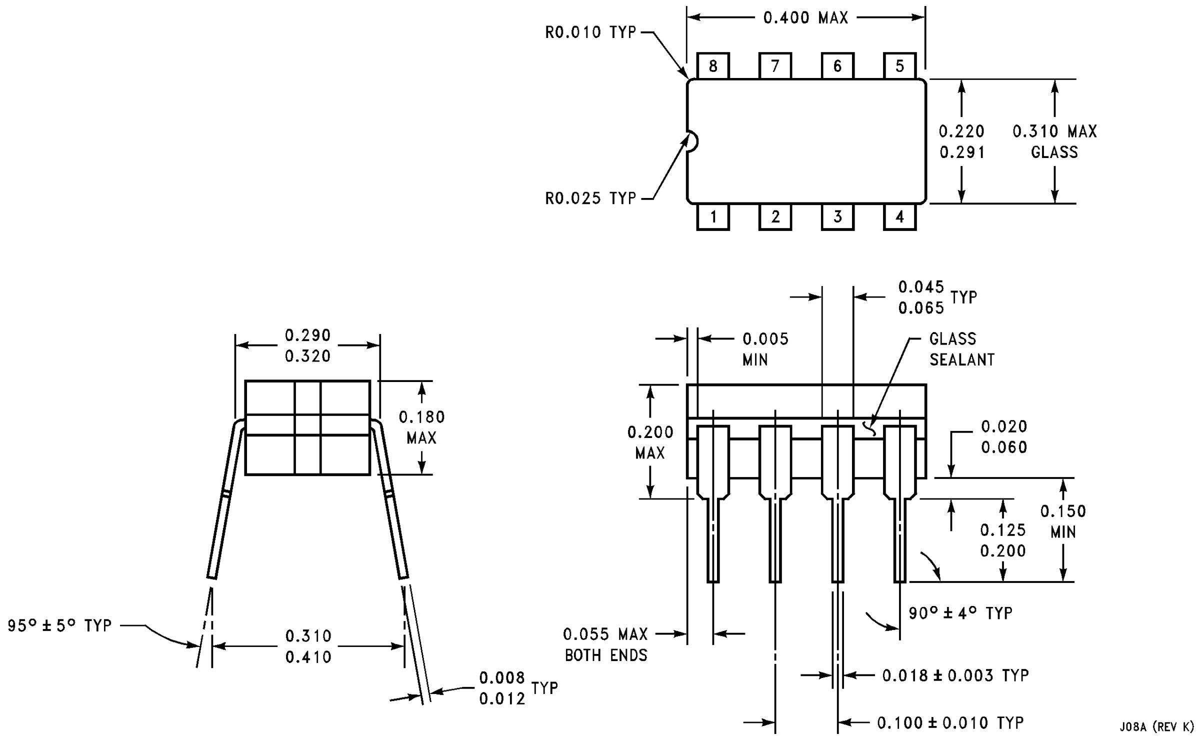


Physical Dimensions inches (millimeters) unless otherwise noted

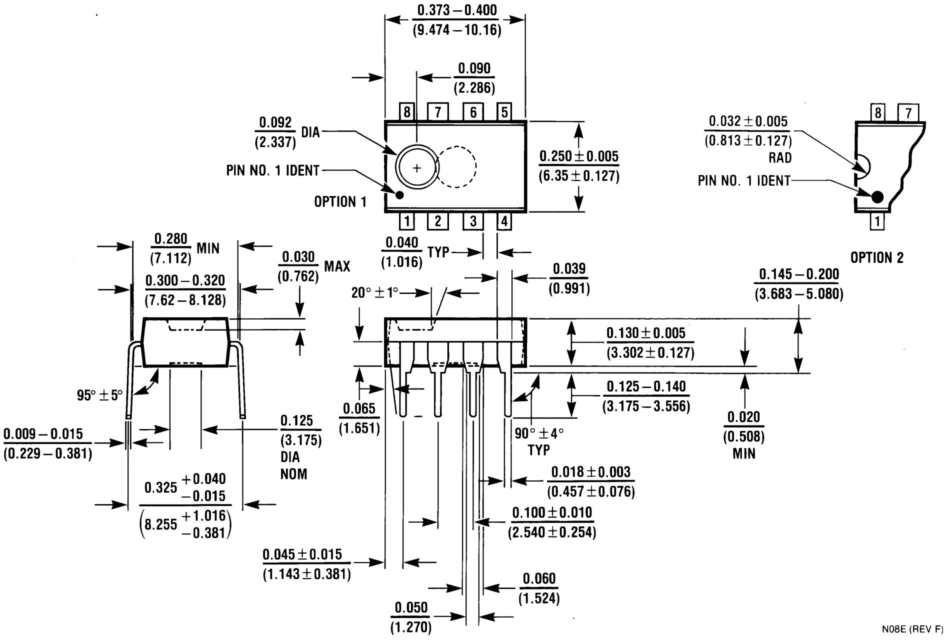


Metal Can Package (H)
Order Number LM741H, LM741H/883, LM741AH/883, LM741AH-MIL or LM741CH
NS Package Number H08C

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

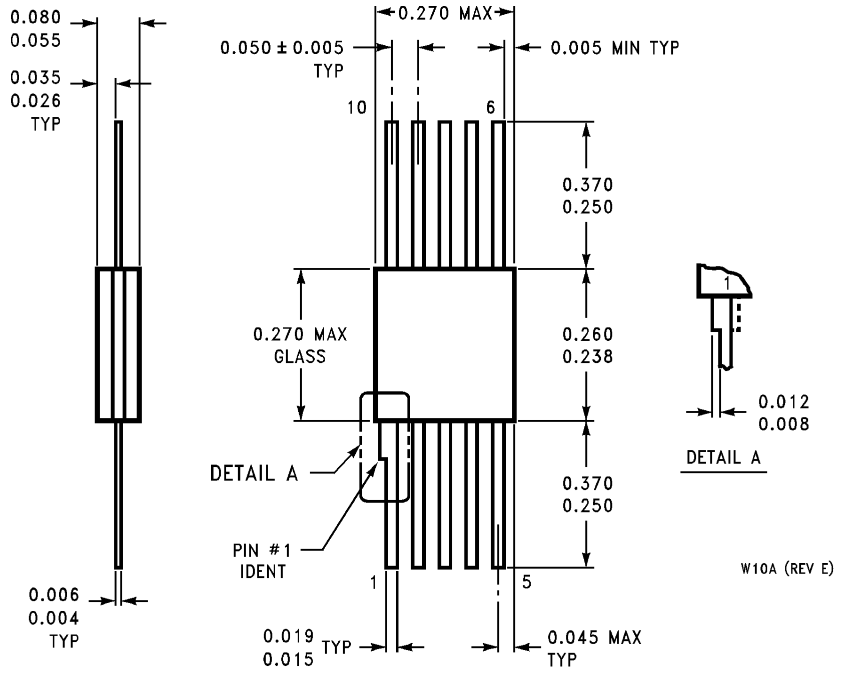


Ceramic Dual-In-Line Package (J)
Order Number LM741J/883
NS Package Number J08A



Dual-In-Line Package (N)
Order Number LM741CN
NS Package Number N08E

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



10-Lead Ceramic Flatpak (W)
Order Number LM741W/883, LM741WG-MPR or LM741WG/883
NS Package Number W10A

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LF351

Single Operational Amplifier (JFET)

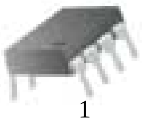
Features

- Internally trimmed offset voltage: 10mV
- Low input bias current : 50pA
- Wide gain bandwidth : 4MHz
- High slew rate : 13V/µs
- High input impedance : $10^{12}\Omega$

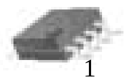
Description

The LF351 is JFET input operational amplifier with an internally compensated input offset voltage. The JFET input device provides wide bandwidth, low input bias currents and offset currents.

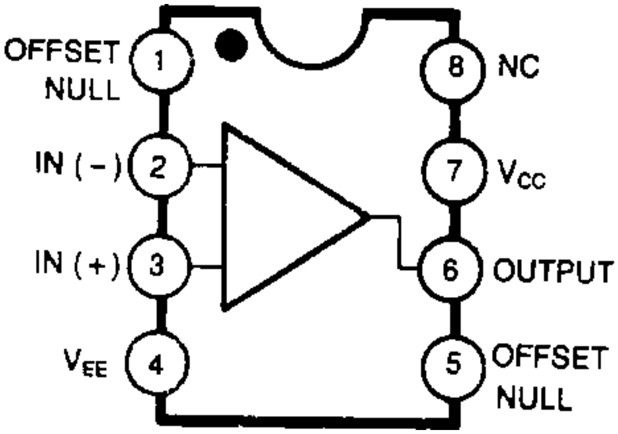
8-DIP



8-SOP

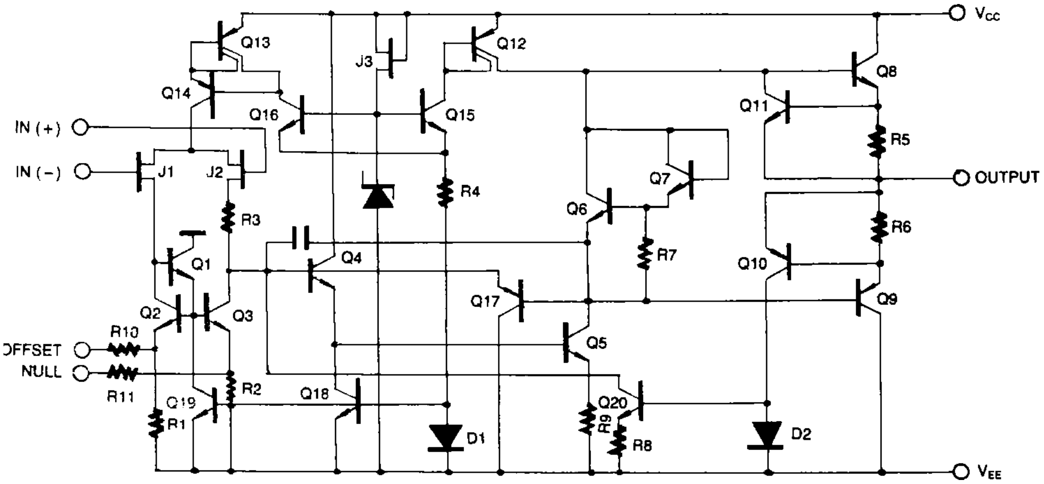


Internal Block Diagram



Rev. 1.0.1

Schematic Diagram



Absolute Maximum Ratings

Parameter	Symbol	Value	Unit
Supply Voltage	V_{CC}	±18	V
Differential Input Voltage	$V_{I(DIFF)}$	30	V
Input Voltage Range	V_I	±15	V
Output Short Circuit Duration	-	Continuous	-
Power Dissipation	P_D	500	mW
Operating Temperature	T_{OPR}	0 ~ +70	°C
Storage Temperature Range	T_{STG}	-65 ~ +150	°C

Electrical Characteristics

(V_{CC} = +15V, V_{EE} = - 15V, T_A = 25 °C. unless otherwise specified)

Parameter	Symbol	Conditions		Min.	Typ.	Max.	Unit
Input Offset Voltage	V_{IO}	R_S = 10kΩ		-	5.0	10	mV
			0 °C≤T_A≤70 °C	-	-	13	
Input Offset Voltage Drift (Note1)	$\Delta V_{IO}/\Delta T$	R_S = 10kΩ	0 °C≤T_A≤70 °C	-	10	-	µV/ °C
Input Offset Current	I_{IO}			-	25	100	pA
			0 °C≤T_A≤70 °C	-	-	4	nA
Input Bias Current	I_{BAIS}			-	50	200	pA
			0 °C≤T_A≤70 °C	-	-	8	nA
Input Resistance (Note1)	R_I	-		-	10^{12}	-	Ω
Large Signal Voltage Gain	G_V	$V_{O(P-P)}$= ±10V		25	100	-	V/mV
		R_L=2kΩ	0 °C≤T_A≤70 °C	15	-	-	
Output Voltage Swing	$V_{O(P-P)}$	R_L = 10kΩ		±12	±13.5	-	V
Input Voltage Range	$V_{I(R)}$	-		±11	+15 -12	-	V
Common Mode Rejection Ratio	C_{MRR}	R_S≤10kΩ		70	100	-	dB
Power Supply Rejection Ratio	P_{SRR}	R_S≤10kΩ		70	100	-	dB
Power Supply Current	I_{CC}	-		-	2.3	3.4	mA
Slew Rate (Note1)	S_R	G_V = 1		-	13	-	V/µs
Gain-Bandwidth Product (Note1)	GBW	-		-	4	-	MHz

Note :

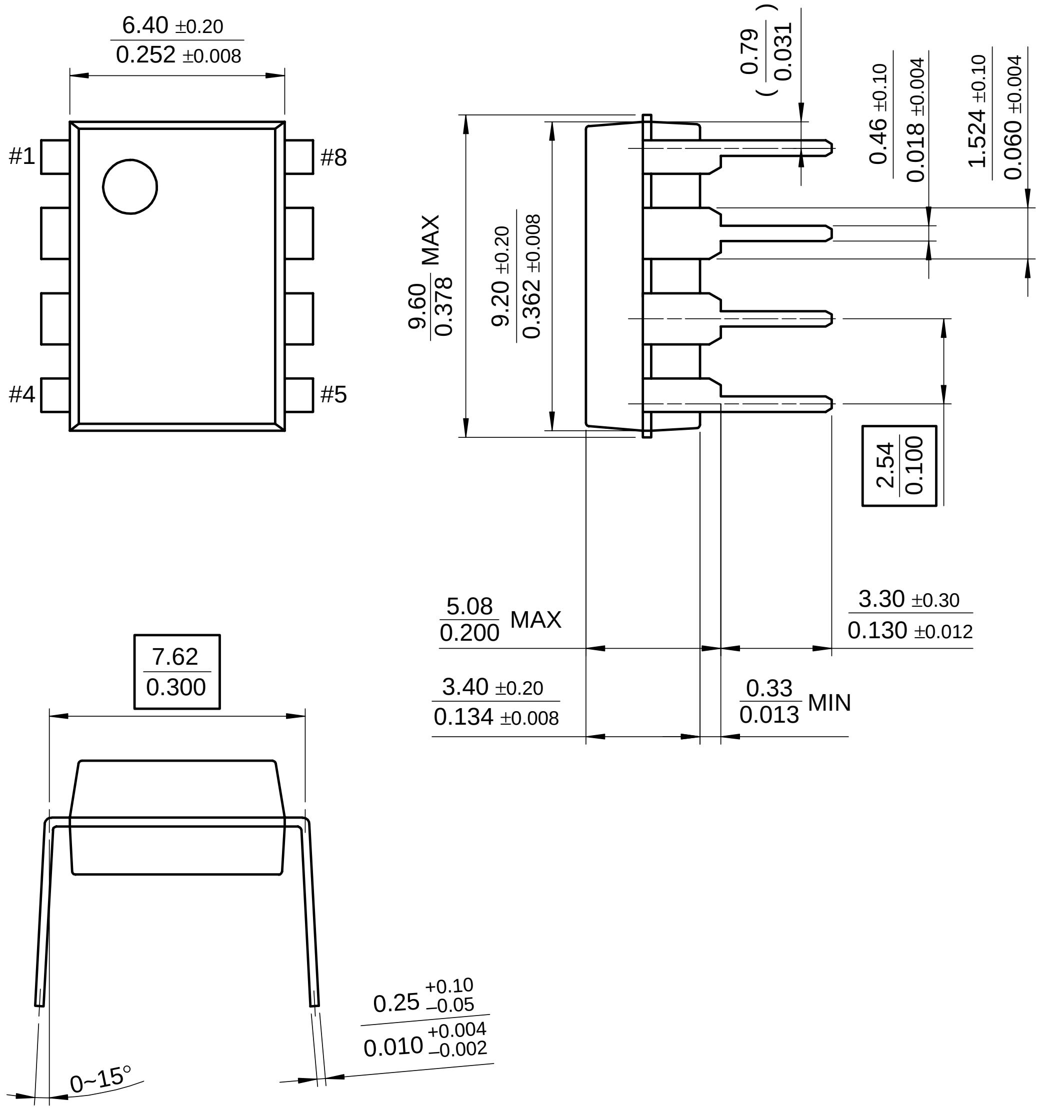
1. Guaranteed by design.

Mechanical Dimensions

Package

Dimensions in millimeters

8-DIP

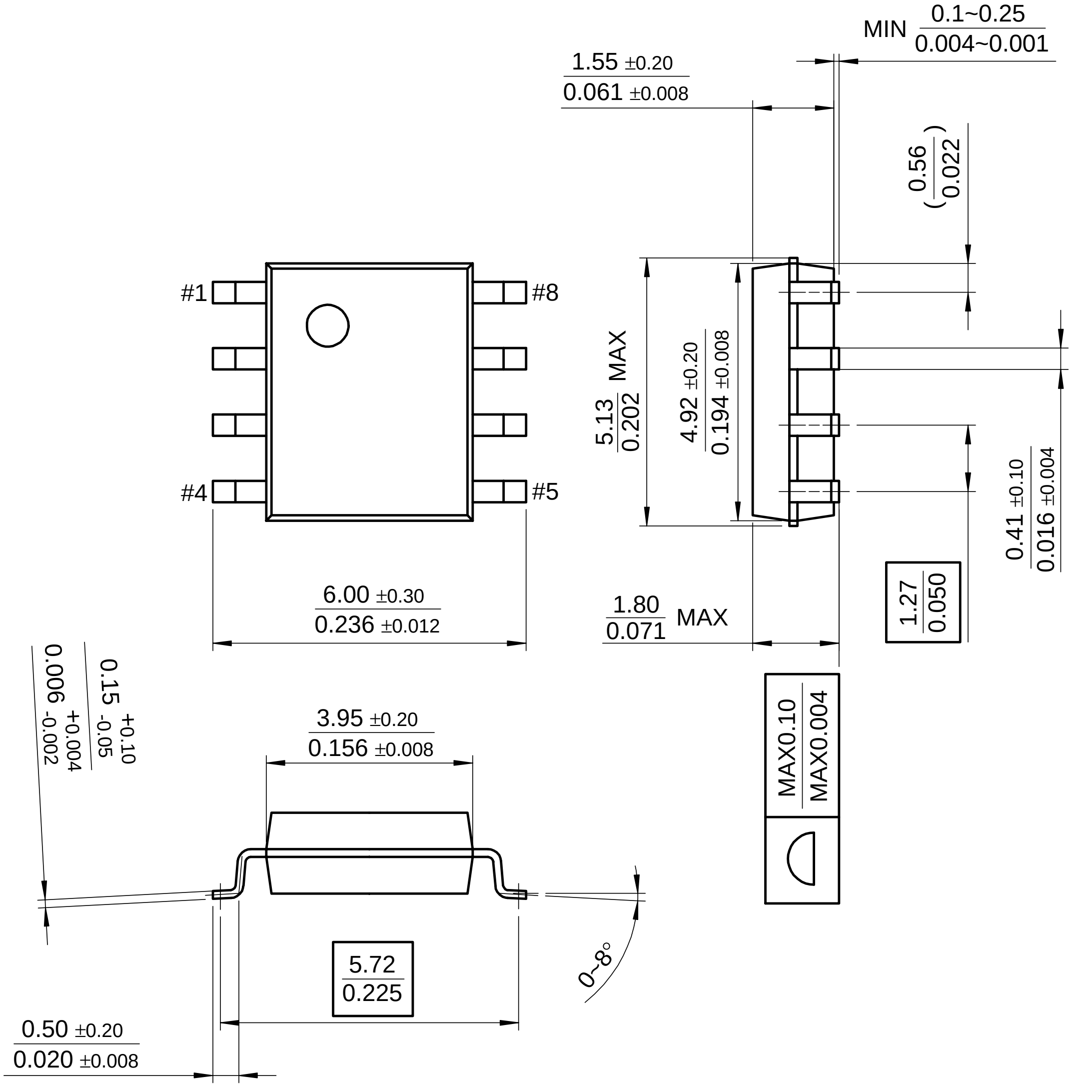


Mechanical Dimensions (Continued)

Package

Dimensions in millimeters

8-SOP



Ordering Information

Product Number	Package	Operating Temperature
LF351N	8-DIP	0 ~ + 70°C
LF351M	8-SOP	

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2. A critical component in any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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National Semiconductor

October 2005

LM158/LM258/LM358/LM2904
Low Power Dual Operational Amplifiers

General Description

The LM158 series consists of two independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

Application areas include transducer amplifiers, dc gain blocks and all the conventional op amp circuits which now can be more easily implemented in single power supply systems. For example, the LM158 series can be directly operated off of the standard +5V power supply voltage which is used in digital systems and will easily provide the required interface electronics without requiring the additional ±15V power supplies.

The LM358 and LM2904 are available in a chip sized package (8-Bump micro SMD) using National's micro SMD package technology.

Unique Characteristics

- In the linear mode the input common-mode voltage range includes ground and the output voltage can also swing to ground, even though operated from only a single power supply voltage.
- The unity gain cross frequency is temperature compensated.
- The input bias current is also temperature compensated.

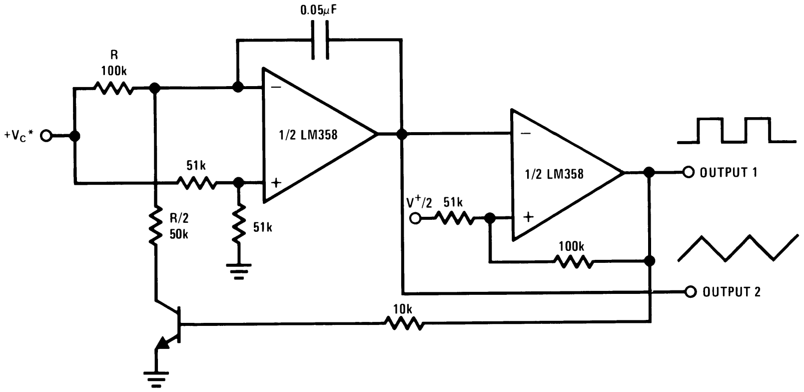
Advantages

- Two internally compensated op amps
- Eliminates need for dual supplies
- Allows direct sensing near GND and V_{OUT} also goes to GND
- Compatible with all forms of logic
- Power drain suitable for battery operation

Features

- Available in 8-Bump micro SMD chip sized package, (See AN-1112)
- Internally frequency compensated for unity gain
- Large dc voltage gain: 100 dB
- Wide bandwidth (unity gain): 1 MHz (temperature compensated)
- Wide power supply range:
  - — Single supply: 3V to 32V
  - — or dual supplies: ±1.5V to ±16V
- Very low supply current drain (500 µA) — essentially independent of supply voltage
- Low input offset voltage: 2 mV
- Input common-mode voltage range includes ground
- Differential input voltage range equal to the power supply voltage
- Large output voltage swing

Voltage Controlled Oscillator (VCO)



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Absolute Maximum Ratings (Note 9)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

	LM158/LM258/LM358 LM158A/LM258A/LM358A	LM2904
Supply Voltage, V^+	32V	26V
Differential Input Voltage	32V	26V
Input Voltage	−0.3V to +32V	−0.3V to +26V
Power Dissipation (Note 1)		
Molded DIP	830 mW	830 mW
Metal Can	550 mW	
Small Outline Package (M)	530 mW	530 mW
micro SMD	435mW	
Output Short-Circuit to GND		
(One Amplifier) (Note 2)		
$V^+ \leq 15V$ and $T_A = 25˚C$	Continuous	Continuous
Input Current ($V_{IN} < -0.3V$) (Note 3)	50 mA	50 mA
Operating Temperature Range		
LM358	0˚C to +70˚C	−40˚C to +85˚C
LM258	−25˚C to +85˚C	
LM158	−55˚C to +125˚C	
Storage Temperature Range	−65˚C to +150˚C	−65˚C to +150˚C
Lead Temperature, DIP		
(Soldering, 10 seconds)	260˚C	260˚C
Lead Temperature, Metal Can		
(Soldering, 10 seconds)	300˚C	300˚C
Soldering Information		
Dual-In-Line Package		
Soldering (10 seconds)	260˚C	260˚C
Small Outline Package		
Vapor Phase (60 seconds)	215˚C	215˚C
Infrared (15 seconds)	220˚C	220˚C

See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering surface mount devices.

ESD Tolerance (Note 10)	250V	250V

Electrical Characteristics

$V^+ = +5.0V$, unless otherwise stated

Parameter	Conditions	LM158A			LM358A			LM158/LM258			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	(Note 5), $T_A = 25˚C$		1	2		2	3		2	5	mV
Input Bias Current	$I_{IN(+)}$ or $I_{IN(-)}$, $T_A = 25˚C$, $V_{CM} = 0V$, (Note 6)		20	50		45	100		45	150	nA
Input Offset Current	$I_{IN(+)} - I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25˚C$		2	10		5	30		3	30	nA
Input Common-Mode Voltage Range	$V^+ = 30V$, (Note 7) (LM2904, $V^+ = 26V$), $T_A = 25˚C$	0		$V^+-1.5$	0		$V^+-1.5$	0		$V^+-1.5$	V
Supply Current	Over Full Temperature Range $R_L = \infty$ on All Op Amps										
	$V^+ = 30V$ (LM2904 $V^+ = 26V$)		1	2		1	2		1	2	mA
	$V^+ = 5V$		0.5	1.2		0.5	1.2		0.5	1.2	mA

Electrical Characteristics

$V^+ = +5.0V$, unless otherwise stated

Parameter	Conditions	LM358			LM2904			Units
		Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	(Note 5) , $T_A = 25^\circ C$		2	7		2	7	mV
Input Bias Current	$I_{IN(+)}$ or $I_{IN(-)}$, $T_A = 25^\circ C$, $V_{CM} = 0V$, (Note 6)		45	250		45	250	nA
Input Offset Current	$I_{IN(+)} - I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25^\circ C$		5	50		5	50	nA
Input Common-Mode Voltage Range	$V^+ = 30V$, (Note 7) (LM2904, $V^+ = 26V$), $T_A = 25^\circ C$	0		$V^+–1.5$	0		$V^+–1.5$	V
Supply Current	Over Full Temperature Range $R_L = \infty$ on All Op Amps							
	$V^+ = 30V$ (LM2904 $V^+ = 26V$)		1	2		1	2	mA
	$V^+ = 5V$		0.5	1.2		0.5	1.2	mA

Electrical Characteristics

$V^+ = +5.0V$, (Note 4), unless otherwise stated

Parameter		Conditions	LM158A			LM358A			LM158/LM258			Units
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain		$V^+ = 15V$, $T_A = 25^\circ C$, $R_L \geq 2\ k\Omega$, (For $V_O = 1V$ to 11V)	50	100		25	100		50	100		V/mV
Common-Mode Rejection Ratio		$T_A = 25^\circ C$, $V_{CM} = 0V$ to $V^+–1.5V$	70	85		65	85		70	85		dB
Power Supply Rejection Ratio		$V^+ = 5V$ to 30V (LM2904, $V^+ = 5V$ to 26V), $T_A = 25^\circ C$	65	100		65	100		65	100		dB
Amplifier-to-Amplifier Coupling		f = 1 kHz to 20 kHz, $T_A = 25^\circ C$ (Input Referred), (Note 8)		–120			–120			–120		dB
Output Current	Source	$V_{IN}^+ = 1V$, $V_{IN}^- = 0V$, $V^+ = 15V$, $V_O = 2V$, $T_A = 25^\circ C$	20	40		20	40		20	40		mA
	Sink	$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$ $V^+ = 15V$, $T_A = 25^\circ C$, $V_O = 2V$	10	20		10	20		10	20		mA
		$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$ $T_A = 25^\circ C$, $V_O = 200\ mV$, $V^+ = 15V$	12	50		12	50		12	50		μA
Short Circuit to Ground		$T_A = 25^\circ C$, (Note 2), $V^+ = 15V$		40	60		40	60		40	60	mA
Input Offset Voltage		(Note 5)			4			5			7	mV
Input Offset Voltage Drift		$R_S = 0\Omega$		7	15		7	20		7		μV/˚C
Input Offset Current		$I_{IN(+)} - I_{IN(-)}$			30			75			100	nA
Input Offset Current Drift		$R_S = 0\Omega$		10	200		10	300		10		pA/˚C
Input Bias Current		$I_{IN(+)}$ or $I_{IN(-)}$		40	100		40	200		40	300	nA
Input Common-Mode Voltage Range		$V^+ = 30\ V$, (Note 7) (LM2904, $V^+ = 26V$)	0		$V^+–2$	0		$V^+–2$	0		$V^+–2$	V

Electrical Characteristics (Continued)

$V^+ = +5.0V$, (Note 4), unless otherwise stated

Parameter		Conditions		LM158A			LM358A			LM158/LM258			Units
				Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain		$V^+ = +15V$ (V_O = 1V to 11V) $R_L \geq 2$ kΩ		25			15			25			V/mV
Output Voltage Swing	V_{OH}	$V^+ = +30V$ (LM2904, $V^+ = 26V$)	$R_L = 2$ kΩ	26			26			26			V
			$R_L = 10$ kΩ	27	28		27	28		27	28		V
	V_{OL}	$V^+ = 5V$, $R_L = 10$ kΩ			5	20		5	20		5	20	mV
Output Current	Source	$V_{IN}^+ = +1V$, $V_{IN}^- = 0V$, $V^+ = 15V$, $V_O = 2V$		10	20		10	20		10	20		mA
	Sink	$V_{IN}^- = +1V$, $V_{IN}^+ = 0V$, $V^+ = 15V$, $V_O = 2V$		10	15		5	8		5	8		mA

Electrical Characteristics

$V^+ = +5.0V$, (Note 4), unless otherwise stated

Parameter		Conditions	LM358			LM2904			Units
			Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain		$V^+ = 15V$, $T_A = 25^\circ C$, $R_L \geq 2$ kΩ, (For V_O = 1V to 11V)	25	100		25	100		V/mV
Common-Mode Rejection Ratio		$T_A = 25^\circ C$, V_{CM} = 0V to $V^+ - 1.5V$	65	85		50	70		dB
Power Supply Rejection Ratio		V^+ = 5V to 30V (LM2904, V^+ = 5V to 26V), $T_A = 25^\circ C$	65	100		50	100		dB
Amplifier-to-Amplifier Coupling		f = 1 kHz to 20 kHz, $T_A = 25^\circ C$ (Input Referred), (Note 8)		−120			−120		dB
Output Current	Source	$V_{IN}^+ = 1V$, $V_{IN}^- = 0V$, $V^+ = 15V$, $V_O = 2V$, $T_A = 25^\circ C$	20	40		20	40		mA
	Sink	$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$ $V^+ = 15V$, $T_A = 25^\circ C$, $V_O = 2V$	10	20		10	20		mA
		$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$ $T_A = 25^\circ C$, $V_O = 200$ mV, $V^+ = 15V$	12	50		12	50		μA
Short Circuit to Ground		$T_A = 25^\circ C$, (Note 2), $V^+ = 15V$		40	60		40	60	mA
Input Offset Voltage		(Note 5)			9			10	mV
Input Offset Voltage Drift		$R_S = 0\Omega$		7			7		μV/˚C
Input Offset Current		$I_{IN(+)} - I_{IN(-)}$			150		45	200	nA
Input Offset Current Drift		$R_S = 0\Omega$		10			10		pA/˚C
Input Bias Current		$I_{IN(+)}$ or $I_{IN(-)}$		40	500		40	500	nA
Input Common-Mode Voltage Range		$V^+ = 30$ V, (Note 7) (LM2904, $V^+ = 26V$)	0		$V^+ - 2$	0		$V^+ - 2$	V

Electrical Characteristics (Continued)

$V^+ = +5.0V$, (Note 4), unless otherwise stated

Parameter		Conditions		LM358			LM2904			Units
				Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain		$V^+ = +15V$ (V_O = 1V to 11V) $R_L \geq 2\ k\Omega$		15			15			V/mV
Output Voltage Swing	V_{OH}	$V^+ = +30V$ (LM2904, $V^+ = 26V$)	$R_L = 2\ k\Omega$	26			22			V
			$R_L = 10\ k\Omega$	27	28		23	24		V
	V_{OL}	$V^+ = 5V$, $R_L = 10\ k\Omega$			5	20		5	100	mV
Output Current	Source	$V_{IN}^+ = +1V$, $V_{IN}^- = 0V$, $V^+ = 15V$, $V_O = 2V$		10	20		10	20		mA
	Sink	$V_{IN}^- = +1V$, $V_{IN}^+ = 0V$, $V^+ = 15V$, $V_O = 2V$		5	8		5	8		mA

Note 1: For operating at high temperatures, the LM358/LM358A, LM2904 must be derated based on a +125˚C maximum junction temperature and a thermal resistance of 120˚C/W for MDIP, 182˚C/W for Metal Can, 189˚C/W for Small Outline package, and 230˚C/W for micro SMD, which applies for the device soldered in a printed circuit board, operating in a still air ambient. The LM258/LM258A and LM158/LM158A can be derated based on a +150˚C maximum junction temperature. The dissipation is the total of both amplifiers — use external resistors, where possible, to allow the amplifier to saturate or to reduce the power which is dissipated in the integrated circuit.

Note 2: Short circuits from the output to V^+ can cause excessive heating and eventual destruction. When considering short cirucits to ground, the maximum output current is approximately 40 mA independent of the magnitude of V^+. At values of supply voltage in excess of +15V, continuous short-circuits can exceed the power dissipation ratings and cause eventual destruction. Destructive dissipation can result from simultaneous shorts on all amplifiers.

Note 3: This input current will only exist when the voltage at any of the input leads is driven negative. It is due to the collector-base junction of the input PNP transistors becoming forward biased and thereby acting as input diode clamps. In addition to this diode action, there is also lateral NPN parasitic transistor action on the IC chip. This transistor action can cause the output voltages of the op amps to go to the V^+voltage level (or to ground for a large overdrive) for the time duration that an input is driven negative. This is not destructive and normal output states will re-establish when the input voltage, which was negative, again returns to a value greater than −0.3V (at 25˚C).

Note 4: These specifications are limited to $-55˚C \leq T_A \leq +125˚C$ for the LM158/LM158A. With the LM258/LM258A, all temperature specifications are limited to $-25˚C \leq T_A \leq +85˚C$, the LM358/LM358A temperature specifications are limited to $0˚C \leq T_A \leq +70˚C$, and the LM2904 specifications are limited to $-40˚C \leq T_A \leq +85˚C$.

Note 5: $V_O \simeq 1.4V$, $R_S = 0\Omega$ with V^+ from 5V to 30V; and over the full input common-mode range (0V to V^+ −1.5V) at 25˚C. For LM2904, V^+ from 5V to 26V.

Note 6: The direction of the input current is out of the IC due to the PNP input stage. This current is essentially constant, independent of the state of the output so no loading change exists on the input lines.

Note 7: The input common-mode voltage of either input signal voltage should not be allowed to go negative by more than 0.3V (at 25˚C). The upper end of the common-mode voltage range is V^+ −1.5V (at 25˚C), but either or both inputs can go to +32V without damage (+26V for LM2904), independent of the magnitude of V^+.

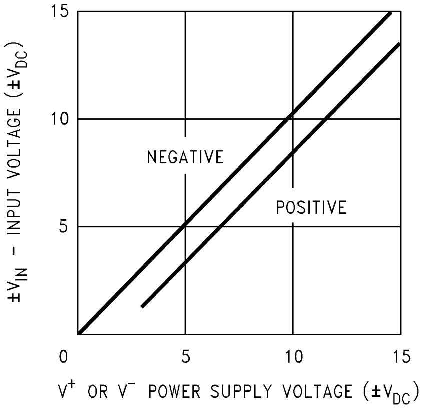
Note 8: Due to proximity of external components, insure that coupling is not originating via stray capacitance between these external parts. This typically can be detected as this type of capacitance increases at higher frequencies.

Note 9: Refer to RETS158AX for LM158A military specifications and to RETS158X for LM158 military specifications.

Note 10: Human body model, 1.5 kΩ in series with 100 pF.

Typical Performance Characteristics

Input Voltage Range



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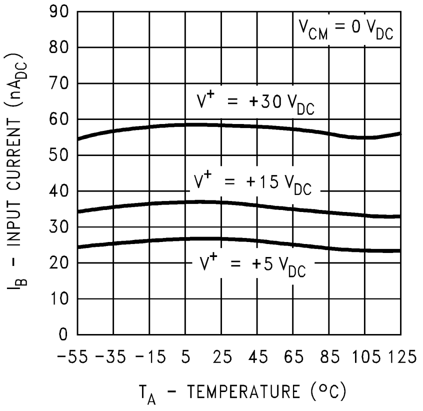
Input Current



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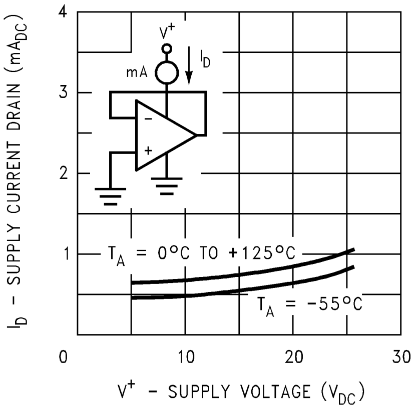
Supply Current



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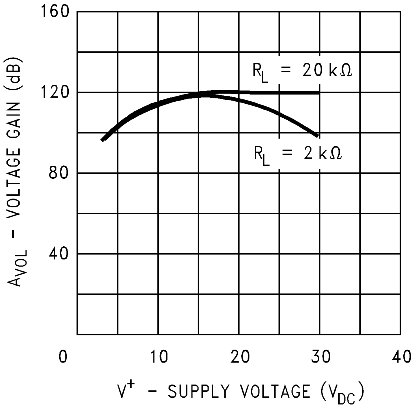
Voltage Gain



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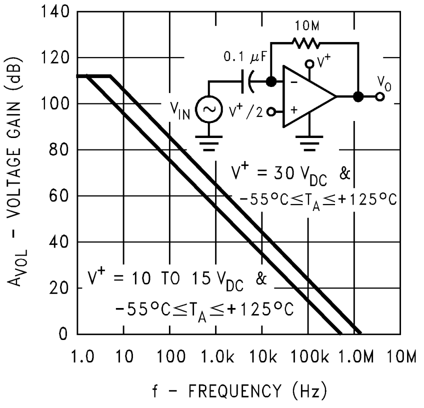
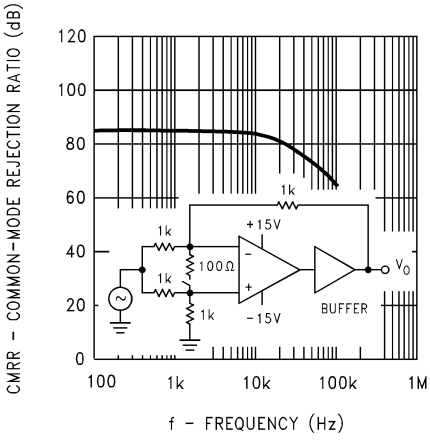
Open Loop Frequency Response



00778738

Common-Mode Rejection Ratio



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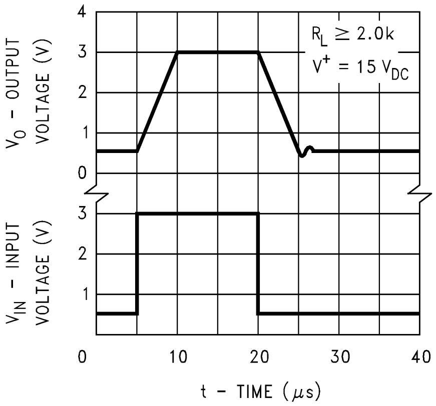
Typical Performance Characteristics (Continued)



Voltage Follower Pulse Response

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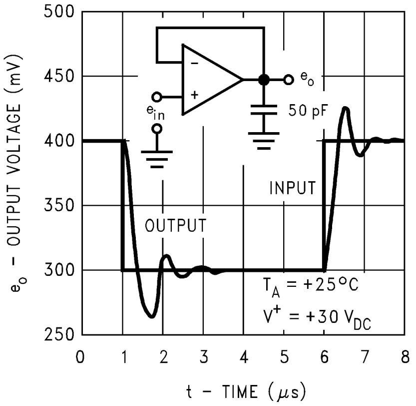
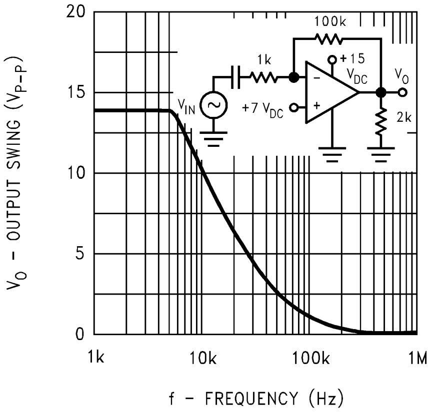


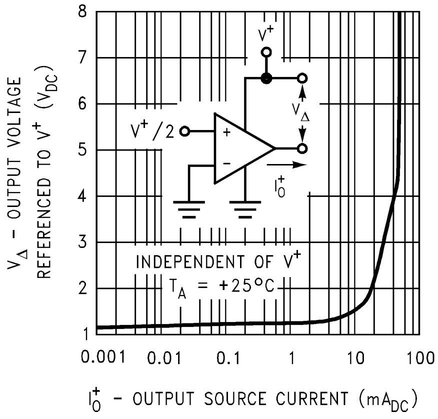
Voltage Follower Pulse Response (Small Signal)

00778741



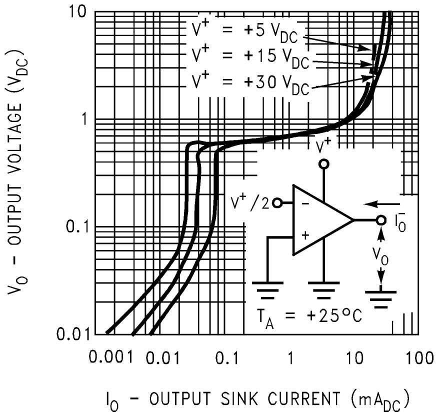
Large Signal Frequency Response

00778742



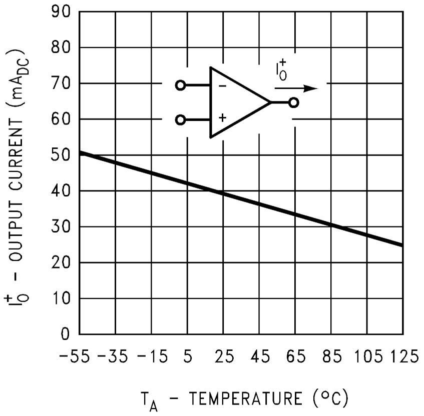
Output Characteristics Current Sourcing

00778743



Output Characteristics Current Sinking

00778744

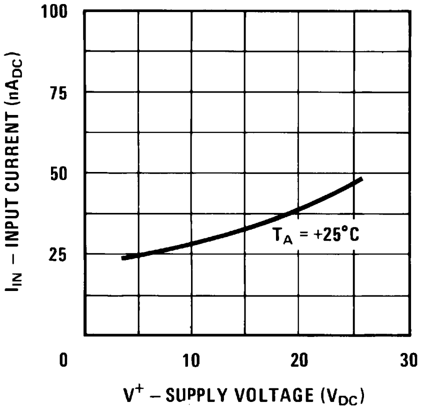


Current Limiting

00778745

Typical Performance Characteristics (Continued)

Input Current (LM2902 only)



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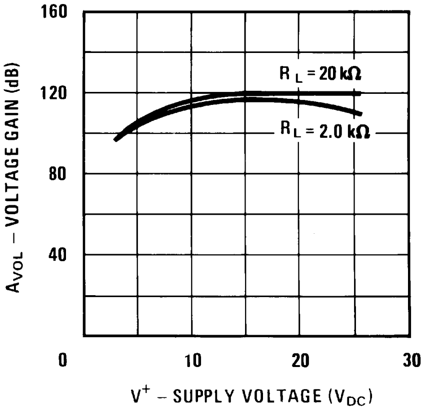
Voltage Gain (LM2902 only)



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Application Hints

The LM158 series are op amps which operate with only a single power supply voltage, have true-differential inputs, and remain in the linear mode with an input common-mode voltage of 0 V_{DC}. These amplifiers operate over a wide range of power supply voltage with little change in performance characteristics. At 25˚C amplifier operation is possible down to a minimum supply voltage of 2.3 V_{DC}.

Precautions should be taken to insure that the power supply for the integrated circuit never becomes reversed in polarity or that the unit is not inadvertently installed backwards in a test socket as an unlimited current surge through the resulting forward diode within the IC could cause fusing of the internal conductors and result in a destroyed unit.

Large differential input voltages can be easily accomodated and, as input differential voltage protection diodes are not needed, no large input currents result from large differential input voltages. The differential input voltage may be larger than V^+ without damaging the device. Protection should be provided to prevent the input voltages from going negative more than −0.3 V_{DC} (at 25˚C). An input clamp diode with a resistor to the IC input terminal can be used.

To reduce the power supply current drain, the amplifiers have a class A output stage for small signal levels which converts to class B in a large signal mode. This allows the amplifiers to both source and sink large output currents. Therefore both NPN and PNP external current boost transistors can be used to extend the power capability of the basic amplifiers. The output voltage needs to raise approximately 1 diode drop above ground to bias the on-chip vertical PNP transistor for output current sinking applications.

For ac applications, where the load is capacitively coupled to the output of the amplifier, a resistor should be used, from the output of the amplifier to ground to increase the class A bias current and prevent crossover distortion. Where the load is directly coupled, as in dc applications, there is no crossover distortion.

Capacitive loads which are applied directly to the output of the amplifier reduce the loop stability margin. Values of 50 pF can be accomodated using the worst-case non-inverting unity gain connection. Large closed loop gains or resistive isolation should be used if larger load capacitance must be driven by the amplifier.

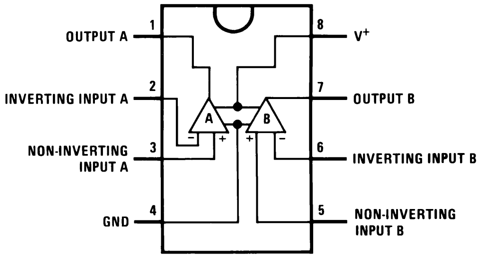
The bias network of the LM158 establishes a drain current which is independent of the magnitude of the power supply voltage over the range of 3 V_{DC} to 30 V_{DC}.

Output short circuits either to ground or to the positive power supply should be of short time duration. Units can be destroyed, not as a result of the short circuit current causing metal fusing, but rather due to the large increase in IC chip dissipation which will cause eventual failure due to excessive function temperatures. Putting direct short-circuits on more than one amplifier at a time will increase the total IC power dissipation to destructive levels, if not properly protected with external dissipation limiting resistors in series with the output leads of the amplifiers. The larger value of output source current which is available at 25˚C provides a larger output current capability at elevated temperatures (see typical performance characteristics) than a standard IC op amp.

The circuits presented in the section on typical applications emphasize operation on only a single power supply voltage. If complementary power supplies are available, all of the standard op amp circuits can be used. In general, introducing a pseudo-ground (a bias voltage reference of $V^+/2$) will allow operation above and below this value in single power supply systems. Many application circuits are shown which take advantage of the wide input common-mode voltage range which includes ground. In most cases, input biasing is not required and input voltages which range to ground can easily be accommodated.

Connection Diagrams

DIP/SO Package



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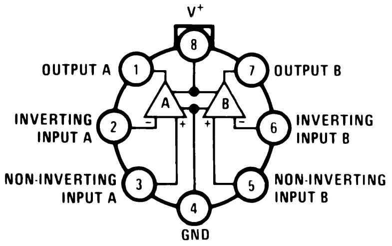
Top View

Metal Can Package



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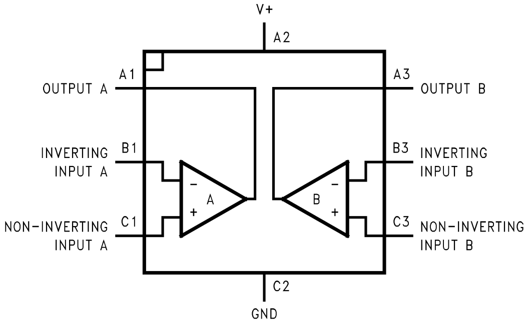
Top View

8-Bump micro SMD



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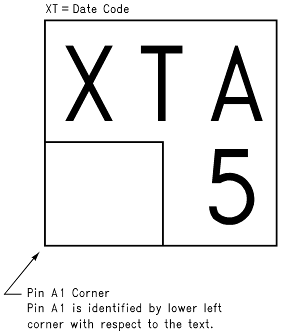
Top View
(Bump Side Down)

LM358BP micro SMD Marking Orientation



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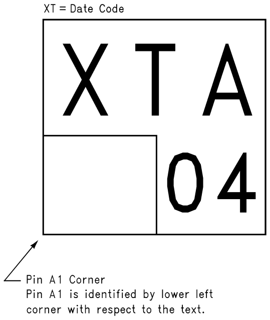
Top View

LM2904IBP micro SMD Marking Orientation



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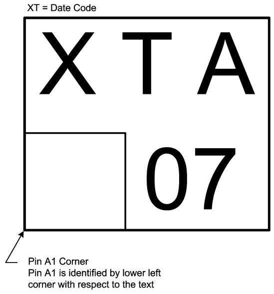
Top View

LM358TP micro SMD Marking Orientation



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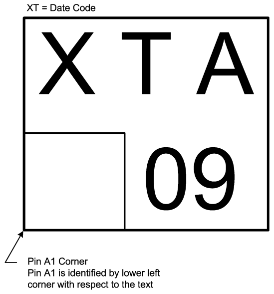
Top View

LM2904ITP micro SMD Marking Orientation



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Top View

Ordering Information

Package	Temperature Range				NSC Drawing
	–55˚C to 125˚C	–25˚C to 85˚C	0˚C to 70˚C	–40˚C to 85˚C	
SO-8			LM358AM LM358AMX LM358M LM358MX	LM2904M LM2904MX	M08A
8-Pin Molded DIP			LM358AN LM358N	LM2904N	N08E
8-Pin Ceramic DIP	LM158AJ/883(Note 11) LM158J/883(Note 11) LM158J LM158AJLQML(Note 12) LM158AJQMLV(Note 12)				J08A
TO-5, 8-Pin Metal Can	LM158AH/883(Note 11) LM158H/883(Note 11) LM158AH LM158H LM158AHLQML(Note 12) LM158AHLQMLV(Note 12)	LM258H	LM358H		H08C
8-Bump micro SMD			LM358BP LM358BPX	LM2904IBP LM2904IBPX	BPA08AAB 0.85 mm Thick
8-Bump micro SMD Lead Free			LM358TP LM358TPX	LM2904ITP LM2904ITPX	TPA08AAA 0.50 mm Thick
14-Pin Ceramic SOIC	LM158AWG/883				WG10A

Note 11: LM158 is available per SMD #5962-8771001

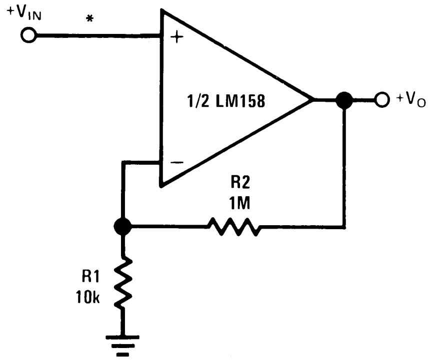
LM158A is available per SMD #5962-8771002

Note 12: See STD Mil DWG 5962L87710 for Radiation Tolerant Devices

Typical Single-Supply Applications

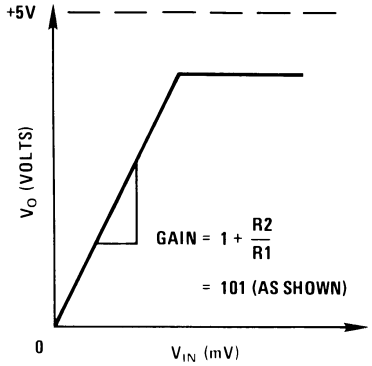
($V^+ = 5.0\ V_{DC}$)

Non-Inverting DC Gain (0V Output)



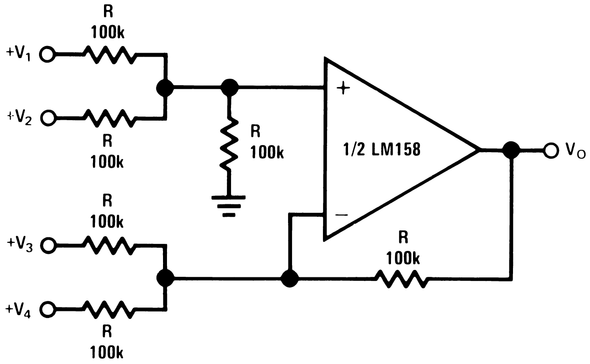
00778706

*R not needed due to temperature independent I_{IN}



00778707

DC Summing Amplifier ($V_{IN'S} \geq 0\ V_{DC}$ and $V_O \geq 0\ V_{DC}$)

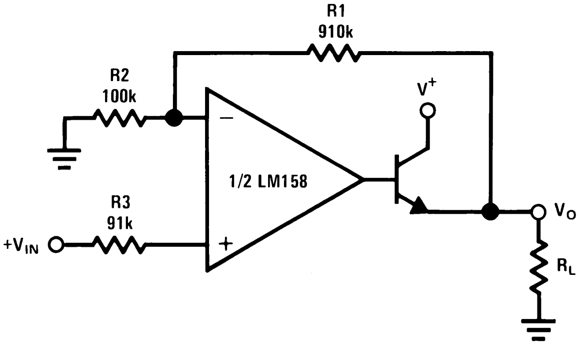


00778708

Where: $V_O = V_1 + V_2 - V_3 - V_4$

$(V_1 + V_2) \geq (V_3 + V_4)$ to keep $V_O > 0\ V_{DC}$

Power Amplifier



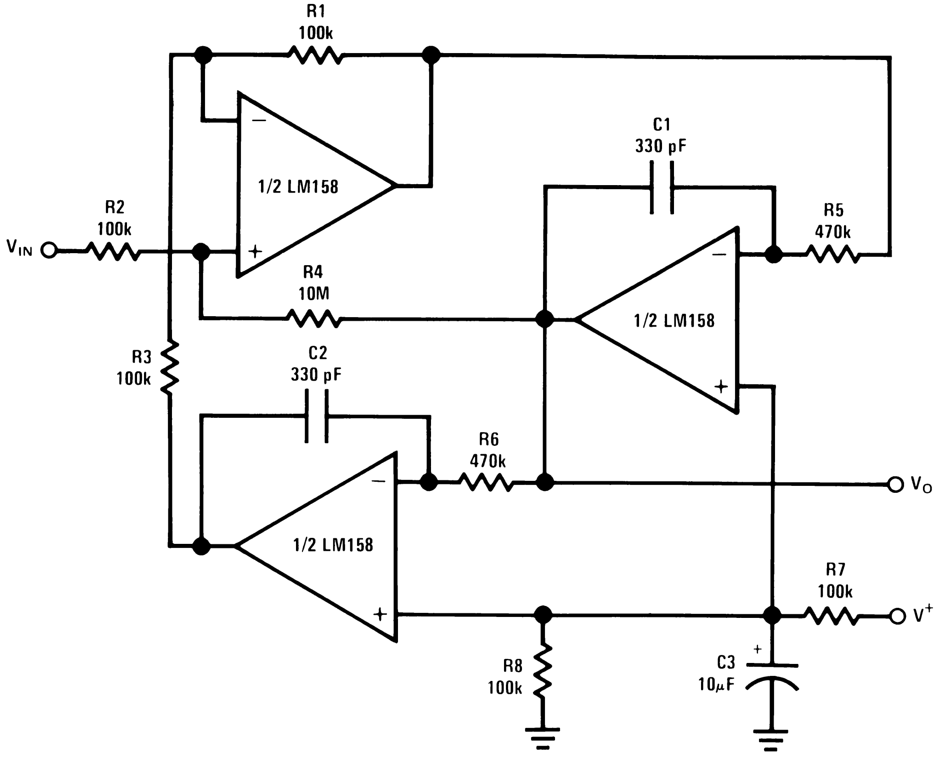
00778709

$V_O = 0\ V_{DC}$ for $V_{IN} = 0\ V_{DC}$

$A_V = 10$

Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

"BI-QUAD" RC Active Bandpass Filter



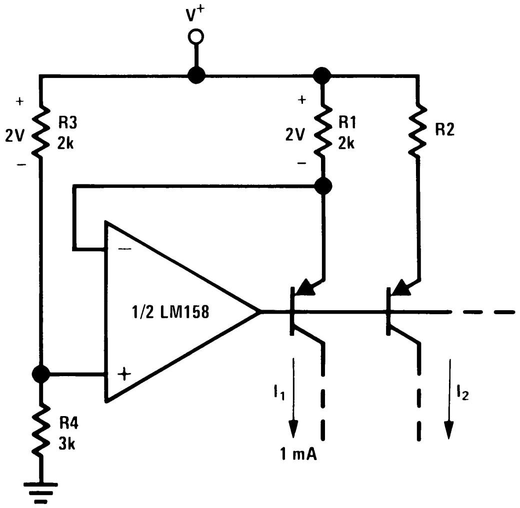
00778710

$f_O = 1$ kHz

Q = 50

$A_V = 100$ (40 dB)

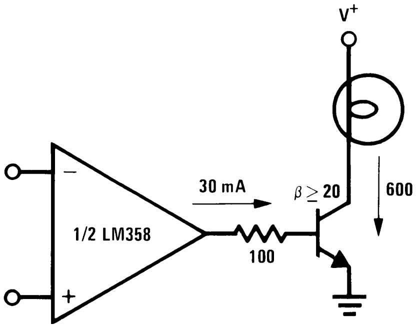
Fixed Current Sources



00778711

$$I_2 = \left(\frac{R1}{R2}\right) I_1$$

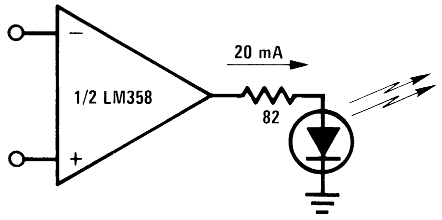
Lamp Driver



00778712

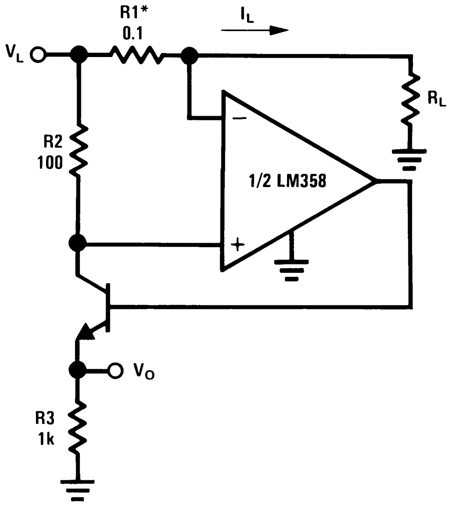
Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

LED Driver



00778713

Current Monitor

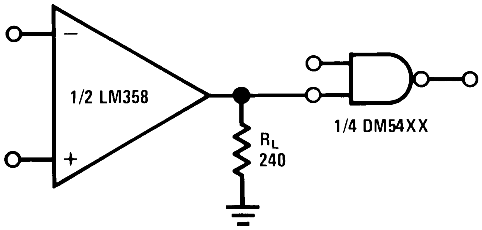


00778714

$$V_O = \frac{1V\,(I_L)}{1A}$$

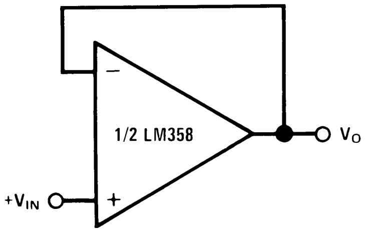
*(Increase R1 for I_L small)
$V_L \leq V^+ - 2V$

Driving TTL



00778715

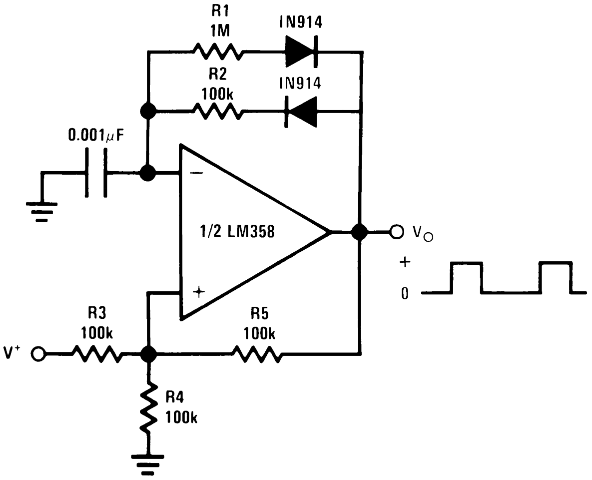
Voltage Follower



00778717

$V_O = V_{IN}$

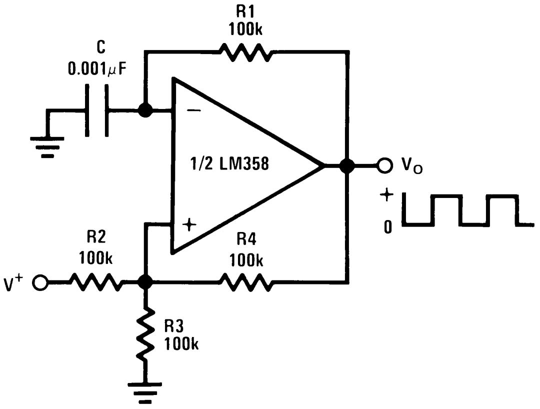
Pulse Generator



00778716

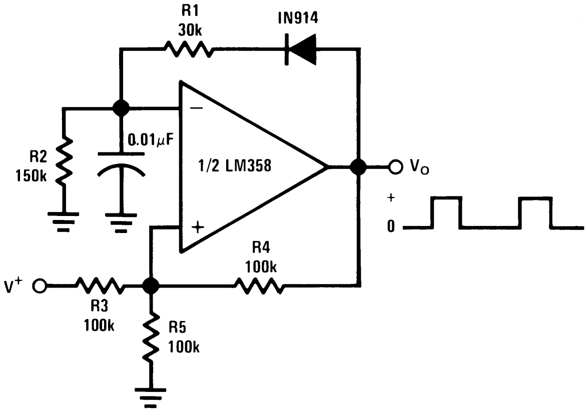
Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

Squarewave Oscillator



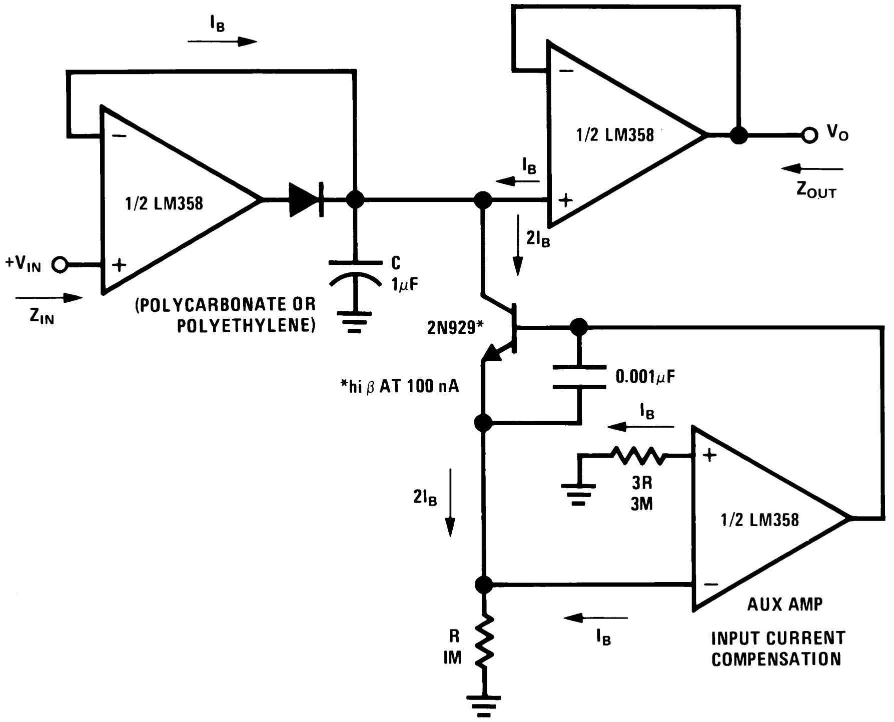
00778718

Pulse Generator



00778719

Low Drift Peak Detector

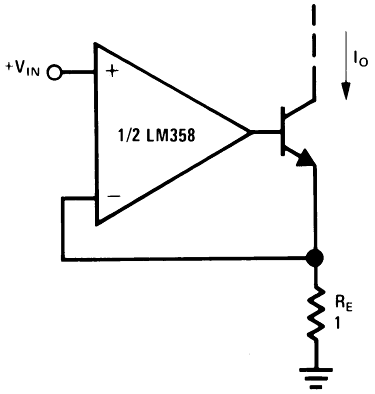


00778720

HIGH Z_{IN}
LOW Z_{OUT}

Typical Single-Supply Applications (V+ = 5.0 V_{DC}) (Continued)

High Compliance Current Sink

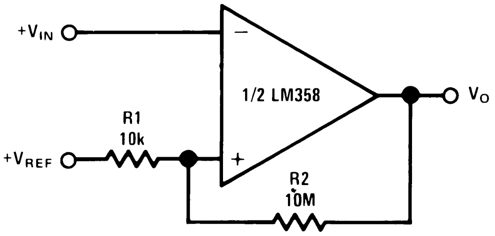


00778721

I_O = 1 amp/volt V_{IN}

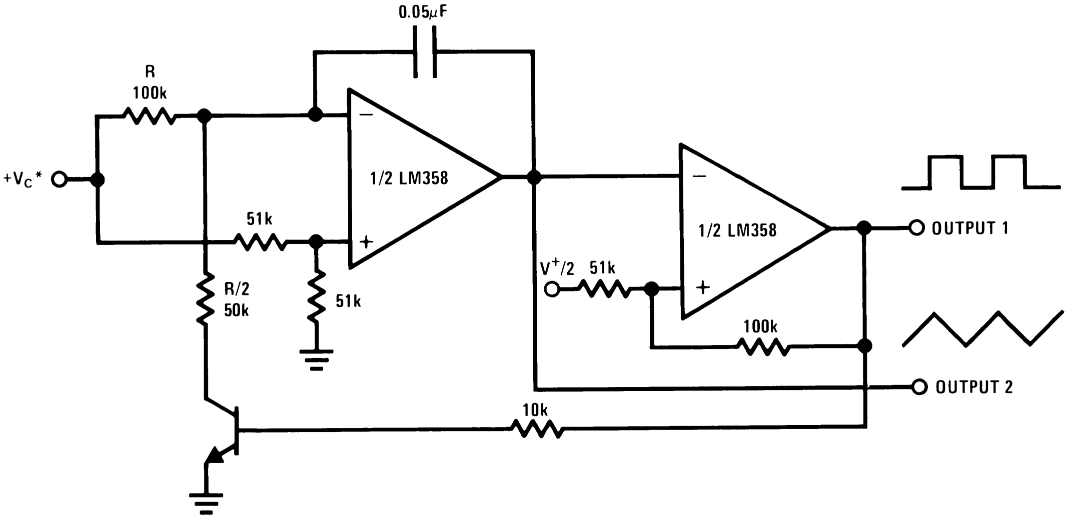
(Increase R_E for I_O small)

Comparator with Hysteresis



00778722

Voltage Controlled Oscillator (VCO)

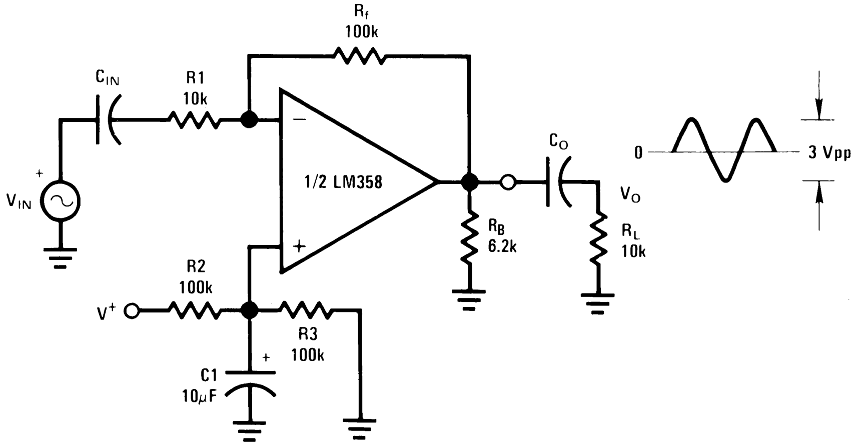


00778723

*WIDE CONTROL VOLTAGE RANGE: 0 $V_{DC} \leq V_C \leq 2\ (V^+ - 1.5V_{DC})$

Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

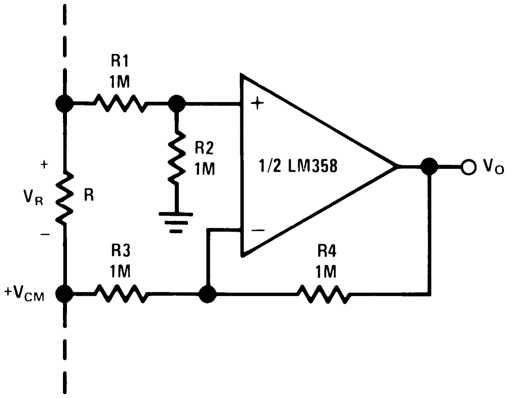
AC Coupled Inverting Amplifier



00778724

$$A_V = \frac{R_f}{R1} \quad \text{(As shown, } A_V = 10\text{)}$$

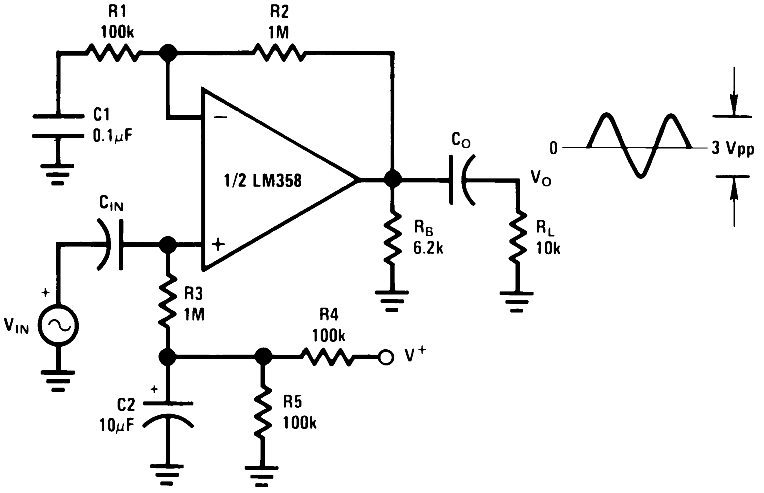
Ground Referencing a Differential Input Signal



00778725

Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

AC Coupled Non-Inverting Amplifier

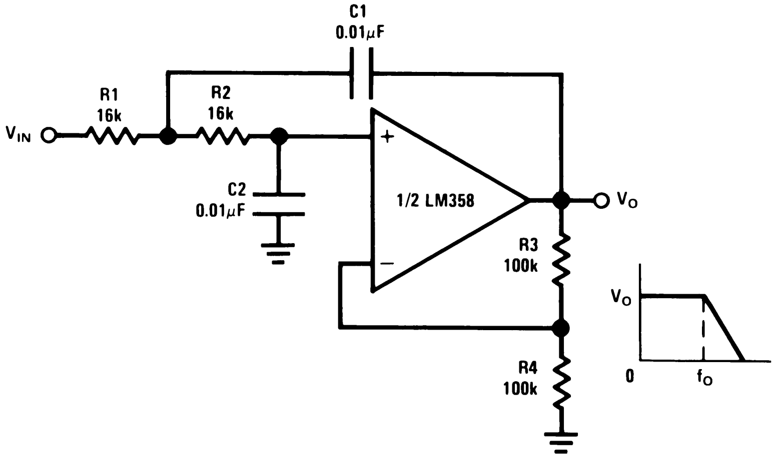


00778726

$$A_V = 1 + \frac{R2}{R1}$$

$A_v = 11$ (As Shown)

DC Coupled Low-Pass RC Active Filter



00778727

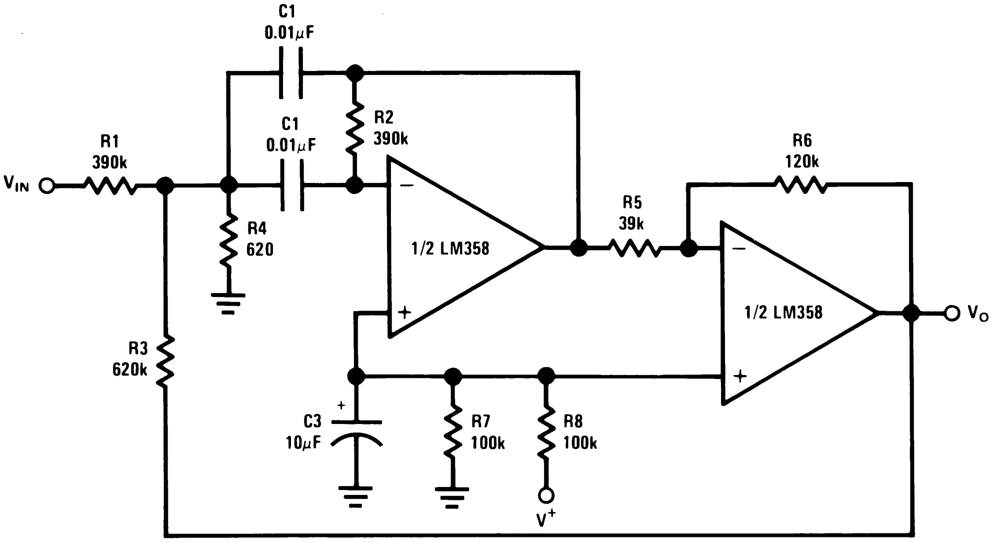
$f_o = 1$ kHz

$Q = 1$

$A_V = 2$

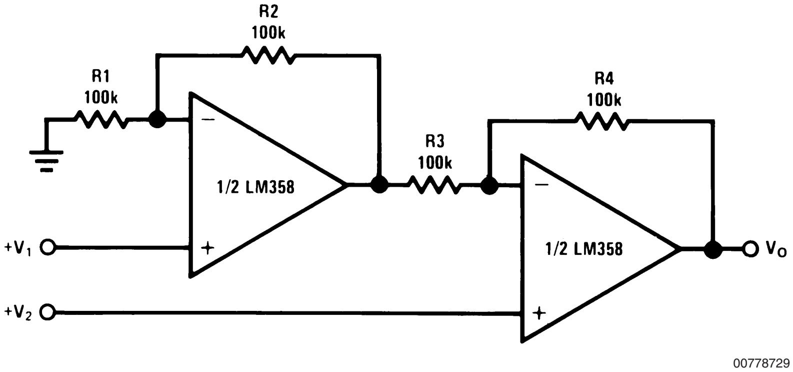
Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

Bandpass Active Filter



$f_O = 1$ kHz
$Q = 25$

High Input Z, DC Differential Amplifier



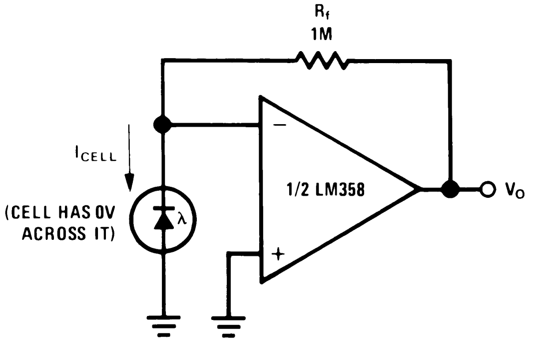
For $\frac{R1}{R2} = \frac{R4}{R3}$ (CMRR depends on this resistor ratio match)

$$V_O = 1 + \frac{R4}{R3} (V_2 - V_1)$$

As Shown: $V_O = 2 (V_2 - V_1)$

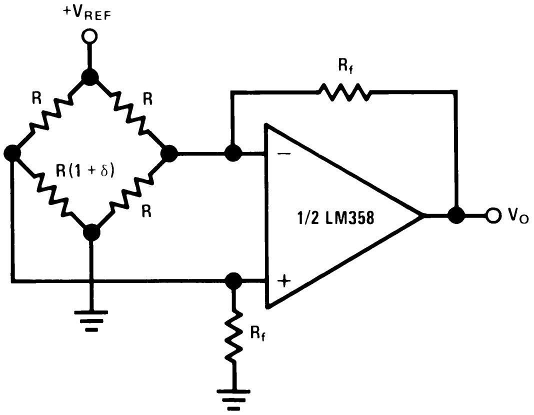
Typical Single-Supply Applications ($V^+ = 5.0\ V_{DC}$) (Continued)

Photo Voltaic-Cell Amplifier



00778730

Bridge Current Amplifier

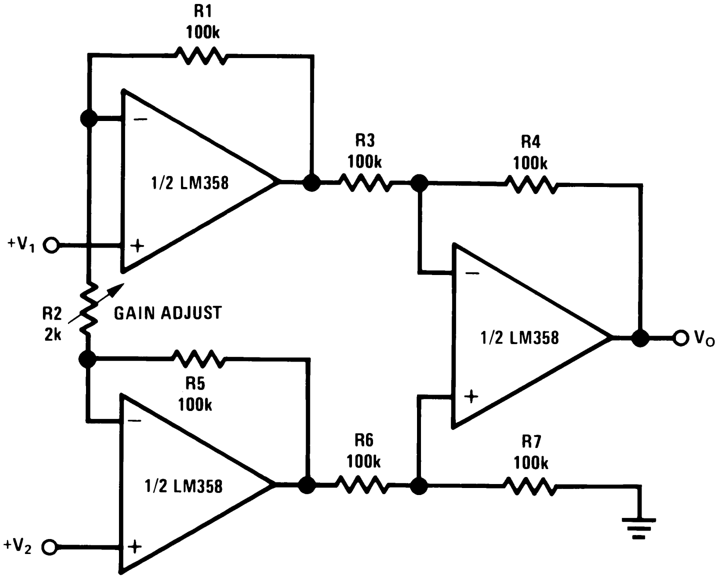


00778733

For $\delta << 1$ and $R_f >> R$

$$V_O \cong V_{REF}\left(\frac{\delta}{2}\right)\frac{R_f}{R}$$

High Input Z Adjustable-Gain DC Instrumentation Amplifier



00778731

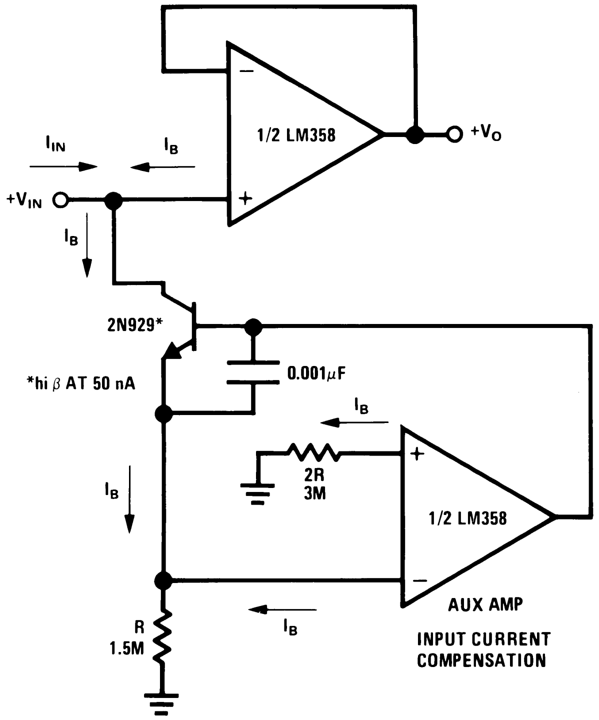
If R1 = R5 & R3 = R4 = R6 = R7 (CMRR depends on match)

$$V_O = 1 + \frac{2R1}{R2}\ (V_2 - V_1)$$

As shown $V_O = 101\ (V_2 - V_1)$

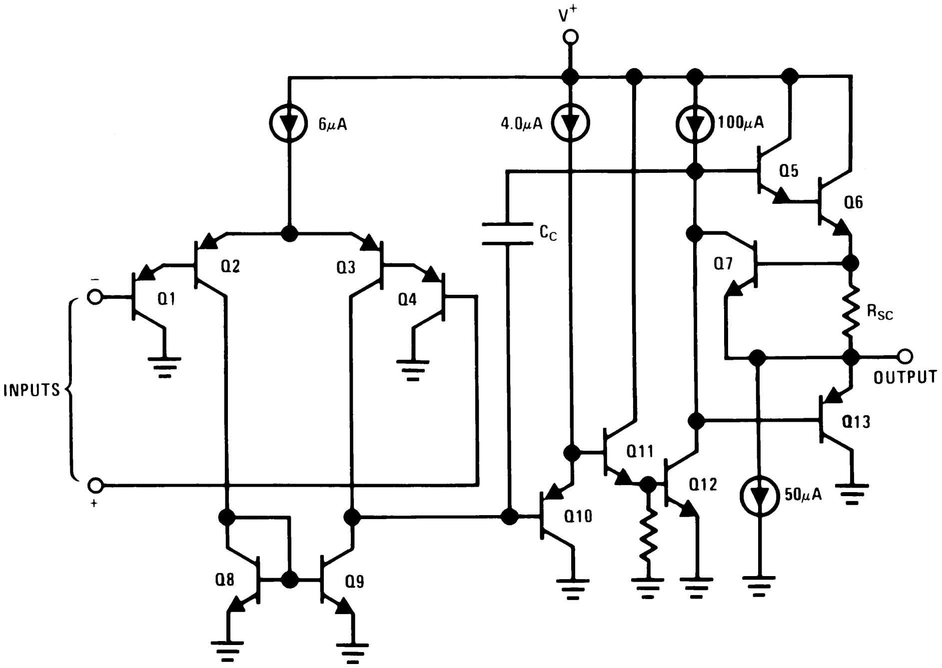
Typical Single-Supply Applications (V+ = 5.0 V_{DC}) (Continued)

Using Symmetrical Amplifiers to Reduce Input Current (General Concept)



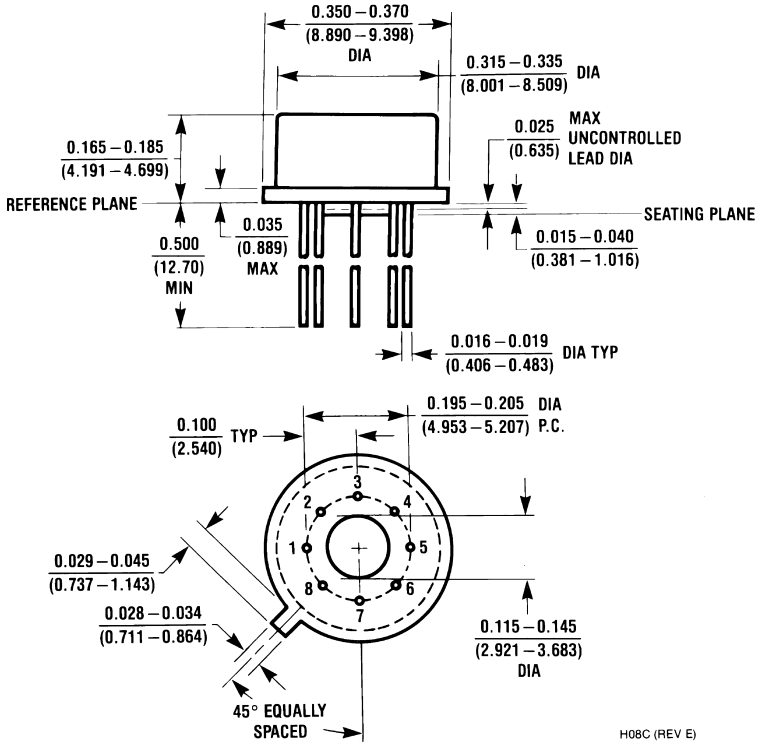
00778732

Schematic Diagram (Each Amplifier)



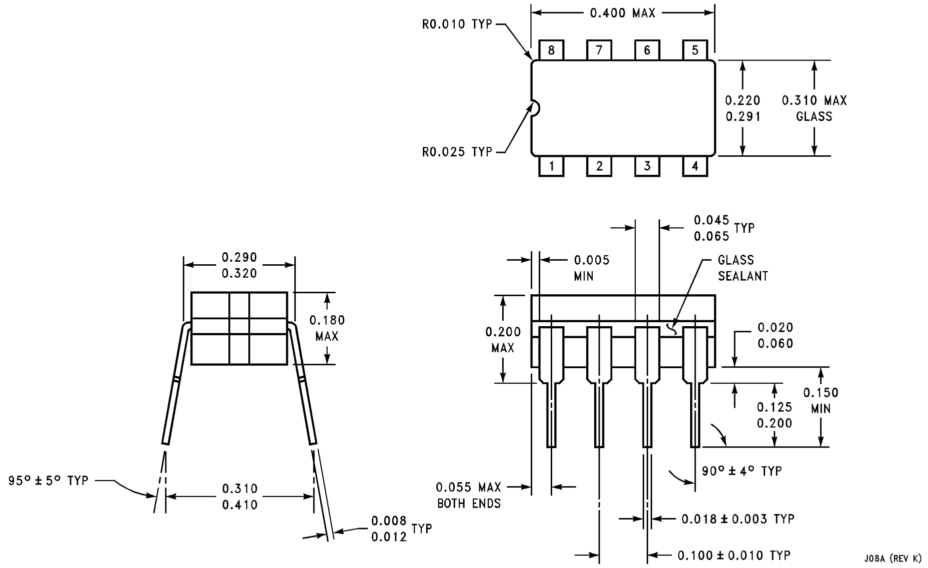
00778703

Physical Dimensions inches (millimeters) unless otherwise noted



H08C (REV E)

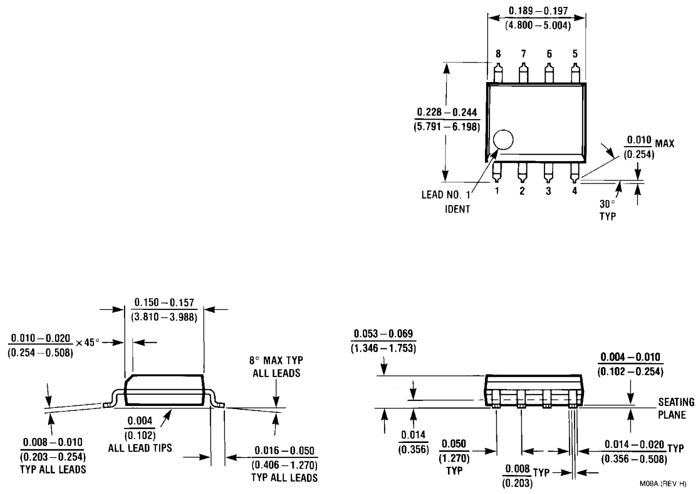
Metal Can Package (H)
NS Package Number H08C



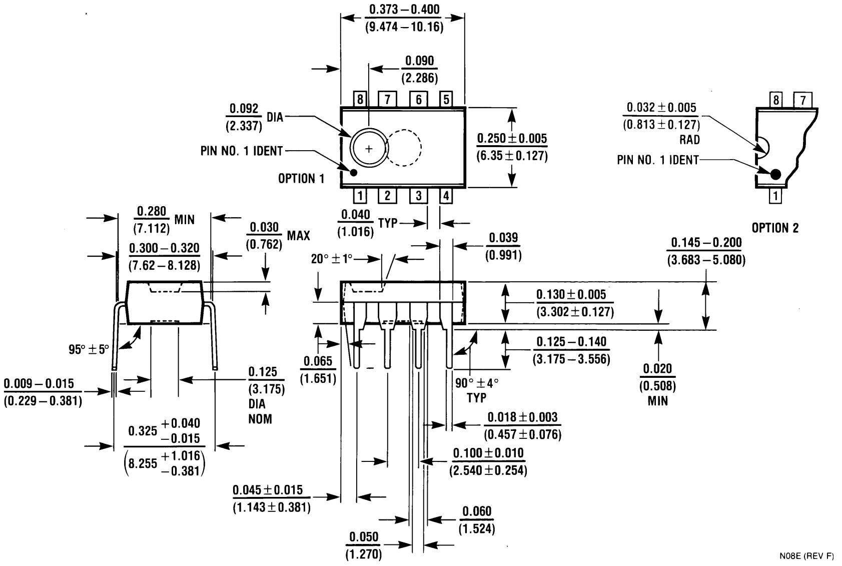
J08A (REV K)

Cerdip Package (J)
NS Package Number J08A

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

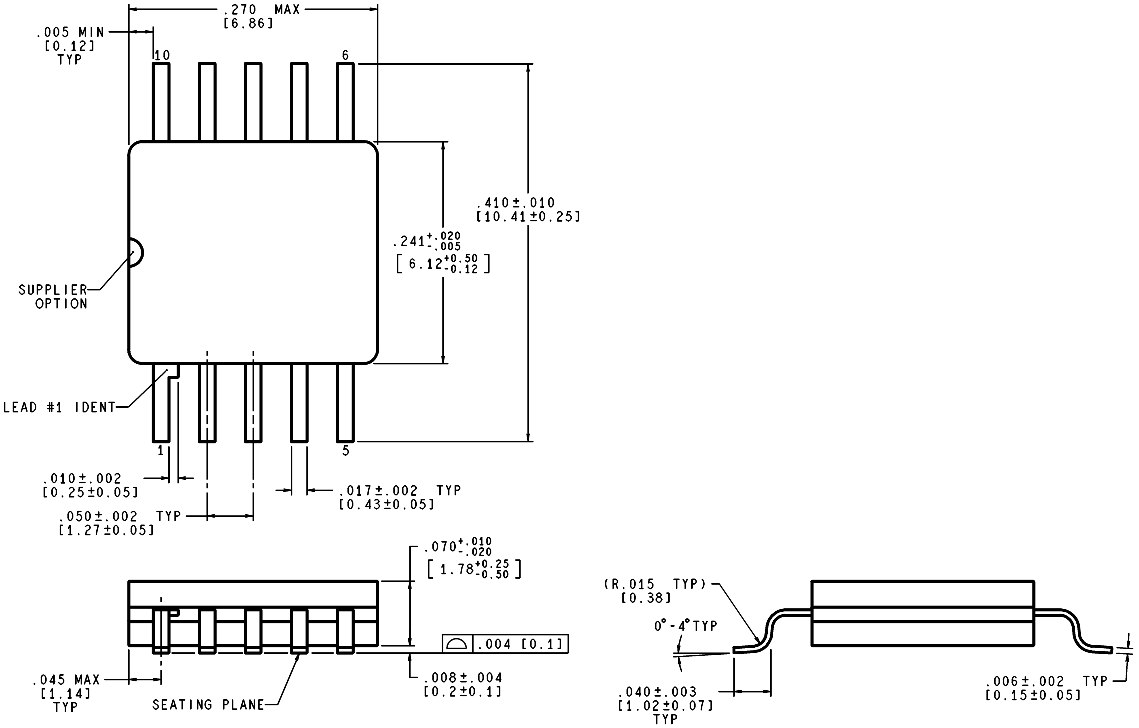


SOIC Package (M)
NS Package Number M08A



Molded Dip Package (N)
NS Package Number N08E

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

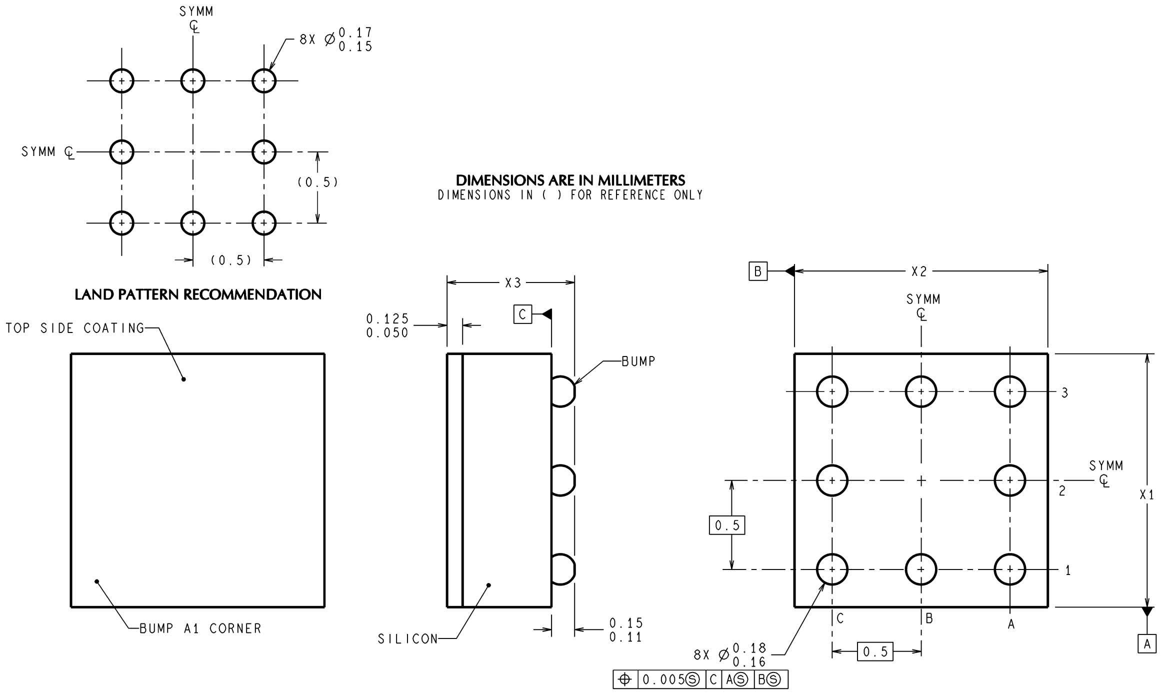


CONTROLLING DIMENSION IS INCH
VALUES IN [ ] ARE MILLIMETERS

WG10A (Rev C)

Order Number LM158AWG/883
NS Package Number WG10A

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



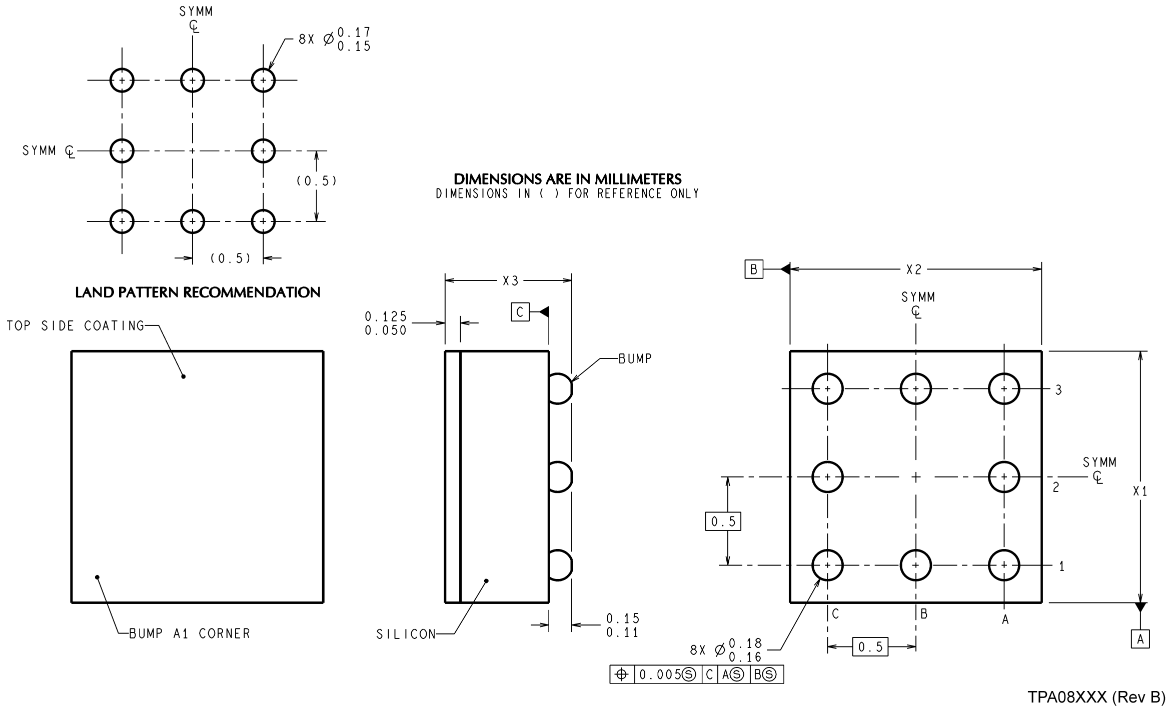
BPA08XXX (Rev D)

NOTES: UNLESS OTHERWISE SPECIFIED

1. EPOXY COATING
2. 63Sn/37Pb EUTECTIC BUMP
3. RECOMMEND NON-SOLDER MASK DEFINED LANDING PAD.
4. PIN A1 IS ESTABLISHED BY LOWER LEFT CORNER WITH RESPECT TO TEXT ORIENTATION REMAINING PINS ARE NUMBERED COUNTERCLOCKWISE.
5. XXX IN DRAWING NUMBER REPRESENTS PACKAGE SIZE VARIATION WHERE X_1 IS PACKAGE WIDTH, X_2 IS PACKAGE LENGTH AND X_3 IS PACKAGE HEIGHT.
6. REFERENCE JEDEC REGISTRATION MO-211, VARIATION BC.

8-Bump micro SMD
NS Package Number BPA08AAB
X_1 = 1.285 X_2 = 1.285 X_3 = 0.850

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



NOTES: UNLESS OTHERWISE SPECIFIED

1. EPOXY COATING
2. RECOMMEND NON-SOLDER MASK DEFINED LANDING PAD.
3. PIN A1 IS ESTABLISHED BY LOWER LEFT CORNER WITH RESPECT TO TEXT ORIENTATION REMAINING PINS ARE NUMBERED COUNTERCLOCKWISE.
4. XXX IN DRAWING NUMBER REPRESENTS PACKAGE SIZE VARIATION WHERE X_1 IS PACKAGE WIDTH, X_2 IS PACKAGE LENGTH AND X_3 IS PACKAGE HEIGHT.
5. REFERENCE JEDEC REGISTRATION MO-211, VARIATION BC.

8-Bump micro SMD Lead Free
NS Package Number TPA08AAA
$X_1 = 1.285$ $X_2 = 1.285$ $X_3 = 0.500$

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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