

LM318,LM394

6 i]`X]b[`Ub`Cd`5 a d`K]h `6]dc`Uf`Hf Ubg]ghc fg
5 `<]ghcf]WU`5 dd`]WU]cb`BchY`VmFc VYfh5 "DYUgY

5 dd`]WU]cb`F Ydcfh



Building an Op Amp With Bipolar Transistors

A Historical Application Note

National Semiconductor
Linear Brief 52
Robert A. Pease
December 1980



It is well known that the voltage noise of an operational amplifier can be decreased by increasing the emitter current of the input stage. The signal-to-noise ratio will be improved by the increase of bias, until the base current noise begins to dominate. The optimum is found at:

$$I_{e(\text{optimum})} = \frac{KT}{q} \frac{\sqrt{h_{FE}}}{r_s}$$

where r_s is the output resistance of the signal source. For example, in the circuit of *Figure 1*, when $r_s = 1 \text{ k}\Omega$ and $h_{FE} = 500$, the I_e optimum is about $500 \mu\text{A}$ or $560 \mu\text{A}$. However, at this rich current level, the DC base current will cause a significant voltage error in the base resistance, and even after cancellation, the DC drift will be significantly bigger than when I_e is smaller. In this example, $I_b = 1 \mu\text{A}$, so $I_b \times r_s = 1 \text{ mV}$. Even if the I_b and r_s are well matched at each input, it is not reasonable to expect the $I_b \times r_s$ to track better than 5 or $10 \mu\text{V}/^\circ\text{C}$ versus temperature.

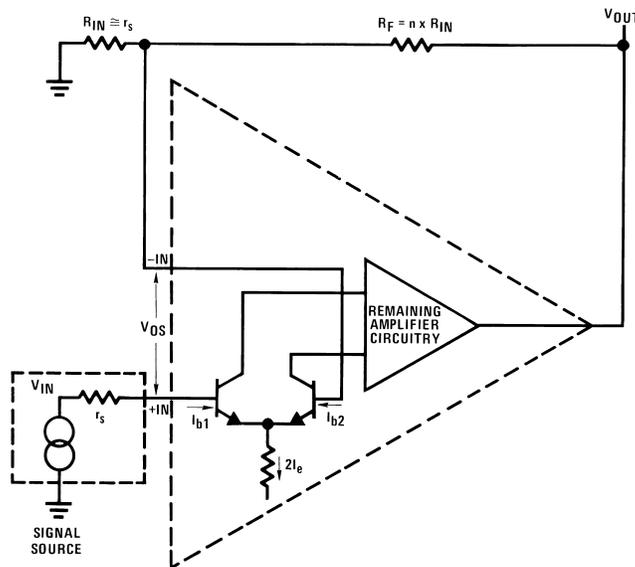
A new amplifier, shown in *Figure 2*, operates one transistor pair at a rich current, for low noise, and a second pair at a much leaner current, for low base current. Although this looks like the familiar Darlington connection, capacitors are added so that the noise will be very low, and the DC drift is very good, too. In the example of *Figure 2*, Q2 runs at $I_e = 500 \mu\text{A}$ and has very low noise. Each half of Q1 is

operated at $11 \mu\text{A} = I_e$. It will have a low base current (20 nA to 40 nA typical), and the offset current of the composite op amp, $I_{b1} - I_{b2}$, will be very small, 1 nA or 2 nA. Thus, errors caused by bias current and offset current drift vs. temperature can be quite small, less than $0.1 \mu\text{V}/^\circ\text{C}$ at $r_s = 1000\Omega$.

The noise of Q1A and Q1B would normally be quite significant, about $6 \text{ nV}/\sqrt{\text{Hz}}$, but the $10 \mu\text{F}$ capacitors completely filter out the noise. At all frequencies above 10 Hz, Q2A and Q2B act as the input transistors, while Q1A and Q1B merely buffer the lowest frequency and DC signals.

For audio frequencies (20 Hz to 20 kHz) the voltage noise of this amplifier is predicted to be $1.4 \text{ nV}/\sqrt{\text{Hz}}$, which is quite small compared to the Johnson noise of the $1 \text{ k}\Omega$ source, $4.0 \text{ nV}/\sqrt{\text{Hz}}$. A noise figure of 0.7 dB is thus predicted, and has been measured and confirmed. Note that for best DC balance $R_6 = 976\Omega$ is added into the feedback path, so that the total impedance seen by the op amp at its negative input is $1 \text{ k}\Omega$. But the 976Ω is heavily bypassed, and the total Johnson noise contributed by the feedback network is below $\frac{1}{2} \text{ nV}/\sqrt{\text{Hz}}$.

To achieve lowest drift, below $0.1 \mu\text{V}/^\circ\text{C}$, R1 and R2 should, of course, be chosen to have good tracking tempco, below 5 ppm/ $^\circ\text{C}$, and so should R3 and R4. When this is done, the drift referred to input will be well below $0.5 \mu\text{V}/^\circ\text{C}$, and this has been confirmed, in the range $+10^\circ\text{C}$ to $+50^\circ\text{C}$.



$$V_{OUT} = (n + 1) V_{IN} + V_{OS} \times (n + 1) + (I_{b2} - I_{b1}) \times r_s \times (n + 1) + V_{\text{noise}} \times (n + 1) + I_{\text{noise}} \times (r_s + R_{IN}) \times (n + 1)$$

FIGURE 1. Conventional Low-Noise Operational Amplifier

Overall, we have designed a low-noise op amp which can rival the noise of the best audio amplifiers, and at the same time exhibits drift characteristics of the best low-drift ampli-

fiers. The amplifier has been used as a precision pre-amp (gain = 1000), and also as the output amplifier for a 20-bit DAC, where low drift and low noise are both important.

6 i T X | b | . u b . C d ` 5 a d i K | A ` 6] d c ` U ` H r U b g | d r c f g

OB-52

To optimize the circuit for other r_s levels, the emitter current for Q2 should be proportional to $1/\sqrt{r_s}$. The emitter current of Q1A should be about ten times the base current of Q2A. The base current of the output op amp should be no more than 1/1000 of the emitter current of Q2. The values of R1 and R2 should be the same as R7.

Various formulae for noise:

Voltage noise of a transistor,

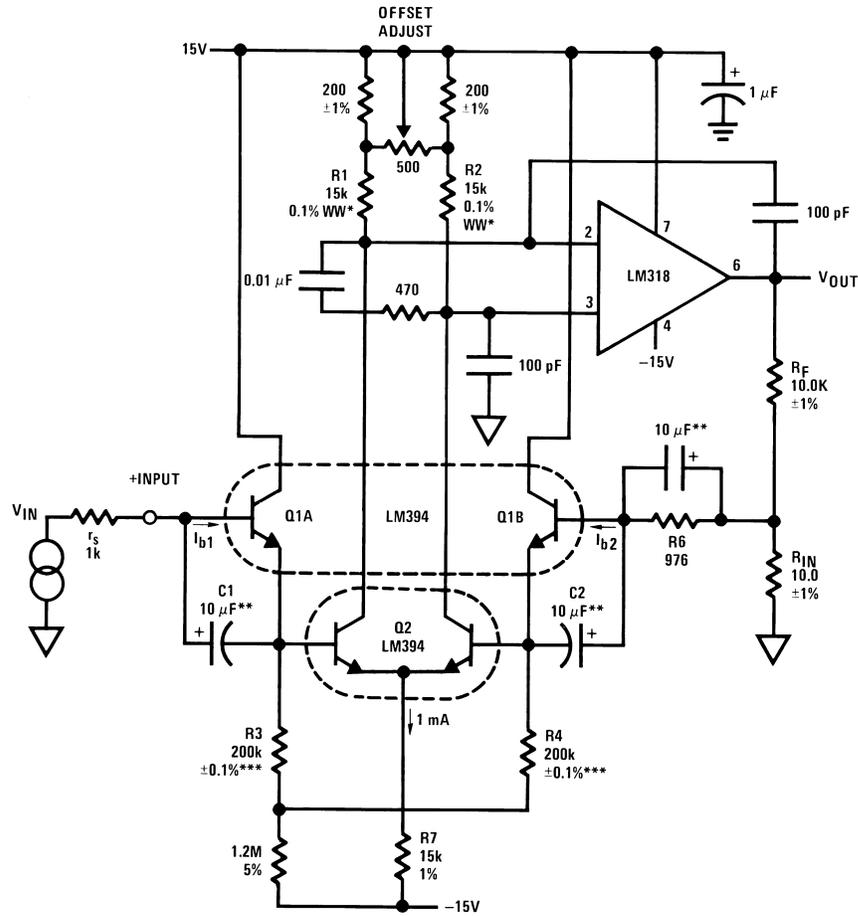
$$\text{per } \sqrt{\text{Hz}}, e_n = KT \sqrt{\frac{2}{qI_C}}$$

Current noise of a transistor,

$$\text{per } \sqrt{\text{Hz}}, i_n = \sqrt{\frac{2qI_C}{h_{FE}}}$$

Voltage noise of a resistor, per $\sqrt{\text{Hz}}, e_n = \sqrt{4KTR_s}$

For a more complete analysis of low-noise amplifiers, see AN-222, "Super Matched Bipolar Transistor Pair Sets New Standards for Drift and Noise", Carl T. Nelson.



*Tracking TC < 5 ppm/°C

**Solid tantalum

***Tracking TC < 5 ppm/°C, Beckman 694-3-R100K-D or similar

00849902

FIGURE 2. New Low-Noise Precision Operational Amplifier as Gain-of-1000 Pre-Amp

Notes

6 i [T]X]b[. U b . C d . 5 a d . K . J A . 6 [d c \ U . H . H U b g] g l f c f g
.....

LIFE SUPPORT POLICY

NATIONAL'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT AND GENERAL COUNSEL OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
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.



National Semiconductor Corporation
Americas
Email: support@nsc.com

www.national.com

National Semiconductor Europe

Fax: +49 (0) 180-530 85 86
Email: europe.support@nsc.com
Deutsch Tel: +49 (0) 69 9508 6208
English Tel: +44 (0) 870 24 0 2171
Français Tel: +33 (0) 1 41 91 8790

National Semiconductor Asia Pacific Customer Response Group

Tel: 65-2544466
Fax: 65-2504466
Email: ap.support@nsc.com

National Semiconductor Japan Ltd.

Tel: 81-3-5639-7560
Fax: 81-3-5639-7507

.....
LB-58

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products

Audio	www.ti.com/audio
Amplifiers	amplifier.ti.com
Data Converters	dataconverter.ti.com
DLP® Products	www.dlp.com
DSP	dsp.ti.com
Clocks and Timers	www.ti.com/clocks
Interface	interface.ti.com
Logic	logic.ti.com
Power Mgmt	power.ti.com
Microcontrollers	microcontroller.ti.com
RFID	www.ti-rfid.com
OMAP Applications Processors	www.ti.com/omap
Wireless Connectivity	www.ti.com/wirelessconnectivity

Applications

Automotive and Transportation	www.ti.com/automotive
Communications and Telecom	www.ti.com/communications
Computers and Peripherals	www.ti.com/computers
Consumer Electronics	www.ti.com/consumer-apps
Energy and Lighting	www.ti.com/energy
Industrial	www.ti.com/industrial
Medical	www.ti.com/medical
Security	www.ti.com/security
Space, Avionics and Defense	www.ti.com/space-avionics-defense
Video and Imaging	www.ti.com/video

TI E2E Community

e2e.ti.com