
PART IB EXPERIMENTAL ENGINEERING

SUBJECT: ELECTRICAL ENGINEERING EXPERIMENT E1 (SHORT)

LOCATION: ELECTRICAL & INFORMATION ENGINEERING
TEACHING LABORATORY

INTEGRATED CIRCUIT POWER AMPLIFIER

OBJECTIVES

1. To measure the gain of the circuit as a function of frequency.
2. To repeat the measurement of gain after changing the amount of negative feedback and to compare the results with theoretical predictions.
3. To determine the slew rate of the operational amplifier.
4. To measure the large signal full power bandwidth and compare the result with a prediction based on the measured value of the slew rate.
5. To measure power output and output efficiency with a resistive load.
6. To confirm that the input offset voltage is within specification.

1. Introduction

High-gain voltage amplifiers are widely available for instrumentation and other applications in a single integrated circuit, usually called an 'operational amplifier'. However, commonly used types have limited output currents, about 15 mA, precluding their use in higher power applications, such as audio amplifiers and drives for small motors. For these applications, power operational amplifiers have been developed which retain the basic characteristics of operational amplifiers but have increased output capability.

As with standard devices, power operational amplifiers have loosely specified characteristics and feedback is used to define the working conditions. In this experiment, the gain and frequency response will be measured, along with the large signal handling capacity, for the type 759 power operational amplifier.

2. Measurement of gain

It is expected that the output of an operational amplifier will be proportional to the differential input voltage over a wide range of input voltages.

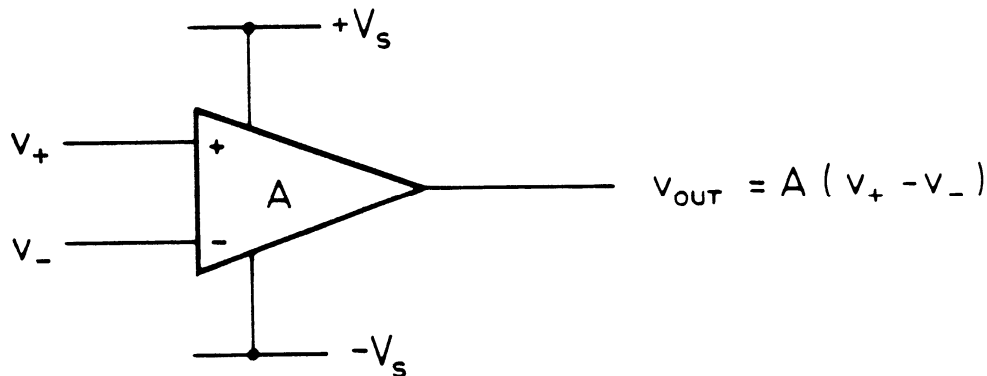


Fig. 1.

The output voltage will, of course, be limited by the supply voltages $\pm V_s$, and the output current will be restricted also. The voltage gain can be conveniently expressed in decibels, $20 \log_{10} \frac{V_{out}}{V_{in}}$. The experimental arrangement for measuring the gain is shown in Fig. 2.

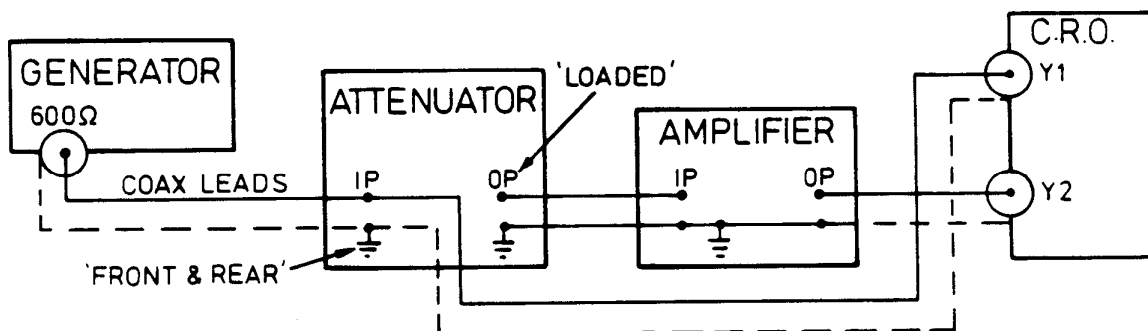


Fig. 2.

The generator voltage is attenuated and fed to the amplifier. If the attenuator is set so that the amplifier output equals the generator voltage then the amplifier gain equals the attenuator setting, provided that the gains of the Y_1 and Y_2 channels of the oscilloscope are equal. This can be verified by interchanging the two input leads – the oscilloscope displays should remain of equal amplitude. Measuring gain by this method permits the direct determination of gain from the attenuator setting.

3. Frequency response

The gain of an operational amplifier is usually constant from dc to a frequency at which the designer causes the gain to fall as a result of simple capacitive effects. The gain falls to $1/\sqrt{2}$ of its dc value at a frequency f_0 , known as the -3 dB (half power) frequency, turnover frequency or corner frequency. The fall is asymptotic to 20 dB per decade of frequency, and tends to a phase

shift of -90° as shown in Fig. 3. Provided that this rate of fall is not exceeded to an extent that the phase shift reaches 180° over the frequency range where the gain of the amplifier is greater than unity, the circuit is stable no matter how much feedback is used.

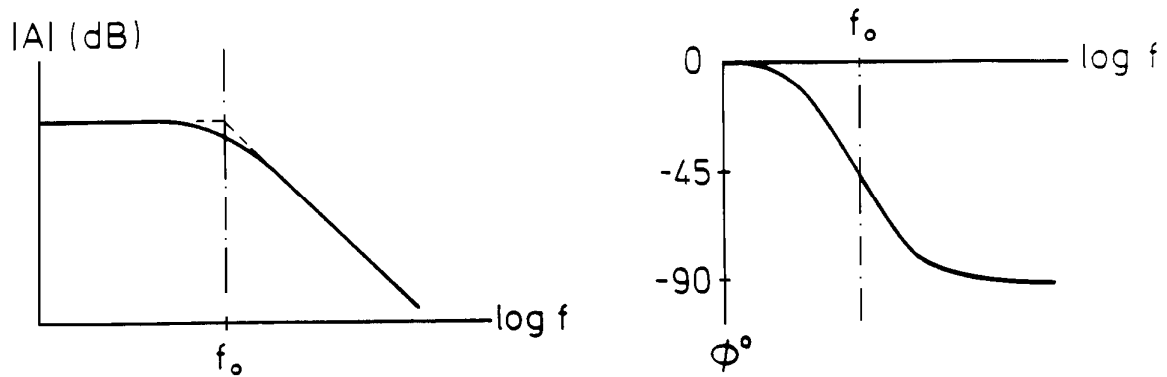


Fig. 3.

4. Feedback theory

Feedback is used to set the overall gain of the amplifier circuit, and gives a degree of immunity to variations in the precise values of parameters such as the open-loop gain.

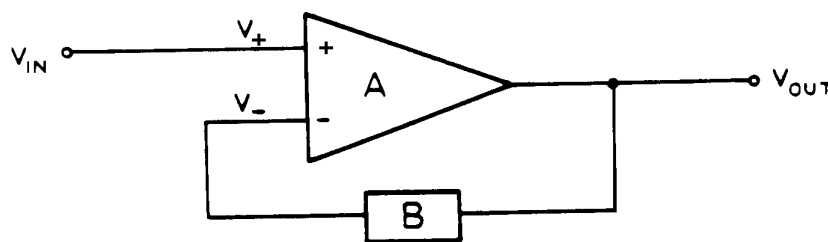


Fig. 4.

Using $v_{out} = A(v_+ - v_-)$, the output voltage, V_{out} , is given by $v_{out} = A(v_{in} - Bv_{out})$, assuming that the output resistance of the operational amplifier, R_o , is small and the input resistance, R_i , is large. Rearranging gives the gain, G , as

$$G = \frac{v_{out}}{v_{in}} = \frac{A}{1 + AB} \quad (1)$$

In many cases $AB \gg 1$ so $G \rightarrow \frac{1}{B}$.

For many operational amplifiers, the open loop gain A depends on frequency as described in paragraph 3, and can be described mathematically as:

$$A(f) = \frac{A_o}{1 + jf / f_o} \quad (2)$$

Substituting this into (1) gives

$$G = \left(\frac{A_o}{1 + A_o B} \right) \left(\frac{1}{1 + j \frac{f}{(1 + A_o B) f_o}} \right) \quad (3)$$

or gain equals (theoretical low frequency gain) \times (frequency factor)

Compared to open-loop operation, the d.c. gain is reduced by $(1 + A_o B)$ and the half power frequency increased by $(1 + A_o B)$; the gain bandwidth product is expected to be constant. You confirm this in the experiment.

5. Large signal considerations

When operated from a power supply of $\pm V_S$, the output voltage swing can approach the supply rail, but there will be a drop in the output transistors, the exact value of which depends on the load current and the design of the operational amplifier. The output current is internally limited. The efficiency is given by a.c. power out divided by d.c. power in. The d.c. input power is the product of the supply voltage and average supply current, as indicated on the power supply meters. Remember to add the powers drawn from the positive and negative rails. The a.c. output power is determined by measurement of the load voltage. For a sine wave output of amplitude \hat{V} , the RMS power P_{RMS} , is

$$P_{RMS} = \frac{\hat{V}^2}{2R_L} \quad (4)$$

where R_L is the load resistance.

The efficiency can be calculated conveniently by considering a half cycle of the waveform, say the positive half-cycle as shown in Fig. 5.

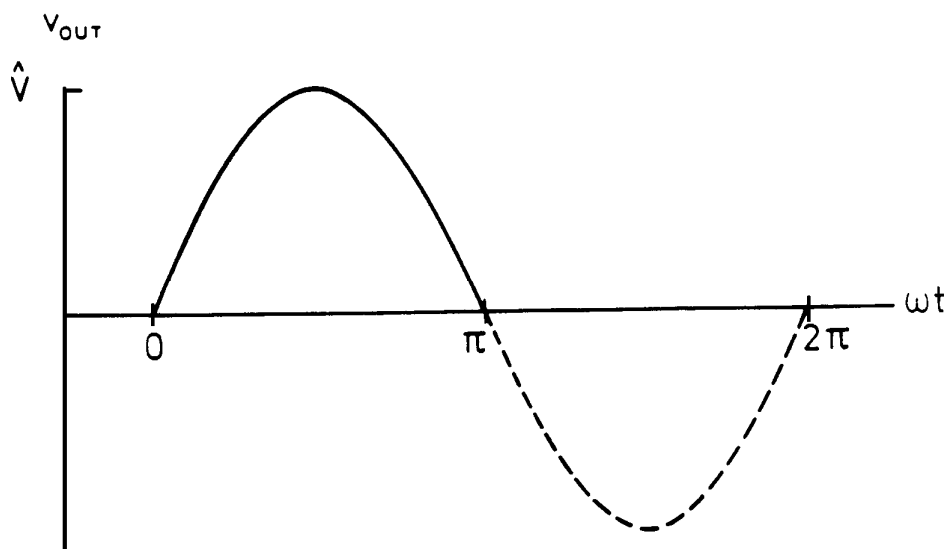


Fig. 5.

The average current, I_S , drawn is

$$I_S = \frac{1}{2\pi} \int_0^\pi \frac{\hat{V}}{R_L} \sin \omega t d(\omega t) = \frac{1}{\pi} \frac{\hat{V}}{R_L}$$

The d.c. power supplied from each rail is

$$I_S V_S = \frac{\hat{V} \cdot V_S}{\pi R_L}$$

so the total d.c. power is

$$\frac{2}{\pi} \frac{\hat{V}}{R_L} \cdot V_S \quad (5)$$

Using equations (4) and (5) the efficiency η is then

$$\eta = \frac{\frac{\hat{V}^2}{2 R_L}}{\frac{2 \hat{V} V_S}{\pi R_L}} = \frac{\pi}{4} \cdot \frac{\hat{V}}{V_S} \quad (6)$$

This has a limiting value of $\pi/4$ when \hat{V} approaches V_S , i.e. when the output amplitude is at its theoretical maximum, and falls with reducing output. In addition, the operational amplifier draws current even when there is no a.c. output, further reducing efficiency. The balance of the d.c. power will be dissipated as heat so a suitable heatsink is needed. In this experiment you will measure the efficiency at maximum output.

The available output voltage is limited at high frequencies by the maximum slewing rate of the amplifier. This slewing rate is the maximum rate of change of output voltage, usually expressed in V/ μ s. The implications are as follows. Consider amplifying a sine signal $\hat{V} \sin \omega t$. By differentiation the rate of change of voltage is $\hat{V} \omega \cos \omega t$. When $\cos \omega t = 1$, the maximum rate of change is $\hat{V} \omega$. Linear amplification is only possible for signals with a rate of change of voltage less than the slew rate. The highest frequency which can be amplified without distortion, often called the *full power bandwidth*, f_p , is equal to $\omega / 2\pi$. The full power bandwidth is given by:-

$$f_p = \frac{1}{2\pi} \cdot \frac{S}{\hat{V}}$$

where S is the slew rate. The value of the slew rate will be checked in this experiment and the full power bandwidth investigated.

6. Setting-up the apparatus

6.1 Switch on the oscillator, oscilloscope and power supply, ensuring that the power supply 'output' button is set to 'off'.

6.2 Connect the amplifier box to the power supply: brown lead to +15 V, blue to -15 V and green/yellow to COM1. It is a good idea to check the supply voltages with the digital multimeter.

6.3 The amplifier is to be used in the non-inverting configuration. On the amplifier box connect 600 Ω for Z_1 and 390 k Ω for Z_3 . Leave Z_4 and Z_L open circuit; use a short for Z_2 and short the inverting input.

6.4 Connect the circuit as shown in Fig. 2 using co-axial leads. The attenuator output should be set to 'loaded', and the input to 'front and back'.

6.5 With the oscilloscope channels both set to 0.1 V/division and the generator at 300 Hz with an output of about 0.5 V p-p, operate the 'output' button on the supply. Adjust the attenuator so that the traces Y_1 and Y_2 are of equal amplitude. Setting the oscilloscope to a.c. coupling is recommended. Some residual hum may be visible, but should not cause difficulty in making measurements. The signal level is deliberately low to avoid the large signal effects which will be explored in section 8.

7. Frequency response plot

(a) Plot gain in dB against frequency on Fig. 6. Begin at 30 Hz and increase frequency in the sequence 100 Hz, 300 Hz, 1 kHz etc. up to 300 kHz, putting readings directly onto the graph. About ten points will suffice. Using the range multiplier buttons to take readings at 30 Hz, 300 Hz etc. and then at 100 Hz, 1 kHz etc makes the measurements quicker. An initial gain of about 60 dB is expected.

(b) Repeat the gain measurements for a value of feedback resistor, Z_3 , of 22 k Ω , restricting the readings to the frequency range above 300 Hz, again plotting readings directly on the graph.

(c) Estimate the corresponding 3 dB points and the frequency at which the gain falls to unity (0 dB) by extrapolating the slope of the roll-off in the gain-frequency characteristic.

Enter your measured low frequency gains and half power frequencies in Table 1, remembering that gain expressed in dB = $20 \log_{10} v_{out}/v_{in}$. From the gain-frequency plot given in Fig. 1 on page 11, find the expected half power frequencies for the two low frequency gains used and enter these in the table. Finally, compute the gain bandwidth products by multiplying the measured numerical gains by the measured half power frequencies, and enter your results.

Table 1.

Z3	Measured low frequency gain in dB	Measured numerical low frequency gain	Measured frequency at half power	Measured gain bandwidth product
390 kΩ
22 kΩ				

The gain bandwidth product is also equal to the bandwidth at unity gain.

The quoted unity gain bandwidth (given on page 10) is MHz

Measured gain-bandwidth products agree to within %.

These values are in agreement with the manufacturer's quoted value to within %.

8. Measurement of slew rate

(a) The finite value of slew rate prevents the linear amplification of rapidly changing signals, even though the gain for small signals may be high. Set up the amplifier box with Z₃ equal to 6 kΩ to give a nominal gain of 11 and Z_L = 50 Ω. With the attenuator set to 20 dB, adjust the output of the signal generator to a 10V p-p square wave at a frequency of 50 kHz.

Measure the slew rate.

Slew rate, S, is V/μs

Enter this in Table 2 overleaf

(b) Reduce the frequency to 1 kHz and change to sine wave. Reduce the attenuation until distortion, in the form of clipping of the waveform, is seen – this will be at about 20 to 25 V peak-to-peak.

The maximum value of the peak-to-peak undistorted output, 2V̂, is V.

Increase the frequency until distortion of the waveshape occurs as a result of the finite slew rate of the amplifier. Note this frequency, the so-called *full power bandwidth*, in Table 2 and confirm that reducing the amplitude of the signal, and hence the rate of change of voltage, removes the distortion. The full power bandwidth can be predicted from equation (7) in section 5, using the slew rate measured in 8(a) and the amplitude of the output voltage, V̂, which equals half the peak-to-peak voltage measured in 8(b).

$$\text{Full power bandwidth, } f_p, = \frac{1}{2\pi} \cdot \frac{S}{\hat{V}}$$

Enter this value in Table 2 overleaf.

Table 2.

	Measured	Predicted	Manufacturer's data *
Slew rate V/ μ s		_____	
Full power bandwidth kHz	_____

* See tabulated data on page 10.

Measured slew rate and manufacturer's value agree to within %

Measured and predicted values of full power bandwidth agree to within %.

9. Power output and efficiency

With the amplifier set to a nominal gain of 11 with $Z_3 = 6 \text{ k}\Omega$ and operating at 1 kHz, measure the power developed in a $50 \text{ }\Omega$ load. The maximum power is obtained when the output waveform is at a level just below that at which clipping is visible.

Measure the d.c. power drawn at maximum power output, which is the sum of the powers supplied by the negative and positive rails. Measuring currents with a digital multimeter will give greater accuracy. Calculate the efficiency and compare with the theoretical efficiency calculated using equation (6). Enter results in Table 3.

Table 3.

Output amplitude \hat{V}	AC power out $\hat{V}^2 / 2 R_L$	Total dc power in *	Measured efficiency η	Theoretical efficiency from equation (6)

* Note that the total dc power supplied is $V_S I_S$ (positive rail) + $V_S I_S$ (negative rail).

Suggest reasons for any discrepancy between measured and theoretical efficiencies.

.....

10. Input offset voltage (optional, perform if time permits)

With the input to the amplifier short circuited, measure the output voltage. The amplifier should be set up for a nominal gain of 1001 using $Z_3 = 600 \text{ k}\Omega$. Hence estimate the input offset voltage.

Measured input offset voltage mV

Input offset voltage quoted by the manufacturer

..... mV (typical)mV (maximum)

Comment
.....

11. Conclusions

Compare your measured data for the 759 power operational amplifier with the specification.

.....
.....

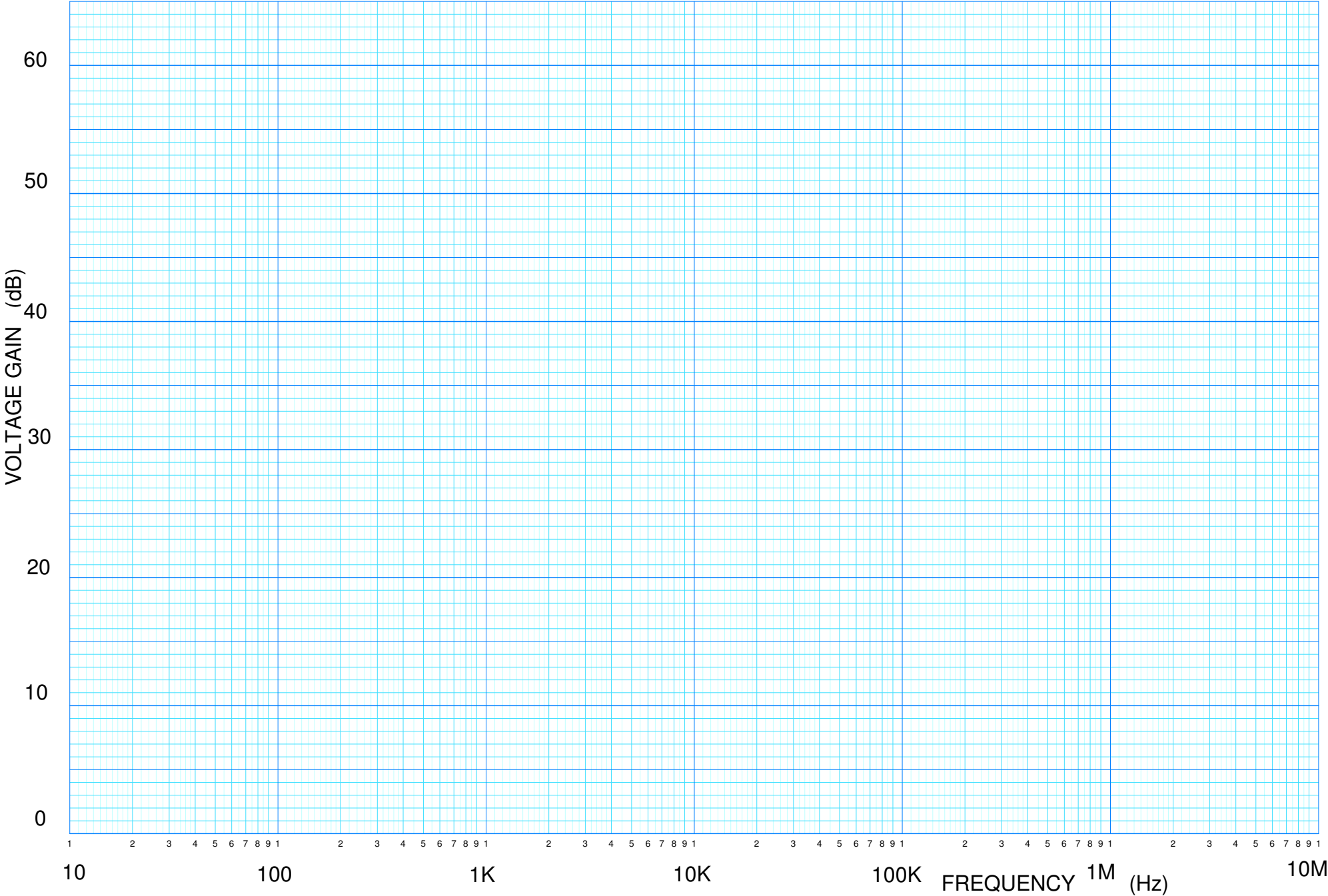
Comment on the implications of the measured performance of this device for its use as an audio power amplifier, covering a frequency range from 20 Hz to 20 kHz.

.....
.....
.....

R.A. McMahon, August, 1993.
Revisions 1994-2015
D M Holburn, September 2015

THIS PAGE DELIBERATELY LEFT BLANK

FIG 6. FREQUENCY RESPONSE





Data Sheet

High powered operational amplifiers 759 and 165

RS stock numbers 172-8917, 301-599

Two high power operational amplifiers featuring high current output stages. Ideally suited for use in applications where conventional operational amplifier output current (typically 16mA) is insufficient.

759

An operational amplifier with characteristics similar to a 741 but featuring a power output stage capable of providing a minimum of 325mA output current into a 50Ω load. Operation is from a single or dual rail supply and the input common mode voltage range includes the ground or negative rail. This device features internal current limiting, thermal shutdown protection and safe operating area protection for increased reliability. Suited for a wide range of applications including voltage regulators, servo amplifiers, power drivers, etc. 4-lead package with heat sink tab.

Absolute maximum ratings

Supply voltage (between V_+ and V_-) _____ 36V

Differential input voltage (see note) _____ 30V

Input voltage (see note) _____ ($V_- - 0.3V$) to V_+

Operating junction temperature
range _____ 0°C to +125°C

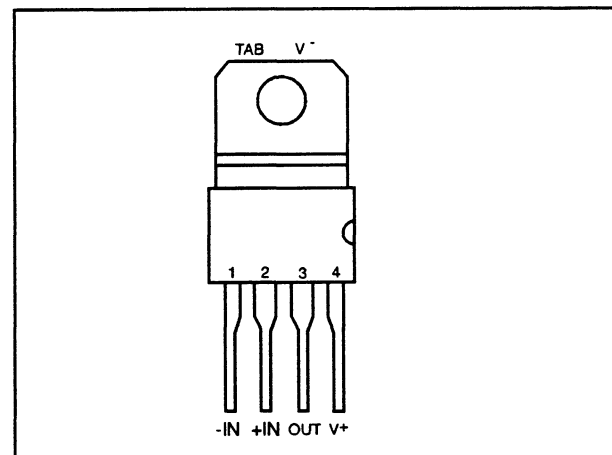
Storage temperature range _____ -55°C to +150°C

Lead temperature (soldering 10s) _____ 260°C

Note: For a supply voltage less than 30V between V_+ and V_- , the absolute maximum input voltage is equal to the supply voltage.

Features

- Minimum output current of 325mA
- Internal short-circuit current limiting
- Internal thermal overload protection
- Safe area protection of internal output transistors
- Input common mode voltage range includes ground or negative supply.



Electrical characteristics $V_S = \pm 15V$, $T_J = 25^\circ C$ unless otherwise specified

Characteristic	Condition	Min.	Typ.	Max.	Unit
Input Offset Voltage	$R_S \leq 10k\Omega$		1.0	6.0	mV
Input Offset Current			5.0	50	nA
Input Bias Current			50	250	nA
Input Resistance		0.25	1.5		MΩ
Input Voltage Range		+13 to $-V_S$	+13 to $-V_S$		V
Large Signal Voltage Gain	$R_L \geq 50\Omega$, $V_{OUT} = \pm 10V$	25	200		V/mV
Supply Current			12	18	mA
Peak Output Current	$3V \leq V_S - V_{OUT} < 10V$	± 325	± 500		mA
Short Circuit Current	$ V_S - V_{OUT} = 30V$		± 200		mA
Transient Response (Unity Gain)	Risetime	$R_L \geq 50\Omega$	300		ns
	Overshoot	$R_L \geq 50\Omega$	10		%
Slew Rate	$R_L \geq 50\Omega$		0.5		V/μs
Unity Gain Bandwidth			1.0		MHz

The following specifications apply for $-55^{\circ}\text{C} \leq T_J \leq 125^{\circ}\text{C}$

Characteristic	Condition	Min.	Typ.	Max.	Unit
Input Offset Voltage $R_S \leq 10\text{k}\Omega$				7.5	mV
Input Offset Current				100	nA
Input Bias Current				400	nA
Common Mode Rejection Ratio	$R_S \leq 10\text{k}\Omega$	70	100		dB
Power Supply Rejection Ratio	$R_S \leq 10\text{k}\Omega$	80	100		dB
Output Voltage Swing	$R_L \geq 50\Omega$	± 10	± 12.5		V

Thermal resistance

Typ	Max	Typ	Max
θ_{JC}	θ_{JC}	θ_{JA}	θ_{JA}
$^{\circ}\text{C}/\text{W}$	$^{\circ}\text{C}/\text{W}$	$^{\circ}\text{C}/\text{W}$	$^{\circ}\text{C}/\text{W}$
8.0	12	75	80

$$P_{D(\text{MAX})} = \frac{T_{J(\text{MAX})} - T_A}{\theta_{JC} + \theta_{CA}} \text{ or } \frac{T_{J(\text{MAX})} - T_A}{\theta_{JA}}$$

(Without a heat sink)

$$\theta_{CA} = \theta_{CS} + \theta_{SA}$$

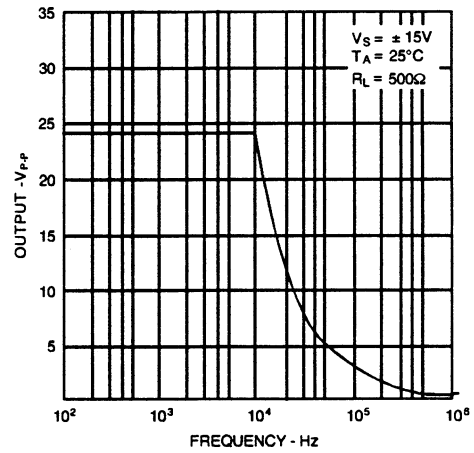
Solving for T_J : $T_J = T_A + P_D (\theta_{JC} + \theta_{CA})$ or $T_A + P_D \theta_{JA}$
 (Without heat sink)

- Where:
- T_J = Junction temperature
 - T_A = Ambient temperature
 - P_D = Power Dissipation
 - θ_{JA} = Junction to ambient thermal resistance
 - θ_{JC} = Junction to case thermal resistance
 - θ_{CA} = Case to ambient thermal resistance
 - θ_{SA} = Heat sink to ambient thermal resistance

Heat sinking

The RS 759 is designed to be attached by the tab to a heat sink. The heat sink can be either; a conventional type (see current RS catalogue) or a piece of metal such as the equipment chassis. It is important to remember that the negative power supply connection to the op-amp must be made through the tab. Furthermore, adequate heat sinking must be provided to keep the junction temperature below 125°C under worst case load ambient temperature conditions.

Figure 2 Output voltage as a function of frequency



Typical performance curves

Figure 1 Open loop gain and phase response as a function of frequency

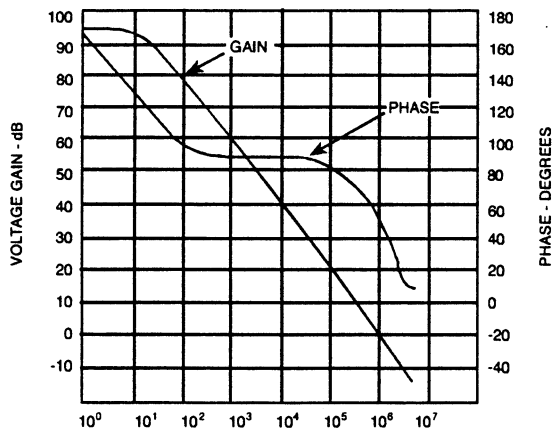


Figure 3 P-P output voltage as a function of load resistance

