With one LM394 at a collector current of 1.6 mA the noise voltage spectral density is 0.8 nV/$\sqrt{\text{Hz}}$ per transistor, or 1.13 nV/$\sqrt{\text{Hz}}$ for a differential pair; and a noise-current spectral density of 1.0 pA/$\sqrt{\text{Hz}}$ yields a 0.6-dB noise index at the optimum source resistance of 1 kΩ. Above 8 kΩ the noise index exceeds 2 dB, and at 50 kΩ the noise index is 6 dB. So a high-impedance inductive source may exhibit rising high-frequency noise. The noise contribution of the second stage is less than 0.5 dB at unity gain.

The equivalent input noise voltage level of the complete JE-990 operational amplifier as a function of source ac resistance is shown in Fig. 5.

2.3 Noise Measurement Filters and Corrections

The noise measurement bandwidth was limited with an 8-pole (48-dB per octave) active low-pass filter [6]. To exclude hum from affecting the data, a single-pole high-pass filter at 800 Hz was used. This reduces the bandwidth of the measurement by 500 Hz [800 Hz/(π/2)], requiring a +0.11 dB correction to restore the data to 20-kHz bandwidth. The hum filter also removes the low-frequency $1/f$ noise of the amplifier. We verified, however, that the $1/f$ noise of the JE-990 operational amplifier contributes an insignificant part of the noise for the total 20-kHz bandwidth.

The voltmeter used was a Hewlett-Packard 400 FL, which is an average responding rectifier with a scale calibrated for the rms value of a sine wave. For the Gaussian noise waveform a correction level of +1.05 dB has been added to give the equivalent rms value of noise voltage.

2.4 Preventing Noise Due to the Emitter Resistors

The noise graphs shown for the LM394 do not include the noise due to the emitter resistors which are required to limit the gain–bandwidth product of the first stage in the case that someone connects the input to a zero-impedance source. If this is done without sufficient emitter resistance, the time delay of the other stages will cause insufficient phase margin of the first stage for unity-gain stability and accurate transient response. Emitter resistors of 30 Ω are required for high-frequency stability, but these increase the noise voltage level more than 3 dB above the case without emitter resistors. To prevent this noise increase, emitter inductors can be placed in parallel with the emitter resistors. The impedance of 20-μH inductors is 30 Ω at 240 kHz; so at higher frequencies the emitter circuit impedance is 30Ω. But at 10 kHz the 20-μH, 25-mΩ inductor lowers the emitter circuit impedance to 1.3 Ω. This reduces the noise voltage level in a 20-kHz bandwidth to within 0.4 dB of the case without emitter resistors.

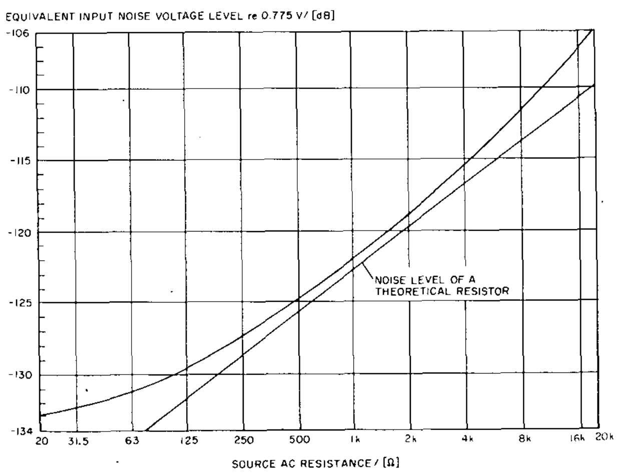

Fig. 5. Equivalent input noise voltage level of the complete JE-990 operational amplifier versus source ac resistance. Calculated from a measurement in a 20-kHz bandwidth. Noise level of a theoretical resistor is shown for reference.

The emitter impedance of the LM394 at a collector current of 1.6 mA is 16 Ω. This results in a first-stage single-pole response up to 83 kHz, where the 20-μH and 10.4-Ω impedance zero creates a two-pole response to 240 kHz, where the 20-μH and 30-Ω impedance pole creates a response zero, returning the response to that of a single pole.

3 STABILITY ANALYSIS

3.1 Open-Loop Response Compensation

The schematic of the JE-990 operational amplifier is shown in Fig. 6. Tobey et al. [7] and Roberge [8] discuss stability analysis in detail. The phase margin criterion for a "universal gain block" suggested the merits of a Miller-compensated two-stage amplifier. Initially the poles requiring compensation were located by observing the unity gain transient response while adjusting R9. The frequencies were input as the coefficients of a transfer function given in the Hewlett-Packard Transfer Function Analysis program. The output is a selection of topologies with values to synthesize the response function. With the zero of R9 and C1 coinciding with the unity-gain frequency f_t, the synthesis is completed in the emitter circuit of Q6 with C2, C3, and R8. The amplifier was constructed and analyzed in the laboratory to document the resulting unity-gain frequency f_t, phase margin, and transient response. Then an iterative series of calculations, component changes, and measurements was used to adjust the frequencies of the three zeros and the pole of the compensation circuit to obtain optimum phase margin and transient response. This method ensures that any response characteristics not isolated and identified in the modeling are nevertheless included in the optimization.

The result uses a capacitor and a series RC network across the emitter resistor of Q6 to create two zeros, one at 3.3 MHz and one at 25.4 MHz, with a pole at 5.8 MHz. The zero of R9 and C1 is at 8.1 MHz. The H-P AC Circuit Analysis (CNAP) program was used to model the response and to balance the impedance ratio of the feedback and emitter circuits of the second stage to give a 45° phase margin by adjusting f_t to approximately $1/8T$, where T is the amplifier response time.

The resulting response magnitude (Fig. 7) and phase angle (Fig. 8) show a unity-gain frequency f_t of 10 MHz with about 38° phase margin, increasing to above 60° below 2 MHz, including the region of the first-stage emitter circuit 83-kHz response pole and 240-kHz response zero. The gain–bandwidth product is greater than 50 MHz in the 10-kHz to 100-kHz range and 25 MHz in the 1-MHz range, with an increasing rate of attenuation to the actual frequency of unity gain, 10 MHz.

The transistors for Q5, type 2N4250A or PN4250A, must have an input capacitance C_{ib} lower than the Jedec specification in order to achieve the short response time which favors good phase margin, stability, and transient

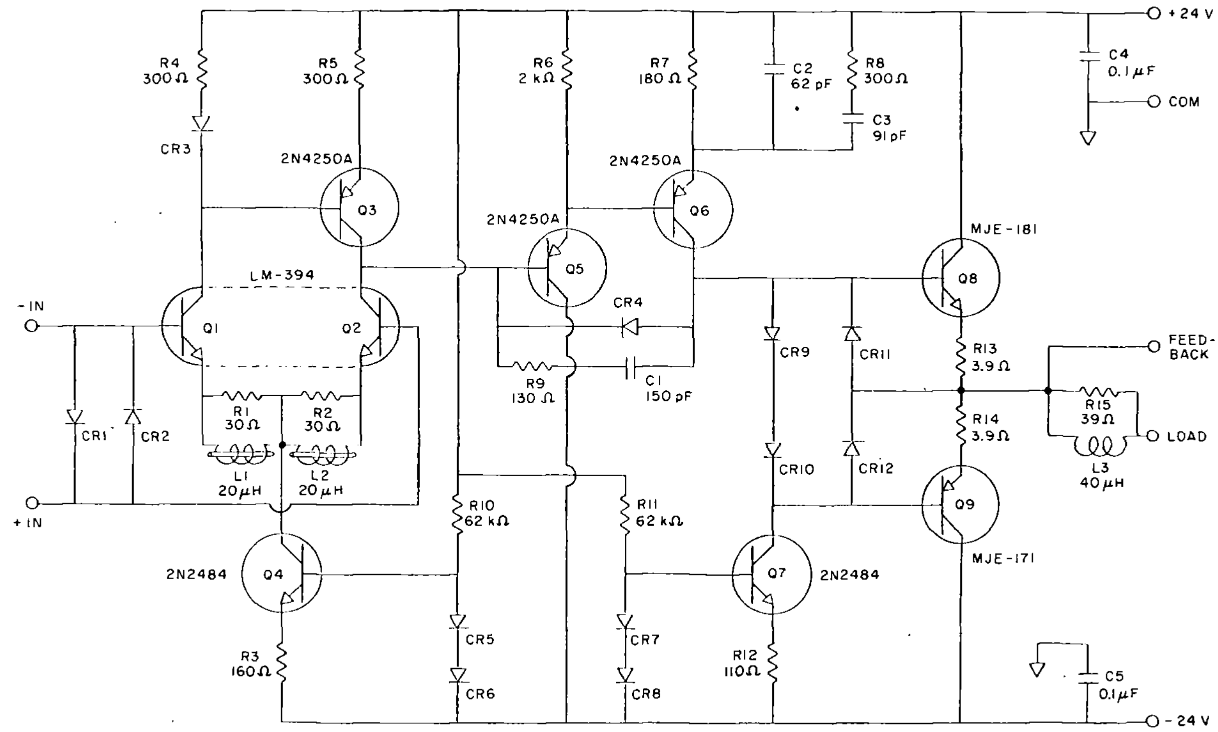

Fig. 6. Schematic drawing of the JE-990 operational amplifier.

JE-990 Operational Amplifier: Parts List

Quantity	Circuit #	Identification	Description	Manufacturer
1	Q1,2	LM-394H	Dual npn transistor	National Semiconductor
3	Q3,5,6	2N4250A,PN4250A	pnp transistor	National Semiconductor or Fairchild
2	Q4,7	2N2484,PN2484	npn transistor	National Semiconductor or Fairchild
1	Q8	MJE-181 (1)	npn transistor	Motorola
1	Q9	MJE-171 (1)	pnp transistor	Motorola
12	CR1-12	1N914B	Diode	Fairchild
2	R1,2	30 Ω	Resistor 5%, 1/4 W	Amperex film
1	R3	160 Ω	Resistor 5%, 1/4 W	Amperex film
3	R4,5,8	300 Ω	Resistor 5%, 1/4 W	Amperex film
1	R6	2 kΩ	Resistor 5%, 1/4 W	Amperex film
1	R7	180 Ω	Resistor 5%, 1/4 W	Amperex film
1	R9	130 Ω	Resistor 5%, 1/4 W	Amperex film
2	R10,11	62k Ω (2)	Resistor 5%, 1/4 W	Amperex film
1	R12	110 Ω	Resistor 5%, 1/4 W	Amperex film
2	R13,14	3.9 Ω	Resistor 5%, 1/4 W	Amperex film
1	R15	39 Ω (5)	Resistor 5%, 1 W	Allen Bradley
1	C1	150 pF 5%	Capacitor	
1	C2	62 pF 5%	Capacitor	
1	C3	91 pF 5%	Capacitor	
2	C4,5	0.1 μF	Capacitor CY20C104P	Centralab/USCC
2	L1,2	20 μH (4)	Shield bead 2673225111	Fair-Rite Prod.
1	L3	40 μH (5)	Inductor	
Thermal Coupling Aids:				
2	(1)	3/32 wire area	Clamp # C-201	Waldom
2	(1)	2-56 × 1/4	Screw # KF-461	Waldom
2	(1)	2-56 × 3/16 × 1/4	Nut # KF-554	Waldom
	(1)	4951 or 4952	Thermal adhesive	Thermalloy
1	(6)	256 D	Brass clip	Wakefield

Notes: (1) CR9 must be thermally coupled to Q8 with clamp or adhesive.
CR10 must be thermally coupled to Q9 with clamp or adhesive.
(2) R10,11 = 62 kΩ for bipolar 24-V supply. R10,11 = 33 kΩ for bipolar 15-V supply.
(3) R4,5 may be trimmed for dc balance (also affects slew symmetry).
(4) L1,2 starter kit with sample assembly is available from Jensen.
(5) L3 (40 turns #30 wire wound around R15) is available assembled.
(6) Wakefield brass clip can be used to thermally couple two transistors for Q3 and CR3 (see text).