DEPARTMENT OF SUPPLY
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AERONAUTICAL RESEARCH LABORATORIES

Mechanical Engineering Technical Memorandum 297

DESIGN OF PRE-AMPLIFIERS FOR AN ENGINE VIBRATION MEASURING SYSTEM

by

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SUMMARY

A description is given of the instrumentation employed for the recording of in-flight engine vibration, pressures and noise in R.A.A.F. Vampire Aircraft. Details of the recording system and, in particular, the pre-amplifiers designed at A.R.L. are provided.

CONTENTS

1. INTRODUCTION

In the course of an investigation of Goblin engines, Flight Research Group was called upon to provide suitable instrumentation for making in-flight vibration and noise measurements on Vampire aircraft for the R.A.A.F.. It was decided that recording of such data could best be accomplished using the seven channel Ampex AR200 magnetic tape recorder which had been specifically designed for operation in aircraft environments. However as the Ampex recorder required 1 volt R.M.S. for 100% recording level it was necessary to design and manufacture suitable pre-amplifiers for amplifying the outputs from the vibration velocity transducers used for measuring the vibrations. As the need for similar pre-amplifiers frequently arises in other applications it was decided that the amplifiers should be designed such that gain and bandwidth could readily be changed. Details of the recording system with particular reference to the pre-amplifiers are presented in this paper.

The complete system outlined above has been fitted to Vampire No. A78-627 belonging to the R.A.A.F.. Recordings so obtained have been analysed using the data reduction facilities at A.R.L..

2. GENERAL DESCRIPTION OF THE DATA ACQUISITION SYSTEM

The frequency band of interest for the vibration measurements was 5 cycles per second to 2000 cycles per second. The only method of recording such a frequency band with the existing equipment was the FM recording system. At the time when the recordings were taken only 4 FM record channels were available in the Ampex AR200. Since 6 vibrations and 1 pressure had to be recorded using FM techniques it was necessary to include a changeover transducer selector switch for time sharing between channels. A block schematic of the complete data acquisition system for a typical set of transducers is given in Fig. 1.

Transducers 1, 2 and 3 have sensitivities of 60 mV/ips; transducers 4 and 5 have sensitivities of 110 mV/ips.. For the levels of vibration to be recorded the vibration channel pre-amplifiers (within the signal conditioning box in Fig. 1) required a maximum gain of approximately 15. Details of these pre-amplifiers are given in section 3. The output from the piezo-electric pressure transducer was amplified using a Columbia Model 5203 pre-amplifier. Frequencies up to 10 kilocycles per second had to be measured on this channel. Both cockpit noise and the aircraft intercommunication were recorded on direct record channels.

A tape speed of 30 ips was chosen. At this speed the bandwidth (± 0.5 db) obtainable using wideband FM recording is 10,000 cycles per second which was adequate for recording the signals from the pressure transducer. Recording at the above tape speed also provided a sufficient length of tape per recording condition to enable tape loops to be made for replay analysis. The vibration signals recorded using velocity pick-ups were integrated on replay to obtain vibration amplitude.

3. PRE-AMPLIFIERS FOR USE WITH VELOCITY PICK-UPS

3.1 General Description

Four pre-amplifiers were required to amplify the outputs from the vibration velocity transducers to a level suitable for recording on the Ampex AR200 magnetic tape recorder. The general requirements for these amplifiers are summarised below:

Voltage Gain	Up to 15.
Frequency Response	5 cycles per second to 2000 cycles per second.
Input Resistance	10,000 ohm and must be fairly stable in value.
100% Output Level	1 volt R.M.S.

As outlined earlier it was desirable to make these amplifiers sufficiently versatile to cover a range of applications. The recent availability of suitable integrated circuit amplifiers led to the adoption of an operational amplifier using one of these. The complete circuit of the pre-amplifier has been drawn in Fig. 2 and a schematic diagram of the Fairchild type μA702A integrated circuit has been drawn in Fig. 3. By changing a few of the passive circuit components gain, input impedance and frequency response can be readily changed.

An emitter follower, with an input resistance R2 (in the present instance 10,000 ohms), has been added to the input. The μA702A is a differential DC amplifier having the following characteristics for + 12V and - 6V supply rails:

Input Offset Voltage	5 mV (max.)
Input Offset Current	2 μA (max.)
Input Impedance	8000 ohm (min.)
Common Mode Rejection Ratio	70 db (min.)
Open Loop Voltage Gain	1400 (min.)

Open Loop Bandwidth	550 Kc (min.)
Output Impedance	500 ohm (max.)
Output Voltage Swing	± 5V (min.).

Clamping diodes CR3 and CR4 have been added to the input of the differential amplifier to remove the possibility of catastrophic failure due to switching transients which can cause the input common mode voltage limit to be exceeded (See Ref. 2).

In order to realize a stable amplifier of broad bandwidth various frequency compensation techniques have been employed (See Ref. 3). Capacitor C6 provides leading phase shift in the open loop frequency response and increases the bandwidth attainable. Additional compensation in the form of a lag network at the input comprising R10 and C2 was added. Bypass capacitor C3 was also required at the non-inverting input to the amplifier. The closed loop bandwidth of the amplifier without feedback components C4 and R13, which produce the high frequency roll off, was not measured but was certainly in excess of 1 megacycle/sec. (the highest frequency obtainable from the test oscillator). Components C4 and R13 were added to restrict the upper frequency limit to the value specified for the present application. The integrating capacitor C4 when connected directly across the feedback resistor produced an unstable condition. Addition of resistor R13 in series to limit the feedback at high frequencies removed this tendency of the circuit to instability.

It was found that the circuit was prone to oscillation when loaded with about 30 foot of co-axial cable (680 pF approximately) as required in the aircraft. Addition of a small resistor R14 in series with the output caused the oscillations to cease. As the input resistance to the FM amplifiers is approximately 30 kilohm the above value of resistance produced negligible attenuation of the output signal.

The output DC may be adjusted to zero via R7. The adjustment enables small increments of either positive or negative offset voltage to be fed to the input of the differential amplifier.

3.2 Gain of Pre-amplifier

The gain of the pre-amplifier (with the potentiometer adjusted for maximum gain) may be readily derived with the aid of the simplified amplifier schematic of Fig. 4.

At mid frequencies the gain is given by:

$$A_{MID} = -\frac{R_{12}}{R_5}$$

(Note that the component numbers are written as suffices in mathematical formulae).

At high frequencies the shunt feedback path consisting of C4 and R13 will cause a gain roll off. The gain will be given by:

$$A_{HIGH} = -\frac{R_{12}}{R_5} \quad \frac{R_{13} + \frac{1}{j\omega C_4}}{R_{12} + R_{13} + \frac{1}{j\omega C_4}}$$

$$|A_{HIGH}| \simeq \frac{R_{12}}{R_5 \sqrt{1 + (2\pi f \; R_{12} \; C_4)^2}}$$

$$\text{for} \quad f \ll \frac{1}{2\pi \; R_{13} \; C_4}$$

Hence the gain will be approximately 3 db down on the midband value at

$$f = \frac{1}{2\pi \; R_{12} \; C_4}$$

At much higher frequencies $(f \gg \frac{1}{2\pi \; R_{13} \; C_4})$

$$|A| \simeq \frac{R_{13}}{R_5}$$

This is an idealized expression for the gain at very high frequencies. Actually as the loop gain falls at very high frequencies and as stray capacitance increases the feedback, the gain will drop off further.

The low frequency response is limited by the values of the coupling capacitors C1 and C8.

$$\left|\frac{A_{LOW}}{A_{MID}}\right| = \frac{1}{\sqrt{\left[1 + \left(\frac{1}{2\pi f \; C_1 \; R_5}\right)^2\right] \left[1 + \left(\frac{1}{2\pi \; f \; C_8 \; R_L}\right)^2\right]}}$$

With the 30 kilohm load (R_L) used the lower half power frequency for the circuit of Fig. 2 was about 4.5 cycles per second.

Potentiometer R4 allows the gain to be trimmed. If it is assumed that the emitter follower has unity gain then the signal attenuation due to the potentiometer is, referring to Fig. 5, given by:

$$\frac{e_1}{e_i} = \frac{(1 - k)\ R_5}{R_5 + k\,(1 - k)\ R_4}$$

The frequency response of the complete amplifier of Fig. 2 has been determined experimentally and plotted in Fig. 6. The response is 3 db down at 4.5 cycles per second and 2.5 kilocycles per second.

3.3 Supply Rails

The supply rails used for the pre-amplifier were nominally + 12 volt and - 6 volt. These supplies were derived from a higher voltage battery pack using zener diode regulators. Type N67 Nickel Cadmium cells were used in the battery pack.

It was found essential to decouple the regulated supplies right at the supply terminals of the μA702A to prevent high frequency oscillation of the pre-amplifier.

4. VERSATILITY OF THE PRE-AMPLIFIER

The amplifiers have been constructed in a printed circuit form on plug-in cards as shown in the photograph of Fig. 7. Changing of the components referred to in Fig. 4 enables a different amplifier performance to be realized. The mid band gain may be altered by changing the ratio of R12 to R5. Coupling capacitors C1 and C8 may be changed to provide a different low frequency cut-off. Feedback capacitor C4 may be changed to obtain a different high frequency cut-off.

However there are certain limitations to the maximum closed loop gain which can be obtained consistent with operational amplifier performance. The gain of the pre-amplifier will be given by the ratio of feedback to input resistances only if the open loop gain is much higher than the closed loop gain. For this amplifier the maximum closed loop gain attainable is approximately 100 if a reasonably high insensitivity to active parameter changes is to be achieved.

The input impedance to the amplifier may be varied by changing the value of R2. For much higher input impedances it would be necessary to use a higher gain transistor for Q1 which in turn would enable a much higher value of R2 to be used.

A photograph of the complete signal conditioning unit is given in Fig. 8.

REFERENCES

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2. WIDLAR, R.J. — The Improved μA702 Wideband DC Amplifier. Fairchild Application Bulletin APP-111/2, July 1965.

3. GILES, J.N. — Frequency Compensation Techniques for an Integrated Operational Amplifier. Fairchild Application Bulletin APP-117, August 1965.

4. A702 Circuit Design Ideas. Fairchild Application Bulletin APP-114, May 1965.

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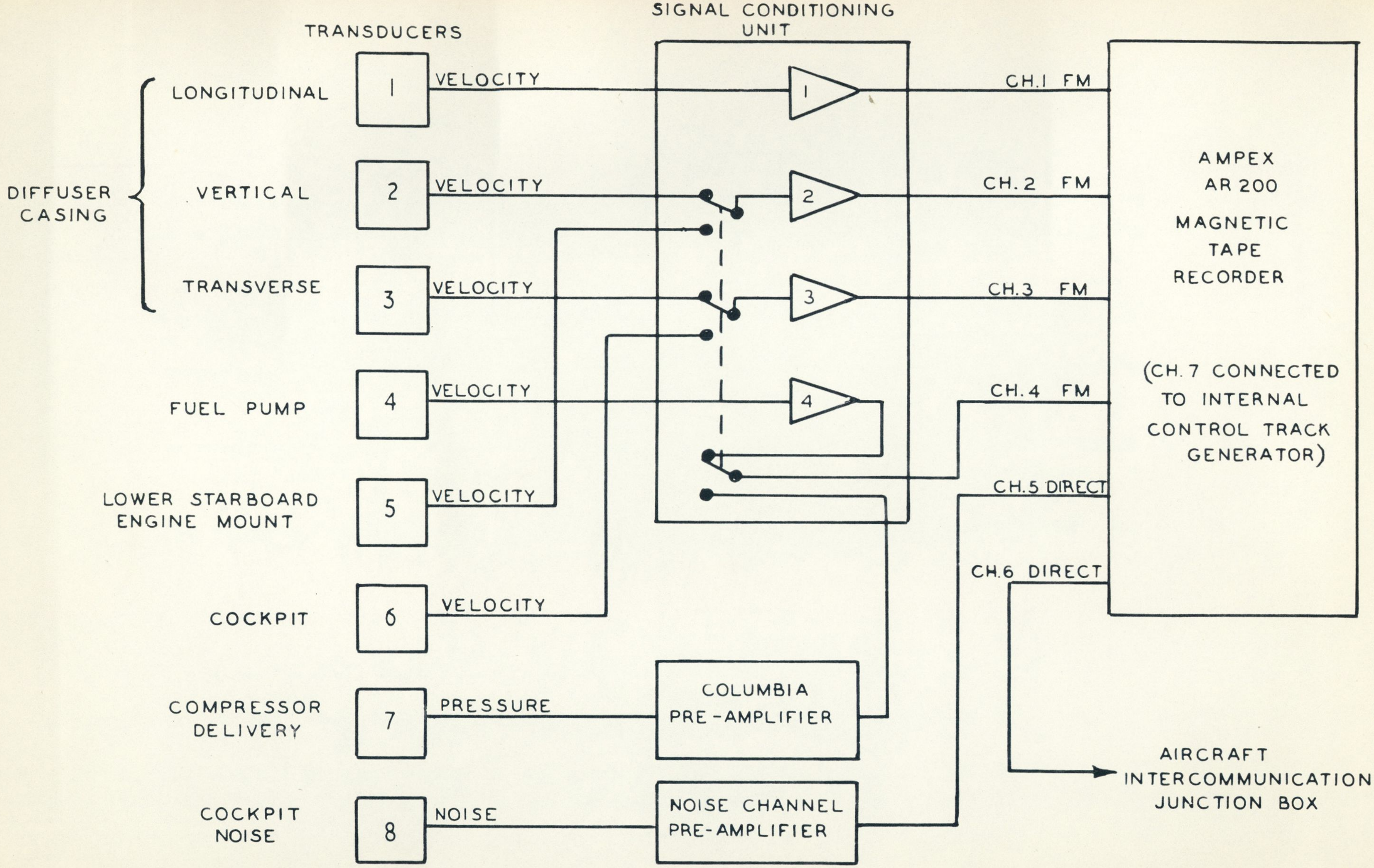

BLOCK SCHEMATIC OF DATA ACQUISITION SYSTEM

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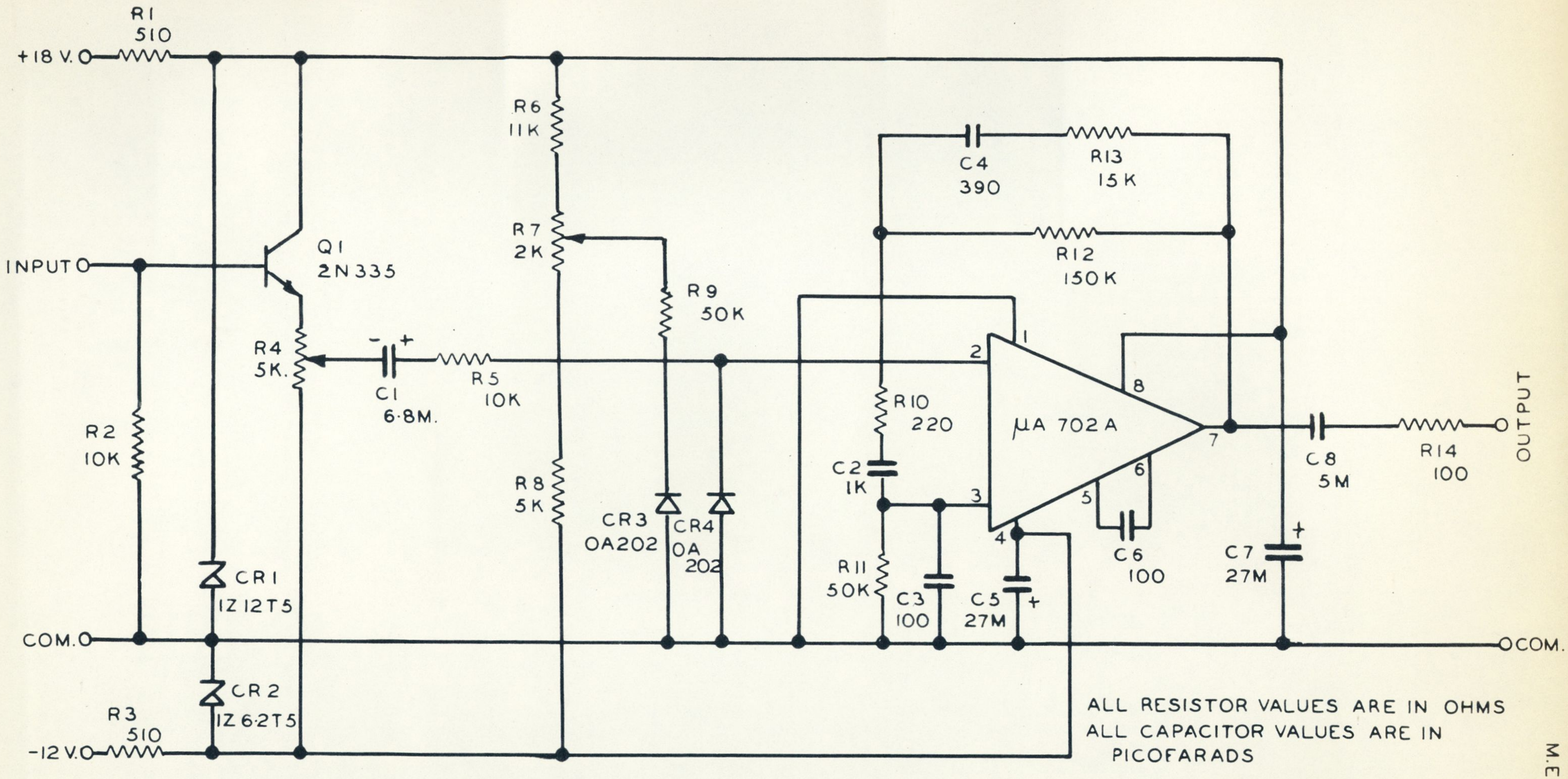
FIG. 1



GENERAL PURPOSE PRE-AMPLIFIER

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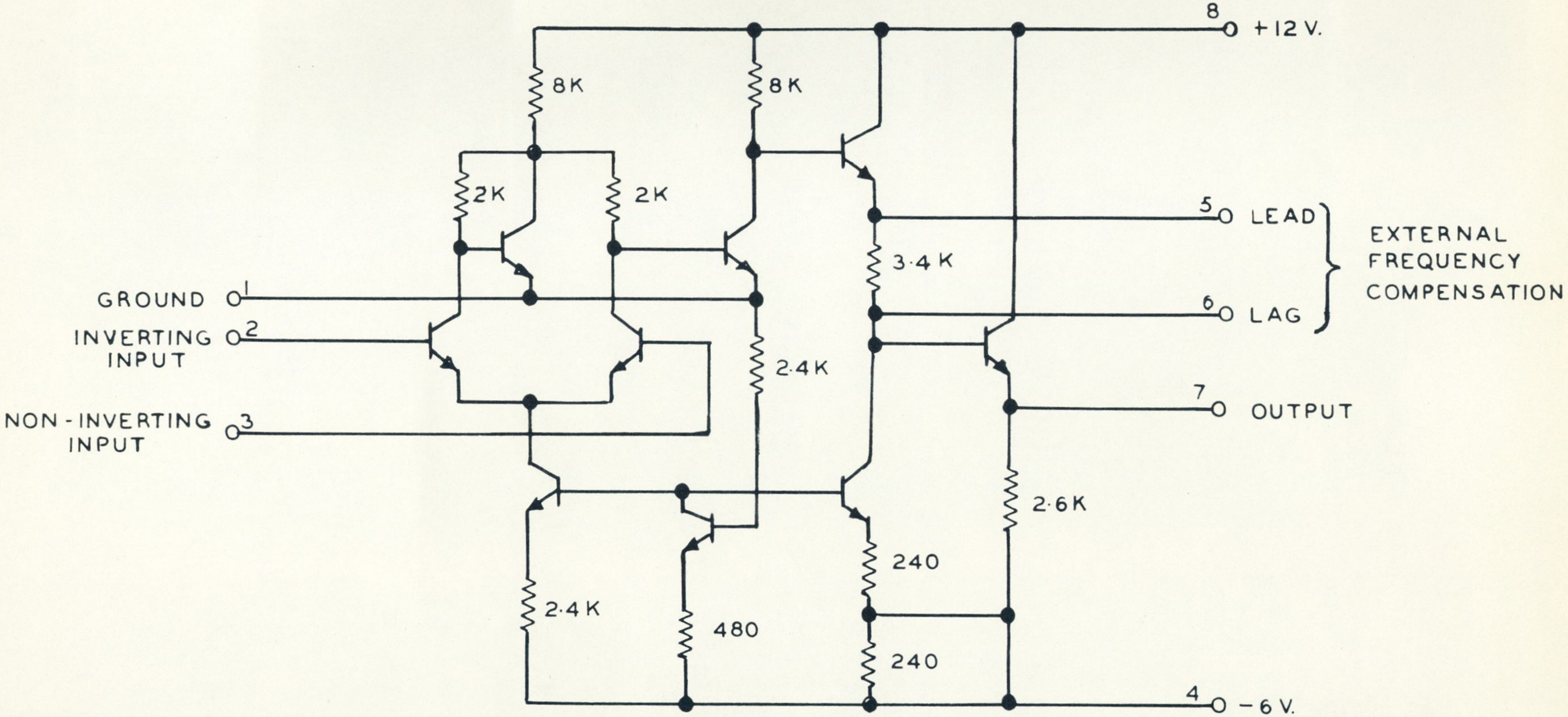
FIG.2



SCHEMATIC DIAGRAM OF μA702A INTEGRATED CIRCUIT AMPLIFIER

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FIG. 3

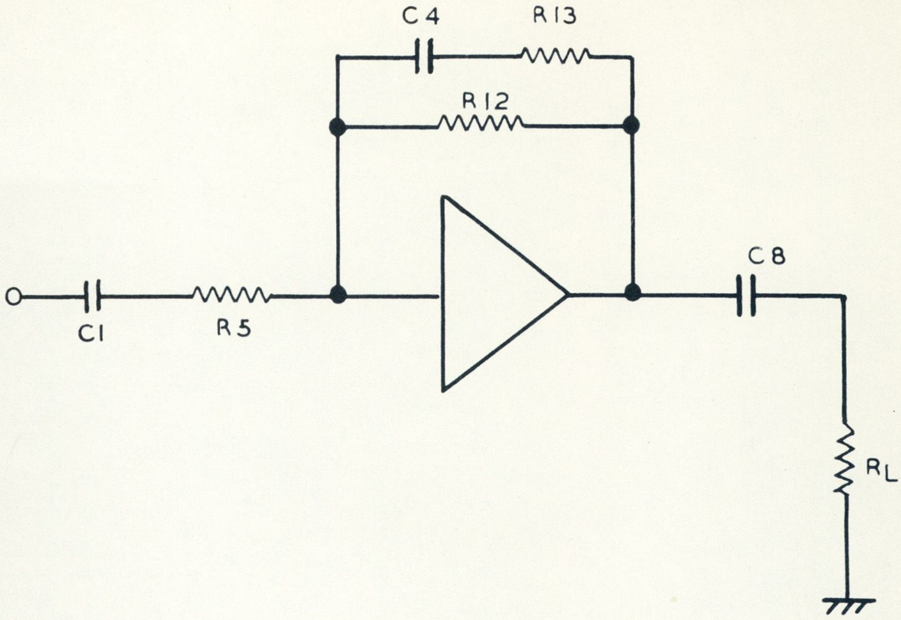


FIG. 4 SIMPLIFIED AMPLIFIER SCHEMATIC

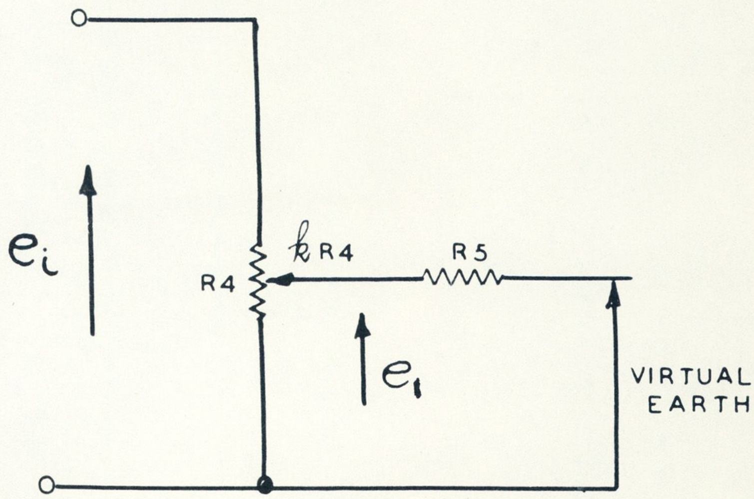
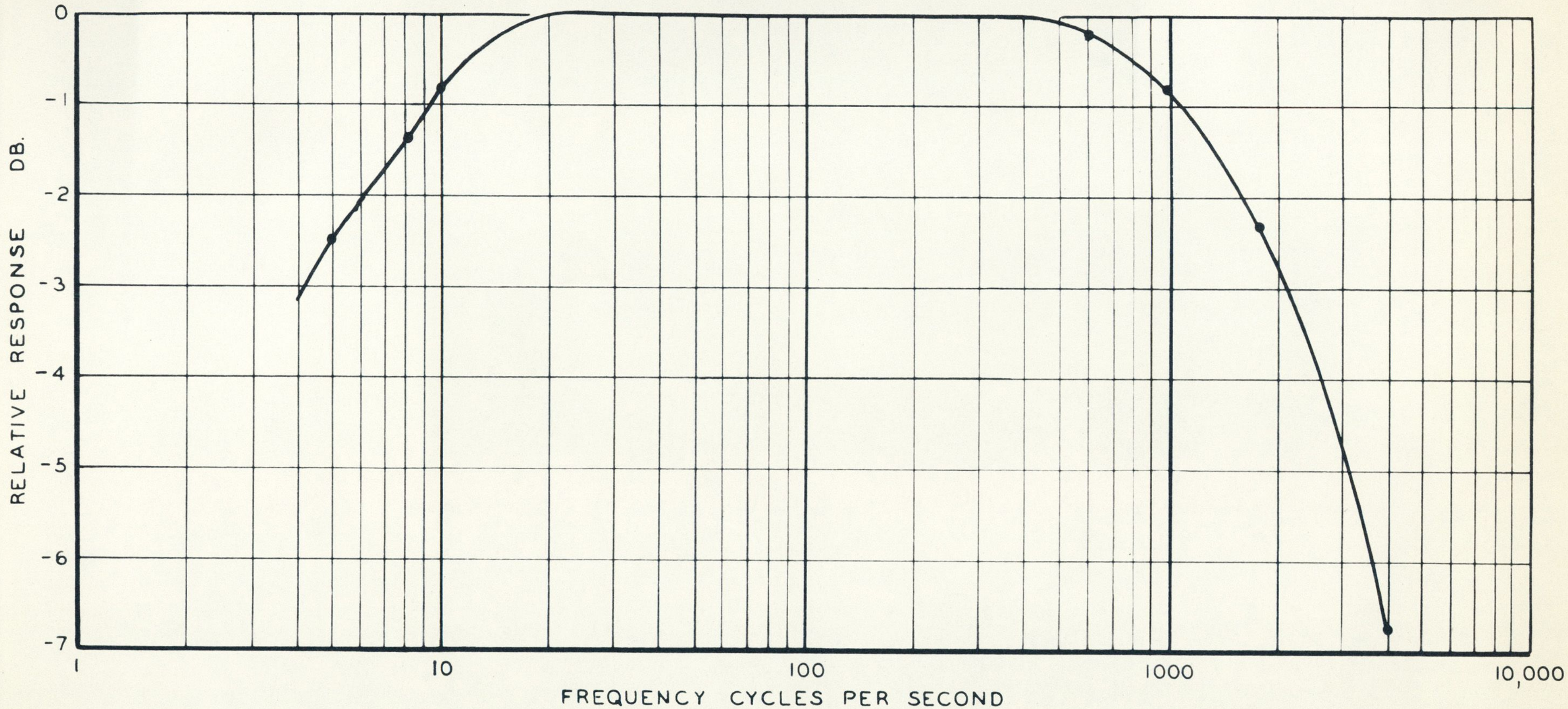


FIG. 5 GAIN ADJUSTMENT CIRCUIT



FREQUENCY RESPONSE OF THE COMPLETE AMPLIFIER

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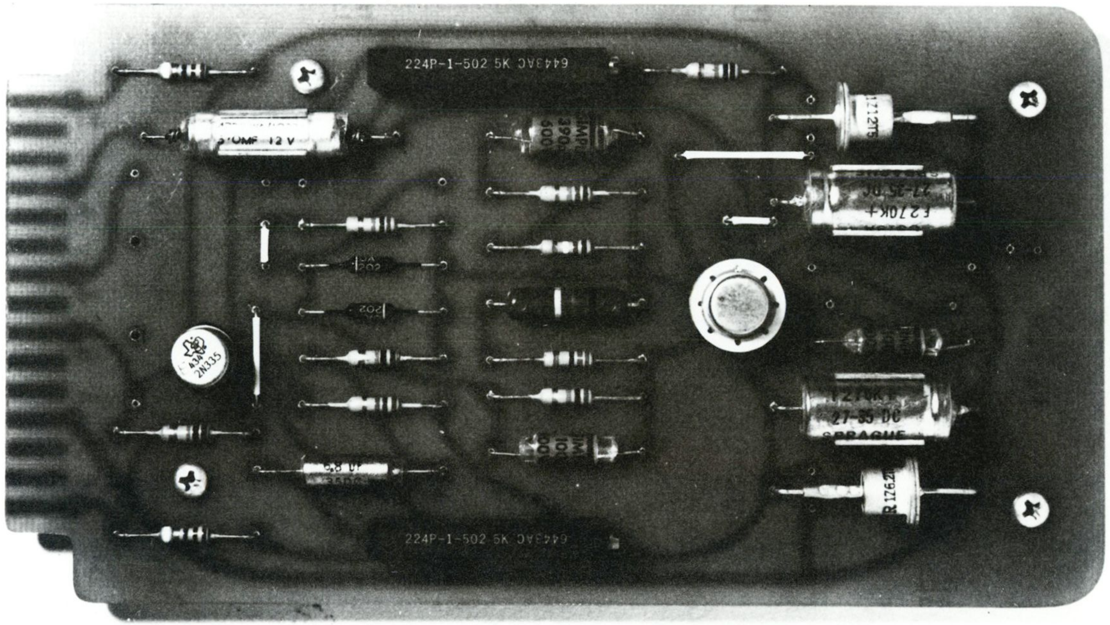
FIG. 6



PLUG-IN PRE-AMPLIFIER

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FIG. 7

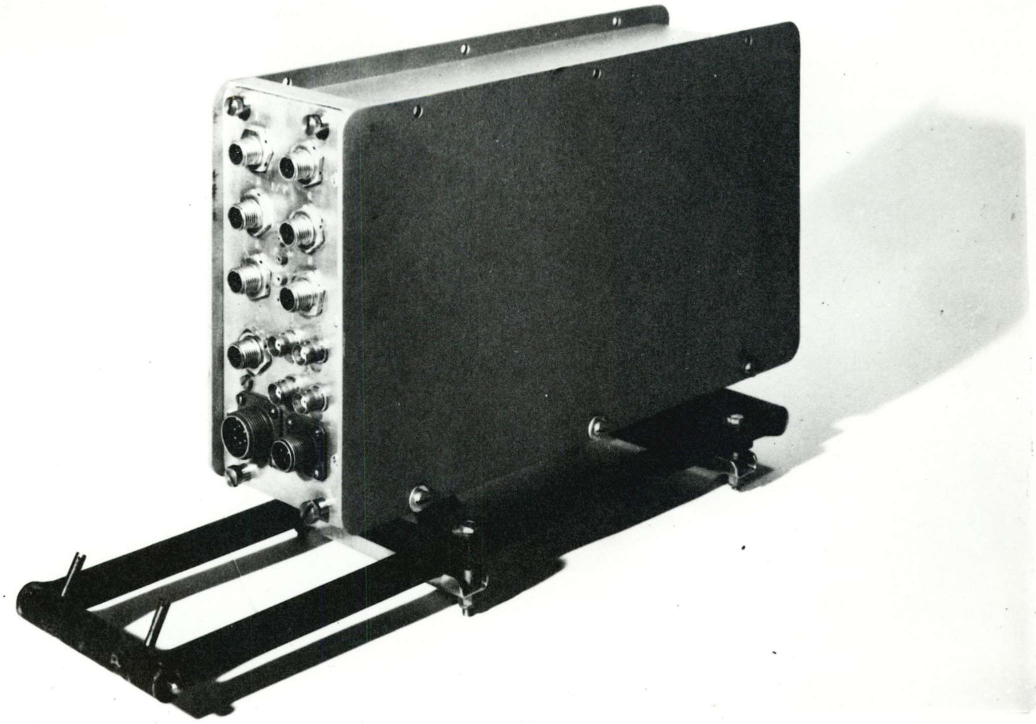

FIG. 8a EXTERNAL VIEW OF SIGNAL CONDITIONING UNIT

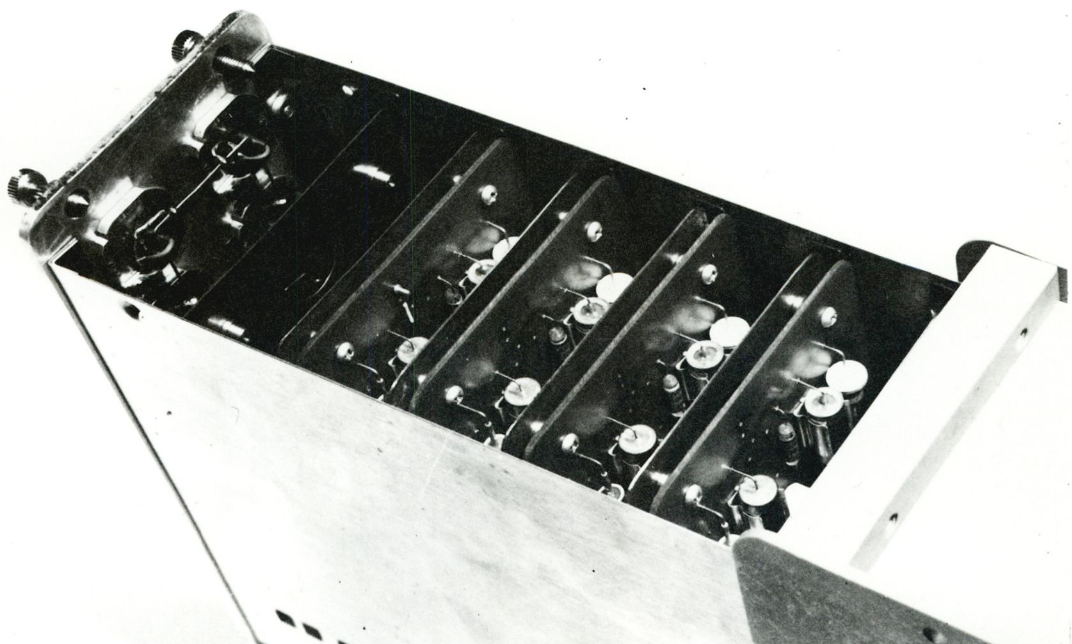

FIG. 8b INTERNAL VIEW OF SIGNAL CONDITIONING UNIT