Scherer Marc
2/01/69

INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3, avenue Circulaire, UCCLE - BRUXELLES 18

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# Low and very low level DC amplifiers (Part IV)
# A modulated DC amplifier for microvolt signals

## by P. VILLE

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3, Ringlaan, UKKEL - BRUSSEL 18

# FOREWORD

In Ref.[61] it is stated that "The ability to process these low level d-c voltages to a range suitable for transmission is one of the major problems of modern telemetry".

This text is an attempt to bring together in a clear and orderly manner the basic information about the theory and the design of low level and very low level d-c amplifiers. Two such d-c amplifiers were built and their performance is discussed.

The text is subdivided into five parts :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.

V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Part I and II deal with the basic theory of d-c amplifiers proper. The types of modulators and demodulators used in modulated d-c amplifiers are discussed in Part III. In Part IV we take up the design of a d-c amplifier with characteristics (performance, weight, size, power requirements,...) suitable for space applications. Finally Part V contains the abstracted references to which we refer in the text.

M. Nicolet.

# AVANT-PROPOS

Dans la référence[61], on note que : "La possibilité d'adapter ces basses tensions continues à un domaine adéquat pour la transmission est un des principaux problèmes de la télémesure moderne".

Ce texte est un essai pour rassembler, sous une forme claire et ordonnée, les informations fondamentales concernant la théorie et l'utilisation des amplificateurs de tensions continues de faibles et de très faibles niveaux.

Le texte est divisé en cinq parties :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
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V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Les deux premières parties se rapportent à la théorie fondamentale des amplificateurs d-c. Les types de modulateurs et de démodulateurs utilisés dans les amplificateurs d-c modulés sont discutés dans la partie III. L'utilisation d'un amplificateur d-c pour les applications spatiales ainsi que les caractéristiques (performance, poids, forme, puissance, exigences,...) sont discutées dans la partie IV. Finalement, la partie V contient les références citées dans le texte ainsi que leurs résumés.

M. Nicolet.

# VOORWOORD

In Ref.[61] wordt gezegd dat "Het beheersen van de technieken die nodig zijn om deze zwakke gelijkspanningen om te zetten in signalen die kunnen overgeseind worden één van de grootste problemen is van de moderne telemeting".

Deze tekst is een poging om op een klare en ordelijke wijze de grondgegevens samen te brengen betreffende de theorie en het ontwerpen van gelijkstroomversterkers voor zwakke en zeer zwakke signalen. Twee zulke gelijkstroomversterkers werden gebouwd en hun eigenschappen worden besproken.

De tekst is onderverdeeld in vijf delen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.
II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.
III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.
IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.
V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Deel I en II behandelen de basistheorie van de eigenlijke gelijkstroomversterker. De types van modulatoren en demodulatoren, die gebruikt worden in gemoduleerde gelijkstroomversterkers, worden besproken in deel III. In deel IV handelen we over het ontwerpen van een gelijkstroomversterker met eigenschappen (gewicht, afmetingen, voedingsvereisten,...) die hem geschikt maken voor ruimtetoepassingen. Deel V eindelijk bevat de referentiën met korte inhoud, naar dewelke we in de tekst verwijzen.

M. Nicolet.

# VORWORT

In Referenz[61] steht geschrieben dass : "Die Möglichkeit dieser schwachen d-c Spannungen zu einem Gebiet nützlich für die Übertragung zu verwenden, ist eines der wichtigsten Problemen der moderne Fernmessung".

Dieser Text ist ein Versuch, um die Grundinformationen über die Theorie und die Benützung der d-c Verstärker für schwachen und sehr schwachen Spannungen in einer klaren und geordneten Weise vorzustellen.

Der Text besteht aus fünf Teilen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.
II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.
III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.
IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.
V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Die zwei ersten Teile haben Bezug auf die Grundtheorie der d-c Verstärker. Die verschiedenen Modulatoren und Demodulatoren die in modulierten d-c Verstärker gebraucht werden, sind im dritten Teil diskutiert. Die Verwendung eines d-c Verstärker für Raumforschung sowie die technischen Daten (Leistung, Gewicht, Form, Kraft, Anforderung,...) sind im vierten Teil diskutiert. Der fünfte Teil enthält die im Text angegebenen Referenzen sowie die Zusammenfassungen.

M. Nicolet.

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# LOW AND VERY LOW LEVEL DC AMPLIFIERS (Part IV)

## A MODULATED DC AMPLIFIER FOR MICRO-VOLT SIGNALS

by

Paul VILLE

Centre National de Recherches de l'Espace,
3, Avenue Circulaire
UCCLE - BRUXELLES 18

## A MODULATED AMPLIFIER CAPABLE OF AMPLIFYING DC SIGNALS IN THE MICROVOLT RANGE

### PURPOSE

The object of this chapter is to discuss the design and construction of a transistorized d-c amplifier which is intended to amplify very low level d-c signals (= signals in the microvolt range) with a maximum input of 1 millivolt. This amplifier should be able to recognize as low a voltage difference as possible (a resolution of 10 microvolt or lower should be obtained).

### LIMITATIONS UPON THE AMPLIFIER

The device is meant to be used as a means to amplify thermocouple voltages in airborne equipment. The following requirements are to be met :

#### A. Requirements dictated by the environment :

The size should be small.
The weight should be low.
The power requirements should be low.
The amplifier should work satisfactorily over a temperature range from -20°C up to + 60°C.
The amplifier must be reliable at least for one year.
Vibration and shocks should not affect the amplifier.

## B. Requirements upon the amplifier in order to yield satisfactory operation :

The drift should be low (over the temperature range from -20°C up to + 60°C).
The zero offset should be low.
The overall gain should be stable in time as well as for temperature variations.
The gain should be linear.
The input impedance should be high (in order to drain as little current as possible from the thermocouple).
The noise should be low. Attempt should be made to keep the noise as low as a few microvolts ($\cong$ 10 μV or lower).
The output impedance should be low.

## C. Requirement for our particular purpose :

The gain should be about 5,000 (to get an output of 5 Volts for an input of 1 mV).

## GENERALITIES

As easy as the design of a very low level d-c amplifier seems to be on paper, as difficult is it in practice. The difficulties arise especially because of the low level of the incoming signal. It is evident, therefore, that the design of the input circuitry and the first amplifier stage (or even stages) is of primary importance. Since we expect to measure voltages down to a few microvolts any disturbance of the same order when referred to the input should be carefully avoided. This is, however, a very vague statement, but commonplace. Let us, therefore, investigate briefly which disturbances can be expected and how we may avoid them. (Note : A lengthy discussion of all this has already been given in chapter 5 of Part I under the heading "Zero Stability".)

### Electric disturbances :

Any electric disturbing signal appearing in the amplifier and due to the action of potentials (either electrostatic or not) is called an electric disturbance. It is evident that especially the electric disturbances at the input are important. They can arise because :

1. Ground paths may allow d-c voltages or voltages of modulating frequency to reach the input. To avoid this the input circuit should be as short as possible and a common grounding for amplifier and modulator driving source (to bring them to equal potential) should not be placed too close to the input. Furthermore, in order to prevent feedback from the modulator driving source to the amplifier each of them shall have a separate supply with no common grounding wire. In building our amplifier we have found that the latter point is very important, especially if the leads to the supplies are long. However, it may be possible to use a common ground lead if special care is taken to decouple the a-c amplifier supply-voltage : a good Zener-diode may prove adequate to eliminate the ripple fed back from the modulator driving source. The input circuit should not have two groundings because this would introduce an error voltage in series with the input. Since a common grounding of the input circuit with the amplifier is necessary, this means that there should be no external grounding if no transformer is used. However, if an external grounding is unavoidable, a transformer has to be inserted between the input modulator and the amplifier, because a transformer allows different grounding potentials at its primary and its secondary windings. Because of reasons explained later on we do not use an input transformer.

2. Electrostatically induced d-c or low-frequency voltages should be avoided wherever the input impedance is rather high (as required for voltage measurements). We have found that the operator's hand or other large objects are able to upset the input. By using an aluminum box as a shield, this effect is largely reduced.

3. Another problem is the instrumentation used to simulate the input signal for amplifier testing. We used a potentiometer with a voltage divider at its output built up from two precision resistors. It was not possible to prevent all disturbing signals from reaching this potentiometer. However, when measurements were made under

analogous conditions we then found the same outputs. This suggests to calibrate the amplifier for a particular application after all the final connections are made.

Note that the remark above holds not only for measurements over a time interval of a few hours, but we found it to be true even for measurements over an interval of four weeks.

4. Thermoelectric voltages are likely to arise in the input circuitry. Certainly the easiest way to prevent them is to keep complementary junctions in close thermal proximity. In addition special solder may be used in order to avoid thermoelectric potentials. (We have not used it.)

5. Although unwanted signals on higher frequencies could be filtered out at the input, we do not do so because this would require additional capacitors and resistors (the latter not necessarily) at the input. Also as the number of elements in the input circuit is increased disturbing signals may find more paths to get into this input circuit. Furthermore, if radio frequency disturbing signals are expected, it is better to enclose the whole low level part of the amplifier (that is the input circuit and the first two or even three stages of the amplifier) in a high-permeability shield. If strong fields may come in then it may be necessary to enclose the entire amplifier in such a shield.

At the output we use a low-pass filter which will serve the purpose of eliminating all sorts of higher frequency disturbing signals. Shielding would then almost be unnecessary unless the incoming disturbing signals are strong enough to saturate any of the stages of the amplifier.

## Magnetic disturbances :

These disturbances are generated by the action of varying magnetic fields.

1. Any varying magnetic field should, as far as possible, be kept out of the meshes of the amplifier and especially out of the early ones. This is particularly true for the stray magnetic fields of modulating frequency. The modulating waveform generator is a first source of trouble of this kind. The a-c amplifier and especially its output is another one. The problem is very hard to solve if transformers are used : the input transformer with its high permeability is easily affected by magnetic fields and adequate shielding is absolutely necessary (even more than one shield should be used); the output transformer can be a source of relatively high intensity magnetic fields. This problem of magnetic disturbances is one of the reasons why we did not want to use transformers in any part of the circuit. (Even the output chopper circuitry does not contain one.)

It is important to note that varying magnetic fields do not induce voltages in wires, if the net amount of flux which links these wires in zero. This is, for example, the case if two wires are perpendicular to each other : the magnetic field resulting from the current in one of them will not induce voltages in the other. We kept this principle in mind while building our amplifier.

2. If external varying magnetic fields are expected (radio frequency signals were discussed in 5. of "Electric Disturbances") then it may be necessary to use a high permeability (for example mumetal) shield in order to prevent the magnetic fields from reaching the low level parts of the circuitry (at least the input circuit and the first stage(s)).

## Mechanical disturbances :

The only item which might be subject to mechanical disturbances is the electromechanical input chopper. As the requirement of vibration and shocks cannot be waived in the design of the amplifier the only way to satisfy these requirements is to use a chopper which can easily stand vibration and shock tests. Choppers without moving parts cannot be used because their performance is still far from that of electromechanical choppers. It then amounts to choosing an electromechanical chopper with good vibration and shock characteristics.

## Thermal disturbances :

1. In order to minimize temperature effects on the transistor characteristics, we use all silicon transistors. The variations of the transistor characteristics do not only influence a-c gain but they can also limit the available swing of the a-c output voltage if the quiescent operating point of the last amplifier stage drifts away too much so that during part of the a-c cycle the transistor of that stage is driven into saturation. It should be noted also that for the driving source and for the transistors used in the input and output chopper circuitry temperature variations can have the effect of either completely stopping their working or of seriously impairing it.

2. Thermoelectric voltages (especially the ones at the input) should be kept as small as possible by bringing complementary junctions in as close thermal proximity as possible.

## Other practical design considerations :

1. A second reason why in our circuitry we did not want to use transformers is that the latter usually have an optimal frequency range. However, we wanted to test choppers which are to be run on 60 cps. as well as others which are run on 400 cps. or even higher (transistor choppers can be run on a frequency as high as 100 kcs.) Hence it is apparent that some transformer problems were going to arise if we wanted the circuit to work equally well at all these frequencies.

2. A third reason why we avoided transformers in the a-c amplifier circuit is that we want to eliminate phase shifts of the a-c signal as much as possible, because these phase shifts combined with a

relatively high forward gain for the a-c amplifier, may tend to make the amplifier unstable, especially if compactness of the whole device is to be considered. This reason, however, is not so strict as the others because in the a-c amplifier we built in a filter in order to reduce the noise level. This filter is essentially a low-pass one and so would also block eventual higher frequency oscillations.

## DESIGN OF THE DC AMPLIFIER

In order to build a modulated d-c amplifier we really have to consider the building of four different items :

1. The a-c amplifier.
2. The input circuit containing the input chopping device.
3. The output circuit containing the output chopping device.
4. The driving source for the input and the output choppers.

Evidently we cannot just build the four devices and connect them together; there is a problem of matching them to each other. We, therefore, started building an a-c amplifier having high forward gain. Then a square wave generator was built to test choppers that had to be run on frequencies other than the frequency of the power lines (60 cps. in the USA). The frequency of the generator was made variable from 25 cps. up to 5,000 cps. As the performance of the output demodulator does not have tp be as good as the input modulator we used for the output a chopper that only had to convert our ac amplifier output back to a dc signal : hence any chopper could do the job for the first set-up. It should also be noted that for the first circuitry we did not worry about the power.

When we got the d-c amplifier(including overall dc-feedback) to work, the next obvious step was to optimize the system : we wanted to select as good an input chopper as possible. The output demodulator should preferably not have moving contacts (to exclude mechanical trouble as much as possible). Let it be said also that we have tried to use transistor choppers at the input and that we have also considered the possibility of using other types of modulators. However, as seen in Part III of this text no other modulator can yet attain the performance of a contact modulator (= electromechanical chopper.) We then considered only an electromechanical chopper to be adequate for our purpose. A good low-noise unit* was selected and tested. This chopper had to be run on about 60 cps. for optimum performance so that we used the power line to drive both input and output choppers. (This frequency was not optimum for the output chopper, but the phase of the latter as well as its dwell times were adjustable so that it was not hard to adapt it to the input chopper).

Using the low-noise input chopper we were able to amplify d-c signals and to have a resolution of about 2 microvolts. At the same time we had also optimized the input circuit (short wiring, shielded leads, no wrong grounding). When it turned out that the chopper worked fine over the desired temperature range (-20°C up to +60°C) we decided to next improve the rest of the circuit. This means that we now had to consider the use of an output chopper without moving parts and that we had to build a generator to drive both the input and the output choppers synchronously. At the same time we had to test all the devices built to see if they worked properly over the entire desired temperature range. Also we now have to limit the power required by each item.

Since the a-c amplifier failed to work at both higher and lower temperatures because the transistors used were germanium ones, we built a new one using silicon transistors and careful testing the latter to see if their operating point did not shift too much with temperature variations. At the same time we decided to try a transistor chopper at the output because these choppers combine such interesting features as low power requirement, no inertia problems, rather long life, small in size, light in weight ...

Also a driving generator was to be built. Since transistor choppers require a square wave driving source for best performance, the obvious choice

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* The Airpax Model 30 Chopper

was to build an astable transistorized multivibrator. Special care was taken to make the square wave edges as steep as possible (since it is because of the steep edges that a square wave form is recommended for transistor choppers). This same driving generator was, of course, to be used to drive the input chopper. We then found that in order to keep the power requirements low it was better not to drive the input chopper (which needs about 30 milliwatts) directly from the driving generator, but via the intermediary of an interconnecting power amplifying circuit.

After design and redesign we then ended up with the final circuit as given in Fig. 143. We shall now discuss each of the four parts separately. (1. AC amplifier, 2. Input circuit and input chopper, 3. Output circuit and output chopper, 4. Driving source). We will, of course, also discuss the matching of the four parts to each other and will furthermore occasionally point out the major problems we encountered and how we solved them.

## THE A-C AMPLIFIER

The scheme of the a-c amplifier is shown in Fig. 144. Principally it is a rather simple circuit consisting of five amplifying stages interconnected by means of coupling capacitors. The latter are large in value in order to produce as little phase shift as possible, so that no oscillations can occur. The capacitor between the base of the last stage transistor and the grounding wire has the purpose of filtering out the amplified noise. If this were not done, this noise would saturate the last transistor so that the latter would then be useless for the purpose we meant it for. The filter capacitor does, of course, also attenuate the useful signal and for this reason the gain of the a-c amplifier decreases from several millions down to about 450,000. The major part of the information contained in the useful signal is in the low-frequency range (the chopping frequency is about 70 cps.) whereas the noise is spread out over a very wide frequency band (white noise). Hence, by using a lowpass filter as we really do here it is possible to considerably reduce the noise while leaving the useful signal relatively unaffected. The size of the capacitor to use for this filter application was determined experimentally : it was chosen large enough so that the noise can in no way saturate the last stage transistor. However, it should not be larger than necessary in order not to attenuate the useful signal too much.

It shall also be noticed that although the input voltage is a square wave the voltages between input and output and even the output voltage are not at all. This results from the fact that transistors are current devices and the amplifying is done by means of current amplification. However, even the current is not in the form of a square wave throughout the entire amplifier. This does not matter. The only thing that is really important is the phase relationship between input and output of the amplifier as well as the gain of the latter. If the input changes then this change should also appear at the output but amplified many times. In our case the input and output phases turn out to be in opposition because there is an odd number of amplifying stages. The phase is afterwards reversed again by the output chopper which is driven in synchronism with but in phase opposition with respect to the input chopper. Hence, the net overall phase shift of the useful signal will be zero as it has to be in order to make the d-c output polarity the same as the d-c input.

It may also be mentioned here that the output capacitor of the a-c amplifier was chosen so as to adapt the a-c amplifier output to the succeeding circuitry. Indeed, the last stage of the a-c amplifier will, through the output chopper, be connected in turn to the ground and to a filter capacitor (see Fig. 143). In fact the output capacitor of the a-c amplifier will have the purpose of picking up electrical charge from the ground when it is connected to ground and of afterwards storing it on the filter capacitor. The filter capacitor now has a voltage which is such that the charge this capacitor receives per modulation period is equal to the charge that flows away during the same period (because of the load, the losses and the feedback network). Let us consider the equivalent a-c Thevenin circuit of the a-c amplifier output and the succeeding circuitry. This is given in Fig. 145. The function of $R_1$ will be shown when the output circuitry is discussed.

Let us for simplicity assume that the e.m.f. E is a square wave (only to make the discussion easily understandable) and let us also assume that E is negative when the connection to ground is made. Note also (in Fig. 143) that $R_1 \ll R_2$. If capacitor $C_o$ is rather small, then during the part of the cycle during which the ground connection is made this capacitor acquires a charge :

$$Q_o = C_o . E_C \cong C_o . E$$

When then the connection to the filter capacitor is made, part of the charge $Q_o$ flows to the filter capacitor under the influence of the voltage

$$E + E_C - E_F$$

However, as the charge leaves capacitor $C_o$ the voltage across the latter decreases quickly because the capacitor $C_o$ is small. This means that not much charge will actually be transferred to the filter capacitor and the average voltage across the latter will be rather low : the overall d-c gain is not high.

If capacitor $C_o$ is rather large, then much charge can be stored on it but the voltage $E_C$ will not be appreciably high. Hence, when connected to the filter capacitor the circuit will not work optimally either in this case, the voltage

$$E - E_C - E_F$$

being not high enough.

Hence between the two cases above there is some optimum one that will be reached when the optimum value is used for capacitor $C_o$. (Curves are given later on in Fig. 150). Although calculation is possible (in an analogous way as we did in chapter 5 to find the output resistance of modulated d-c amplifiers) it is easier to determine $C_o$ experimentally.

This is what we did. It is noteworthy also that the optimum value of the output capacitor is dependent upon the chopping frequency and the load. The higher the chopping frequency the lower the capacitor value should be: this is one of the reasons why we have tried to keep the chopping frequency as constant as possible, over the entire temperature range (as will be seen later). The higher the load (that is : the lower the load resistance) the higher the capacitor value should be.

It is also worhtwhile to note that the transistors used in the a-c amplifier are not critically selected. The only requirement is that they should be able to work over the entire temperature range desired (-20°C to +60°C) and that over the same range none of the transistors should have its operating point shifted into the saturation region. The operating point of the last stage transistors should in addition not approach too closely to the saturation region either.

If a rather stable overall d-c gain is desired, then the forward gain of the a-c amplifier shall be high, which means that high-β transistors are recommended unless more amplifying stages are added. However, too much increased forward gain will also increase the noise level so that the noise filter may have to be readapted (or so that another noise filter must be added in an earlier stage) whereby the gain is decreased a little again.

Our first a-c amplifier used all PNP transistors (with other resistor values) but these failed to work over the desired temperature range. Another amplifier we built used all Tr1* transistors, but since the d-c current transfer ratio β is only about 30 for these transistors, the a-c gain was not high enough (about 125,000) so that the overall d-c gain varied too much with temperature (of the order of 0.1 per cent per °C). At last then we decided to test the circuit as it is given in Fig. 144 and good results were obtained. (This will be discussed later in this chapter under the heading "Performance of the d-c amplifier)." The much better results are due as well to the better temperature stability of the Tr2* transistors as to their higher current gain.

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* See end of this Part.

A last point to be noted is that the maximum swing of the output voltage of the last amplifier stage is about 10 Volts (the a-c supply voltage is 12 Volts) so that in no case outputs higher than 10 Volts can be gotten unless an output transformer is used or the supply voltage is increased (which also involves an increase in the power).

A better method to get higher outputs is to combine the modulated d-c amplifier with a direct-coupled d-c amplifier the latter amplifying the d-c output of the modulated amplifier. (In that case the feedback is taken from the output of the direct-coupled amplifier). No appreciable error will be added if the direct-coupled amplifier is not too bad, because its input and hence its equivalent offset and drift have to be divided by the gain of the modulated d-c amplifier ($\cong$ 450,000) in order to be referred to the overall input. As will be seen when the output chopper is discussed the requirements for the latter (such as driving voltage, Zener voltage ...) get more severe when the amplitude of the signal to be demodulated increases. This is another reason (and not the least one) to prefer a direct coupled d-c amplifier to be added if more gain is desired.

## INPUT CIRCUIT AND INPUT CHOPPER

This part of the system is without doubt the most important one.

The quality of the entire d-c amplifier will in a high degree depend upon the quality of the input chopper. The latter should, therefore, be a very good unit introducing as little disturbance (= noise) as possible in the circuit. This is the reason why it was not possible to use any other than an electromechanical modulator. As seen in Part III only the latter can (up till now) be made with noise levels in the microvolt and submicrovolt range. It should be noticed that because of the moving contacts electromechanical contact modulators (= choppers) may be affected by vibrations or shocks. So the unit chosen should have good performance even under rather severe shock and vibration conditions.

In order to keep possible electric and magnetic disturbances out of the input circuit as much as possible we do not include a transformer in the latter and we keep the wiring as short as possible. It is obvious that if the voltage to be measured is far away from the amplifier extreme care should be taken of the input wiring : shielding may be necessary and twisting of the wires will prove to be very useful.

Voltages due to temperature differences are likely to appear if the device has to work in varying temperature conditions. We have tried to bring complementary junctions which may give rise to differential thermoelectric voltages as close together as possible but complete cancellation of thermal voltages is of course not possible. Furthermore, voltages may arise because of temperature differences in a conducting wire and also this effect cannot be completely overcome (though it is very small).

As seen in Fig. 143 the input circuitry is such that only a single pole single throw (SPST) chopper is really necessary : the chopper alternately connects and disconnects the d-c input signal. The latter is compared against the overall d-c feedback signal which is never disconnected: if the two d-c signals are not equal a difference a-c signal is generated by the modulation technique. This a-c signal is amplified and demodulated at the a-c amplifier output so that it changes the d-c output in such a sense as to make the d-c feedback signal very nearly equal to the d-c input signal. This type of set-up where some part of the input circuit is never disconnected has the advantage of helping to avoid incoming disturbing electric and magnetic signals : as seen in Fig. 143 the feedback resistor of 619 ohms is rather low and so makes the input resistance as seen by disturbing signals equally low. The input resistance as seen by the useful d-c signal is not lowered much, however, because the input current is determined by the differences between the d-c input voltage and the d-c voltage across the 619 ohm resistor and since these two voltages will be very closely equal the input current will be rather low and hence the d-c input resistance rather high.

We once tried to use a single pole double throw (SPDT) "break before make" system so that the input of the a-c amplifier was connected in turn to the input d-c signal and to the feedback d-c signal. However, we found this circuitry to be unsatisfactory because a relatively high impedance was seen by disturbing signals during the fractions of the modulation cycle that the a-c amplifier input did not make contact with any of the two d-c signals : as seen above the chopper is of the "break before make" type, so that there is a small time interval between the opening of one contact and the closing of the other. Excessive disturbance was therefore generated and passed through the a-c amplifier during these time intervals.

A problem that remains is : how shall the input chopper be driven ? We do not want to use a transformer because of the disadvantages of the latter :

1. Stray fields would be generated and shielding might, therefore, be necessary.
2. The leakage and the parasitic capacitances of the transformer determine an optimal frequency range for the latter.
3. For best performance we want the current through the chopper coil to be about constant during each of the two parts of the modulating cycle.This is rather hard to realize with transformers (this point is in fact closely related to point 2).

The reason why we want the chopper coil current to be in the form of a square wave is the following : The chopper we use has to be activated in order to make good contact. As we then want the contact always to be good (in order to avoid as much as possible noise due to loose contacts) we prefer to use a square wave current to drive the chopper.

Experimentally we determined the current for which the contacts are always closed : this current is 6.5 mA. However, from the specifications of the chopper (6,3 V sinusoidal driving voltage ; 60 cps.; coil impedance 300 ohms) we learned that 10 mA is certainly not excessive. Therefore, we decided to drive the chopper by means of a square wave with peak-to-peak value of about 2 x 10 = 20 mA in order that the requirement of 2 x 6.5 = 13 mA would always be met even if the current decreased because of temperature variations. (Actually the current decreases a little for lower temperatures, but remains about constant for higher temperatures).

The last point then is to realize the desired driving circuit. The solution we used is given in Fig. 146 : the base of the transistor used receives a square wave voltage signal coming from the basic driving source which is an astable transistorized multivibrator. By this action the two capacitors in series with the chopper coil are successively charged and discharged : the charging takes place via the chopper coil and the transistor and the discharging via the chopper coil and the 1.5 kilohm resistor. The two capacitors are chosen large enough so that they do not affect the form of the current wave. The base resistor of 100 kilohms was chosen high enough in order that the driving circuit would not load the astable multivibrator which was made to run on low power; however, that resistor should also be low enough to allow proper opening and closing of the transistor gate by the driving voltage. The 1.5 kilohm resistor was chosen so that the current through the chopper coil was the desired one. Indeed, the higher the value of this resistor the lower the coil current is. Evidently the transistor used has to be able to handle the power required for driving the chopper.

The only purpose of the two 10 kilohm resistors is to balance the voltage across the chopper coil against the ground in order to minimize input circuit disturbances due to this voltage. The current through these resistors is negligible with respect to the one through the coil.

The 10 ohm resistor is only used to check the amplitude and the wave form of the coil current : the voltage in mV across this resistor is 10 times the current through the chopper coil in mA.

The current necessary to drive the input circuit chopper was measured to be about 12mA.

## OUTPUT CIRCUIT AND OUTPUT CHOPPER.

It was said before that the output chopper should introduce an additional phase reversal for the ac output signal so that the polarity of the dc output will be the same as that of the dc input. What we then want to do is :

to connect the ac amplifier output to ground whenever its input is disconnected from the d-c input. We obviously see that the <u>input</u> of the output chopper has to be connected in turn to ground and to the d-c output circuitry. Most commercial transistor choppers available alternately connect the <u>output</u> of the chopper to input and to ground. Using such a chopper in the reverse direction (using its input for output and vice-versa) proved to be unsatisfactory so that we decided to build our own output chopper. The result is shown in Fig. 147. The set-up is such that each of the transistors is opened and closed successively, the one being opened when the other is closed. In order to get synchronism of the output chopper with the input chopper, they are both driven by the same driving source.

As seen no transformer is used in this circuitry either (Fig. 143 and Fig. 147).

Although the output chopper works in a way that was not meant initially it turns out to work quite well. Let us consider Fig. 147. When the lower transistor is "conducting" points 3 and 4 are at ground potential (about) but point 2 is at a relatively high negative potential. However in that case the base-collector junction of the upper transistor is working as a Zener diode and the upper capacitor gets charged up. The 10 kilohm resistor avoids excessive current through the base-collector junction of the upper transistor, so that the latter is not damaged. In the next part of the modulating period, the upper transistor is in the normal "conducting" state and the lower transistor is in the non-conducting state.

A) If the d-c amplifier input is positive then point 3 has a positive potential now and also point 2 has a positive potential. Positive charge is passed from the base (point 2) to the emitter (point 1) of the upper transistor. Point 1 is part of the output circuitry, so that positive charge flows to the output as desired. It is true that in the first part of the cycle positive charge was flowing away through the emitter-base junction in the same way as it did through the collector-base junction of the upper transistor. This was, of course, not desired. However, in the second part of the cycle that loss of charge is largely compensated for, so that the net result is a flow of positive charge to the output : at the output a capacitor is charged up this way. The voltage of this capacitor is such that the net amount of charge that the capacitor receives per modulating period is zero. The positive charge coming from the output chopper will hence tend to increase the output voltage as desired. Let us note that also the junctions of the lower transistor operate in the Zener region when this transistor is in the non-conducting state. Hence the lower 1µF capacitor is charged up so as to provide a relatively high current in the other part of the modulating cycle (that is : when the lower transistor is conducting). This is a good point because it makes the potential of point 3 very nearly equal to ground potential in this part of the cycle (as desired).

B) If the d-c amplifier input is negative then the potential of point 3 will be negative when the upper transistor is in the normal conducting state. In that case negative charge will pass from the collector to the emitter of this transistor because when the latter enters the conducting region point 3 will have a negative potential, point 1 will have a less negative potential,(because of loss of charge of the output) and point 2 will try to follow the point (1 or 3) having the lowest potential (hence 3). We see that we now have a transistor working in the reverse direction (its emitter has the role of a collector and its collector has the role of an emitter). When the upper transistor is in the "non-conducting" state positive charge is found to pass also in this case from point 3 to point 2. Since point 1 is then negative however with respect to point 2 some positive charge will flow to the output via the base-emitter junction of the upper transistor. This flow of charge impairs the performance of the device for high negative input voltages for which the output is indeed very negative (up to a few volts). To reduce this unwanted effect a resistor (the 2.7 kilohm resistor) is inserted in the output circuitry.

The purpose of the 10 kilohm resistors is (as said) to match the output chopper to the driving source and their value was determined experimentally. Their resistance is high enough not to load the driving source more than necessary (the latter runs on low power as seen before) but low enough so that even the highest a-c output voltages can be chopped. Note that the swing of the driving voltages and hence the d-c supply voltage of the driving source was to be adapted to this latter requirement which turned out to be a rather hard one. Obviously the chopper transistors should be able to stand the applied voltages without being damaged.

The value of the 1 μF capacitors is high enough to easily pass the driving signal but it is not necessary to make that value higher than required for the latter purpose.

The 2.7 kilohm resistor serves the purpose of matching the transistor chopper to the d-c output circuitry. This resistor is (as briefly mentioned before) necessary for the following reason : Let us assume the input d-c signal to be very negative. When the d-c input signal is negative then the output chopper input will be negative when the upper transistor of this chopper is conducting (that is : when its base-collector junction is forward biased). Its base has a voltage which is slightly higher than the voltage of its collector and the voltage of its emitter will be the same as the voltage across the first capacitor of the output filter (if the 2.7 kilohm resistor is not present) (Fig. 143). The more negative the input voltage of the overall d-c amplifier is the more negative the average voltage across the latter capacitor will be. The latter voltage now is such that the net amount of charge reaching the capacitor in one modulating cycle is zero. The voltage of point 3 in Fig. 147 (collector voltage) swings between zero (when the lower transistor is conducting) and a negative value (when the upper transistor is conducting). The voltage of point 2 in Fig. 147 (base of upper transistor) swings between a negative value (when the upper transistor is non-conducting) and a more negative value (when the upper transistor is conducting). This seems paradoxical but is only due to the fact that the voltage of the base of the upper transistor has to follow the voltage of the collector of the latter when the base-collector junction of this transistor is forward biased. (A large voltage square wave appears across the 10 kilohm resistor of the upper transistor). When then the upper transistor is conducting negative charge will pass from the collector to the emitter of this transistor. When however this transistor is "non-conducting", that is when its base-collector junction is reverse-biased then the voltage of its collector is zero (as seen before) but the voltage of its base is higher than in the conducting state (because of the high difference of voltage drop across the upper 10 kilohm resistor). This makes the base-emitter junction forward biased and some positive charge flows to the output. This is not wanted and the role of the 2.7 kilohm resistor is to reduce this effect : this resistor indeed limits this flow of positive charge by the voltage drop that is developed across it. It is thus seen that the 2.7 kilohm resistor reduces the adverse effects which prevent the output from becoming very negative. As a matter of fact in our circuit this resistor is necessary. Its value should not be too large however because :

1. When the overall input d-c signal is negative this resistor should not adversely affect the flow of negative charge as necessary to provide for the losses in the output circuitry.
2. This resistor should not adversely affect the flow of positive charge when the overall input d-c signal is positive.

The value of the 2.7 kilohm resistor was determined experimentally. If however no resistor value can be found which makes the working of the output chopper satisfactory for the required range of d-c input values then the values of the other elements (10 kilohm resistor, etc.) have to be changed. Actually we had to do this once before we had the right combination.

The rest of the output circuitry consists of a filter including two capacitors and an interconnecting resistor. The value of these three elements depends upon the bandwidth required for the overall d-c amplifier and upon the ripple allowable in the final output. Unfortunately the lower the ripple content has to be, the lower the bandwidth will be too and vice-versa. So a compromise has to be made. By choice of the capacitors and the second resistor (150 kΩ) either the bandwith or the ripple contend can be controlled or a compromise can be made without affecting the working of the 2.7 kilohm resistor. The values for capacitors and resistor in our circuit were chosen so as to give a low ripple (so that the bandwidth is low also).

## DRIVING SOURCE

The driving source for both input and output choppers consists of an astable transistorized multivibrator as shown in Fig. 148. This driving source runs on relatively low power (28 V; 2 mA). The 28 Volt supply is only necessary to provide an output voltage swing which is high enough for adequate driving of the transistorized output chopper. The multivibrator uses two Tr2* silicon transistors to allow operation over a wide temperature range. The rest of the circuit was designed to make the output square wave edges rather steep (for best performance of the transistorized output chopper) and to protect the transistor junctions against possible breakdown (this is the real purpose of the diodes in series with the 100 kilohm resistors in the base circuit of the transistors). The driving source itself operates within a temperature range from lower than - 60°C to + 75°C (we did not try higher temperatures in order not to run the risk of damaging the transistors as it was not necessary to do so).

Over the above temperature range the frequency of the device changes from 68 cps. up to 80 cps. An effort was indeed made to keep the frequency within a range like this one, especially in order to maintain good performance of the 60 cps. input chopper and in order to preserve the matching of the output ~~circuitry~~ (as seen before under the heading "The a-c amplifier.") The 60 cps. frequency, however, was avoided in order to eliminate disturbances from the power lines (60 cps. frequency in the USA). The frequency of the driving source can be changed (for example, if it is desired to use 400 cps. choppers instead of 60 cps. ones) by changing the value of the .022μF capacitors and by changing the value of some resistors (especially the 680 kilohm ones), the latter being necessary to keep the edges of the output square waves rather steep.

## THE D-C AMPLIFIER AS A WHOLE.

The entire circuit was shown in Fig. 143. It is seen that feedback from output to input is used : two 1 per cent precision resistors having values of 619 ohms and 3.11 megohms, perform the attenuating function so that

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* See end of this Part.

the feedback ratio is about

$$\frac{619}{3.11 \times 10^6} \approx \frac{1}{5,025}$$

Hence the overall gain would be about 5,025, if the gain of the a-c amplfier were infinite.

The input chopper has some lag so that the synchronism of input and output chopping is not perfect. We tried to correct this by using an additional trigger circuit, but the idea failed to give good results largely because temperature dependence of the trigger circuit could not be avoided entirely and the overall size, weight and power requirement of the amplifier increased. Also an attempt to convert the input driving square wave to a sinusoidal wave and inserting a phase-leading network in the appropriate circuit to secure rather perfect synchronism of input and output chopping was made, but the results were no better than for the not perfectly synchronized circuit.

## PERFORMANCE OF THE D-C AMPLIFIER.

### 1.- DC INPUT RESISTANCE

Since we do not use a capacitor at the input, the d-c input current will not be continuous. There will be current only when the input chopper connects the d-c input signal to the a-c amplifier. Let us then measure or calculate the input resistance for the case that there is a current. To do this we use a potentiometer with attenuator $R_3 - R_4$ as shown in Fig. 149. (Note : the output resistance of the potentiometer is neglected as it is very low = a few tens ohms).

Let $R_i$ be the input resistance and let $R_1$ be the resistance of a resistor that we insert into the circuitry as shown in Fig. 149.

Let us now consider some output voltage $E_o$ of the potentiometer. This voltage will produce an input voltage of $E_i$ across the input resistance. This voltage is amplified and we measure its output $A.E_i$ (A=gain). As we will see later the gain of the amplifier is very linear so that it is not dependent upon the input voltage.

By then varying the value of $R_1$ we can derive the value of $R_i$ as follows : as seen in Fig. 149 the value of $R_4$ is 511 ohms. $R_i$ should be much higher (and indeed is) so that in first approximation the voltage $E'_o$ across $E_4$ is independent of the $R_1$-$R_i$ circuit.

Then

$$E_i = \frac{R_i}{R_i + R_1} \cdot E'_o$$

and the dc amplifier voltage $E_{out}$ is :

$$E_{out} = A.E_i = \frac{AR_i}{R_i + R_1} \cdot E'_o \cong \frac{AR_i}{R_i + R_1} \cdot \frac{R_4}{R_3 + R_4} \cdot E_o$$

For two different values of $R_1$, say $R_{11}$ and $R_{12}$, we measure two different outputs $E_{out\ 1}$ and $E_{out\ 2}$ so that :

$$E_{out\ 1} = A.E_{i1} = \frac{A.R_i}{R_i + R_{11}} \cdot \frac{R_4}{R_3 + R_4} E_o \text{ and } E_{out\ 2} = A.E_{i2} = \frac{AR_i}{R_i + R_{12}} \cdot \frac{R_4}{R_3 + R_4} \cdot E_o$$

By dividing the two we get :

$$\frac{E_{out\ 1}}{E_{out\ 2}} = \frac{R_i + R_{12}}{R_i + R_{11}}$$

and from here we find by solving for $R_i$ :

$$R_i = \frac{R_{11} \cdot E_{out1} - R_{12} \cdot E_{out2}}{E_{out2} - E_{out1}}$$

By taking several values for $R_i$ we find that the input resistance is of the order of

480 kilohms.

This is, as seen, only the input resistance for the part of the modulating period that the d-c input is connected to the a-c amplifier via the input chopper. For the rest of the period the input resistance is infinite.

It may be convenient to consider an overall equivalent d-c input resistance which has the same effect (for example, as far as power is concerned) as the combination of $R_i$ (for a part of the modulation period) and an infinite input resistance (for the other part of the period). For example in the case that the dwell times are exactly a half period, then the equivalent input resistance is approximately double the value of $R_i$ as found above provided the output resistance of the input voltage source is rather low (for example lower than one tenth of $R_i$).

## 2. - DC OUTPUT RESISTANCE

We have seen before that the output circuitry (especially the ac- amplifier output capacitor) had to be adapted to the value of the load. For this reason the circuit will work rather well only for a certain range of load values. A diagram showing the output voltage as a function of the a-c amplifier output capacitor and with the value of the load resistance $R_L$ as a parameter is shown in Fig. 150. The value of the a-c amplifier output capacitor we use in our circuit is denoted by $C_o$ in Fig. 150. Apparently if the load resistance value is low the d-c amplifier output will be low too, but there is always some maximum for a particular load.

Obviously the output characteristic curve (output voltage versus output current) will depend upon the particular value of the a-c amplifier output capacitor used. An experimental curve of this characteristic for our circuit is given in Fig. 151 and was found by measuring the d-c output voltage as a function of the load for a certain fixed d-c input voltage.

The output resistance of a device is by definition

$$R_o = - \frac{dE_{load}}{dI_{load}}$$

where the changes of $E_{load}$ and $I_{load}$ are due only to changes of the value of the load as seen in earlier parts of this text (chapter 3, section 3 and chapter 5, section 7). It then follows that $R_o$ is the opposite of the slope of the curve in Fig. 151. From there we find that $R_o$ is rather low (about 1.5 kilohm) for load values higher than 100 kilohms and for inputs of about 500 µV. Although $R_o$ varies a little with varying input signal we have found experimentally that the diagram in Fig. 151 gives a good general picture of the output characteristic of the d-c amplifier for the entire range of input values (from zero up to 1 millivolt).

## 3.- POWER REQUIREMENTS OF THE CIRCUIT.

The circuit needs two separate power supplies :

1. one of 12 Volts delivering 3.4 mA to the a-c amplifier.
2. one of 28 Volts delivering 14 mA to the driving source circuitry of which 12 mA are necessary to drive the input chopper.

The total power absorbed by the circuit is hence about

$$(12 \times 3.4) + (28 \times 14) \text{ milliwatts} \cong 432 \text{ mW}$$

## 4.- SIZE AND WEIGHT OF THE AMPLIFIER

The size and the weight are primarily dependent upon the size of the capacitors used in the circuit. As for the polarized capacitors, nowadays small, light electrolytic capacitors of high capacitance are available and can be used if desired.

The test unit was mounted on a board of about 6 inches by 4 inches in order to have the possibility of measuring voltages, of changing elements, etc.., whenever wanted. However, the size can be made smaller if the accessibility is no longer important.

The actual weight is a few ounces.

## 5.- EXPERIMENTAL DATA OBTAINED

In table 11.1 is shown the data which gives the d-c output voltages measured for corresponding d-c input voltages. The data covers the entire desired temperature range from -20°C up to +60°C for positive as well as for negative input voltages. For each of nine temperatures (-20°C, -10°C, 0°C, 10°C, 20°C, 30°C, 40°C, 50°C and 60°C) 41 measurements were made for inputs from zero up to about 1130 microvolts. They are plotted in Fig. 152. For convenience, however, we have plotted only the values for inputs up to 900 μV. This was done only in order to keep the ordinate scales sufficiently small. Furthermore, the scale is still too large to show any difference between the data for different temperatures. Therefore, in Fig. 153 are plotted the measured values for input voltages up to 180 microvolts for the two extreme temperatures (-20°C and + 60°C). All the other curves are situated very closely to the ones shown and are not plotted in order not to overload the diagram.

The values above were measured for each temperature after we allowed the amplifier to reach equilibrium within an aluminum box enclosure. However, no special heat sink (for example an oil bath) was used.

From the data and the plots we see that there is some basic offset which when referred to the input, drifts from about -2 microvolts (at -20°C) to about -5 microvolts (at +60°C). (Note that the gain is about 5,000). No drift in time has been found over small time intervals (minutes or hours), nor over long time intervals (several days of either continuous or non-continuous operations). However, we noticed that the offset can change when a modification is made in the input circuitry.

The noise as referred to the input is of the order of 1 to (maximum) 2 microvolts. This noise limits the output stability to within about 5 to 10 millivolts.

We calculated the average offset and the average gain for the whole set of data. The average offset turns out to be about -3.2 µV when referred to the input (-16 mV at the output) and the average gain was found to be

$$A_{average} = 4{,}969.5$$

Assuming the offset and gain to be constant over the entire temperature range, we calculated the output values we should get for the 41 positive and 41 negative input voltages from zero up to 1133 µV. The results are given in table 11.2. When comparing this table with the real outputs that we measured we see that errors are introduced by assuming a constant gain and a constant offset. For all of the 18 x 41 = 738 measurements we calculated the error we would make by simply assuming constant gain and offset. We found that

3 (≅ 0.4 $^{o}/_{o}$) gave an error between 4 and 5 µV

12 (≅ 1.6 $^{o}/_{o}$) gave an error between 3 and 4 µV

46 (≅ 6.2 $^{o}/_{o}$) gave an error between 2 and 3 µV

231 (≅ 31.0$^{o}/_{o}$) gave an error between 1 and 2 µV

446 (≅ 60.8$^{o}/_{o}$) gave an error of less than 1 µV

all the errors being referred to the input.

As seen above all the errors are smaller than 5 µV. Furthermore 99.6 per cent of the errors are small than 4 µV, 98 per cent of the errors are smaller than 3 µV, 91,8 per cent of the errors are smaller than 2 µV and 60,8 per cent of the errors are smaller than 1 µV.

Although all the above data was taken during the same day we have also taken regular samples of output versus input values over a time interval of several days of continuous operation of the amplifier. The offset as well as the gain were found to be very stable. (no change at all was noticed).

## FINAL CONCLUSIONS.

The modulated d-c amplifier described above turns out to be a very stable unit in time as well as for temperature variations. Its characteristics are :

1. Gain = 4,969.5
2. Internal a-c gain ≅ 450,000
3. Average zero offset = -3.2 µV (when referred to the input)
4. Drift in time : unmeasurably low.
5. Drift for temperature variations : The offset (as referred to the input) drifts from -2 µV (at -20°C) to -5 µV (at +60°C).
6. Temperature range at least from -20°C up to +60°C.
7. Power :

   For a-c amplifier ≈ 40.8 mV
   For chopper driving source ≈ 392 mV
   Total ≈ 432.8 mV

8. Input impedance ≈ 480 kilohms
9. Output impedance ≈ 1.5 kilohm for load values higher than 100 kilohms.
10. Noise : not greater than 2 µV when referred to the input.

It should be noted that shielding (electrostatic as well as magnetic) may prove to be necessary. If the amplifier does not work properly one of the first causes of trouble to look for is magnetically induced voltages within the input circuit or within the a-c amplifier. Especially power lines at 60 cps. (in USA) may be very disturbing as they can induce in the unshielded or not well-enough shielded system voltages which are strong enough to saturate the a-c amplifier output transistor and so make the device useless. Not only can the amplifier itself pick up stray magnetic fields, but also the wires leading to the power supplies can do so even if they contain filtering capacitors : it should not be forgotten that the amplifier works in the microvolt range and the first stages of the a-c amplifier even in the submicrovolt range.

**NOTE :**

**Tr1** = Silicon NPN Transistor

$\beta \cong 35$ (not critical)

$\beta$ and other characteristics are more or less stable from -30°C to +70°C.

Unit used :

021 - J406

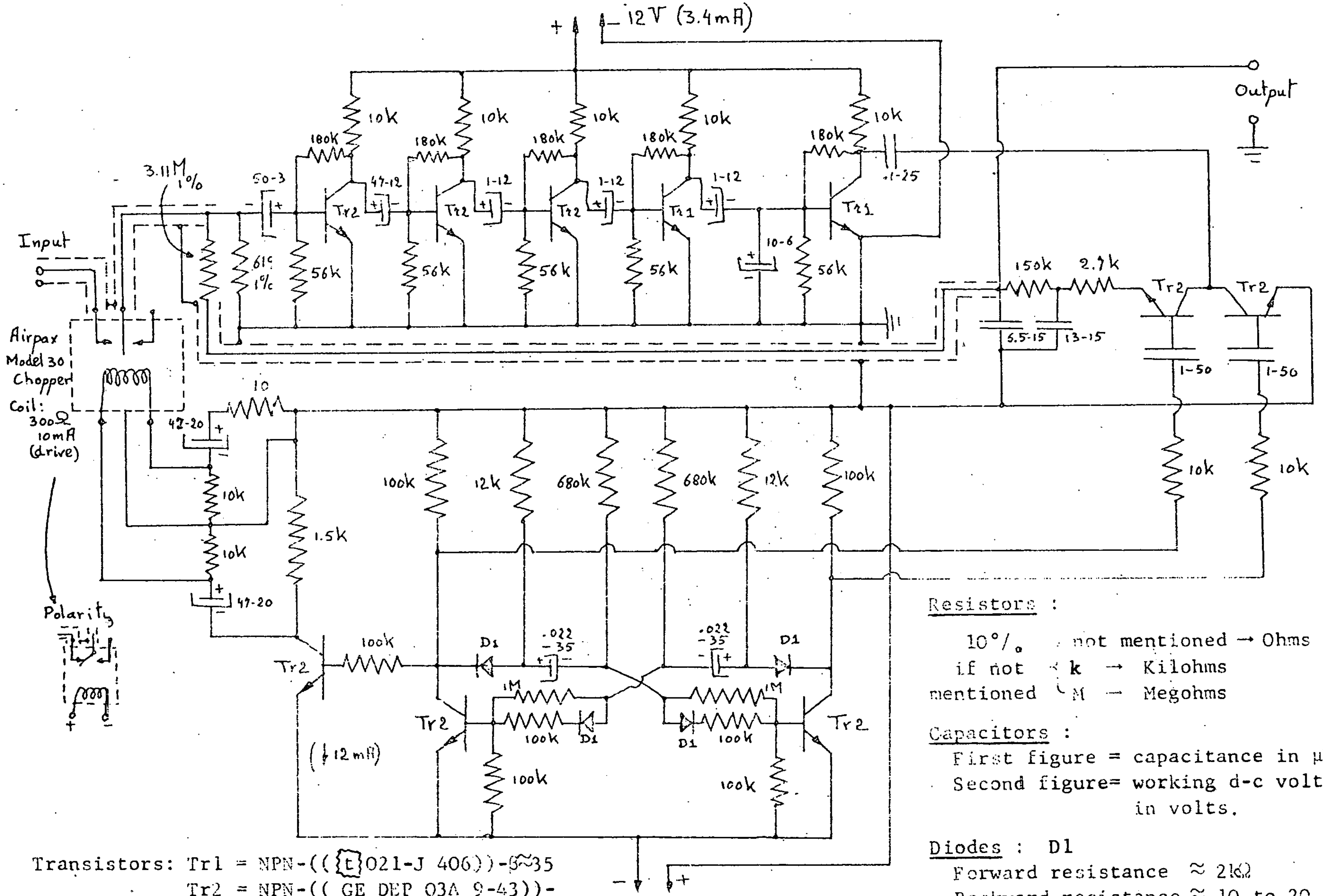
**Tr2** = Silicon NPN Transistor

$\beta \cong 90$ (not critical)

$\beta$ and other characteristics are very stable at least from - 60°C to +80°C

Unit used :

GE DEP 03A 9-43



Transistors: Tr1 = NPN-(( t 021-J 406))-β≈35

Tr2 = NPN-(( GE DEP 03A 9-43))-β ≈ 90.

(See end of Part IV)

28 V(14mA)

Chopping frequency ≈ 70 cps

Fig. 143

Resistors :

10°/₀ if not mentioned : not mentioned → Ohms

k → Kilohms

M → Megohms

Capacitors :

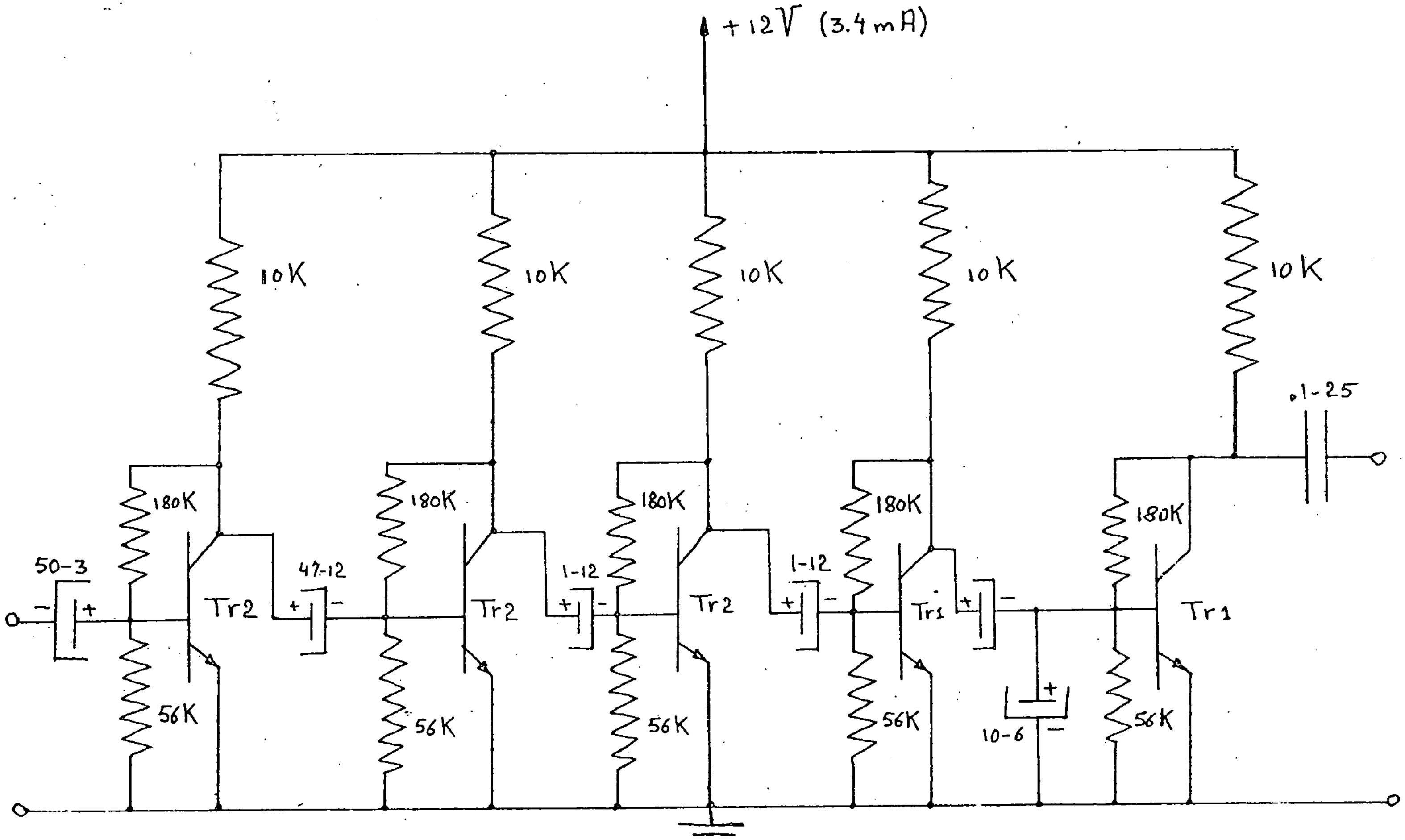
First figure = capacitance in μF.

Second figure= working d-c voltage in volts.

Diodes : D1

Forward resistance ≈ 2kΩ

Backward resistance ≈ 10 to 20 MΩ



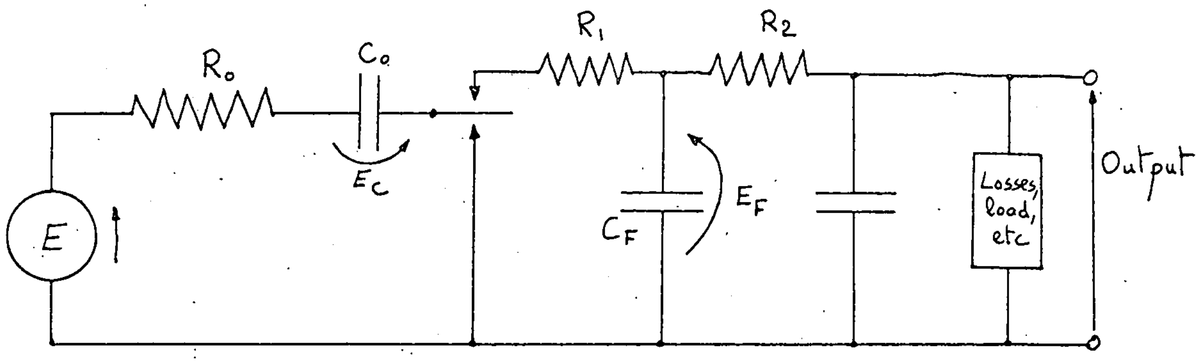
A-C Amplifier

Fig. 144

Tr 1 : NPN - β ≈ 35 } (See end of Part IV)
Tr 2 : NPN - β ≈ 90

Resistors : (all 10°/。)
not mentioned → Ohms
K → Kilohms
M → Megohms

Capacitors :
first figure = capacitance in μF
second figure = working d-c voltage in volts.

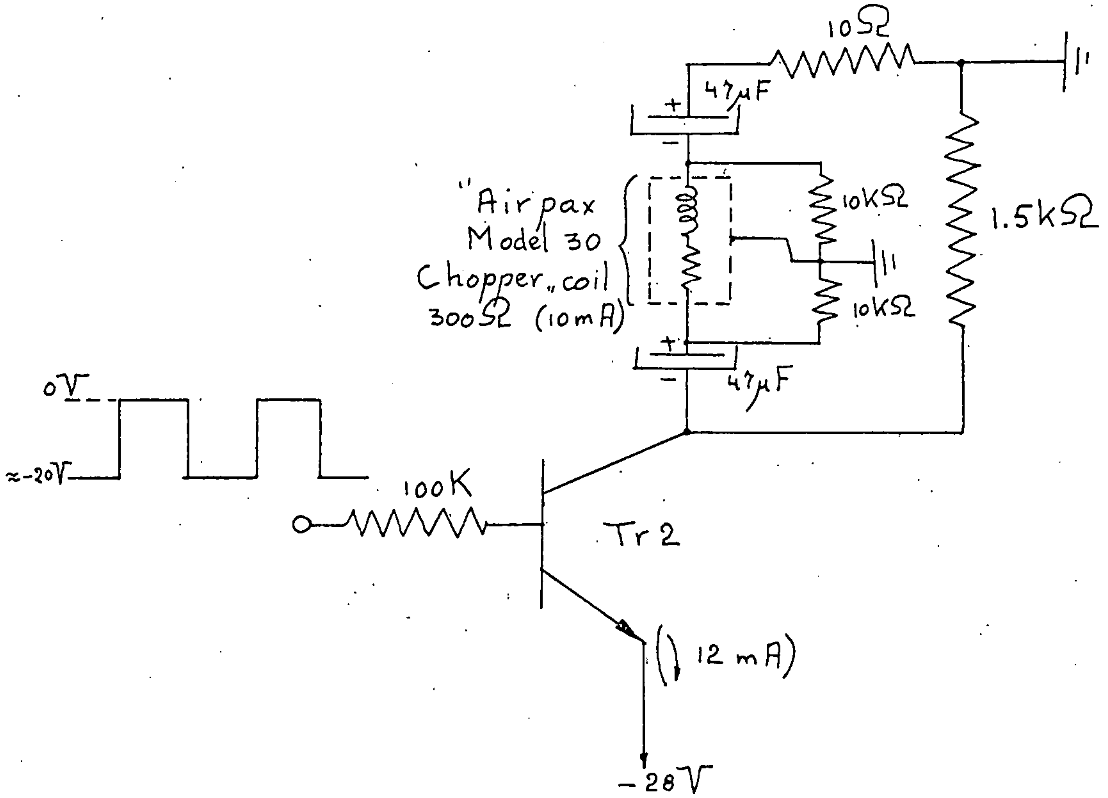


$R_o$ = Output resistance of last amplifier stage.

$C_o$ = Output capacitance.

$C_F$ = Filter capacitance.

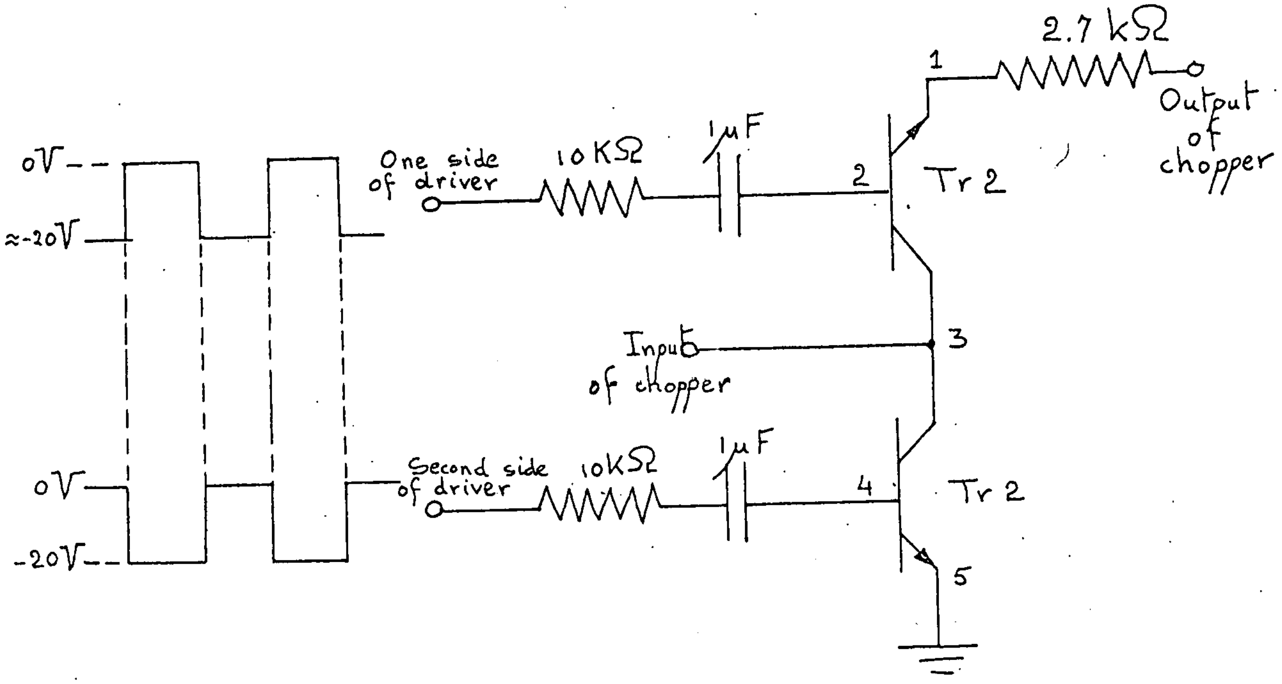
Fig. 145



Tr 2 : NPN - $\beta \approx 90$
(See end of Part IV)

Input chopper drive

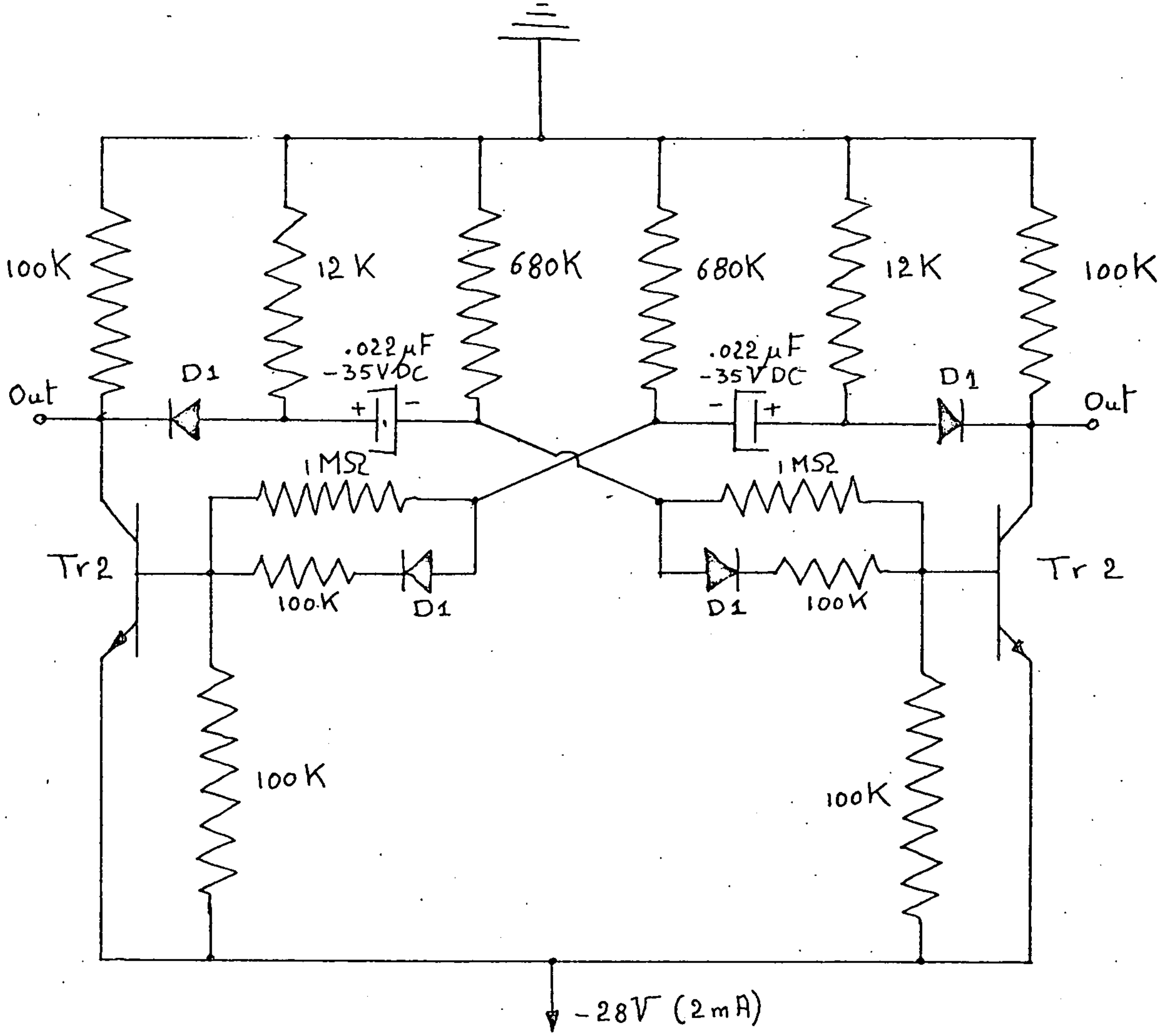
Fig. 146



Tr 2 : NPN - β ≈ 90
(See end of Part IV)

Transistorized output chopper.

Fig. 147



Tr 2 : NPN - β ≈ 90
(See end of Part IV)
Diodes : D1 : Forward resistance ≈ 2kΩ
Backward resistance ≈ 10 to 20 MΩ

Chopper driver (Square wave generator)
f ≈ 70 cps.

Fig.148

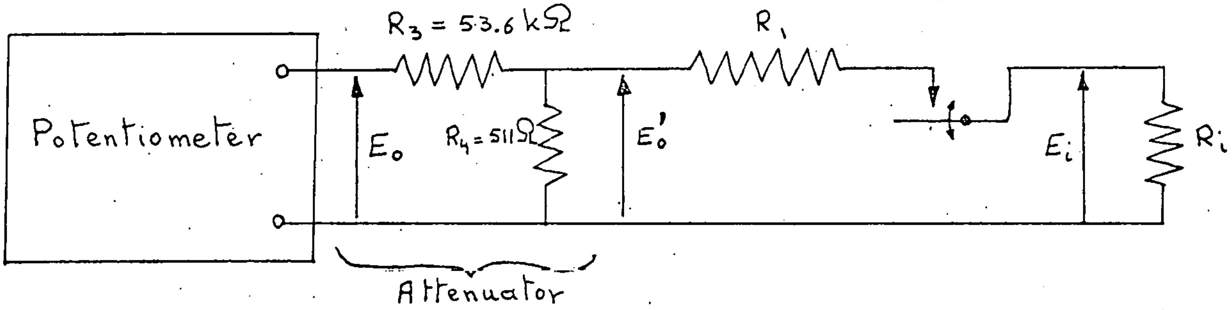


Fig. 149

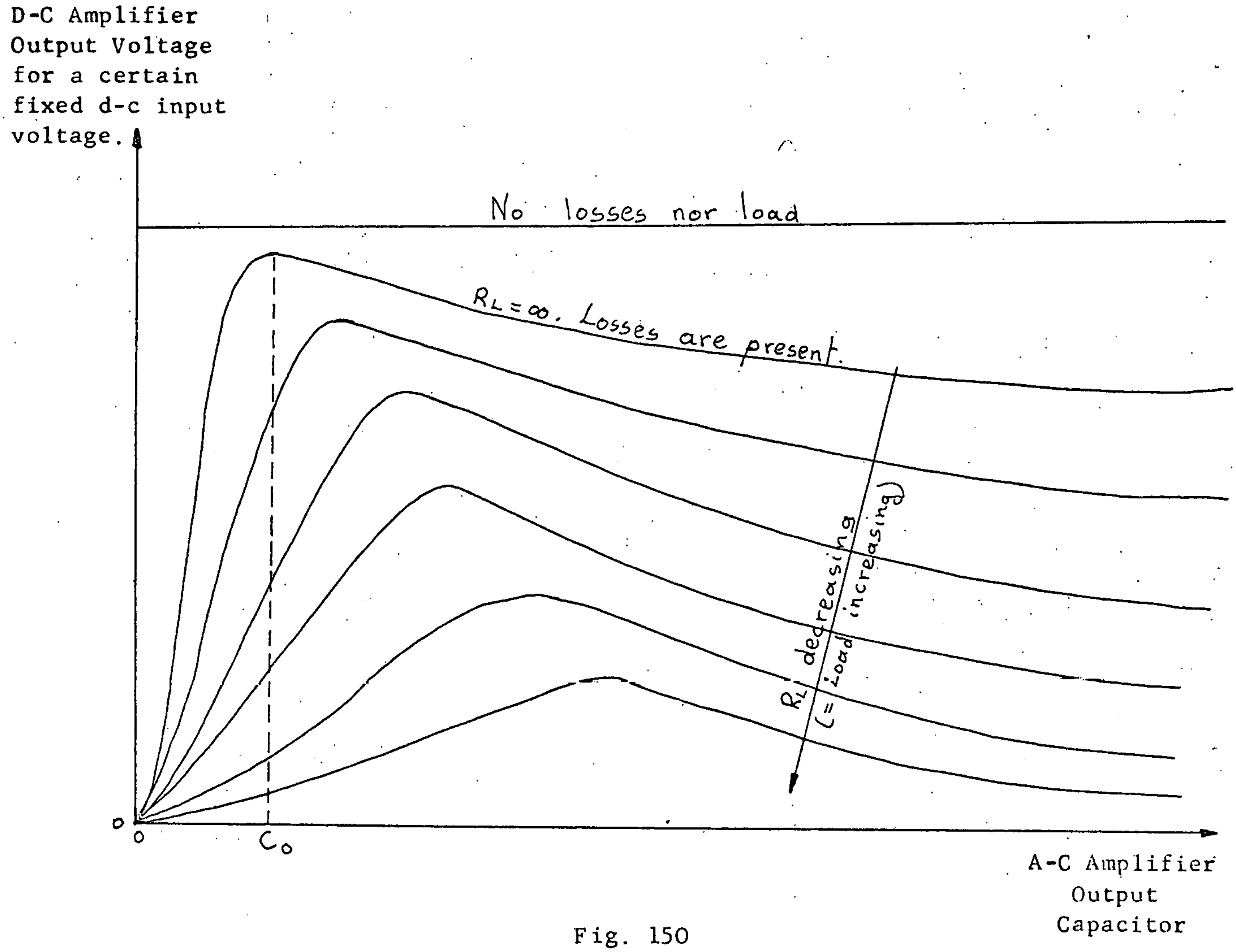
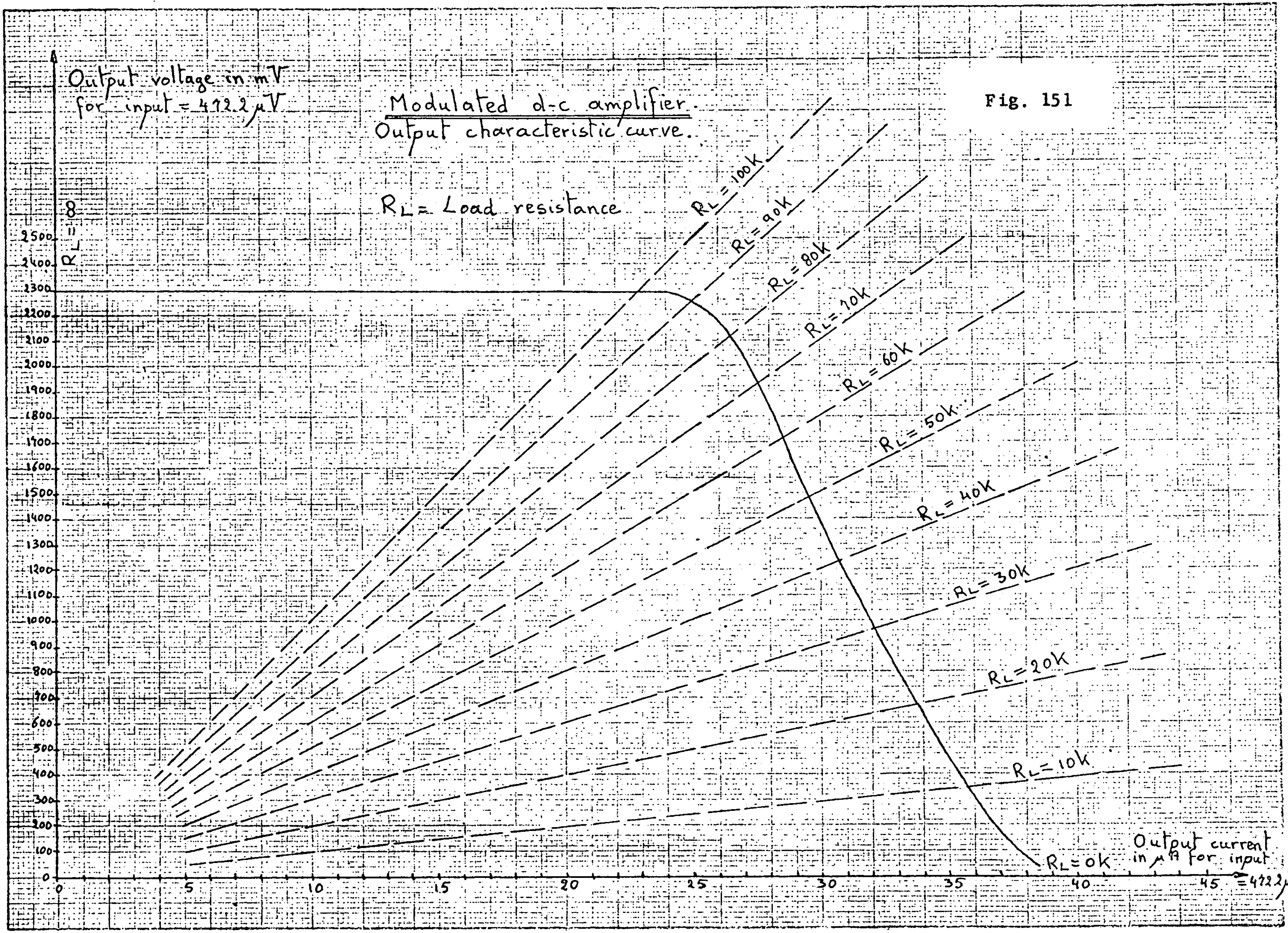


Fig. 150

**Fig. 151**



Modulated d-c amplifier

Output characteristic curve.

RL = Load resistance

## TABLE 11.1.- Modulated DC Amplifier. Output vs. Input.

### 1) Positive Input Values.

| INPUT | | OUTPUT in mV | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Potentiometer mV | Input µV | -20°C | -10°C | 0°C | 10°C | 20°C | 30°C | 40°C | 50°C | 60°C |
| 0 | 0 | -10 | -9 | -10 | -14 | -14 | -15 | -19 | -23 | -25 |
| 1 | 9.5 | 39 | 39 | 34 | 35 | 36 | 37 | 32 | 23 | 24 |
| 2 | 18.9 | 88 | 88 | 84 | 84 | 84 | 84 | 79 | 70 | 74 |
| 3 | 28.3 | 139 | 134 | 131 | 130 | 130 | 130 | 126 | 116 | 119 |
| 4 | 37.7 | 180 | 179 | 176 | 175 | 177 | 177 | 174 | 162 | 164 |
| 5 | 47.2 | 229 | 229 | 225 | 223 | 226 | 224 | 217 | 209 | 209 |
| 6 | 56.7 | 278 | 274 | 271 | 271 | 273 | 272 | 266 | 255 | 257 |
| 7 | 66.1 | 323 | 320 | 319 | 316 | 318 | 317 | 311 | 304 | 299 |
| 8 | 75.5 | 371 | 367 | 365 | 363 | 363 | 364 | 361 | 349 | 351 |
| 9 | 85.0 | 418 | 412 | 413 | 410 | 412 | 409 | 407 | 396 | 398 |
| 10 | 94.4 | 465 | 462 | 459 | 458 | 457 | 458 | 452 | 446 | 447 |
| 11 | 103.9 | 510 | 509 | 506 | 507 | 506 | 506 | 498 | 490 | 492 |
| 12 | 113.3 | 556 | 554 | 553 | 553 | 552 | 550 | 545 | 538 | 540 |
| 13 | 122.8 | 603 | 602 | 599 | 600 | 600 | 598 | 595 | 586 | 590 |
| 14 | 132.2 | 651 | 650 | 647 | 647 | 644 | 644 | 641 | 634 | 636 |
| 15 | 141.7 | 698 | 697 | 694 | 692 | 692 | 690 | 690 | 683 | 682 |
| 16 | 151.0 | 748 | 744 | 743 | 741 | 740 | 738 | 735 | 329 | 731 |
| 17 | 160.5 | 795 | 788 | 786 | 788 | 784 | 784 | 786 | 777 | 780 |
| 18 | 170.0 | 836 | 839 | 835 | 835 | 830 | 827 | 829 | 822 | 828 |
| 19 | 179.4 | 883 | 882 | 879 | 881 | 879 | 877 | 876 | 870 | 872 |
| 20 | 188.9 | 928 | 924 | 920 | 922 | 921 | 919 | 918 | 914 | 917 |
| 25 | 236.1 | 1164 | 1161 | 1157 | 1157 | 1153 | 1154 | 1152 | 1146 | 1155 |
| 30 | 283.3 | 1397 | 1395 | 1395 | 1399 | 1391 | 1391 | 1386 | 1384 | 1384 |
| 35 | 330.5 | 1635 | 1629 | 1629 | 1626 | 1627 | 1624 | 1625 | 1613 | 1619 |
| 40 | 377.7 | 1865 | 1862 | 1862 | 1861 | 1859 | 1857 | 1856 | 1847 | 1852 |
| 45 | 425.0 | 2106 | 2101 | 2100 | 2100 | 2097 | 2093 | 2095 | 2087 | 2093 |
| 50 | 472.2 | 2338 | 2334 | 2332 | 2332 | 2332 | 2323 | 2324 | 2320 | 2324 |

## TABLE 11.1.- Contd. Modulated DC Amplifier. Output vs. Input.

### 1) Positive Input Values.

| INPUT | | OUTPUT in mV | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Potentiometer mV | Input µV | -20°C | -10°C | 0°C | 10°C | 20°C | 30°C | 40°C | 50°C | 60°C |
| 55 | 519.4 | 2579 | 2575 | 2572 | 2570 | 2568 | 2564 | 2565 | 2555 | 2555 |
| 60 | 566.6 | 2811 | 2806 | 2802 | 2799 | 2803 | 2795 | 2796 | 2787 | 2790 |
| 65 | 613.8 | 3043 | 3044 | 3035 | 3038 | 3038 | 3029 | 3030 | 3024 | 3025 |
| 70 | 661.0 | 3279 | 3272 | 3269 | 3273 | 3270 | 3262 | 3264 | 3257 | 3258 |
| 75 | 708.3 | 3512 | 3511 | 3504 | 3503 | 3503 | 3497 | 3495 | 3487 | 3489 |
| 80 | 755.5 | 3750 | 3745 | 3742 | 3738 | 3739 | 3731 | 3731 | 3722 | 3728 |
| 85 | 802.7 | 3985 | 3983 | 3975 | 3977 | 3974 | 3969 | 3967 | 3959 | 3958 |
| 90 | 849.9 | 4222 | 4219 | 4215 | 4214 | 4211 | 4204 | 4199 | 4194 | 4196 |
| 95 | 897.1 | 4457 | 4451 | 4448 | 4443 | 4443 | 4439 | 4437 | 4423 | 4432 |
| 100 | 944.3 | 4691 | 4681 | 4679 | 4677 | 4676 | 4671 | 4669 | 4653 | 4658 |
| 105 | 991.5 | 4925 | 4919 | 4915 | 4908 | 4908 | 4903 | 4899 | 4894 | 4893 |
| 110 | 1038.8 | 5161 | 5156 | 5150 | 5146 | 5149 | 5142 | 5137 | 5126 | 5126 |
| 115 | 1086.0 | 5395 | 5388 | 5381 | 5377 | 5378 | 5371 | 5367 | 5363 | 5357 |
| 120 | 1133.2 | 5628 | 5624 | 5616 | 5614 | 5614 | 5607 | 5607 | 5593 | 5597 |

TABLE 11.1.- Contd. Modulated DC Amplifier. Output vs. Input.

2) Negative Input Values.

| INPUT | | OUTPUT in mV | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Potentiometer mV | Input µV | -20°C | -10°C | 0°C | 10°C | 20°C | 30°C | 40°C | 50°C | 60°C |
| 0 | 0 | -11 | -12 | -10 | -14 | -15 | -16 | -19 | -25 | -24 |
| -1 | -9.5 | -62 | -58 | -58 | -60 | -61 | -61 | -66 | -74 | -73 |
| -2 | -18.9 | -106 | -104 | -103 | -108 | -109 | -110 | -113 | -121 | -121 |
| -3 | -28.3 | -153 | -153 | -150 | -154 | -157 | -158 | -163 | -169 | -166 |
| -4 | -37.7 | -202 | -198 | -199 | -203 | -204 | -205 | -209 | -216 | -216 |
| -5 | -47.2 | -246 | -244 | -246 | -249 | -250 | -253 | -254 | -269 | -263 |
| -6 | -56.7 | -294 | -293 | -293 | -298 | -297 | -298 | -304 | -312 | -313 |
| -7 | -66.1 | -339 | -340 | -342 | -343 | -343 | -347 | -349 | -357 | -361 |
| -8 | -75.5 | -387 | -388 | -385 | -391 | -394 | -391 | -403 | -401 | -401 |
| -9 | -85.0 | -435 | -434 | -434 | -437 | -438 | -437 | -440 | -446 | -450 |
| -10 | -94.4 | -484 | -480 | -483 | -484 | -484 | -485 | -490 | -493 | -493 |
| -11 | -103.9 | -528 | -529 | -529 | -531 | -533 | -533 | -537 | -537 | -546 |
| -12 | -113.3 | -574 | -575 | -575 | -579 | -581 | -579 | -577 | -586 | -585 |
| -13 | -122.8 | -622 | -623 | -623 | -624 | -625 | -627 | -629 | -632 | -633 |
| -14 | -132.2 | -670 | -671 | -669 | -673 | -674 | -672 | -681 | -679 | -682 |
| -15 | -141.7 | -716 | -716 | -719 | -718 | -723 | -721 | -721 | -725 | -725 |
| -16 | -151.0 | -765 | -763 | -766 | -765 | -768 | -770 | -772 | -769 | -776 |
| -17 | -160.5 | -814 | -808 | -813 | -814 | -816 | -813 | -815 | -818 | -824 |
| -18 | -170.0 | -858 | -855 | -856 | -861 | -864 | -858 | -857 | -861 | -864 |
| -19 | -179.4 | -899 | -900 | -900 | -903 | -907 | -905 | -902 | -905 | -908 |
| -20 | -188.9 | -946 | -949 | -948 | -949 | -953 | -949 | -953 | -951 | -954 |
| -25 | -236.1 | -1179 | -1182 | -1181 | -1184 | -1187 | -1183 | -1182 | -1187 | -1187 |
| -30 | -283.3 | -1416 | -1415 | -1421 | -1418 | -1423 | -1423 | -1424 | -1422 | -1427 |
| -35 | -330.5 | -1654 | -1653 | -1653 | -1654 | -1655 | -1656 | -1653 | -1657 | -1657 |
| -40 | -377.7 | -1884 | -1888 | -1883 | -1888 | -1889 | -1888 | -1886 | -1889 | -1891 |
| -45 | -425.0 | -2124 | -2125 | -2126 | -2124 | -2128 | -2125 | -2126 | -2128 | -2129 |
| -50 | -472.2 | -2355 | -2357 | -2357 | -2359 | -2359 | -2352 | -2353 | -2353 | -2359 |

### TABLE 11.1.- Contd. Modulated DC Amplifier. Output vs. Input.

### 2) Negative Input Values.

| INPUT | | OUTPUT in mV | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Potentiometer mV | Input µV | -20°C | -10°C | 0°C | 10°C | 20°C | 30°C | 40°C | 50°C | 60°C |
| -55 | -519.4 | -2597 | -2598 | -2597 | -2597 | -2597 | -2596 | -2601 | -2598 | -2600 |
| -60 | -566.6 | -2829 | -2825 | -2827 | -2826 | -2829 | -2826 | -2825 | -2823 | -2832 |
| -65 | -613.8 | -3063 | -3062 | -3062 | -3063 | -3068 | -3064 | -3065 | -3063 | -3066 |
| -70 | -661.0 | -3297 | -3294 | -3295 | -3298 | -3299 | -3297 | -3298 | -3295 | -3300 |
| -75 | -708.3 | -3534 | -3532 | -3532 | -3533 | -3534 | -3531 | -3532 | -3532 | -3535 |
| -80 | -755.5 | -3769 | -3766 | -3765 | -3764 | -3770 | -3766 | -3769 | -3769 | -3768 |
| -85 | -802.7 | -4003 | -4000 | -4000 | -4000 | -4001 | -4000 | -4002 | -4001 | -4000 |
| -90 | -849.9 | -4243 | -4239 | -4238 | -4243 | -4243 | -4238 | -4242 | -4239 | -4242 |
| -95 | -897.1 | -4474 | -4474 | -4473 | -4475 | -4472 | -4471 | -4474 | -4472 | -4479 |
| -100 | -944.3 | -4705 | -4705 | -4709 | -4707 | -4706 | -4702 | -4703 | -4702 | -4706 |
| -105 | -991.5 | -4944 | -4943 | -4945 | -4944 | -4941 | -4937 | -4937 | -4938 | -4944 |
| -110 | -1038.8 | -5179 | -5176 | -5179 | -5173 | -5182 | -5177 | -5175 | -5178 | -5175 |
| -115 | -1086.0 | -5415 | -5410 | -5408 | -5406 | -5413 | -5407 | -5405 | -5407 | -5411 |
| -120 | -1133.2 | -5648 | -5645 | -5646 | -5645 | -5644 | -5640 | -5640 | -5641 | -5641 |

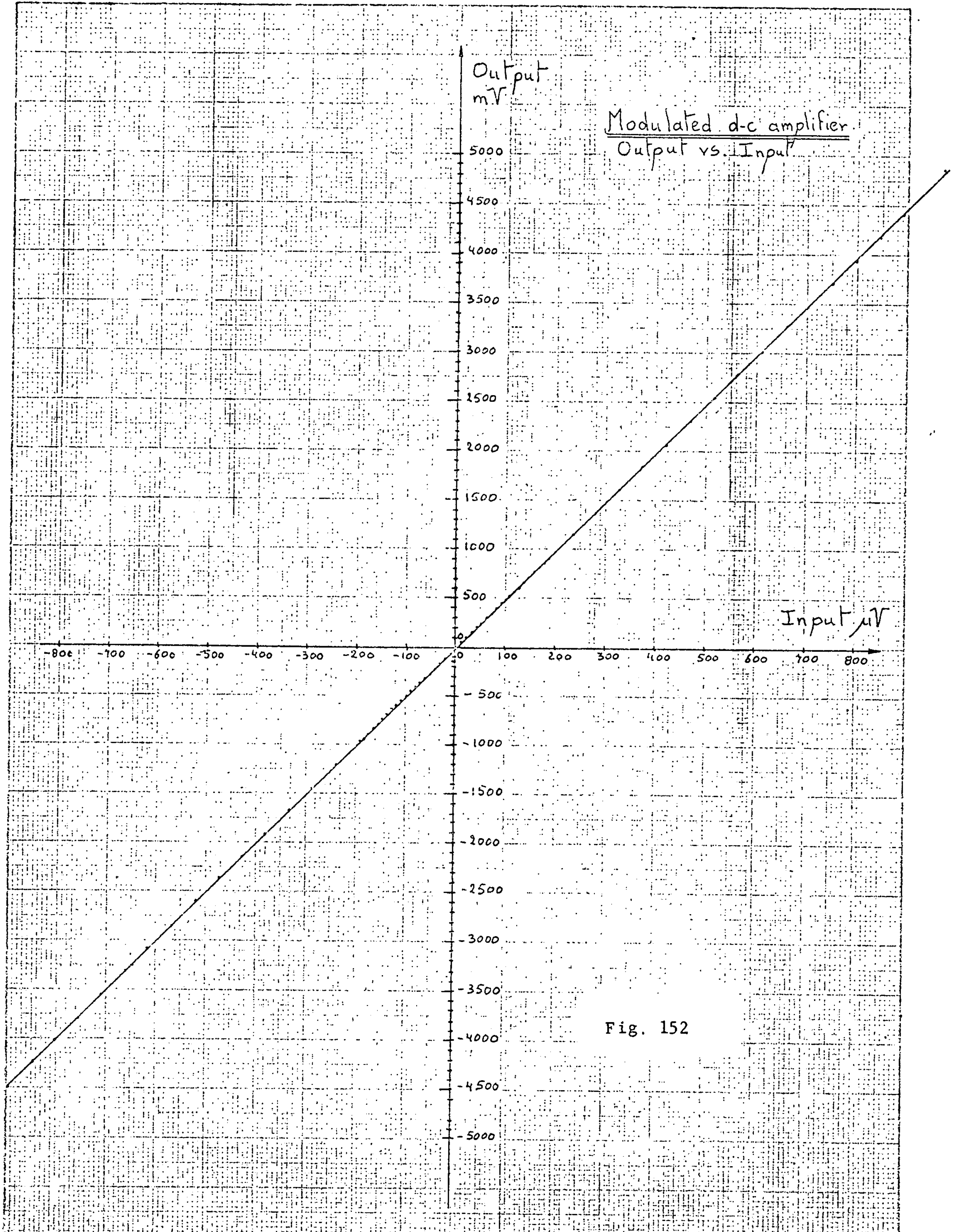

Output mV
Modulated d-c amplifier
Output vs. Input
Input µV
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
500
600
700
800

Fig. 152

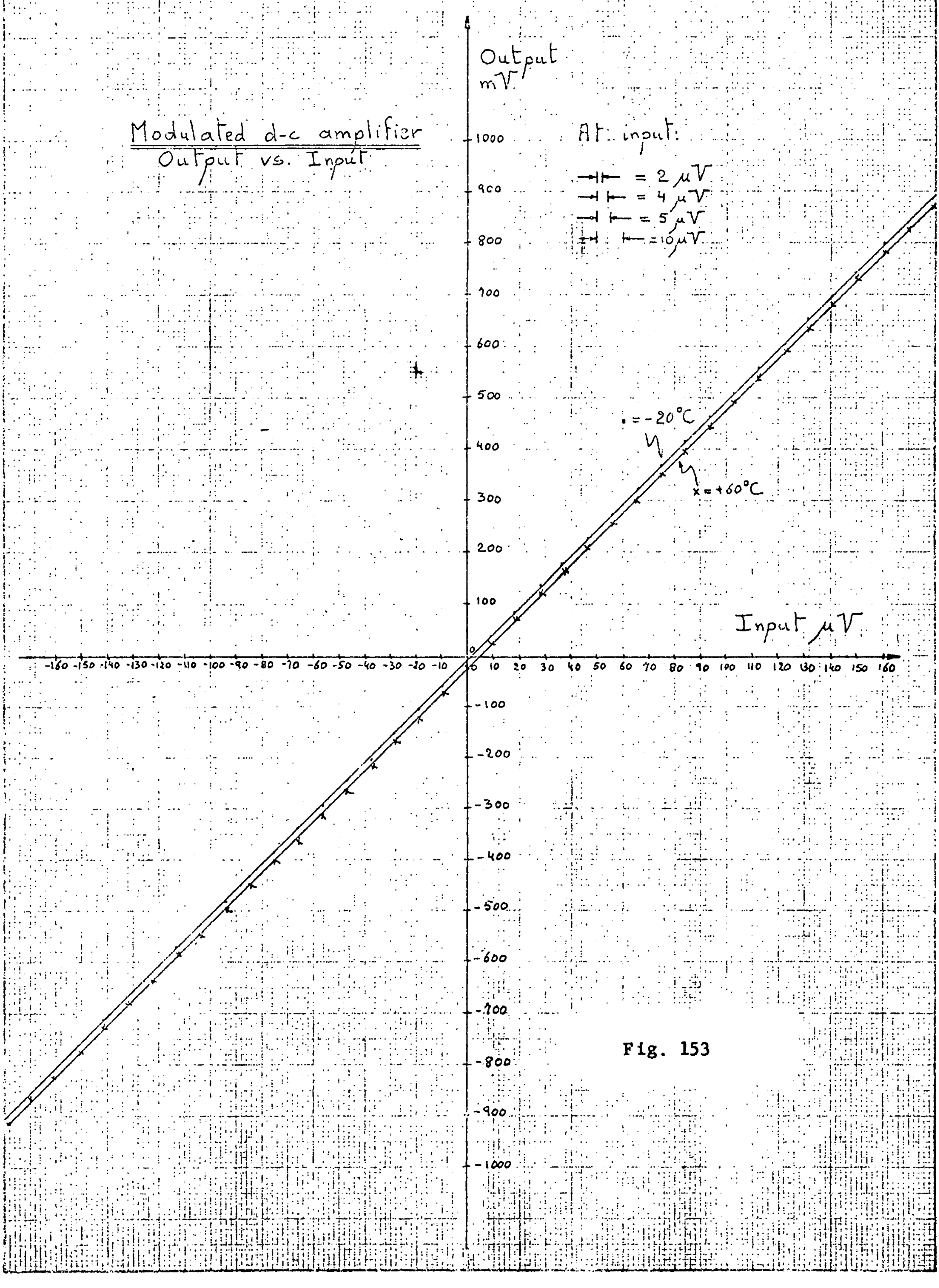

Modulated d-c amplifier
Output vs. Input
Output mV
At input:
= 2 μV
= 4 μV
= 5 μV
= 10 μV
• = -20°C
x = +60°C
Input μV
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160

Fig. 153

TABLE 11.2.- Modulated DC Amplifier. Theoretical values for offset = - 16 mV (at output); gain = 4,969.5.

| Potentiometer mV | Input µV | Theoret. Output for positive input mV | Theoret. Output for negative input mV |
|---|---|---|---|
| 0 | 0 | -16 | -16 |
| 1 | 9.5 | 31 | -63 |
| 2 | 18.9 | 78 | -110 |
| 3 | 28.3 | 125 | -157 |
| 4 | 37.7 | 172 | -204 |
| 5 | 47.2 | 219 | -251 |
| 6 | 56.7 | 266 | -298 |
| 7 | 66.1 | 313 | -345 |
| 8 | 75.5 | 359 | -391 |
| 9 | 85.0 | 406 | -438 |
| 10 | 94.4 | 453 | -485 |
| 11 | 103.9 | 500 | -532 |
| 12 | 113.3 | 547 | -579 |
| 13 | 122.8 | 594 | -626 |
| 14 | 132.2 | 641 | -673 |
| 15 | 141.7 | 688 | -720 |
| 16 | 151.0 | 735 | -767 |
| 17 | 160.5 | 782 | -814 |
| 18 | 170.0 | 829 | -861 |
| 19 | 179.4 | 876 | -908 |
| 20 | 188.9 | 923 | -955 |
| 25 | 236.1 | 1157 | -1189 |
| 30 | 283.3 | 1392 | -1424 |
| 35 | 330.5 | 1627 | -1659 |
| 40 | 377.7 | 1861 | -1893 |
| 45 | 425.0 | 2096 | -2128 |
| 50 | 472.2 | 2330 | -2362 |

TABLE 11.2.- Contd. Modulated DC Amplifier. Theoretical values for offset ≈ - 16 mV (at output) ; gain = 4.969.5.

| Potentio-meter mV | Input µV | Theoret. Output for positive input mV | Theoret. Output for negative input mV |
|---|---|---|---|
| 55 | 519.4 | 2565 | -2597 |
| 60 | 566.6 | 2800 | -2832 |
| 65 | 613.8 | 3034 | -3066 |
| 70 | 661.0 | 3269 | -3301 |
| 75 | 708.3 | 3504 | -3536 |
| 80 | 755.5 | 3738 | -3770 |
| 85 | 802.7 | 3973 | -4005 |
| 90 | 849.9 | 4207 | -4240 |
| 95 | 897.1 | 4442 | -4474 |
| 100 | 944.3 | 4677 | -4709 |
| 105 | 991.5 | 4912 | -4944 |
| 110 | 1038.8 | 5146 | -5178 |
| 115 | 1086.0 | 5381 | -5413 |
| 120 | 1133.2 | 5616 | -5648 |