Simple Amplifier for Muscle Voltages

A low-frequency amplifier for use in examining the electrical activity of voluntary muscles

*by R. E. George**

When a muscle contracts, electrical activity is produced throughout the muscle and this increases with the force exerted. Two small metal electrodes placed on the skin over the muscle will detect this activity. With small contractions the amplitude of the electro-myogram is only a few microvolts. At strong contractions it rises to several millivolts with a spectrum spanning 20Hz to 5kHz, and in the larger muscles rises to a maximum in the region 40 to 70Hz. An amplifier for muscle potentials, in common with biological amplifiers, must have a high absolute sensitivity, a high rejection to common-mode interference, and an input impedance substantially greater than the source impedance. A transformer at the amplifier input can satisfy these three requirements. The input terminals in this case are isolated from the apparatus, so there is no need for the amplifying devices to be arranged in a balanced configuration and provided the capacitance between the primary and all other parts of the transformer is small, mains interference and common-mode signals can be rejected without balancing out stray capacitances. The advantages of negative feedback are obtained simply by connection through the secondary winding. A balanced input using planar junction or field-effect transistors can be designed to fulfil a much more exacting specification than the transformer input. However, the transformer type of input was chosen by the author for its inherent simplicity.

Noise

Early designs of transistor amplifier for electromyography were based on alloyed-junction types of transistor such as the OC70[2,3] whose optimum conditions as a low-noise, low-frequency amplifier in common emitter configuration were obtained at a working point of 80μA collector current, and 0.5V between emitter and collector. The ratio of the voltage to the current generator gave somewhat more than 1kΩ for the equivalent noise resistance. The correlation between the generators was ignored since only an approximate figure was needed. It was fortunate that this value was lower than the usual values of biological source impedance obtained with surface electrodes, for the transformer could be specified with a voltage step-down ratio, permitting easier design when large values of primary inductance have to be considered. The turns ratio is determined by matching the source to the equivalent noise resistance, in the same way that a generator is matched for maximum power loading. The input impedance of the OC70 under the conditions specified was about 10kΩ. Thus, optimum noise conditions and slight loading of the source impedance, even without negative feedback, could be attained. The OC70 was succeeded by the higher frequency types such as the OC44 and GET880. These were run at a collector current of 60μA.

Eight years after the introduction of the alloyed junction transistor, the silicon planar with its superior characteristics, typified in the 2N929, became available. Its use as an amplifier of microvolt level biological signals was reported by Molyneaux and Osselton[4]. The leakage current was less than 1% of that of the alloyed type and it had an inherently higher current gain, which was maintained down to collector currents of only a few microamps. These properties are desirable in a transistor for low-noise amplification[5,6]. At low currents, moderately high values of input impedance are obtained.

A simple model for transistor noise[7], based on the shot effect of current due to electron flow, shows that with random partition of emitter current, the collector and base current generators have zero correlation. The collector current, I_c, a function of mutual conductance, g_m, is transformed to the input as a voltage noise generator, while the base current, I_b, is the current noise generator. The optimum source resistance is given as

$$R_s = 1/g_m \cdot \sqrt{I_c I_b}.$$

The noise performance of planar transistors can be calculated in terms of collector current, current gain and fundamental constants. Excess semiconductor and thermal noise do not contribute materially to the total noise. Walker[8] refers to p-n-p types which, having a lower effective base resistance, offer a marginally better noise performance than n-p-n types.

The author's choice of the 2N930, currently available at a very low price, was made partly for economic considerations and also because the results were adequate. As with the early designs, a step-down transformer can be used for noise matching with the 2N930 (Fig. 1). At a collector current of 125μA, the current gain is well in excess of 100, and R_s (optimum) is somewhat greater than 2kΩ. The transformer primary winding, having a resistance of 16kΩ, contributes materially to the amplifier noise which, measured for a source resistance of 25kΩ and passband 4Hz to 7kHz, was 3.9μV r.m.s.

Circuit

The low-frequency cut-off of the amplifier will depend on the relation between the transformer primary reactance and the source impedance, which is made up of electrode-to-skin plus tissue impedance. For demonstration of the electromyogram, adequate results are obtainable with an inductance of only 30H, but for the measurement of activity and the recording of the lower frequencies in the e.m.g., at least ten times this value is required. With the transformer used (Parmeko type DMSC 2443), even if the source impedance is as high as 50kΩ, the amplifier will respond to the potential (electrocardiogram) produced by the heart at each beat, although the lowest frequency components will suffer some attenuation. The e.c.g. is most conveniently detected between the wrists. The amplifier low-frequency turnover can be extended to below 2Hz by increasing the feedback path capacitor to 1,000μF.

Transistor Tr_1 collector voltage is determined by a potential divider network to the inverting input of the "709" high-gain d.c. amplifier and maintained by overall d.c. negative feedback. The bias current is applied through R_B. The base-to-emitter voltage drop is opposed by the forward voltage of the diode and does not appear at the amplifier output. The gain of the transistor is about 400, giving a loop gain of about 65. Capacitors C_1 and C_2 each produce a phase-lag giving rise to a pair of complex poles in the transfer function of the amplifier. Their position is set by adjustment to R_F (around 800kΩ),

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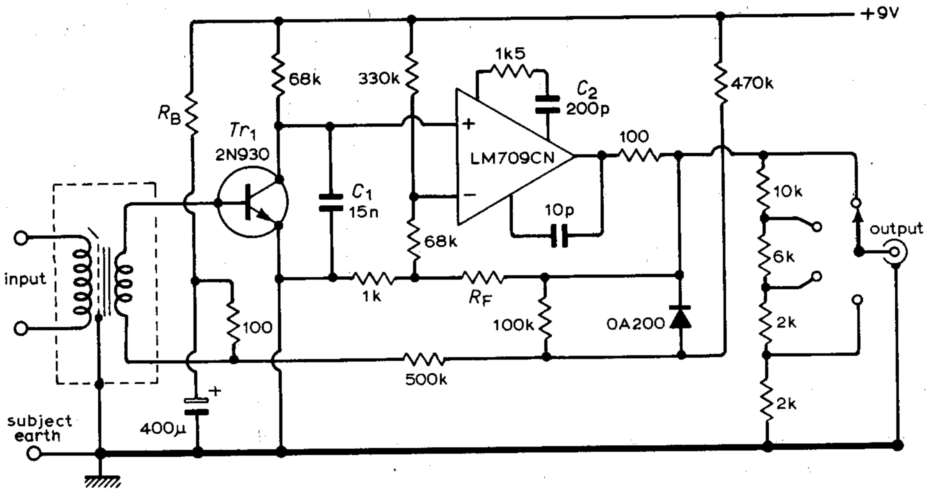

Fig. 1. The circuit of the muscle voltage amplifier.

Transformer type	Primary inductance	Primary resistance	Turns ratio	Secondary resistance	Primary-to-screen plus secondary capacitance
MSC 171	30H	1kΩ	2.5:1	500Ω	43pF (approx.)
DMSC 2443	2,000H	16kΩ	5:1	500Ω	280pF (approx.)

the local feedback resistor, to give a well defined 12dB/octave falling characteristic above the turnover frequency.

The amplifier output can handle a peak-to-peak excursion of 9V, and, with an overall voltage gain of 1,000, is unlikely to overload on the surface electromyogram during a strong muscular contraction.

The design is economical in battery loading. It consumes 1.75 and 1.65mA from the 9V positive and negative supplies, respectively. The two transformers (see table), originally designed by Fortiphone Ltd., are obtainable from Parmeko Ltd., Barking. The second type was produced to a specification by Mr. T. K. Cowell of St. Thomas' Hospital, London.

Electrodes

Metal electrodes made from 13mm diameter discs of thin silver sheet, preferably with a concave contour on the contact side, will give good results. A suitable form of electrode connection is a lightweight, insulated coaxially screened flex, the pair being lightly twisted together to minimize microphonic effects arising from lead movement. The screens should be connected to the amplifier earth and a third earth electrode may be necessary if mains hum interference is a nuisance. The skin needs only the simplest preparation; a few gentle scrapes with a fine abrasive paper will remove the top non-conducting layer. A small cottonwool pad soaked in common salt solution, or a blob of a proprietary gel* should be placed in the concavity. The electrodes may be held down with an adhesive tape.

*Obtainable from Smith and Nephew Ltd.

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