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FORCE FEEDBACK MICROPHONE

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INTRODUCTION

Capacitor microphone capsules usually use viscous damping to control the resonant behaviour of the diaphragm. The amount of damping is governed by the shape of the electrode and its distance from the diaphragm. An unwanted effect of the damping is to increase the self-noise of the microphone. Negative feedback can be used in place of viscous damping to give greater control over the resonant characteristic without increasing the self-noise of the capsule.

CAPSULE RESPONSES

Pressure-responding capsule

The diaphragm of a pressure-responding capsule is subjected to a force which is, at low frequencies (that is frequencies at which the wavelength of the sound is large compared with the dimensions of the capsule), independant of the frequency of the sound wave. If the diaphragm is compliance controlled then the displacement of the diaphragm is also independant of the frequency of the sound wave. To achieve compliance control the fundemental resonance of the diaphragm is placed above the audio range (25-30 kHz). The damping (approximately critical) is adjusted to compensate for the rise in pressure at high frequencies due to diffraction effects [1][2]. Higher resonant modes (drum modes) [3][4] are not significant as they occour at frequencies above the audio range and are smaller in amplitude than the fundemental resonance.

Pressure-difference capsule

The diaphragm of a pressure-difference (or gradient) microphone is subjected to a force which is, at low frequencies, proportional to the frequency of the sound wave. If the diaphragm is resistance controlled then the displacement of the diaphragm is inversely proportional to the frequency of the force, and thus independant of the frequency of the sound wave. To achieve resistance control the fundemental resonance of the diaphragm is placed in the logarithmic centre of the audio range (about 600Hz) and the diaphragm highly damped. In this case the higher resonant modes occour in the audio range but again are not important as they are highly damped. The rise in pressure at high frequencies due to diffraction effects can be compensated for by controlling the frequency at which the capsule changes from being resistance controlled to being mass controlled. This is achieved by control of the resonant frequency and the damping factor.

NEGATIVE FEEDBACK

The basics of negative feedback

If negative feedback is applied around a system, then, assuming the forward path gain is high compared with the desired closed loop gain, the system response is governed by the characteristics of the feedback path. A limit to the amount of feedback that can be applied is that the overall phase-shift must not be zero (or any multiple of 360°) when the gain around the loop reaches unity. To give an adequate phase-margin, the rate of change of loop-gain is usually restricted to 12 dB/octave.

Microphone capsule with negative feedback
If negative feedback were applied around a capsule then the capsule response would be dictated by the characteristics of the feedback path and not by the resonant behaviour of the diaphragm or any cavities present in the capsule. This assumes that the gain-reduction-factor is large which may not be the case with real capsules. If feedback were applied around a pressure difference capsule then the diaphragm could be left relatively undamped, the feedback then dictating the desired frequency response. This has two advantages; first, the mid-band output would not be reduced by damping but by feedback which also reduces the midband noise, and secondly, the broadband noise due to the damping would be reduced [5]. The same arguments apply to pressure capsules, although as the damping used is much smaller the gain in signal-to-noise ratio would not be so great.

PRACTICAL IMPLEMENTATION

So far, the output of the capsule has been assumed to be a displacement of the diaphragm and the input, whether from the incident sound or feedback, a force. In a real microphone capsule the output and feedback signals are more conveniently electrical voltages. The only convenient method of voltage-to-force conversion in the capsule is electrostatic. This is achieved by applying a varying voltage between the diaphragm and electrode or electrodes. Usual capacitor microphone capsules use the constant charge method to produce a voltage from the change in capacitance of the capsule. This is achieved by polarising the capsule through a large resistance (the corner frequency of the resistance and the capacitance of the capsule being below audio frequencies). This method cannot be used if the capsule has electrostatic feedback applied to it. A method commonly used to extend the low-frequency response of capsules is to use the change in capacitance to vary the frequency of an oscillator, thus producing an fm signal. This signal can then be changed to a voltage by demodulation. If the frequency of the oscillator is high compared with audio frequencies then the output and feedback signals are easily separated and further, because the output is an fm signal there should be no interaction.

Applying electrostatic feedback
If a voltage were applied across the plates of a parallel plate capacitor then the resutant force on the plates would be given by :

$$F = \frac{\varepsilon_0 A V^2}{2d^2} \qquad (1)$$

where A is the area of the plates, V is the voltage across the plates and d is the spacing of the plates.

It can be seen that the force would be inversly proportional to the square of the spacing. This is of little importance as the change in spacing is usually small and the action of the negative feedback would be to reduce this still further. The force would also be proportional to the square of the applied voltage and unless a square-root function were included the response would be highly non-linear. This is significant because this function lies in the feedback path and thus would dictate the closed-loop response of the capsule.

Balanced capsule. If a capsule were to have a central diaphragm flanked by equally spaced electrodes, the electrodes having equal and opposite voltages, then the equation for the resultant force would become:

$$F = \frac{\varepsilon_o A 2 V_p V_a}{2d^2} \qquad (2)$$

where V_p is the voltage on the diaphragm and V_a is the voltage on one electrode.

It can be seen that whilst the force would still be inversely proportional to the square of the spacing it would now be proportional to the voltage on the electrodes and not the square of the voltage. This would only be true if the two sides of the capsule were perfectly matched, but a small amount of mismatching could be compensated for by applying differing voltages to the two electrodes. Further advantages of using such a capsule configuration are that the diaphragm would be protected by the electrodes and the directional properties would be improved because of the front-back symmetry. It should be noted that polarising a capsule in this manner would actualy apply positive feedback as regards the diaphragm position. Thus if a slack diaphragm were subjected to a high polarising voltage, and the negative feedback was not operational, then the diaphragm would tend to move towards one or other electrode. Normally, however, the diaphragm is centred by the tension and this is reinforced by the negative feedback.

Frequency modulation

If the capacitance of the capsule were used, along with a fixed inductor, as the frequency determining elements of an oscillator then the frequency of oscillation would be given by:

$$f = \frac{1}{2\pi\sqrt{\{LC\}}} \qquad (3)$$

where f is the frequency, C is the capacitance of the capsule and L is value of the inductor.

It can be seen that the frequency would be inversely proportional to the square-root of the capacitance. This would at first appear to be a highly non-linear relationship, but it should be remembered that the change in capacitance is very small and so for a limited range the relationship would be approximately linear. Further, this function is in the forward path of the loop and as such the non-linearity would be reduced by the negative feedback (It should be remembered that the constant charge technique usually used gives an inverse relationship between capacitance and voltage). The frequency deviation, for a given diaphragm displacement, would be determined by the centre frequency of the oscillator; the higher the centre frequency the greater the deviation.

Frequency demodulation

Any low-noise, linear demodulator would be suitable, the operating frequency range does not have to match that of the oscillator as this can be shifted by mixing with a local-oscillator. An obvious choice would be to use a quadrature detector of the type used in band 2 fm receivers (distortion in these receivers is often caused by bad I.F. filter design and not by bad quadrature detector design).

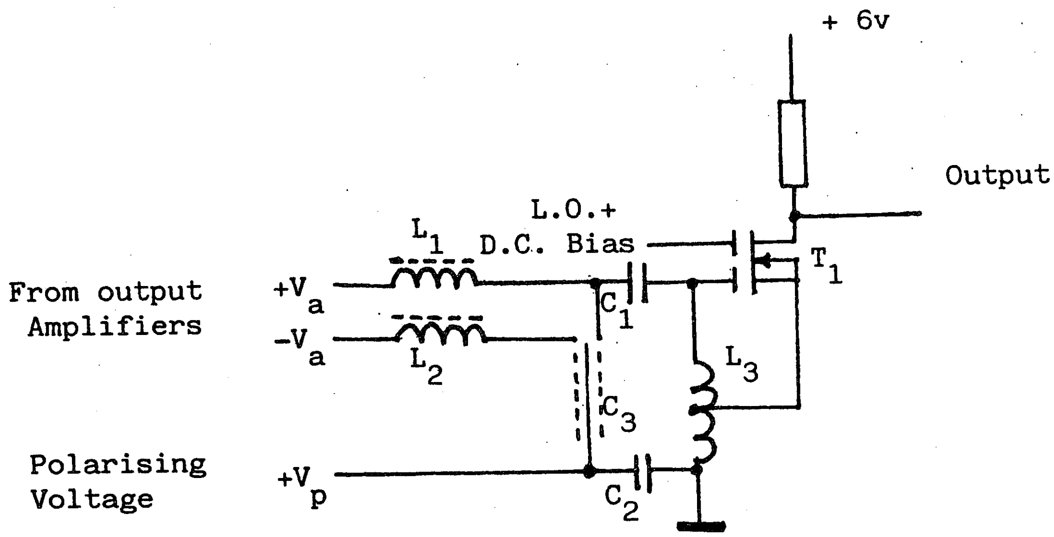
PROTOTYPE CAPSULE

It was decided to build a prototype pressure-difference capsule as this would better show the effects of applying negative feedback than a pressure capsule. As the capsule was to be a prototype, subject to changes in electrode size and shape, diaphragm-to-electrode spacing, and diaphragm tension, it was decided to use a method of construction which was quick and simple. The capsule was made in two parts with the diaphragm stretched and clamped between them. Each half consisted of a 30 mm diameter circular piece of epoxy-glass printed-circuit board. The copper pattern consisted of a central circular area, to act as the electrode, surrounded by a ring to act as the spacer. This ring was then covered with a number of layers of aluminium foil to achieve the desired diaphragm-to-electrode spacing (Typically 0.1 mm). A connection to the electrode was brought out through a gap in the spacing ring to a small lip on the edge of the board. Holes were drilled in the board inside the spacing ring to allow the diaphragm to be subject to the air pressure. The holes were made quite large so as to reduce the damping effect of the electrodes. Further holes were drilled through the spacing ring to allow the two halves to be bolted together. Care was taken to ensure that the number of holes through each electrode was the same so as to keep the areas equal. The diaphragm material was a metallised plastic film of the type used to cover model aircraft. Connection to the diaphragm was made through the aluminium spacing ring. Capsules had typical capacitances of 15-20 pF between each electrode and the diaphragm, the matching between the two sides usually being better than 10%.

The oscillator

To keep stray capacitances to a minimum it is desirable to mount the oscillator as close as possible to the capsule. To enable the oscillator to be kept physically small it should contain as few components as possible. A convenient frequency of oscillation was found to be 100-150 MHz. Available quadrature detectors operate at 10.7 MHz and so a mixer was also required to shift the frequency of the fm signal. It was found possible to combine mixer and oscillator functions by using a dual-gate mosfet in the Hartley configuration, the second gate being used as a mixer input. The circuit diagram is shown below:

Figure 1. Circuit diagram of the oscillator



The capacitor C_3 is the capsule, C_1 isolates the feedback signal V_a from the inductor L_3, C_2 isolates the polarising voltage V_p from ground, the inductor L_1 isolates the R.F. signal from V_a, L_2 is included to preserve symmetry.

The local oscillator frequency is set at 10.7 MHz higher than the main oscillator frequency. An output of about 0.5 volts peak-to-peak is available at the drain of T_1. This is then passed through a filter centred at 10.7 MHz, removing the higher frequency R.F. signals present, and on to the demodulator.

The demodulator

As previously mentioned a suitable demodulator is the quadrature detector. There are a wide number of I.F. integrated circuits available; the one used for the prototype was the low-noise HA12412 manufactered by Hitachi. To keep the distortion to a minimum the detector coil used was the double-tuned 12HF1037 manufactured by Toko. This ensures a high-amplitude audio output whilst maintaining good phase linearity over a wide bandwidth. The circuit used was taken from the manufactures application notes and so is not reproduced here.

The feedback path

The differentiator. As the prototype capsule was of the pressure-difference type the closed-loop response should be inversely proportional to the frequency of the applied force. Thus the feedback path should have a response which is proportional to the frequency of its input. A differentiator has this response but these are difficult to make to cover the desired frequency range. It was decided to roll-off the response at 10 Hz and 100 kHz and to split the circuit into two parts. This limits the amount of gain necessary in the operational amplifiers used. The first stage was made to have a response which rose at 20 dB a decade between 10 Hz and 1 kHz, and the second stage a response which rose at the same rate between 1 kHz and 100 kHz. The operational amplifiers used were the high-frequency, low-noise OP-37. The output from the differentiator was passed to a simple phase splitter, again using an operational amplifier, and thence to the output amplifiers.

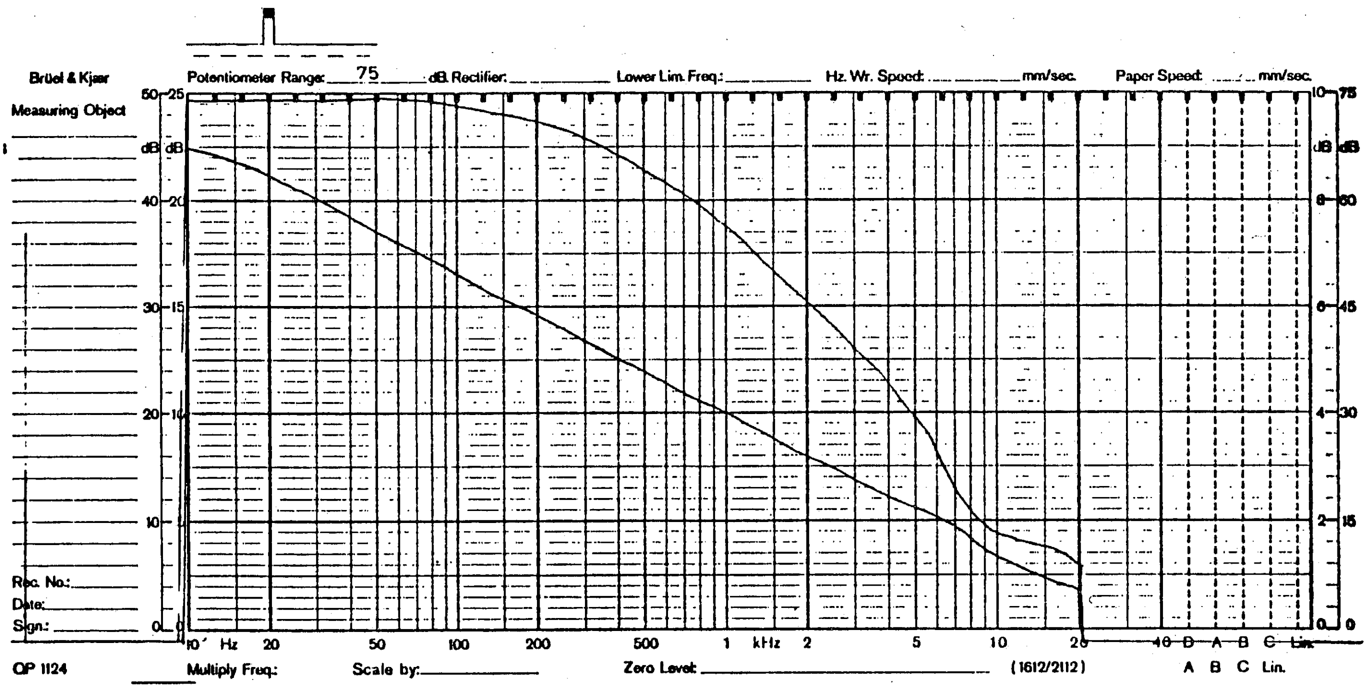
The output amplifiers. These were constructed from discrete components as no suitable high-voltage, high-frequency operational amplifiers were available. The amplifiers were in the class-A configuration and were powered from positive and negative 25 volt supplies. The positive 25 volt supply was also used to polarise the diaphragm. To enable the capsule to be used at higher sound-pressure levels these supplies would have to be increased to a maximum of about 200 volts. This was not deemed necessary in the prototype as this was only intended to demonstrate the principle of negative feedback as applied to microphone capsules. The outputs of the amplifiers were connected to the capsule as shown in figure 1.

EXPERIMENTAL RESULTS

Frequency response

Rather than place the microphone in a sound field, initial tests were performed using electrostatic excitation. This does not take account of how the sound field is effected by the capsule or of the fact that the capsule responds to pressure-difference and not pressure or force. The output of the signal generator was added to the output of the differentiator and thus fed through the phase-splitter and output amplifiers to the electrodes. The system-output was taken from the output of the demodulator. Open-loop measurements were made by breaking the loop between the demodulator output and the differentiator input. The response of a pressure-difference capsule when subjected to a force input should be inversely proportional to the frequency of that input, and so the desired response will fall with frequency at the rate of 20 dB a decade. The prototype capsule used for the tests had a diaphragm-to-electrode spacing of only 0.03 mm and so was significantly damped before feedback was applied. The resonant frequency of the diaphragm was about 500 Hz. In the figure below the upper trace shows the output with the capsule open-loop, and the lower trace after the addition of negative feedback.

Figure 2. Response of prototype capsule with and without negative feedback



It can be seen from figure 2 that the capsule response without negative feedback is compliance controlled below 100 Hz, resistance controlled around 500 Hz, and mass controlled above 1.5 kHz. There is also a 'suck-out' at about 8 kHz. Once negative feedback has been applied the response has the desired 20 dB a decade roll-off over the range 20 Hz to 20 kHz. Below 20 Hz the response flattens off as dictated by the 10 Hz corner frequency of the differentiator in the feedback path. At about 7 kHz there is a slight rise in the response, this is caused by the loop phase approaching 360° at the 'suck-out', and could be compensated in the forward path.

Capsule self-noise

At the time of writing no rigorous tests had been performed to measure the self-noise of the capsule, but listening tests showed it to be at least as good as standard capacitor microphones.

CONCLUDING REMARKS

The initial aim of the work was to realise the potential advantages of using feedback to control the response of a capacitor microphone having little mechanical damping. Experimental results have shown that the concept can be implemented practically, but, because of the limited gain-reduction-factor available, this does not mean that bad capsules can be made good. It should always be the aim when using negative feedback to make a good system better. In this case, because of the way in which the feedback was applied, a prototype capsule was required and this was obviously not up to the standards of professional capacitor microphone capsules. Recent work [6] has shown that there are many factors, for example electrode size, which effect the response of the capsule, and these must be taken into consideration for any type of capsule whether controlled by feedback or by more conventional means.

ACKNOWLEDGEMENT

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