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ACTIVE ELECTRONIC CONTROL OF THE RESPONSE OF A SONAR TRANSDUCER

G.A. Steel (1), B.K. Gazey (2) and B.V. Smith (2)

(1) Marconi Underwater Systems Ltd.
(2) Dept. of Electronic and Electrical Eng., University of Birmingham.

SYNOPSIS

This paper will describe a composite transducer structure which comprises two ceramics and matching and backing layers. One ceramic is the drive ceramic and the other is a control ceramic. Two methods of electronic control, passive and active, are examined. In the passive method the control ceramic is loaded with passive electrical components. In the active method pre-determined voltages are supplied to the control ceramic.

A transducer will be described whose resonant frequency is tunable from 250 kHz to 700 kHz. It is shown that the active method of control gives superior results.

INTRODUCTION

A tunable transducer has been described [1] which operates in air over a frequency range of about 1½ octaves. The structure contains both active and passively loaded ceramic layers. In a recent paper [2] the authors have applied a similar technique to a transducer operating in water at around 500 kHz. This transducer was found to have very low efficiency at some frequencies.

The present paper describes an improved design in which a quarter-wave matching layer is included. The transducer contains two ceramics bonded together. One ceramic, termed the drive ceramic, is connected to a voltage source. The other, termed the control ceramic, has inductive or capacitive electrical loads which determine the resonant frequency. The same transducer can be controlled actively using a second voltage source in place of a passive load.

DETAILS OF TRANSDUCER CONSTRUCTION

The transducer used for this investigation is shown in figure 1. It contains two 50 mm diameter PZT-4 discs and was constructed as follows:

1. Small sections of both ceramics were removed using an ultrasonic cutter.

2. The pair of ceramics were bonded with epoxy-resin and connected to a screened twisted-pair cable as shown in figure 1.

3. The control ceramic was bonded to a composite back of stycast/pulverised fuel ash (fillite) contained in a tufnol tube. This backing has a low impedance of 1.7 MRayls and a high absorption of 5.5 dB/cm at 500 kHz.

4. A 30° cone was cut into the back of the transducer to eliminate standing waves.

5. An epoxy/iron composite of impedance 7.1MRayls was added at the sides of the ceramic to reduce the amplitude of planar vibrations.

6. The stycast/magnesium layer was then added, cured and machined to a thickness of 2 mm (= $\lambda/4$ at 470 kHz). This layer has an impedance of 5.7 MRayls.

7. A thin layer of varnish was sprayed onto the front of the transducer to prevent corrosion of the magnesium.

PASSIVE CONTROL

The total ceramic thickness is 8.5 mm which gives a fundamental thickness resonance at 250 kHz and a third harmonic at 755 kHz. If a voltage source is connected only across the drive ceramic, with the control ceramic open-circuit, then an additional resonance appears at 524 kHz and this can be regarded as the second harmonic of the ceramic pair. Replacing the open-circuit by a short-circuit reduces the second harmonic to 462 kHz but has little effect on the other resonances.

A variable capacitor placed across the control ceramic allows continuous variation of the second harmonic from 462 kHz to 524 kHz. However the front matching layer causes all resonances in this range to have very low Q so the change in centre frequency is small compared with the bandwidth.

Of greater interest is the effect of inductive loads. A very small inductor is approximately a short-circuit so produces a resonance at 462 kHz. Increasing the inductance causes this second harmonic to reduce in frequency tending towards 250 kHz, and third harmonic reduces towards 524 kHz. (The fundamental also decreases in frequency, tending towards zero, but conductance becomes too low to be of practical significance.)

In this way passive control can be used to produce a resonance at any frequency from 250 kHz to 755 kHz. As an example figure 2a shows measured resonances of the transducer in water with various inductive loads. Most peaks have a Q around 12.

A detailed theoretical analysis of this structure was carried out using Mason's equivalent circuit [3]. This is a one-dimensional model and assumes that the ceramics have large diameter in wavelengths or are laterally clamped, so that only thickness mode vibrations need be considered. This analysis reveals two important design conditions:

1. The bond thickness between ceramics must be less than $\lambda/100$ for satisfactory performance. The third harmonic frequency is strongly dependent on bond thickness and the measured figure of 755 kHz corresponds to 26 μm. This is approximately $\lambda/100$ and therefore just acceptable.

2. All inductors have losses which can be represented in terms of series resistance. For satisfactory performance this must be less than 10 ohms.

The dotted line on figure 2a shows the predicted envelope of the resonant peaks for inductors with series resistance of 4 ohms. In practice all inductors had less than 4 ohms series resistance but give lower conductance than predicted. The difference is explained by lateral displacement of the ceramic which causes greater acoustic loading than predicted by a one-dimensional analysis. This effect is most significant at low frequencies where the ceramics have small diameter in wavelengths.

When a continuous-wave signal is applied to the drive ceramic a voltage appears across the control ceramic. This output voltage depends on the passive electrical load. For some inductive loads the output can be greater than the input voltage. An example is given figure 3 which shows predicted and measured results for a passive load of 32 μH + 4 ohms. Voltage maxima occur at each resonant frequency but amplitudes are significantly lower than predicted. Again this can be explained by the effects of lateral displacement. Predicted and measured phase shifts show close agreement and it is interesting to note that at resonance the phase shift is ± 90°.

ACTIVE CONTROL

Inductive or capacitive loading of the control ceramic produces variations in the reactive part of the acoustic impedance seen on the back of the drive ceramic. Hence allowing variations in resonant frequency. An alternative method for controlling resonant frequency is to replace the passive electrical load by a second voltage source (4). The amplitude and phase required for this control voltage can be deduced from the substitution theorem (5), which states that "A known voltage in a circuit can be replaced by an ideal current source". Therefore any passive electrical load can be simulated actively by applying a voltage of the same amplitude and phase as would be measured across that load. It follows that all voltages and currents in the equivalent circuit, and therefore all predicted forces and velocities in the transducer structure, are identical for the active and passive cases.

For example to simulate a passive load of 32 μH + 4 ohms by active control simply apply a voltage of amplitudes and phase shown in figure 3. This produces resonances at 215 kHz (fundamental), 400 kHz (2nd harmonic), 615 kHz (3rd harmonic) and 770 kHz (4th harmonic).

Continuous variation of resonant frequency by passive control requires a variable inductor. To achieve the correct inductance as a function of frequency presents considerable problems but figure 4 shows the predicted output voltage which would be measured across it. Using these values for amplitude and phase allows continuous variation of resonant frequency by active control, which is easier in practice.

Figure 2b shows the transducer performance with active control. Simulation of fixed passive loads produces clearly defined resonances while simulation of a variable load produces a conductance which follows the envelope of the resonant peaks. The required control voltages were applied using a digital technique, hence the stepped appearance of the results. The passive loads simulated in this test include a small frequency-dependent resistance which gives predicted conductance maxima of around 7 mS. These loads are given in table 1. The predicted envelope (dotted line) on figure 2b is therefore slightly different to the predicted envelope on figure 2a, which was plotted for a fixed series resistance of 4 ohms.

It can be seen that active control produces results which are closer to predictions than passive control. This is because active control constrains both ceramics to vibrate according to the applied voltage but passive loads leave the control ceramic unconstrained.

Inductance μH	Resistance ohms	Resonant Frequency kHz
120	11	270
81	7	309
50	5	365
28	1	415
0	0	462
40	13	586
31	8	618
21	5	687
13	9	739

Table 1.

PRESSURE OUTPUT AND EFFICIENCY

At 470 kHz the control ceramic is $\lambda/2$ thick and therefore acoustically transparent. The front matching layer presents a high impedance compared with the backing so input power delivered to the drive ceramic goes mostly to the water load. Predicted efficiency is about 70% at this frequency.

When inductive loads are used to produce resonances at other frequencies there is significant loss of power in the associated series resistance. Zero series resistance gives predicted efficiency close to 100% since the backing becomes purely reactive and absorbs no power. Predictions for the more realistic case of 4 ohms are given in figure 5.

If active control is used to simulate an inductor with series resistance then the control ceramic has negative input conductance. In this case power is delivered from the drive amplifier to the control amplifier via the two ceramics. It follows from the substitution theorem that this power is the same as would be dissipated in the load being simulated. Therefore pressure and efficiency predictions in figure 5 apply equally to active and passive control.

A radiation balance was used to measure the output pressure from the transducer and results are shown by error bars in figure 5. Passive control gives output pressure of less than half the predicted value at some frequencies and efficiency falls to less than 20%. Results with active control are closer to predictions and show efficiency of about 50% at most frequencies.

This test was intended as a direct comparison between active and passive control so 4 ohms series resistance was included in both cases. For passive control it is hard to reduce the resistance much below this value but for active control zero series resistance can be simulated with no difficulty. Therefore in practice active control allows efficiency values significantly higher than shown in figure 5.

CONCLUSION

The transducer described in this paper is suitable for both passive and active control in the frequency range 250 kHz to 755 kHz, approximately $1\frac{1}{2}$ octaves. Passive control requires a variable inductor with complicated frequency dependence. This may be hard to achieve in practice and the associated resistive loss causes low overall efficiency. For most applications active control is preferable as higher efficiency can be achieved with simpler control electronics.

ACKNOWLEDGEMENTS

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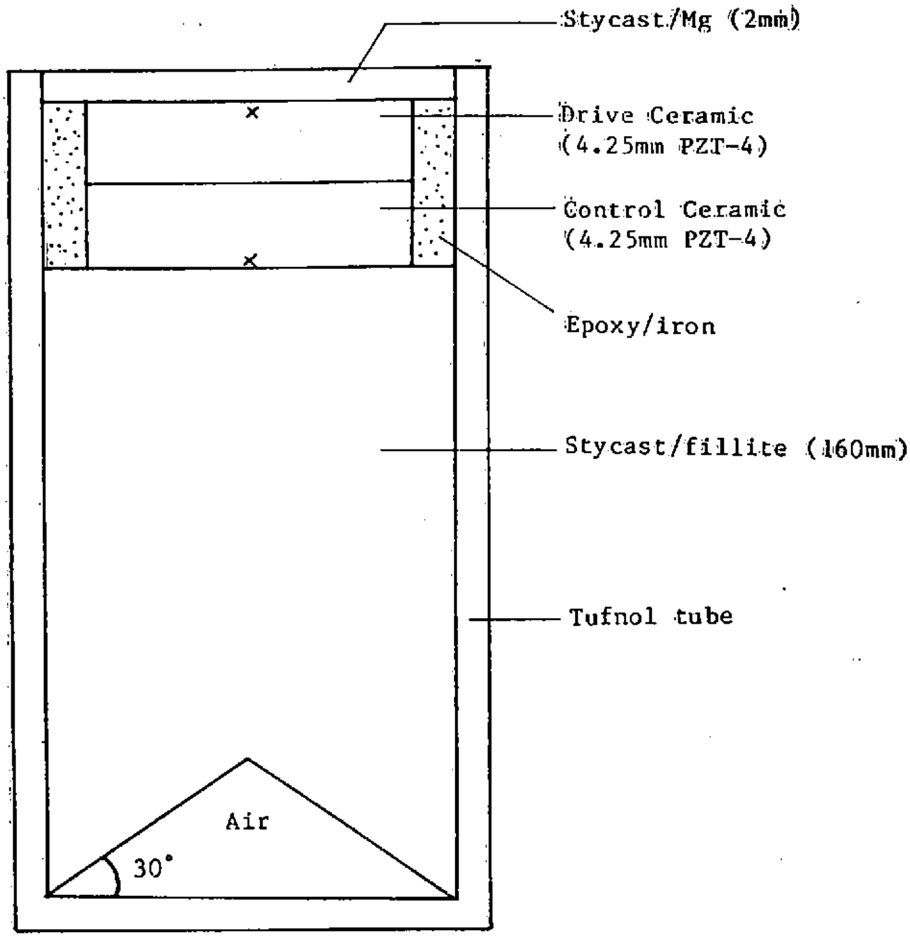
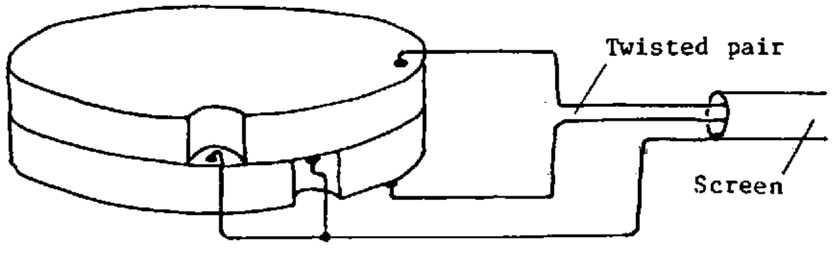


Figure 1 (a) Cross section of transducer

(b) Details of ceramic connections



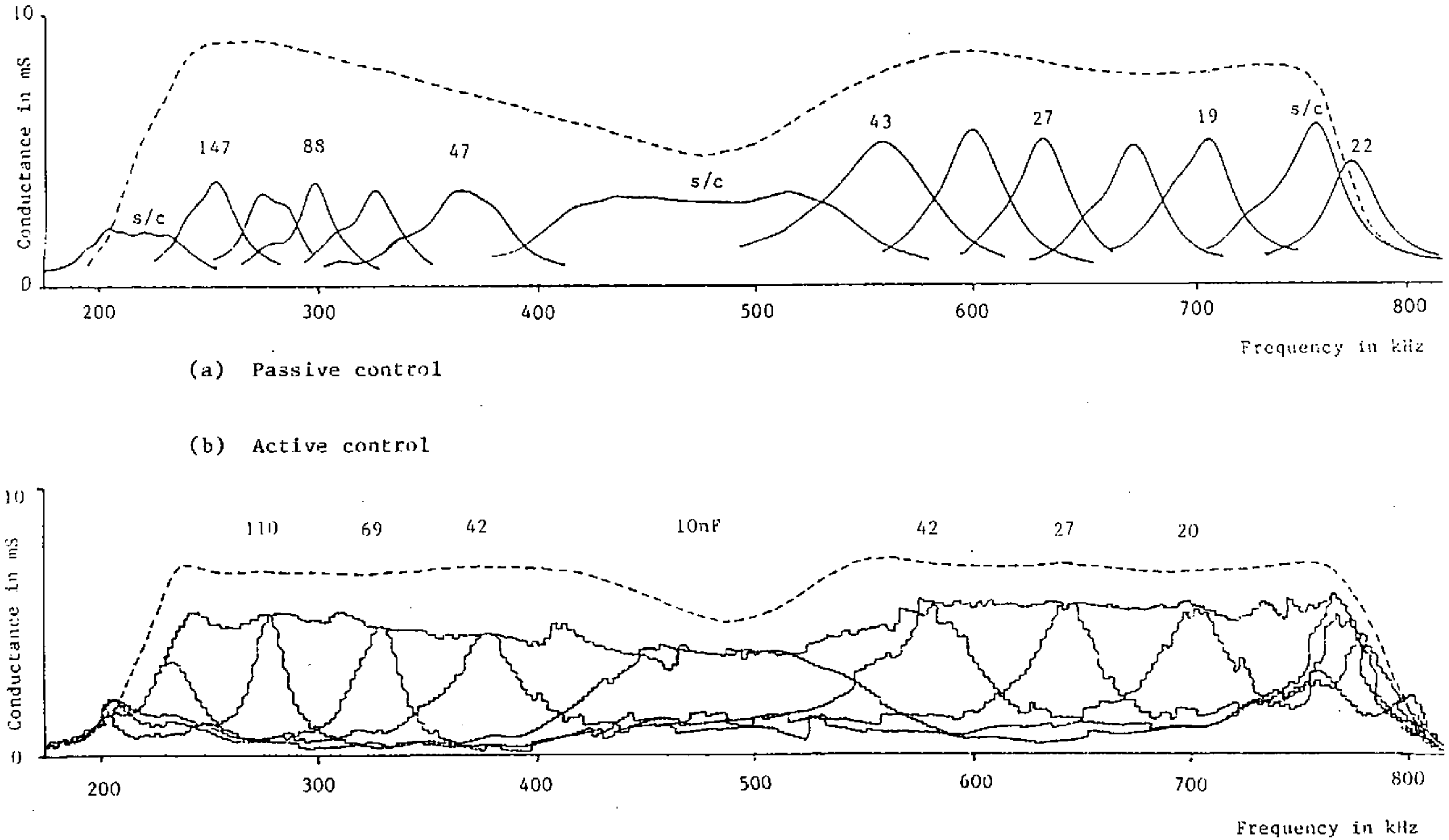


Figure 2   Transducer conductance measurements in water. Dotted lines show predicted envelopes and figures above curves are inductance values in μH.

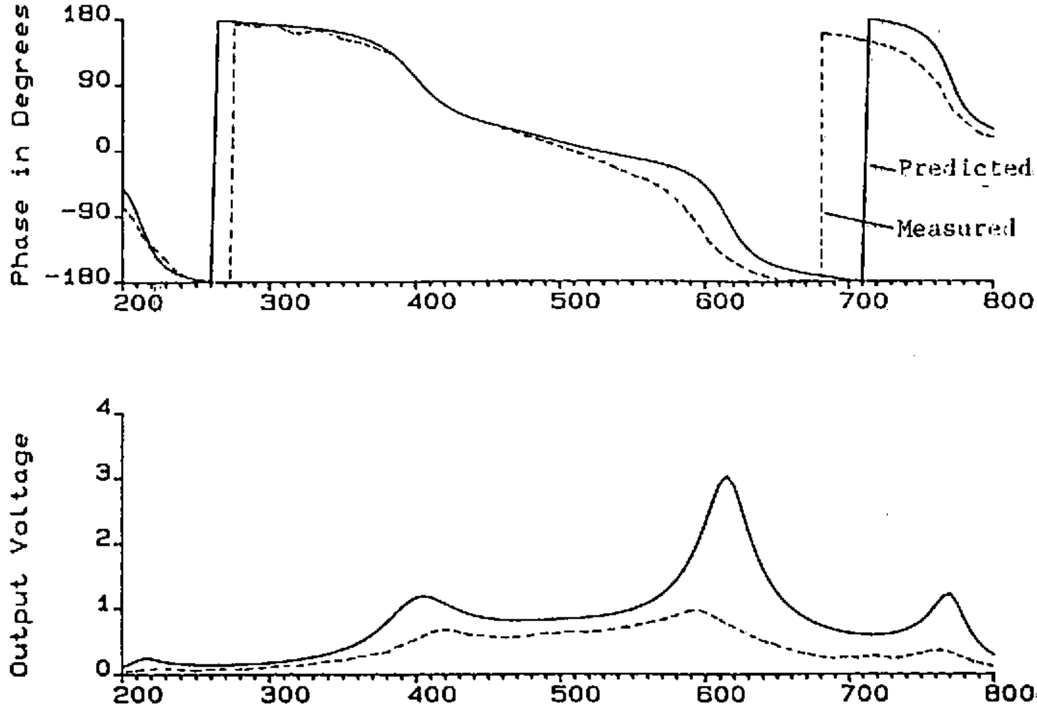
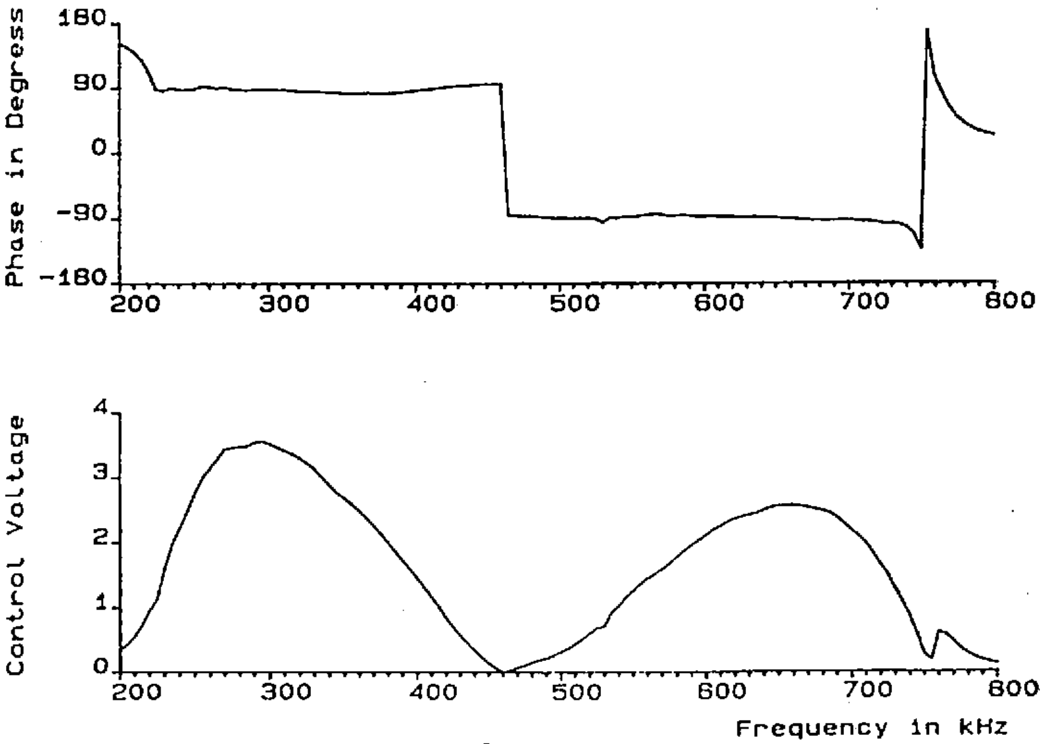


Figure 3 Voltage output across $32\mu H + 4\Omega$ load.

Figure 4 Voltage output across variable passive load.



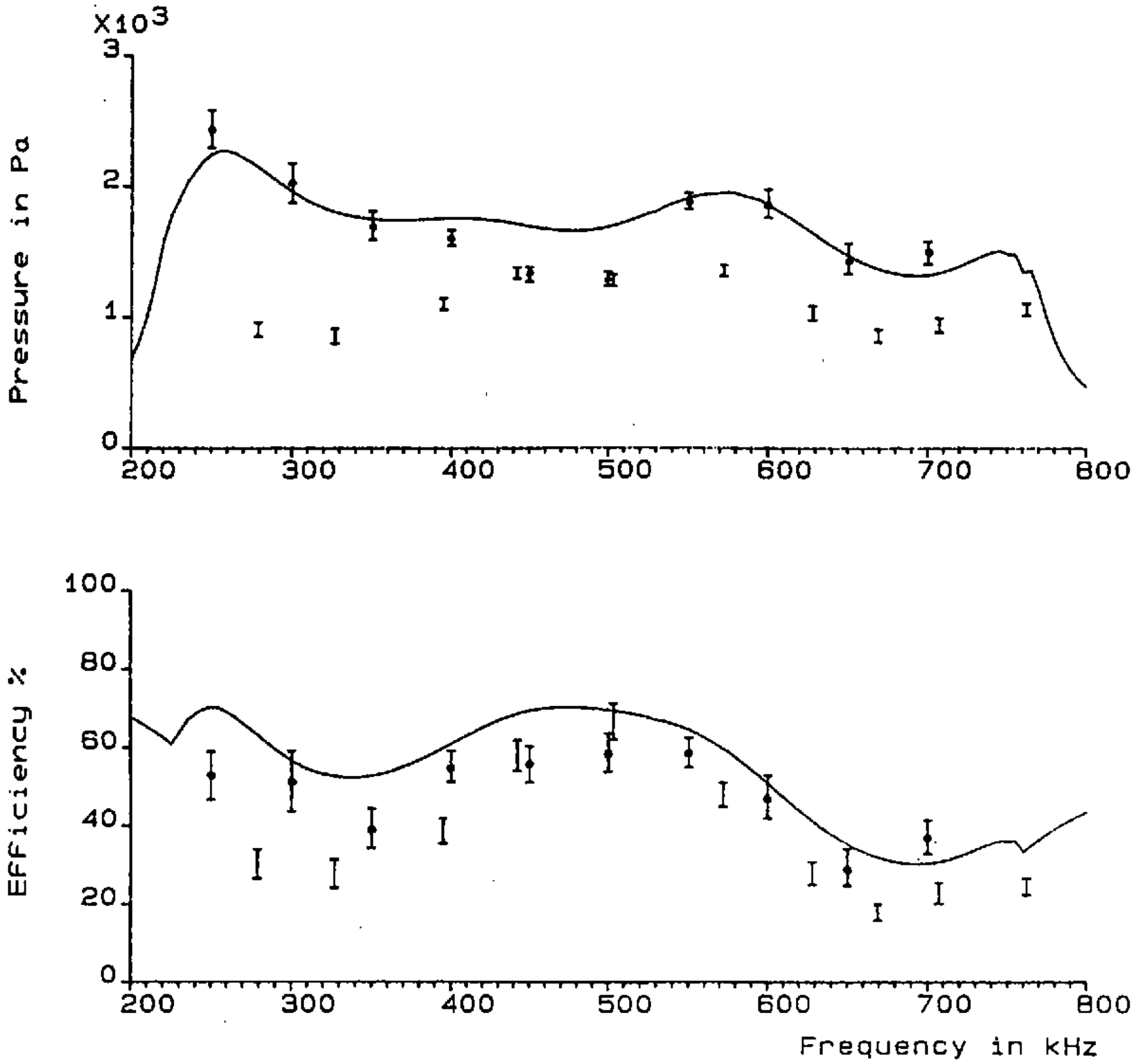


Figure 5 Pressure output and efficiency

Predicted for 4Ω series resistance	——
Measured with active control	⫯
Measured with passive control	I