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A STUDY OF SOUND GENERATION USING ELECTRO-PNEUMATIC SOURCES

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1. INTRODUCTION

Applications of active noise control to low frequency gas turbine and diesel engine exhause noise have highlighted the need for a robust high intensity acoustic source for use as a secondary source. An a.n.c. system was installed by Swinbanks [1] on the exhuast duct of an 11 MW gas turbine compressor. The secondary source consisted of an array of seventy-two 15" moving coil loudspeakers. These are bulky and have to withstand the harsh environment of a gas turbine exhaust duct, i.e. typical gas temperatures of 450^{o}C and velocities of 60 ms^{-1}. Croker [2] installed an a.n.c. system on a diesel engine exhaust stack, again using an array of loudspeakers as the secondary source. He cites the shortcomings of the loudspeakers as the main barrier to a practicable system. Transducers have been developed which produce high intensity acoustic output by modulating an airflow; these are used in warning systems and in acoustic fatigue testing of structures. To be suitable for use in an a.n.c. system the transducer must produce an acoustic output linearity related to the input. The designs most likely to fulfil this criterion use either electro-hydraullic or electro-dynamic exciters to control the relative motion of a pair of slotted plates through which the airstream is passed. The latter are known as electro-pneumatic tranducers (e.p.t's). Hydraullic systems are expensive and bulky, and thus electro-dynamic control of the airflow offers the greatest promise.

In general these devices are aimed solely at producing very high acoustic power outputs (for example 4 - 200 kW) and little data is published on their linearity or harmonic distortion. These aspects of their performance require further investigation. The object of the current work is to determine experimentally whether the acoustic field produced by a sinusoidal modulation of airflow is equivalent to that produced by a source with a sinusoidal variation in volume velocity. Further, the relationship needs to be established between the volume velocity variation produced and the fluctuating gas flow through the valve.

2. REVIEW OF EXISTING TRANSDUCER DESIGN

High intensity electro-pneumatic transducers have been commercially available since the 1950's and there has been little new development in their design since this time. A typical design is shown in figure 1. Air modulation is achieved using a sleeve valve in the form of two concentric cylinders, each with slots around their circumference. The inner cylinder is stationary whilst the outer sleeve is supported on a synthetic flexure and carries a driver coil, which lies between the poles of a large permanent magnet. In the quiescent state, the slots are aligned so that half the total port area is exposed. When the signal voltage is applied to the coil, the outer sleeve reciprocates, opening and closing the ports. The filtered air flowing inwards from the plenum chamber to the throat of the transducer is thus modulated, producing pressure perturbations downstream of the valve which are propagated as acoustic waves. Part of the airstream is directed past the coil to aid cooling.

Provided that the inlet flow in the plenum chamber is symmetrical, the sleeve valve is radially balanced. The valve is mounted so that there is no contact between the stator and the outer sleeve which eliminates friction. Hence the motion of the sleeve is more likely to correspond to the input signal, and also a low force coil can be used. The annular form of the outer sleeve means that pressure loading results solely in a circumferential compression with minimal change in valve clearance. The inherent strength of this design allows the mass and thickness of the sleeve to be kept low. The acoustic power output of the e.p.t. is approximately proportional to the swept valve area [3]; increasing valve area means increased reciprocating mass. The minimum slot width, (in the order of 1 mm) is fixed by fluid dynamic considerations and hence to obtain full modulation with the same bandwidth the driver coil force must be increased, along with the efficiency of its cooling system. This has been achieved by one manufacturer using an inductive drive system, cooled by internal water galleries and a water spray. Although this is robust and eliminates flexible leads it is complex and costly

The e.p.t. design shown in figure 1 has a number of shortcomings. When the slot is partly open the flow through the port results in a pressure difference between either side of the slot and the net force acts to close the valve; this is illustrated in figure 3. The magnitude of this force will vary with valve opening position, being largest when the valve is barely open, and reducing to zero as the valve becomes fully open. This non linearity, which is present on all designs using slots to achieve modulation, will affect the acoustic output and must be compensated for using either electrical or mechanical means. One manufacturer attempted to achieve this by the use of a bias valve, shown in figure 1. However this only allows the setting of the outer sleeve mean position and the force variation during the modulation cycle will still occur. Another problem with the tranducer is scuffing of the valve surfaces caused by misalignment of the outer sleeve. Manufacturers have attempted to reduce friction and resultant wear by coating the valve face with glass filled PTFE. Wear of the sleeve valve will mean increased clearance and hence increased leakage flow when the valve is in the closed position. This reduces the effective modulation of the flow and consequently the acoustic efficiency of the transducer. A similar increase in leakage flow would arise from expansion of the outer sleeve and this design may not work efficiently at high temperatures, for example in a gas turbine exhaust duct.

A further problem with the sleeve design is that flow is rotated through ninety degrees within the valve which reduces the fluid dynamic efficiency of the device.

3. EXPERIMENTAL ELECTRO-PNEUMATIC TRANSDUCERS

An experimental e.p.t. illustrated in figure 2 has been constructed in order to perform a detailed investigation of the operation of this type of transducer.

Air flow is modulated using two slotted plates. The upper plate is driven by an electro-dynamic vibrator and is supported laterally and vertically by aerostatic bearings. The slots are rebated into a circular hole in the centre plate, thus minimising their side area and hence the axial imbalance resulting from the pressure difference on either side of the slot. The slots in the lower plate are machined in a removable insert into which is incorporated the throat of the transducer. This arrangement allows the slot geometry to be altered without changing the bearing block. The block and the vibrator are mounted on a baseplate over which fits a plenum chamber. The vibrator is reverse cooled using plenum pressure.

The use of a aerostatic bearing has several advantages: there is no surface contact, it has a high load capacity, and frictional forces are negligible. The clearance is low (12 μm) which will reduce leakage flow in the tranducer. Clearance is measured using a pair of capacitance transducers mounted above the sliding plate and is controlled with the air bearing supply pressure.

The initial slot width was set at 1mm; full modulation of the flow can be achieved with this slot width up to 160 Hz. A miniature accelometer attached to the sliding plate is used to monitor displacement and thus the degree of flow modulation.

4. EXPERIMENTAL PROCEDURE AND PRELIMINARY RESULTS

The transducer was mounted on a duct 110 mm in diameter and 2 metres in length, as illustrated in figure 4(a). For a series of pure tone input signals in the range 0-200 Hz, simultaneous measurements were made of valve displacement and acoustic pressure; these were analysed using a 2 channel digital signal processor. The plenum pressure was maintained at 246 kPa for all measurements. It was initially found that for complete modulations of the flow, the acoustic signal measured in the duct showed significant harmonic distortion. This was thought to be caused by a combination of distortion at high sound pressure levels (approximately 165 dB) due to non-linear propagation,and overshooting of the valve as a result of misalignment. The latter may have been caused by the slot pressure difference referred to in section 2. For plane waves, the non linear distortion of the wave form, begins to become appreciable at sound pressure levels in excess of 118 dB [4]. By taking measurements using a range of small valve displacements (4-14% of slot width) maximum sound pressure levels of the order of 140 dB were produced and the overshoot of the valve was eliminated. Typical spectra of valve displacement and sound pressure are shown in figures 6a and 6b.

In order to obtain data for input frequencies corresponding to duct resonance or anti-resonance two duct lengths were used and measurements made in the frequency ranges between resonances and anti-resonances. The duct input impedances were determined experimentally (shown in figure 4b) by driving the ducts with loudlimited white noise(0-500 Hz)via a loudspeaker and dividing the instaneous acoustic pressure in the duct by the product of the velocity and area of the speaker cone. The impedances are given in figure 5.

Dividing the modulus of the duct acoustic pressure obtained with the e.p.t., by the modulus of the duct impedance at the same frequency gives the equivalent modulus of the volume velocity of the tranducer. Figure 7 is a plot of this against valve displacement for a range of frequencies. It shows that there is almost an exact linear relationship between displacement and acoustic volume velocity. During the experiments, the pressure ratio across the valve was greater than critical. In this condition gas volume flow is directly proportional to the orifice area. Hence it has been demonstrated that for small valve displacements there is a linear relationship between the acoustic volume velocity of the source and the volume flow through the valve. It can be seen from figure 7 that there are slight frequency dependent variations from the relationship and these have yet to be investigated. A theoretical model of the valve is now being developed which may help to explain these departures.

5. CONCLUSIONS

The acoustic field produced by small amplitude sinusoidal modulation of an airflow is equivalent to that produced by a source with a sinusoidal variation in volume velocity.

Further work is required to determine the range of valve operating parameters over which this relationship holds.

REFERENCES

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[2] M.D. Crocker, 'The active control of internal combustion engine exhaust noise', Proc. Inter-noise, (1983).
[3] W.A. Meyer, 'Theoretical analysis of the performance of an air-modulated speaker', J.A.S.A. 45, 4, (1969).
[4] White & Walker, 'Noise and Vibration', Ellis Horwood, (1982).

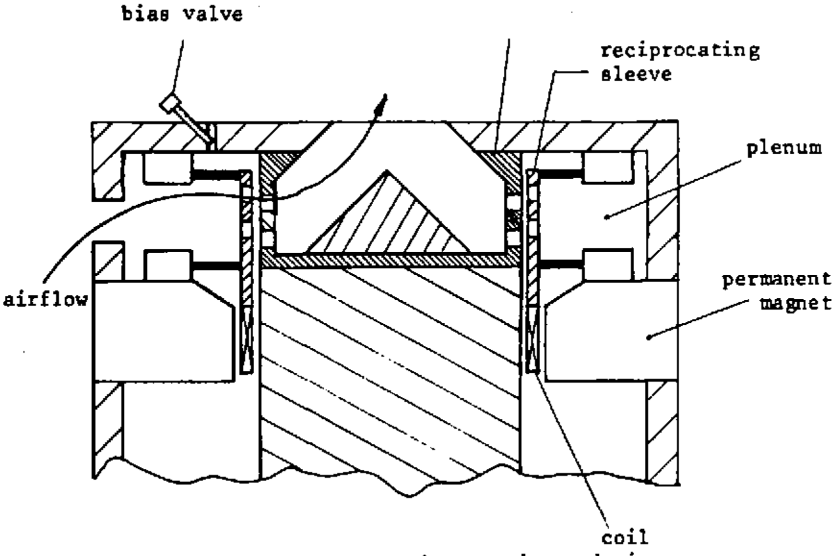

Figure 1: Typical electro-pneumatic transducer design

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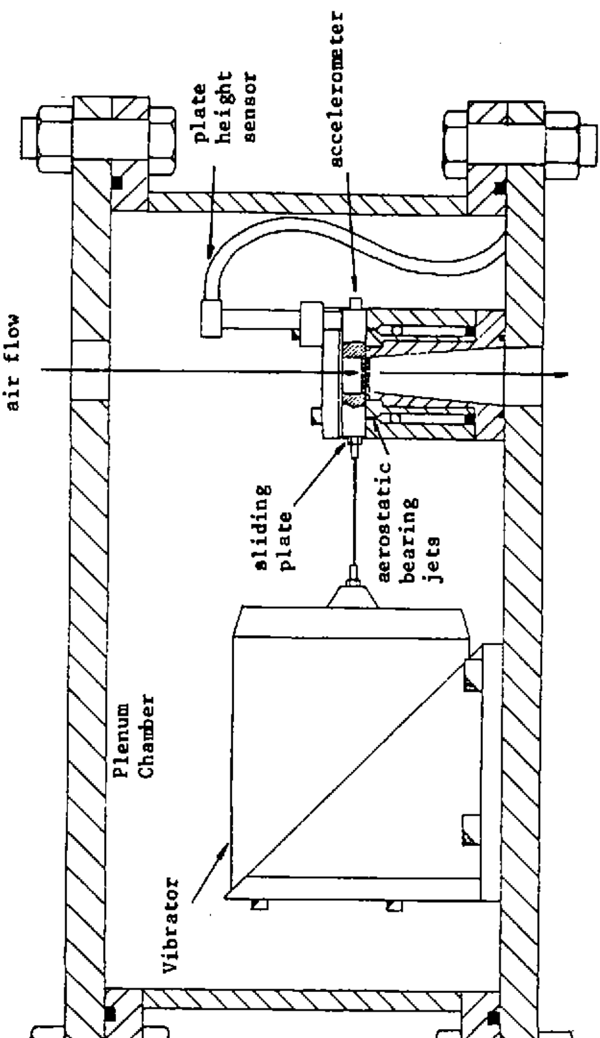

Figure 2: Experimental electro-pneumatic transducer

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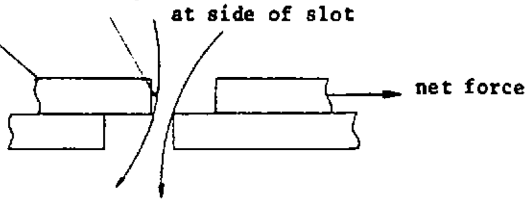

Figure 3: Airflow through slot.

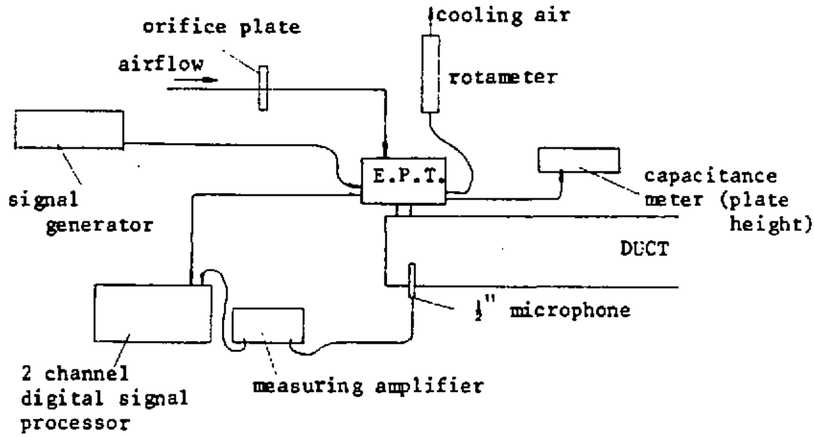

Figure 4a: Electro-pneumatic transducer installation

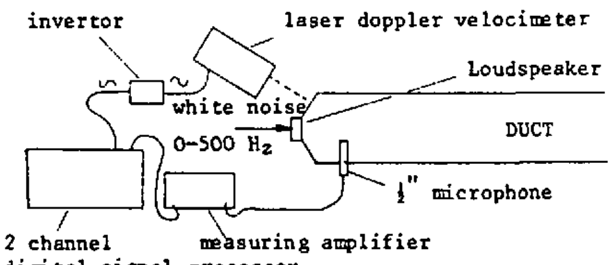

Figure 4B: Duct Impedance Measurement

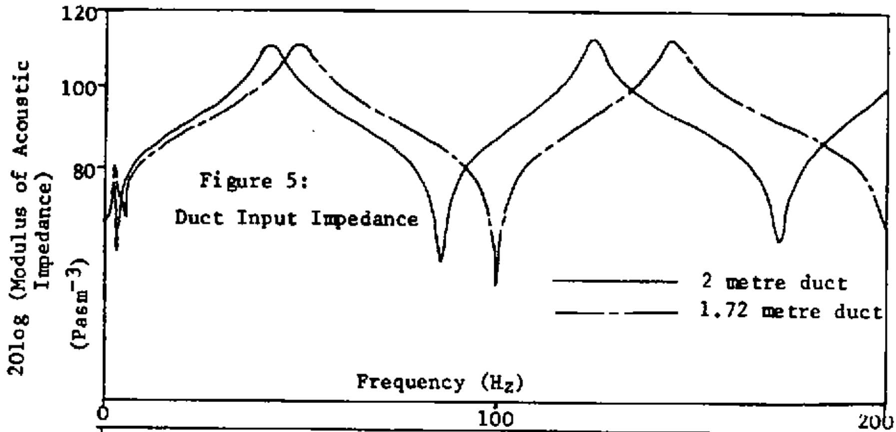

Figure 5: Duct Input Impedance

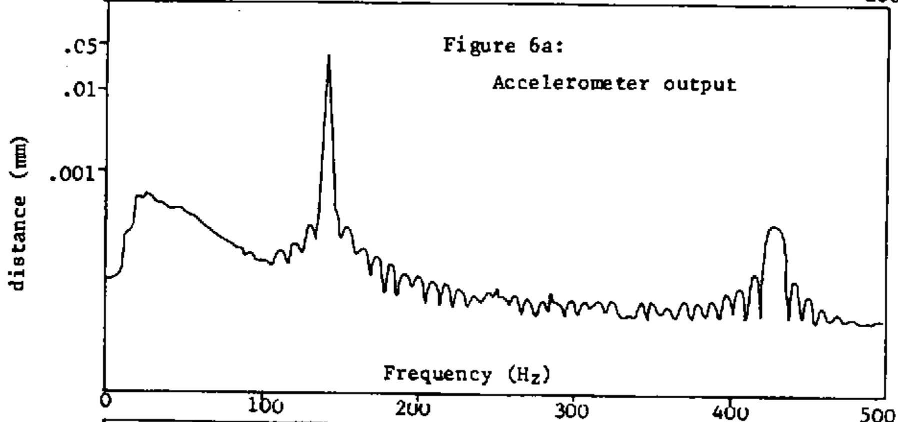

Figure 6a: Accelerometer output

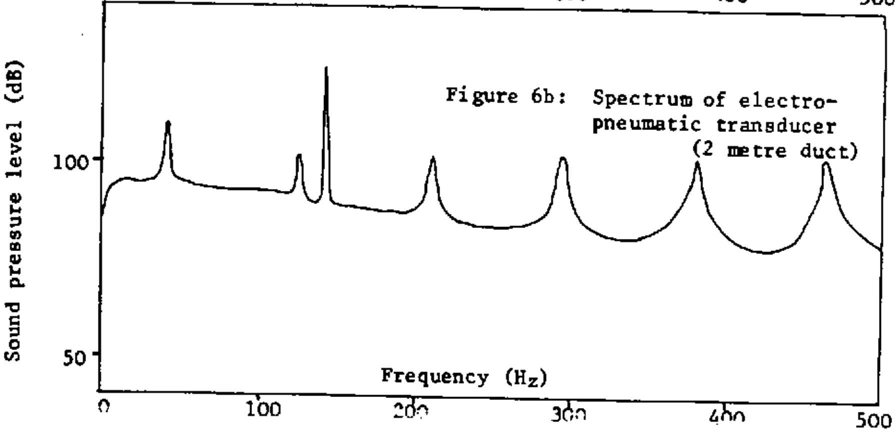

Figure 6b: Spectrum of electro-pneumatic transducer (2 metre duct)

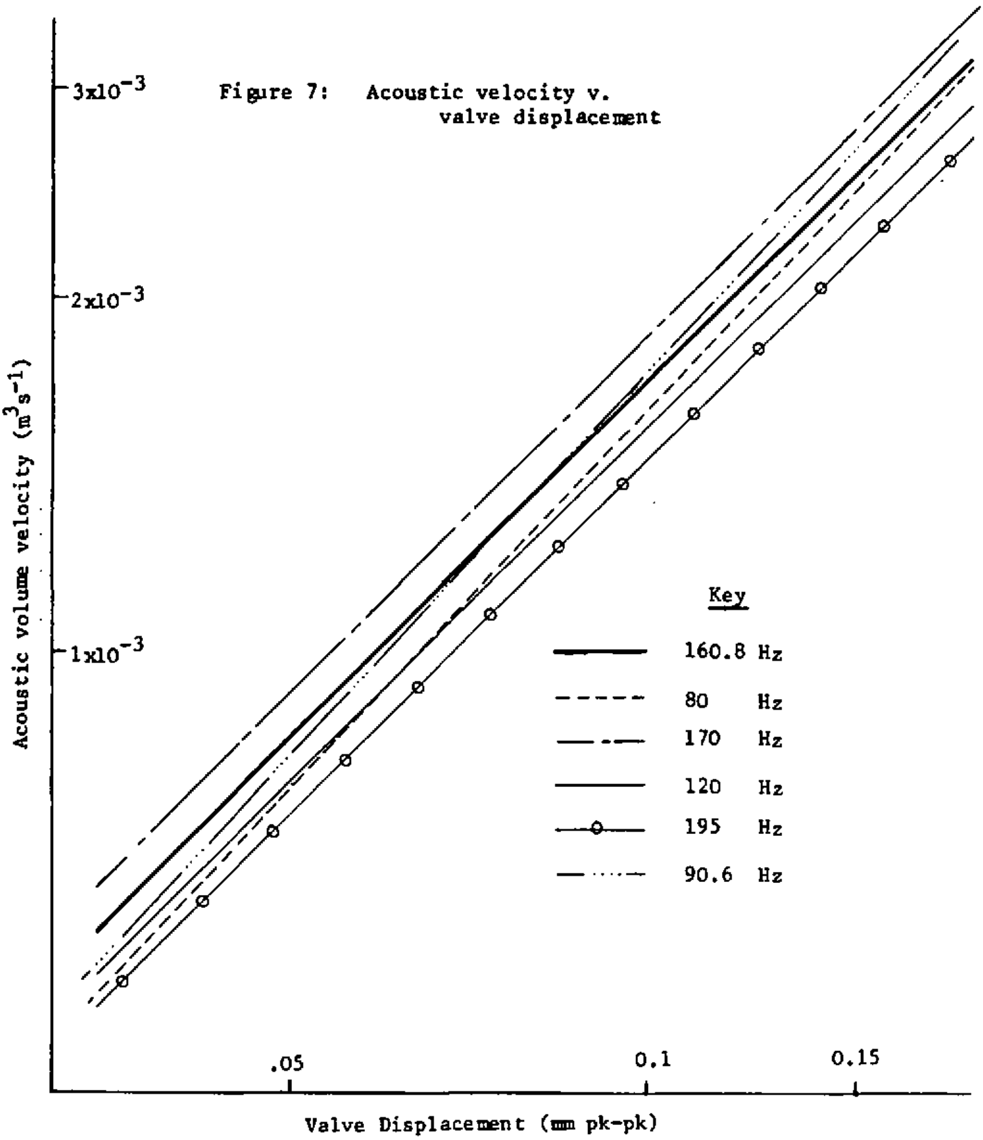

Figure 7: Acoustic velocity v. valve displacement