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ACTIVE CONTROL OF ACOUSTIC ABSORPTION, REFLECTION AND TRANSMISSION

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NOMENCLATURE

F	control forcing function	(N)
K	cone suspension compliance	(m/N)
M	moving mass	(kg)
R	cone suspension damping	(Ns/m)
p	cone pressure	(Pa)
u	cone velocity	(m/s)
ω	angular frequency	(rad/s)
Z	specific acoustic impedance	(Ns/m^3)
C	forward path transfer function	
H	desired Z transfer function	
X	filtered-x compensation transfer function	
W	control filter transfer function	

Subscripts

d desired

1. INTRODUCTION

This paper describes experimental work on the active control of normal-incidence surface acoustic impedance. Previous work has demonstrated this application of active control technology [1,2,3,4]. Much of this previous work has been motivated by the desire to create near-ideal acoustic absorbers. The work described in this paper extends the concept to allow the construction of frequency-dependent acoustic impedances.

The dynamics of a plane, rigid, impervious surface, mounted on a linear suspension, can be modified by applying active control forces. The resulting change in the system dynamics can be used to modify the surface acoustic impedance presented to normally incident plane waves. The success of the technique depends on the creation of suitable control forces.

The range of acoustic impedances which can be implemented using this technique is constrained both by the realizability of the required control filters (stability, causality etc) and by fundamental physical limits. These limits have been considered in [3].

This paper gives some examples of the performance of such a programmable acoustic impedance device, in a laboratory context.

Firstly, the practical absorption demonstrated in [1,2,3,4,5] is reviewed. The novel contribution of the current work is illustrated by a control system which allows implementation of acoustic impedances with frequency dependence.

2. ACTIVE CONTROL OF ACOUSTIC IMPEDANCE

2.1 Theory

Consider an rigid infinite boundary mounted on a simple linear suspension driven by a controlling force F. If normally incident plane acoustic waves hit the boundary, they will be reflected according to an acoustic impedance given by (1) [2].

$$\frac{p}{u} = \frac{F}{u} + R + j\left(M\omega - \frac{K}{\omega}\right) \qquad kgm^{-2}s^{-1} \quad (1)$$

If a control system can create an appropriate forcing function F then the natural surface acoustic impedance can be altered to any physically realizable value.

Notice the velocity variable u is on both sides of equation 1. This couples the required forcing function F with the surface velocity and complicates the design of the required control filter W. Despite this coupling, adaptive signal processing techniques allow optimum digital controllers to be automatically designed.

2.2 Specification of Controlled Acoustic Surface Impedance

The programmable acoustic impedances under study at the University of Salford are built around conventional electrodynamic loudspeaker drivers. These have a linearly suspended diaphragm (which is approximately plane) and a convenient means for applying control forces through the motor system.

The control of the surface acoustic impedance of a loudspeaker is achieved by applying a forcing voltage appropriate to the desired value of surface acoustic impedance to the voice coil. The control system specifies acoustic impedance using information derived by transducing the pressure and acceleration of the surface (Figure 1). This instrumentation measures the acoustic impedance and this information is used to configure the control system. For Figure 1a the desired surface acoustic impedance is programmed into a digital filter H. This filter then operates on the actual cone pressure signal to produce a desired cone velocity (the cone velocity which would be caused by the actual cone pressure if the surface impedance had the desired value). The control system attempts to reduce the difference (the "error") between the desired velocity signal and the actual cone velocity signal.

Since H must be a physically realizable filter, it must always be causally stable. In the system illustrated in Figure 1a, this means that the desired impedance must be minimum phase.

The specification of non-minimum phase desired impedances can be achieved by reconfiguring the system (see Figure 1b).

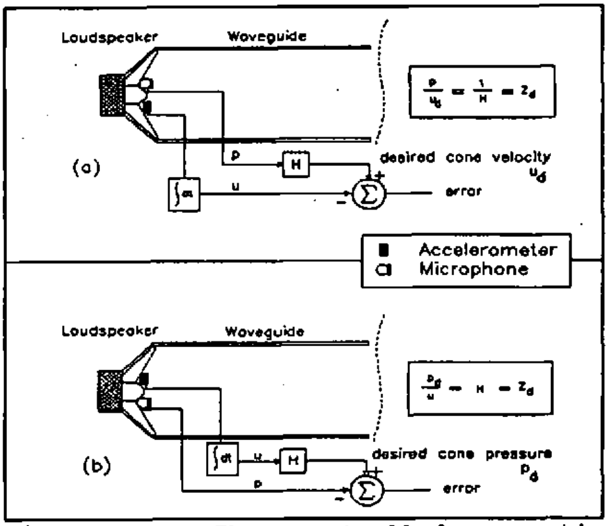

Figure 1. The controlled acoustic impedance is specified by transducing the surface, and designing a digital filter H. 1a and 1b show different permutations.

3. EXPERIMENTAL CONFIGURATION

3.1 Apparatus

The acoustic experimentation has been performed on an circular PVC pipe, 5m in length and 0.16m in diameter. The cut-off frequency of this waveguide is approximately 1000Hz, so that the experimental configuration can be considered as one-dimensional over the frequency-range of interest (<315Hz). Both ends of the pipe are fitted with conventional moving coil loudspeakers (KEF B200A 8 inch units). A microphone inside the duct allows the acoustic field to be surveyed before and after control. Standing wave ratio (SWR) measurements can be used to calculate reflection coefficients at spot frequencies.

The control system is implemented on a Loughborough Sound Images DSP32C System Board which utilizes the AT&T DSP32C floating point digital signal processor. An additional I/O card provides 2 extra pairs of A/D and D/A convertors. The experimental apparatus is illustrated in Figure 2.

3.2 Control Algorithm

The adaptive control algorithm used in this work is based on the "filtered-X" Least Mean Squares (LMS) algorithm developed by Widrow and Stearns [6]. The transfer function required to compensate for the forward-path dynamics is measured off-line before starting the controller, and implemented in a digital finite-impulse response (FIR) filter.

A schematic of the control system is shown in Figure 3. In this figure, W represents the transfer function of the control filter, which is updated using the filtered-X algorithm. C is the transfer function of the forward-path and X is a fixed order approximation of C. The input is taken from the electrical signal driving the source loudspeaker, and the desired pressure is calculated as shown in Figure 1b. The configuration of Figure 1b is chosen because the filter H directly corresponds to the desired Z_d, and there is no minimum-phase criteria (see Section 2.2).

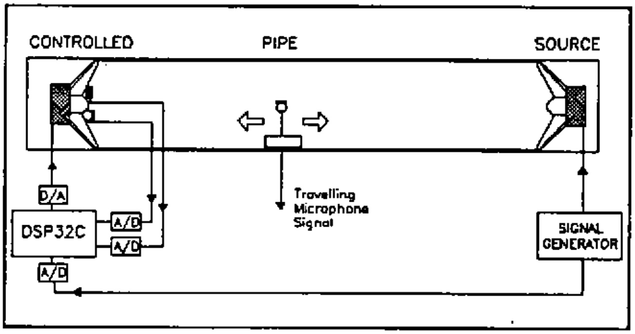

Figure 2. Experimental apparatus setup

4. EXPERIMENTAL RESULTS

The system was tested for several different acoustic impedances - two significant test cases are reported in this paper. The first is for Z_d = 415 Rayls [1,2,3,4,5]; a characteristic termination for the waveguide. In this simple but important case the filter H is of zero'th order and is implemented with a single multiplication. In the second example the desired acoustic impedance is frequency dependent. The termination is absorptive at low frequencies, becoming more reflective at high frequency. The filter H was designed from an analogue bilinear prototype.

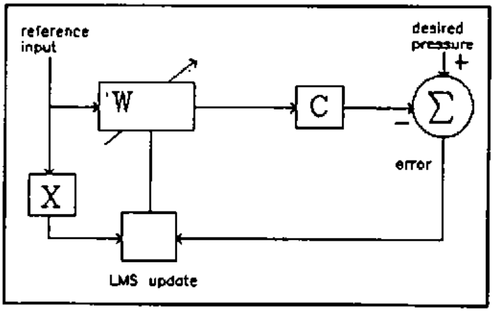

Figure 3. Control schematic

For each desired impedance the control system was trained for about 30 seconds using pink noise, bandlimited to 450Hz. The adaption was then halted, and standing wave ratio measurements were performed at frequencies from 50-315Hz. SWR measurements were also performed to measure reflections from the uncontrolled loudspeaker.

The first case (Z_d = 415) reflection coefficient results are shown in Figure 4. Despite the large reflection coefficient from the uncontrolled loudspeaker, the control system successfully implements an effective acoustic absorber.

The active absorber was also tested by observing the reflections of short pulses of acoustical energy, a technique used in [4]. Figure 5a shows the pressure impulse response 1m from the controlled surface, with the control system disabled. In Figure 5b the reduction in the reverberant components caused by the near-ideal absorptive surface is dramatically shown. Notice that, in this implementation, the direct pulse is not modified.

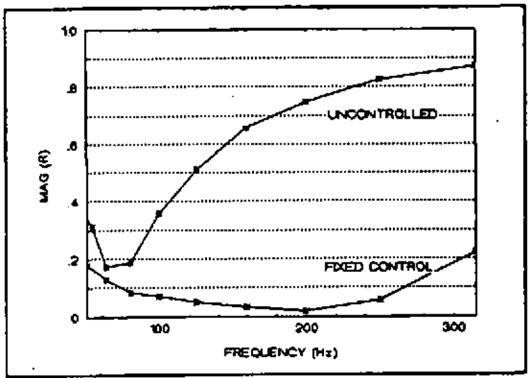

Figure 4. Reflection coefficient of uncontrolled loudspeaker and the fixed active absorber.

The reflection coefficient results for the second case of frequency dependent surface acoustic impedance are shown in Figure 6. The magnitude and phase of the reflection coefficient are compared to the theoretical reflection coefficient, calculated from knowledge of the desired impedance, H. Both magnitude and phase of the reflection coefficient track the theoretical data, indicating that the controlled loudspeaker is successfully implementing both gain and phase of the specified impedance.

5. CONCLUSIONS

This paper has demonstrated that one control system can be programmed (by simple change of filter coefficients) to force a surface to be near-ideally absorptive, or to have general pre-specified acoustic impedance. This device has obvious applications in several areas. Current applications under development include the use of the programmable acoustic impedance as a backload in a loudspeaker enclosure [5] and the development of "acoustic short circuits" for modifying the radiation pattern of constant velocity sources. In the longer term, applications in the active control of the acoustics of architectural spaces are being developed.

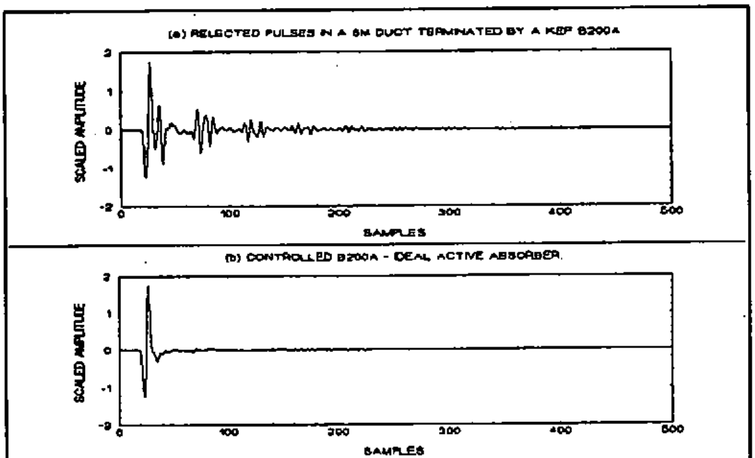

Figure 5. Measurement of pulses in the duct before (a) and after control (b).

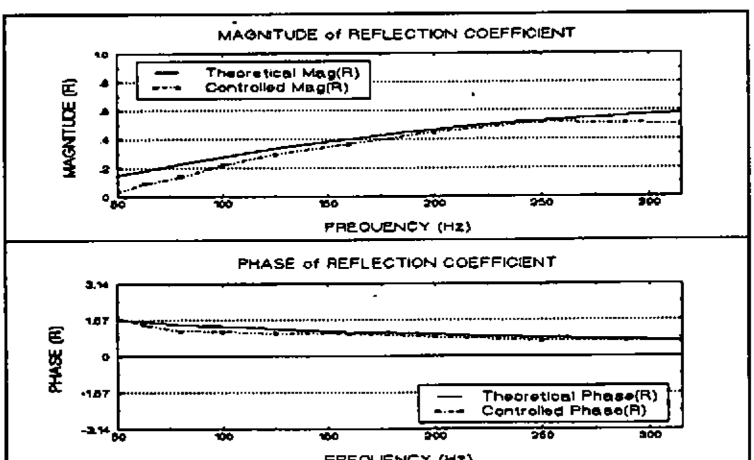

Figure 6. The theoretical and measured reflection coefficient of a pre-specified active controlled acoustic impedance

7. REFERENCES

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