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INTAKE AND EXHAUST MODELLING

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1. INTRODUCTION

Ever tightening legislation coupled with consumer demand for a well refined product has brought road vehicle noise concerns to the attention of the manufacturer. Along with wind, tyre and base engine noise, intakes and exhausts are often dominant sources of interior and / or exterior noise. Intakes / exhausts perform the primary function of conveying gas to and from the engine and unfortunately noise is produced in the process, both by momentum and pressure changes linked to unsteady mass flow through valves and by flow generated noise.

Much work has been undertaken to define the nature of these sources and their modes of propagation. Broadly speaking, this predictive research falls into two classes: those incorporating an engine cycle simulation and considering the unsteady flow behaviour of gases in the time-domain, and those considering acoustic propagation in the frequency domain.

2. FREQUENCY DOMAIN PREDICTIONS

Frequency domain prediction techniques are being successfully used at Lotus to reduce the development time for intake / exhaust programmes. Predictions are based on Davies [Ref: 1] software originating from Southampton England. Here plane wave propagation is assessed by comparing the relative amplitudes and phases of the four wave components $(p_1^+, p_1^-, p_2^+, p_2^-)$ which can be related to four pressures (P_1, P_2, P_3, P_4) at four planes [Ref: 2]

$$P_1 = p_1^+ e^{-i\beta_1^+ x_1} + p_1^- e^{i\beta_1^- x_1}$$
$$P_2 = p_1^+ e^{-i\beta_1^+ x_2} + p_1^- e^{i\beta_1^- x_2}$$
$$P_3 = p_2^+ e^{-i\beta_2^+ x_3} + p_2^- e^{i\beta_2^- x_3}$$
$$P_4 = p_2^+ e^{-i\beta_2^+ x_4} + p_2^- e^{i\beta_2^- x_4}$$

where

$$\beta = \text{complex wave number} = (\omega / c) - i\alpha$$
$$\beta^+ = \beta / (1 + M)$$
$$\beta^- = \beta / (1 - M)$$

w = radial frequency
c = local sound speed for gas in duct
α = attenuation coefficient
M = Mach number

$$\alpha = (1/ac)\sqrt{vw/2}[1+(\gamma-1)\sqrt{1/\mathrm{Pr}}]$$

a = pipe radius (m)
v = kinematic viscosity
γ = Cp/Cv ratio of specific heat capacities
Pr = Prandtl number for gas in duct

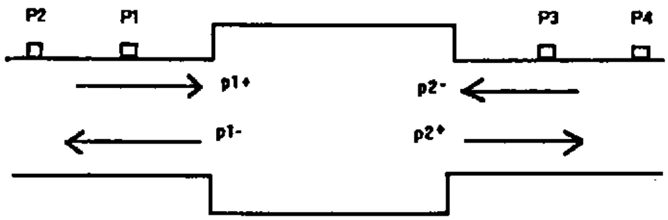

Figure: 1

The technique takes account of temperature distribution down the system, mass flow rate and gas composition, to predict attenuation spectra, insertion loss, reflection / transmission coefficients and system impedance. Virtually all common intake / exhaust geometry may be accommodated by describing them as a series of simple chambers linked together by their inlet / outlet pipes.

3. FREQUENCY DOMAIN VALIDATION

Experimental validation of attenuation and reflection coefficient predictions has been pursued using a custom implementation of the 'Four transducer wave-decomposition technique'. This measurement method uses two upstream and two downstream transducers, at known positions (Fig: 1), to transform the acoustic field's positive and negative going travelling waves, to characteristic frequency dependant wave components.

Figure: 2 shows a plane-wave prediction of attenuation $(20\log_{10}(p_1^+ / p_2^+))$ for a Lotus Elan intake system, versus a four transducer measurement. There is fair agreement at frequencies above 50 Hz (below this the microphone spacing is insufficient to decipher the phase information). The measured results suggest greater levels of damping within the system than the plane-wave model predicts. This is a common feature with frequency domain predictions, possibly due to visco-thermal losses at expansions or case radiation in the experimental rig.

Figure: 3 shows a plane-wave prediction of reflection coefficient (p_1^- / p_1^+) versus a four transducer measurement. The measured modulus is formed by using the transmission coefficient (p_2^+ / p_1^+)

$$\text{Reflection coefficient (modulus)} = 1 - \text{abs}\,(p_2^+ / p_1^+)$$

This makes use of transducers with wider spacing and allows low frequency resolution. The results show a pronounced low frequency dip in the reflection coefficient modulus. Such deviations from unity have been shown for intake plenums, and cast doubt on the validity of simple unity boundary conditions often used in time-domain engine cycle simulations. The measured phase must be formed using the (p_1^- / p_1^+) relationship and hence does not have the low frequency resolution.

A simple experimental technique was sought to complement the four transducer decomposition method. A two transducer 'pressure-ratio' method has been developed to be used as a quick and simple means of determining the potential accuracy of predictions. Here one transducer is placed in the system intake pipe and another in the outlet pipe. The ratio of the pressures is measured using a two channel FFT analyser. The prediction is formed from the sum of the two wave components at each transducer location. Figure: 4 shows a comparison of predicted and measured results. The modulus and phase agreement is very good.

4. TIME DOMAIN PREDICTIONS

Time domain prediction techniques, often based on the 'Method of Characteristics' (MOC) [Ref: 3] form the basis for I.C. engine power performance simulations. This has been extended to the prediction of noise radiation from intakes / exhausts [Ref: 4]. The main advantage of a time domain model is the inherent consideration of unsteady mass flows through the valves which acts to establish the instantaneous source characteristics. However, using an iterative propagation model does have its limitations. Not only is it time consuming to compute, but there are also difficulties in handling reflective boundary conditions. In a step-wise time solution, the boundary condition is an instantaneous, single-value reflection coefficient. However, Fig: 3 clearly shows the modulus of the reflection coefficient varies with frequency of excitation. As the exact value of this modulus cannot be calculated in the time-domain, hybrid time / frequency domain prediction software is being developed which defines the source characteristics in terms of time varying mass flows through the valves, and couples it with frequency domain computed reflective boundaries and a frequency domain propagation model (Fig: 5). Early results from the hybrid approach indicate that it has a positive effect on the accuracy of noise radiation and engine power predictions, whilst reducing computation times.

It should be stated that a full time domain only model is appropriate when there is a time varying reflective boundary in the system, such as an actuator for Active Noise Cancellation, or a variable tuned intake.

5. TIME DOMAIN VALIDATION

Validation of time domain models is complex. Matching of measured pressure time histories is often shown in the literature [Ref: 5] and is relatively straightforward. However, for a robust validation, particle velocities must also be matched, which has proved more difficult to achieve [Ref: 6]. Conservation of mass and momentum throughout the intake / engine / exhaust chain must also be respected.

6. THE USE OF PREDICTIVE NOISE TECHNIQUES IN VEHICLE DEVELOPMENT PROGRAMMES

Proper use of predictive techniques can enhance the quality of an intake / exhaust solution, and greatly reduce it's development time. The predictive methods fulfil different roles at different stages in the development process:

- o **Initial system layout** - Theoretical predictions can help ensure that enough system volume and length is claimed in the vehicle concept-design stage.

- o **System packaging studies** - Theoretical predictions can be used to ascertain the likely effect of modifications to the system layout, thus minimising the number of expensive prototype stages.

- o **Prototype system design** - Theoretical predictions can be used to enhance the detailed design stages, allowing for rapid design refinement.

- o **Prototype vehicle tests** - Theoretical predictions can be used to assess and refine designs directly on the vehicle, allowing for consideration mounting methods and vehicle noise transmission characteristics.

The process from concept design, through prototype engine tests, to on-vehicle development is illustrated by practical results for the development of a filter box and a single Helmholtz resonator as the intake system for a passenger car in Fig: 6

7. REFERENCES

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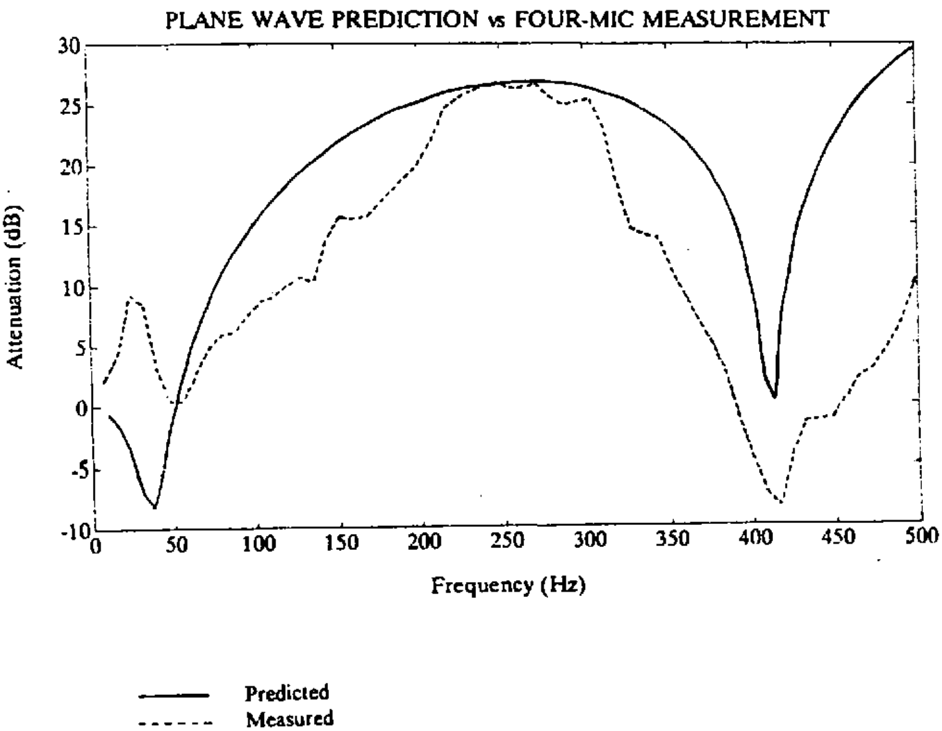
PLANE WAVE PREDICTION vs FOUR-MIC MEASUREMENT
30
25
20
15
10
5
0
-5
-10
0
50
100
150
200
250
300
350
400
450
500
Attenuation (dB)
Frequency (Hz)
Predicted
Measured

Figure: 2

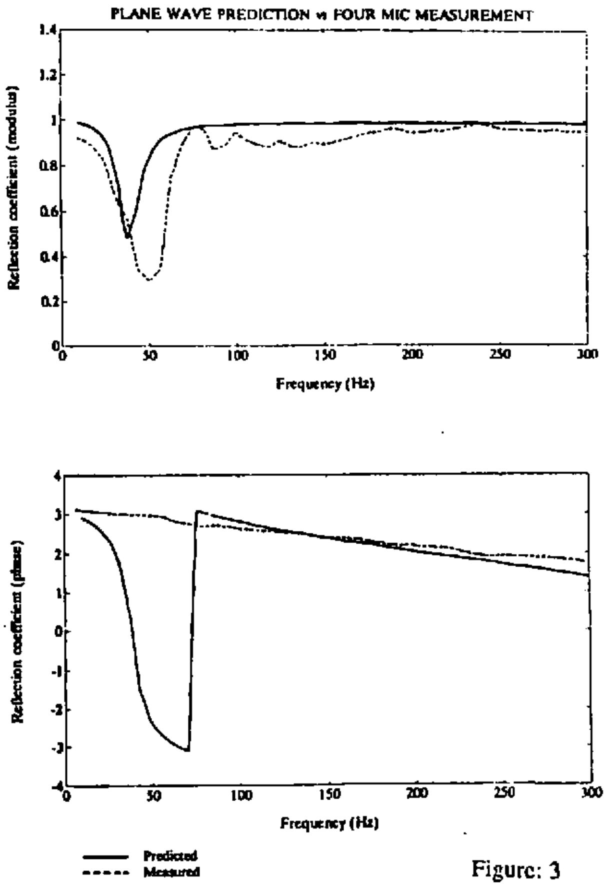

Figure: 3

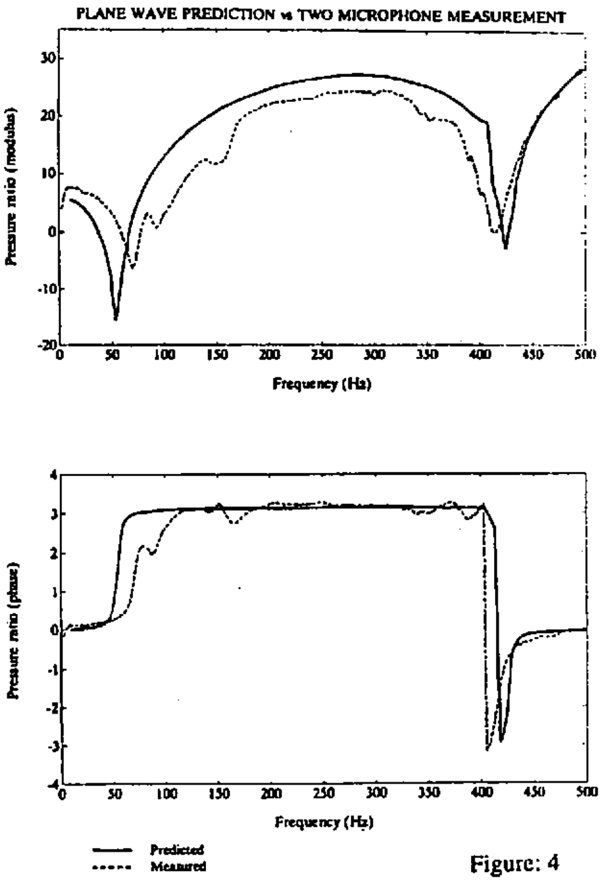

Figure: 4

HYBRID TIME/FREQUENCY DOMAIN MODELLING

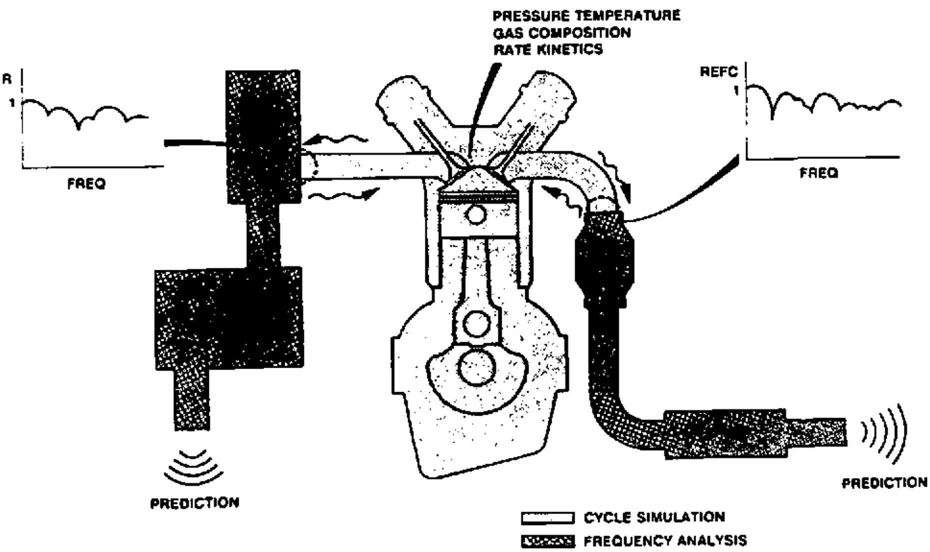

Figure: 5

INTAKE AND EXHAUST MODELLING

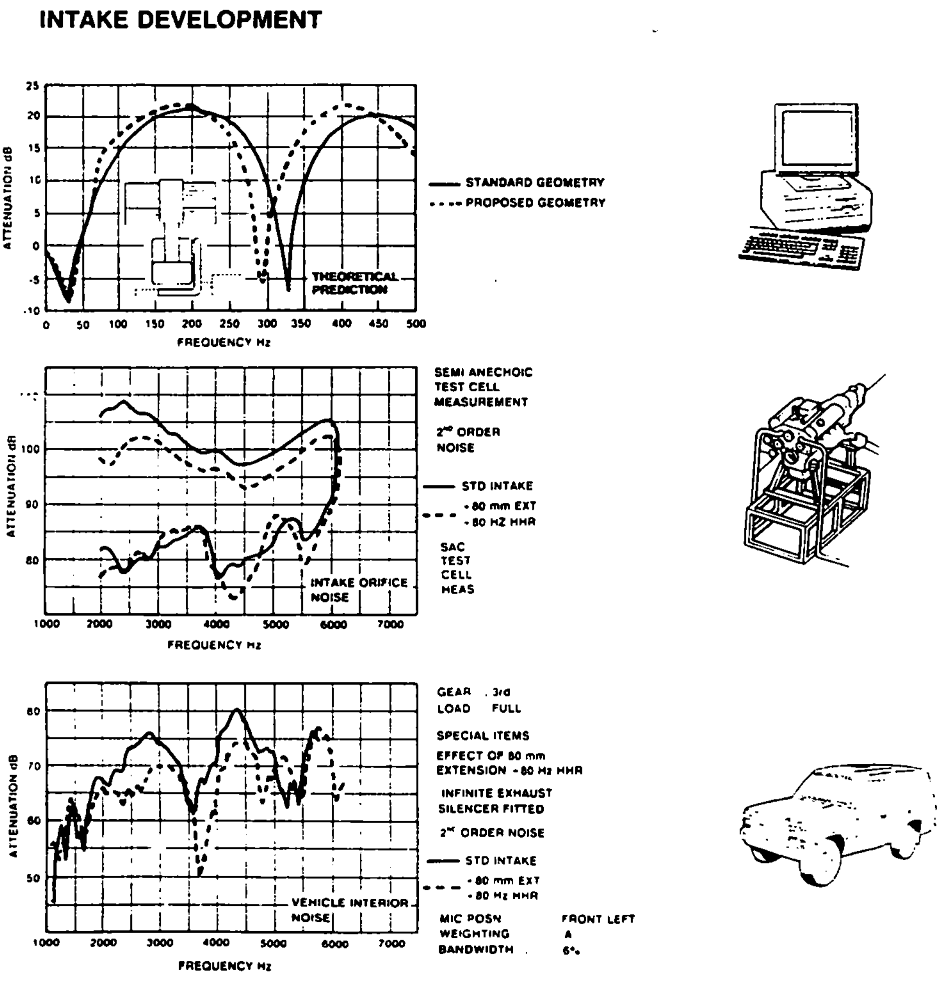

Figure: 6