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THE ACTIVE CONTROL OF INTERNAL COMBUSTION ENGINE EXHAUST NOISE

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Active noise control involves the reduction or cancellation of unwanted sound by using powered acoustic transducers to modify the acoustic field.

The first patent of an active noise control system was taken out in 1936, ref 1, and many theoretical texts on the subject have been published since then.

While the complete active cancellation or absorbtion of sound in three-dimensional space is theoretically possible, ref's 2, 3, 4 and 5, it is extremely complicated. Practical schemes either aim to provide a limited three dimensional zone of cancellation e.g. in a vehicle cab, or to absorb or reflect back acoustic energy propagating one dimensionally e.g. in a duct below the cut-off frequency above which radial acoustic modes occur.

The application of digital processing using frequency response function techniques has greatly simplified the optimisation of the control parameters for active systems, ref. 6. This optimisation is important when the properties of the acoustic medium are changing with time, so that the system can be configured to adapt to changing conditions.

Repetitive processes offer a further simplification where the cyclic repetition rate is greater than any non-stationary drift in the properties of the acoustic medium, ref. 7.

Engine exhausts are such a repetitive process and in addition, are commonly the source of low frequency acoustic energy which can be expensive to control by conventional passive means.

A project to investigate the application of active noise control to engine exhausts has been carried out at Ricardo using the control schemes developed by the Wolfson Centre at Essex University for the Electronic Cancellation of Noise and Vibration.

THEORY

Two adaptive control algorithms based on repetitive cyclic noise have been tested. The two algorithms are called 'Power Sensing Method' and 'Transform Method' and are described below.

Power Sensing Method. This was the original "Essex" algorithm. The signal from the residual detector is considered, engine cycle by engine cycle, each cycle being digitised at 32 points. The algorithm operates by sensing the total residual power during one cycle, adjusting one of the 32 elements of the cancelling waveform and repeating the measurement. If the residual power is reduced then the waveform element is further adjusted in the same direction, if not it is returned to its previous state. This process is repeated for each of the 32 elements of the cancelling waveform. The process takes a minimum of 30 seconds to adapt to a change in noise waveform and can only operate up to the sixteenth cycle harmonic of the exhaust noise (due to the sampling rate limitation). In addition, higher harmonics can be introduced into the exhaust noise unless care is taken to low-pass filter the output control signal to the power transducer(s) effectively.

This system does have the great advantage of not requiring linear power transducers as the aim is to minimise the residual acoustic power. This offers the opportunity of using novel and potentially highly non-linear forms of power transducer. The residual detector must be reasonably linear in amplitude and frequency response in the operating range of the system.

Transform Method. This algorithm makes use of the Fast Fourier Transform, and relies upon both the residual detector and the power transducers both being linear in amplitude and frequency response in the operating range of the system. The synchronisation signal is used in order to 'lock' the harmonic components to the engine cycle.

The residual detector signal is digitised and Fast Fourier Transformed into its component harmonics (up to the 15th cycle order).

The system frequency response function, the complex ratio of the cancelling signal to the residual signal, is determined by driving the power transducer sequentially with the harmonic series of sine waves for the particular engine speed. This maybe carried out in the presence of the noise to be cancelled but must be repeated for each change in engine speed.

EXPERIENCE WITH DIESEL ENGINES

Installations. Three different active noise control installations have been carried out at Ricardo. All were additions to roof mounted anechoic cell exhaust systems.

Power sensing algorithm tests. The first series of tests were carried out on the exhaust of a naturally aspirated 17 litre 8 cylinder direct injection diesel truck engine. The estimated maximum exhaust sound power was 13.4 watts. The five acoustic power transducers were grouped around the 150mm diameter exhaust stack.

Table 1

Speed (rev/min)	Load (%)	Uncontrolled level @ 1.4m (dBA)	Reduction @ 1.4m (dB)	Reduction @ 1.4m (dBA)	Reduction at Detector (db)	Reduction at Detector (dBA)
1200	100	93.6	3.8	1.6	5.6	2.0
1800	75	97.6	6.1	5.6	2.4	1.6
2400	100	100.6	4.6	5.4	8.6	6.4

The use of the active noise control system produced no measureable effect on engine power output or exhaust smoke levels.

Transient tests (accelerating from 1200 rev/min to 2400 rev/min in approximately 2 seconds) showed that the active control system had no beneficial effect on the transient exhaust noise level.

Transform method algorithm tests. Two test series were carried out using this algorithm. The first was on the exhaust of a turbocharged 17 litre 8 cylinder direct injection truck diesel engine. Two acoustic power transducers were positioned either side of the exhaust stack, which had a 230mm by 75mm square section exhaust. The second test was on the exhaust of a 14 litre 6 cylinder turbocharged direct injection diesel engine, again using two acoustic power transducers.

Table 2 - 17 litre engine

Speed (rev/min)	Load (%)	Uncontrolled level @ 2m (dBA)	Reduction @ 2m (dB)	Reduction @ 2m (dBA)	Reduction at Detector (dB)	Reduction at Detector (dBA)
1200	100	82.3	7.7	1.9	19.2	9.9
1550	100	86.5	6.8	7.0	18.0	11.2
1900	100	90.5	4.0	7.1	20.0	15.0

Table 3 - 14 litre engine

Speed (rev/min)	Load (%)	Uncontrolled level @ 2.8m (dBA)	Reduction @ 2.8m (dB)	Reduction @ 2.8m (dBA)	Reduction at Detector (dB)	Reduction at Detector (dBA)
1200	100	81.7	22.2	7.4	17.9	5.1
1600	100	79.8	17.7	6.6	14.1	4.6
2000	100	88.2	21.0	12.4	15.7	9.9

DISCUSSION

Comparison of the results given in Table 1 with those in Tables 2 and 3 shows that the 'Transform Method' algorithm gives much better results when applied to engine exhaust noise under field conditions. The superior acoustic performance of the 'Transform Method' is mainly due to its inherent resistance to background noise. In addition it achieves optimum cancellation within seconds whereas the power sensing system may take minutes.

At present neither of the systems is suitable for transient operation due to the fundamental assumption of a repetitive process. While adaptive schemes for control of non-repetitive noise sources have been devised they usually require a detecting transducer upstream of the controlling acoustic power transducers.

The main practical limitations to the widespread application of active noise control to the exhausts of engines running under steady state conditions are the availability and cost of the transducers, particularly the acoustic power transducers. Commercially available power transducers are not likely to have the long term reliability required for engine exhaust systems but at present there are no practical alternatives and such transducers are being used in long term trials. One additional consideration with acoustic power transducers is the electrical power required, a maximum of 1kW was available for the above tests and this power level was approached on test.

The 'Power Sensing' system does have the theoretical advantage of not requiring a linear amplitude or frequency response from the acoustic power transducer. This might permit exploitation of the heat dissipated via the exhaust gases - typically the heat to exhaust is of similar magnitude to the shaft output power. One means of utilising this waste heat might be modulated water injection into the exhaust pipe near the engine. This modulated vapourisation of the water would produce pressure pulses within the exhaust pipe and provided these could be controlled accurately the only power required would be for the injection equipment.

CONCLUSIONS

Tests on the exhausts of several truck sized diesel engines have shown that steady state engine exhaust noise may be attenuated by greater than 20 dB in a given 1/3 octave band and up to 10 dB(A) on the far field by active noise control equipment with no measureable deterioration in engine performance. There was no reduction in exhaust noise under rapid changes of speed and load. Of the two control algorithms tested the 'Transform Method' system gave a superior performance to the 'Power Sensing' system although the latter does have the ability to use non-linear acoustic power transducers.

Possible non-linear acoustic power transducer schemes include modulated water injection into the engine exhaust.

The use of current electromechanical acoustic transducers is not thought to be a viable long term proposition for active control of engine exhausts but might prove acceptable as a short term solution.

The inability of the schemes tested to control transient noise effectively and the size and weight of existing acoustic power transducers would appear to limit the current application of active noise control schemes to stationary, or non-mass sensitive, installations operating for long periods at steady load and speed.

The application of active noise control to road transport requires control schemes capable of handling transient operation and the development of light, rugged acoustic power transducers.

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