ACTIVE EXHAUST SILENCER USING AN OSCILLATING BUTTERFLY VALVE

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An active exhaust silencer was developed for a reciprocating petrol engine using an oscillating butterfly valve. The active silencer was installed on a Mitsubishi V6 petrol engine loaded by an eddy current dynamometer and was able to withstand exhaust gas temperatures of 500°C. Experimental results showed that the oscillating butterfly valve was able to simultaneously attenuate tonal noise at the 1x and 2x cylinder firing frequencies.

1. Introduction

Reciprocating 4-stroke engines generate significant exhaust noise at the cylinder firing frequency and harmonics. Active exhaust silencers that use cancellation loudspeakers have been commercially available by Eberspächer [1] and can attenuate the harmonic content generated by an engine. The system relies on the use of a loudspeaker that has been protected from the exhaust gas by placing it at the tail end of the exhaust, where the temperatures are much lower compared with the engine end, and sealed to prevent exposure of the loudspeaker to particulates. Another method of protecting a loudspeaker is to place it behind a membrane and inject cooling air [2]. However in some situations the exhaust gas temperature is extremely hot, and it is difficult and often impractical to provide a protected loudspeaker, so an alternative method of providing a cancellation sound source is required.

Several researchers have shown that an oscillating valve placed within the flow of the exhaust can be used to generate a cancellation noise source. Hardouin et al. [3] used an oscillating butterfly valve and an adaptive feedback controller to reduce the amplitude of fluctuations in the gas, and hence reduced the acoustic noise. Similarly Carme et al. [4-5] demonstrated this concept on an 11 litre, 6 cylinder diesel engine, using an oscillating butterfly valve system, but using a feed-forward LMS algorithm controller. The system relied on the exhaust gas flow speed and any change in the exhaust flow caused issues with the stability of the controller. Boonen and Sas [6-7] were able to regulate the gas flow from an engine using an electro-dynamically driven globe valve. Boonen and Sas [6] were able to reduce exhaust noise by 13 dB with only 10 kPa back pressure on the engine.

The work conducted here is similar to previous researchers, where it was desired to create an active exhaust silencer that could provide attenuation of multiple harmonics of the engine noise, where the exhaust gas temperature was approximately 450°C. Cancellation loudspeakers are very unlikely to withstand this temperature, and still generate sound pressure levels greater than 150 dB at 100 Hz. Hence, the selected cancellation device was an oscillating butterfly valve inserted into the exhaust flow. A feed-forward filtered-x LMS controller was used to alter the pulsations of gas flow and reduce the downstream tonal noise. The mechanism by which noise is attenuated was explained by Leclercq et al. [8] and a mathematical model proposed. The back pressure that is developed by the valve is a function of the engine speed and load on the engine. When the valve restricts the opening in the exhaust pipe, the flow is temporarily “stored” in the buffer volume (expansion chamber) and then released when valve opens again. The larger the buffer, the lower the back-pressure on the engine.
2. **Apparatus**

2.1 **General Arrangement**

The system comprises an oscillating butterfly valve inserted into the exhaust gas flow as shown in Figure 1. A linear electro-magnetic shaker (LDS V201) is used to oscillate a crank mechanism, which in turn rotates a shaft on which the butterfly valve is mounted. By precisely adjusting amplitude and phase of the butterfly valve according to the arrival a pressure pulse from the exhaust gas stream, it is possible to smooth pulsations in the exhaust gas flow, thereby reducing the noise that is radiated from the exhaust. There were many design iterations of the device, as described by Morgan et al. [9]. The test configuration had a wire mechanism acting as a variable stiffness torsion spring that was used to increase the resonance frequency of the system to within the operating range of the cylinder firing frequencies.

![Figure 1: Schematic of the actuator and crank mechanism used to oscillate the butterfly valve.](image1)

2.2 **Actuator**

The butterfly valve was oscillated using an air-cooled LDS V201 electromagnetic shaker, as shown in Figure 2. The shaker was powered by a Playmaster 200W audio amplifier. It can be seen in the photo that the shaker is connected to a crank mechanism through a flexible stinger rod. The attachment between the stinger rod to the crank has a pin joint, so that rotational motion of the crank is decoupled from the shaker, to prevent the rotation of the armature on the shaker which would cause the internal coil windings to rub on the internal components, causing damage and rapid failure of the shaker.

![Figure 2: Photograph of the LDS 201 shaker user to oscillate the butterfly valve.](image2)
Figure 3 shows a photograph of the active butterfly valve installed on the exhaust pipe from above.

![Active Butterfly Valve](image)

Figure 3: Photograph of the active butterfly valve installed on the exhaust of the engine.

### 2.3 Test Engine and Dynamometer

Tests were conducted in the engine test cells at the School of Mechanical Engineering, The University of Adelaide on a 3.5 litre, V6 Mitsubishi 6G74M petrol engine that was loaded by a Shenck eddy current dynamometer with a Dyne Systems controller, as shown in Figure 4. This engine type was used in Mitsubishi Magna passenger vehicles. The catalytic converter was removed and the active exhaust silencer was installed, only because of space limitations in the test area.

![Engine Testing Setup](image)

Figure 4: Engine Testing Setup.
Figure 5 shows a close-up photograph of the setup of the active valve installed in the exhaust system. Water cooled microphones were placed before the expansion chamber (Mic 1), upstream of the active butterfly valve (Mic 2), immediately after the active butterfly valve (Mic 3), and further downstream (Mic 4).

2.4 Instrumentation

The acoustic pressure in the exhaust duct was measured using water-cooled PCB 106B pressure sensors. The exhaust gas temperatures were measured using several K-type thermocouples. A magnetic sensor (RS Components part number RS 304-172, TSI Digital Magnetic Pickup) was used to provide a tachometer signal by pointing at 4 bolts attached to end of the dynamometer mounting plate. Each bolt had a magnet embedded in the head.

A dSPACE 1104 controller board was used together with a Matlab-Simulink model of a feedforward filtered-x LMS adaptive control algorithm. The tachometer was used to generate sinusoidal reference signals at the 1x, 2x, and 3x cylinder firing frequencies for the feedforward LMS control algorithm. The error signal was the acoustic pressure measured at a downstream microphone (#4).

The data from sensors were recorded using National Instruments hardware that comprises an NI 9178 8-slot carrier, 2x NI 9234 4-channel analog to digital converter modules, 1x NI 9213 16-channel thermocouple module. The National Instruments Labview Signal Express software was used to record the data to disk for post-processing and online monitoring.

3. Experimental Test Results

The first test involved the engine operating at constant speed of 2400rpm and 150 Nm of load by the dynamometer. The control system was used to simultaneously control the tonal noise at the 1x and 2x cylinder firing frequencies. Figure 6 shows the power spectral densities at the two microphones downstream of the butterfly valve with simultaneous control of the tonal noise at the 1x and 2x cylinder firing frequencies, with the controller turned off and on. The figure shows the controller was able to reduce the tonal noise by 20 dB at the 1x cylinder firing frequency, and more than 15dB at the 2x cylinder firing frequency.
Another test was conducted without control, and then alternatively controlling both tones simultaneously and individually. The engine was operating at 2300 rpm, loaded by 150 Nm of torque, so that the exhaust gas temperature at the valve was approximately 450°C. The sound pressure levels at the four microphones at the 1x and 2x cylinder firing frequencies are shown in Figure 7 and Figure 8, respectively. The results show a fast (1s or less) reduction of the 1x tone by more than 15dB when control is turned on. The 2x tone also shows a fast 7dB reduction, which gradually increases to 15 dB or more over 30 seconds. Faster performance could be achieved by increasing the LMS convergence coefficient for the 2x cylinder firing frequency.

Figure 9 shows the sound pressure level spectra measured at Mic 4, which is downstream of the butterfly valve, for various configurations of the butterfly valve. For the active control tests conducted in this work, the valve was set at about 60 degrees from the horizontal position. Another test was conducted with the valve set at about 10 degrees from the horizontal position. The curve labelled “No Valve” was when the butterfly valve was removed from the exhaust duct and replaced with 3 exhaust flanges, to simulate a straight-through section of pipe. The curve labelled “Engine Off” shows the effective electrical background noise of the measurement system. The results show that the oscillating butterfly valve does not introduce unwanted tonal noise or broadband noise compared to the case where there was a straight-through section of pipe. Figure 10 shows the same results as Figure 9 over a narrower frequency range of 0-600Hz.
Figure 7: SPL at 1x cylinder firing frequency, without and with control, when the engine was operating at 2300 rpm, 150 Nm of torque

Figure 8: SPL at 2x cylinder firing frequency, without and with control, when the engine was operating at 2300 rpm, 150 Nm of torque
The active exhaust system is intended to attenuate tonal noise at multiple frequencies corresponding to the 1x and 2x cylinder firing frequencies. It was found that the system was unable to control the tonal noise at the 3x cylinder firing frequency. The reason was that the shaker was unable to
provide sufficient displacement due to frequency of operation and the force-to-moving-mass ratio. It is desirable to have an actuator that can impart a high force with a low moving-mass connected to the active valve that has low rotary inertia.

4. Conclusions

Active exhaust silencers using cancellation loudspeakers are able to provide attenuation of tonal exhaust noise, but require that the loudspeaker is in a relatively cool environment, and usually unable to withstand sustained high temperatures of 450°C. Alternative technology is required to withstand these adverse conditions. In the work conducted here, an oscillating butterfly valve was placed in the exhaust duct and used to attenuate the tonal noise at the 1x, 2x, and 3x cylinder firing frequencies. In order to provide the required back-pressure, it was necessary to offset the angle of the valve. The authors were unable to find linear actuators with sufficient stroke and force-to-moving-mass ratio, or a rotary actuator that has high torque-to-rotary-inertia, which are necessary to achieve the required operational bandwidth.

The experimental results showed that by using an oscillating butterfly valve with a feedforward LMS controller, it was possible to reduce the tonal noise by up to 20 dB within a few seconds.

5. Acknowledgments

The authors would like to acknowledge the Defence Science and Technology Group for providing the majority of the funding for this project.

REFERENCES