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An adaptive quarter-wave tube that uses the sliding-Goertzel algorithm for estimation of phase

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ABSTRACT

This paper describes an adaptive quarter wave tube used to attenuate a tone from the exhaust noise of a large diesel engine. A sliding-Goertzel algorithm was used to calculate the phase angle of the transfer function between a microphone in the adaptive quarter wave tube and in the main exhaust duct. The control system adjusted the length of the adaptive quarter wave tube until the phase angle was −90° and caused the sound pressure level at the cylinder firing frequency in the exhaust duct to be minimized. The system was able to adapt to changes in engine speed, exhaust gas temperature, and load applied to the engine. The results demonstrate that the sliding-Goertzel algorithm can be used effectively to estimate the phase angle in an adaptive–passive acoustic control system.

1. Introduction

A side-branch quarter-wave tube silencer can be effective at attenuating a single acoustic tone propagating in a duct where plane-wave conditions exist. They have limited application as most sources have varying frequency, varying gas temperature hence varying speed of sound, and can be adversely affected by grazing flow. The use of undamped side-branch resonator silencers is usually avoided to prevent conversion of the energy in the mean gas flow into acoustic energy [1].

This paper describes an adaptive–passive quarter wave tube that comprises a variable length piston, which is adjusted by an automatic control system, and used to attenuate exhaust noise at the cylinder firing frequency of a reciprocating engine. The system is capable of automatically adapt to changes in engine speed, exhaust gas temperature, and load applied to the engine.

The main contributions of this paper are the

- Demonstration of the use of the sliding-Goertzel algorithm in an acoustic application for calculating the phase angle between a pair of microphones, which is used as the cost function for a tuning algorithm. Previous work [2] only considered synthesized (ideal) sine wave vibration signals in a laboratory environment. Whereas the work conducted here involved a realistic noise control application where the frequency and amplitude of the signals varied continuously, and the input signals contained multiple tones and signal noise.
- Demonstration of the use of an adaptive quarter-wave tube (AQWT) attached to the hot flowing exhaust of a large diesel engine, to attenuate noise at the cylinder firing frequency. The system is capable of adapting to changes in engine speed, exhaust gas temperature and engine load.

2. Previous work

A number of researchers have investigated the use of Helmholtz resonators and quarter-wave tubes, both passive and adaptive–passive, to attenuate noise in the exhaust of reciprocating engines. The resonant frequency of a Helmholtz resonator can be varied by adjusting the cavity volume or the neck volume (cross-sectional area or length). Several authors have developed Helmholtz resonators with a variable cavity volume [3–5]. A volume-variable resonator may be the easiest to implement in practice, but becomes unnecessarily bulky at low frequencies. Helmholtz resonators with adjustable neck areas have also been considered, although not widely implemented [6–11].

Yoda and Konishi [12] developed an adaptive–passive Helmholtz resonator where the control system comprised a look-up table for the appropriate position of the linear actuator used to tune the Helmholtz resonator to a particular frequency. Calibration of the system was required before use and would not be suitable where the speed of sound varied, such as in an engine exhaust.

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Nagaya et al. [7] described a dual Helmholtz resonator system that was used to reduce the noise from a blower. The cost function that was minimized by the adaptive algorithm was the amplitude of the Fast-Fourier Transform (FFT) of the signal from a single microphone adjacent to the mouth of the device. One benefit of their system is that only one microphone was required, rather than two microphones that are required for cost functions that use transfer function measurements. One of the disadvantages of their method is that several FFT averages of the fluctuating sound pressure level are required before a decision can be made by the adaptive algorithm of which direction the actuator should rotate.

There is less published research literature about adaptive quarter-wave tubes.

Kashani and Monfort [13] described an adaptive acoustic radiator that could be used to control combustion instabilities. It was proposed that their control algorithm could also be applied to adaptive Helmholtz resonators and adaptive quarter wave tubes.

Howard and Craig [14] experimentally tested a manually adjustable quarter-wave tube for use on the exhaust gas stream of a V6 petrol engine and attained approximately 15 dB attenuation. During this work, the in-duct exhaust noise from the engine was digitally recorded. The recording was replayed through a loudspeaker into another experimental rig that had an adaptive quarter-wave tube and obtained about 25 dB of attenuation.

The work presented here is the continuation of this initial work where an adaptive quarter-wave tube system is used to attenuate the noise at the engine firing frequency on a large diesel engine. This paper describes the development of an adaptive quarter-wave tube side-branch resonator system that is able to adapt to changes in engine speed, engine load, and exhaust gas temperature. A novel contribution from this work is the demonstration that the sliding-Goertzel algorithm can be used successfully to calculate the phase angle between a pair of microphones in a realistic acoustic environment that contains multiple harmonics, varying frequency of the tonal exhaust noise, and hot flowing exhaust gas.

The contents of this paper describe the theory of a quarter-wave tube, description of the experimental apparatus, tests that were conducted and presentation of experimental results that demonstrate the effectiveness of the adaptive quarter-wave tube and the sliding-Goertzel algorithm.

3. Experimental apparatus

The diesel engine used for the experiments is a four stroke, direct injection, Mercedes Benz OM502LA, PP1066 Power drive Unit. The engine configuration is a 90°-V8, with air-to-air intercooled twin-turbochargers and displacement of 15.93 l. The continuous rated power is 350 kW (469 hp).

The engine was loaded using an engine-mounted water brake dynamometer (Taylor Dynamometer model TD-3100) attached to the flywheel of the engine. The water flow was controlled using a PC based Taylor Dynamometer DynPro data acquisition and control system.

The diesel engine was installed within an acoustically lined 20-foot shipping container. The exhaust system was routed through a hole in the roof of the enclosure then turns 90° and extends horizontally along the roof of the acoustic enclosure, as shown in Fig. 1. A side-branch of the main exhaust connects the adaptive quarter-wave tube system. A passive muffler is attached at the end of the exhaust.

The AQWT is attached to a 4.5-in. diameter section of the exhaust pipe via a side-branch, which is positioned approximately 1.8 m from the downstream flange of the 0° elbow at the enclosure penetration. The side-branch geometry had a bell-mouth shape and was connected to the main exhaust duct at 90°. It was found that the shape of the throat in the side-branch was very important, and the bell-mouth shape gave the greatest noise reduction [15]. Due to the limited area available on the roof of the acoustic enclosure, a 90° bend was used on the side-branch resulting in the AQWT being parallel to the exhaust pipe, as shown in Figs. 1 and 2.

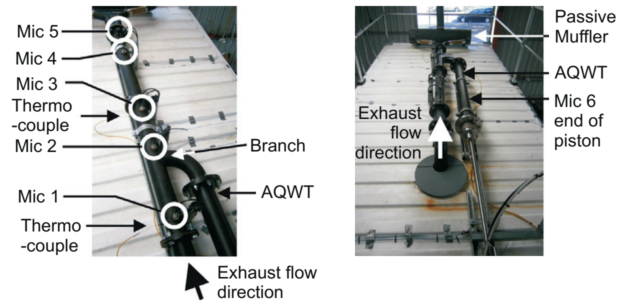

Fig. 1. Photograph of the installed exhaust system showing the adaptive quarter-wave tube, positions of the water cooled microphones, thermocouples, and passive muffler.

Fig. 2 shows a schematic of the adaptive quarter-wave tube, where a side-branch is connected to the main exhaust duct, and a variable length tube forms the quarter wave tube. A linear actuator is used to position the piston along the bore of the tube, and hence changes the acoustic path length of the quarter wave tube. The AQWT is tuned by adjusting the length of the tube until the phase angle at the cylinder firing frequency of the transfer function between the two microphones Mic. 2 and Mic. 6, shown in Fig. 2 is −90°.

The sound in the exhaust was measured using microphones (PCB model 106B) housed within custom-made water-cooled jackets. The microphone was mounted such that its face was flush with the internal diameter of the exhaust pipe. The water-cooled adapters maintain the microphones at about 40 °C, when exposed to exhaust gas temperatures of around 450 °C.

3.1. Control system and actuator

The control system comprises a micro-processor (DSpace model 1104) that implements a control algorithm, two microphones, a tachometer, and a ball-screw linear actuator that is used to position the piston in the AQWT.

The tachometer comprised four magnets attached at equal spacing to the flywheel of the diesel engine, and a magnetic sensor that generated a digital (TTL) signal indicating when a magnet had passed the sensor. The DSpace micro-processor was used to measure the timing between the pulses and estimated the rotational and cylinder firing frequency of the engine.

The cost-function evaluation for this system is based on the phase angle of the frequency response function between a microphone in the face of the piston of the AQWT (Mic. 6 in Fig. 2 and a microphone installed in the main duct (Mic. 2 in Fig. 2). The adaptive algorithm adjusts the position of the piston until the phase angle is −90°. It was shown in Ref. [2] that the sliding-Goertzel

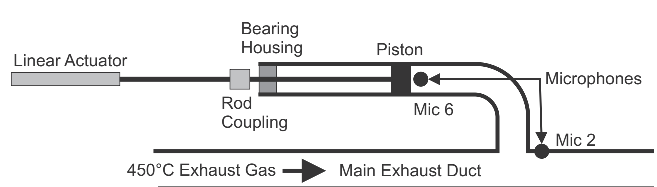

Fig. 2. Schematic of the exhaust system and the adaptive quarter-wave tube.