Adaptive quarter wavelength tube tuned by varying air temperature

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ABSTRACT

An Adaptive Quarter-Wavelength Tube (AQWT) that can be tuned by varying the air temperature was simulated with both a 90° notched and bell-mouth t-piece using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). The QWT was tested experimentally to determine the noise reduction that could be achieved at the fundamental firing frequency of an internal combustion engine (ICE). Electrical air heaters injected hot air into the QWT that varied the speed of sound of air and therefore varied the tuned length of the tube. Results showed that the fundamental firing frequency could be attenuated by approximately 5 dB over a 65-75 Hz range by varying the air temperature within the QWT.

Keywords: Adaptive, QWT, Exhaust   I-INCE Classification of Subjects Number(s): 37

1. INTRODUCTION

A Quarter Wavelength-Tube (QWT) is a device that can attenuate tonal noise within a duct at fundamental and odd-harmonic frequencies. As the length of the QWT is one quarter of an acoustic wavelength of the fundamental frequency, a standing wave forms within the QWT which causes destructive interference within the main duct, providing noise reduction from inlet to outlet. This method can provide high levels of attenuation at a single tone when compared to conventional dissipative mufflers. To attenuate a range of tones with a QWT, an Adaptive Quarter-Wavelength Tube (AQWT) system that has a method to change the fundamental frequency is required. The work presented here considers varying the temperature of the gas within the tube, this varies the speed of sound and therefore the acoustic wavelength of the fundamental frequency.

The system was initially developed through the use of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) which provided the fundamental attenuation frequencies of the system when considering exhaust gas from the engine and injection of air from electrical process heaters along the QWT. This was followed by experimental demonstrations that confirmed that changing the gas temperature within the QWT altered the tuning frequency and was able to attenuate the noise at the fundamental firing frequency of the engine over a range of engine speeds.

2. BACKGROUND AND PREVIOUS WORK

The fundamental firing frequency is the main contributor of the noise produced by an Internal Combustion Engine (ICE) (1). There are many methods to reduce the overall noise produced by an ICE the most conventional way is through the use of mufflers. A muffler provides broadband noise control through the use of baffling plates, expansion chambers, and absorptive materials however a QWT can provide greater noise reduction at the fundamental acoustic frequency (2). This frequency is determined by the length of the QWT and the speed of sound inside the tube both of which may be varied in an adaptive system and is related to the piston firing frequency as,

$$f_{\text{engine}} = \frac{\text{RPM}}{60} \times \frac{\text{Pistons}}{2} \text{ Hz}\,, \tag{1}$$

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where RPM is the measured revolutions per minute of the engine and Pistons is the number of pistons in the engine. The QWT has an attenuating resonance frequency given by,

$$f_{\text{QWT}} = \frac{c}{4L} \text{ Hz}\,, \tag{2}$$

where c is the speed of sound and L is the effective length of the QWT. The speed of sound is related to the temperature of the medium,

$$c = \sqrt{\frac{\gamma R T}{M}} \text{ m/s}\,, \tag{3}$$

it is assumed that the gas properties are of air, where $\gamma = 1.4$ is the ratio of specific heat, R = 8.314 J.mol^{-1}.K^{-1} is the molar universal gas constant, M = 0.02857 kg.mol^{-1} is the average molar mass, and T is the temperature in Kelvin.

A previous attempt at designing an AQWT exhaust silencer used a sliding piston mechanism (3) to change the length of the QWT. The use of the sliding piston mechanism provided high levels of noise reduction at the cylinder firing frequency. The overall length of the device comprised of the length of the QWT, the length of the piston, and a similar length for the actuator, and hence the overall length was slightly more than three times the length of the QWT. Although this design could have been made more compact by installing the actuator adjacent to the QWT, this still would have resulted in a device that was twice the length of the QWT. In the proposed device there is no piston–actuator system, the overall length of the device is approximately the length of the QWT, and hence is significantly more compact that the variable length piston AQWT. Therefore changing only the temperature of the gas within the QWT was chosen as the method of changing the attenuation frequency of the AQWT. Using heat as the method of tuning a QWT has not been experimentally tested before.

The two fundamental geometries that affect the attenuation performance of the QWT are the diameter ratio between the main exhaust duct and the QWT and the length of the QWT. Beranek and Ver have shown the width of the attenuation bell curve changes as the diameter ratio changes (4). As shown in Figure 1, the smaller the ratio the wider the bell curve gets, thus achieving a wider attenuation range. Therefore the diameter ratio between the QWT and the main duct should be as large as possible (i.e. the QWT diameter should be larger than that of the main duct). In practice the QWT is limited to having the same diameter as the main duct.

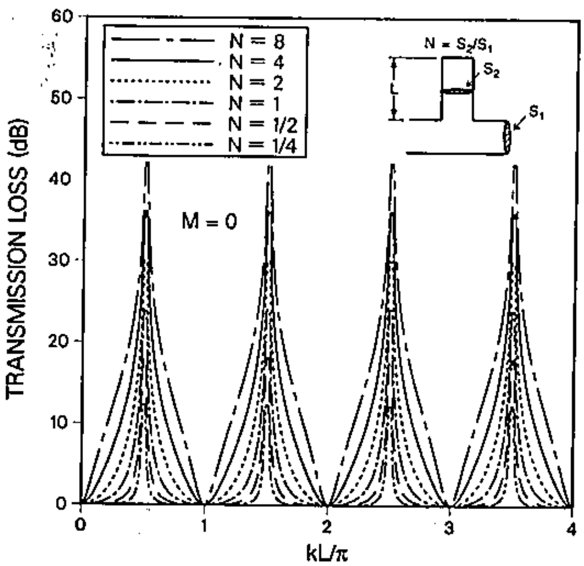


Figure 1 – Predicted transmission loss with respect to main duct and QWT diameter (4)

Previous attempts also showed that different geometries of the branch to the QWT affected the attenuation and the resonance frequency of the QWT. It was experimentally shown that a bell-mouth provided greater attenuation performance when compared to a notched branch geometry (5). Thus these two geometries were used in simulations and the notched QWT was experimentally tested.

3. SIMULATION METHODS

Temperature distributions within a QWT attached to an engine exhaust have shown to have large variations in temperature (6). This creates complexity in providing an analytical solution for the expected response of the system using equations 1, 2 and 3. Numerical methods were used to calculate the attenuation capabilities of the system using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) which used CFX and Mechanical packages in ANSYS 14.5 respectively. CFD was used to calculate the temperature distribution and Finite Element Analysis (FEA) was used to calculate the acoustic response of the system using pressure formulated elements. In both analyses, 3D models were used with a 2.5" Diameter, 1510 mm QWT to match the experimental configuration and mesh density sufficiently refined for accurate solutions.

3.1 Computational Fluid Dynamics Analysis

The purpose of conducting the CFD analysis was to provide an understanding of flow characteristics and expected gas temperature distributions in a QWT when considering fluid flow from an engine and two air process heaters evenly distributed along the QWT, as shown in Figure 2. The calculated temperature distributions in the ducts were mapped onto the acoustic finite element model of the system, which in turn adjusts the speed of sound properties of the gas. The results from the CFD analysis also determined flow characteristics in the proposed AQWT system.

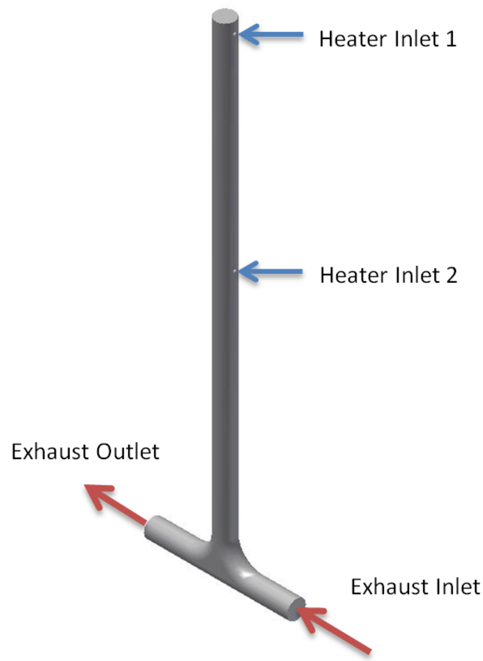


Figure 2 – ANSYS model

The analysis of the AQWT was a steady state, thermal energy analysis which used the shear stress transport turbulence model. A set of boundary conditions were derived from specification of components in the physical system and preliminary testing. These included conditions for walls, inlets and outlets. Inlets and outlets on the system are shown in Figure 2. The vertical pipe and capped end form the wall of the QWT and the horizontal pipe forms the wall for the exhaust duct. Air injected into the QWT was varied from 20° C to 200° C, which was the maximum gas temperature that could be obtained from the electrical gas heaters used in the experimental apparatus. Walls were specified with an overall heat transfer coefficient calculated using geometry and average temperatures from experiment. Table 1 contains a list of boundary conditions used in the models.

Table 1 – Specification summary

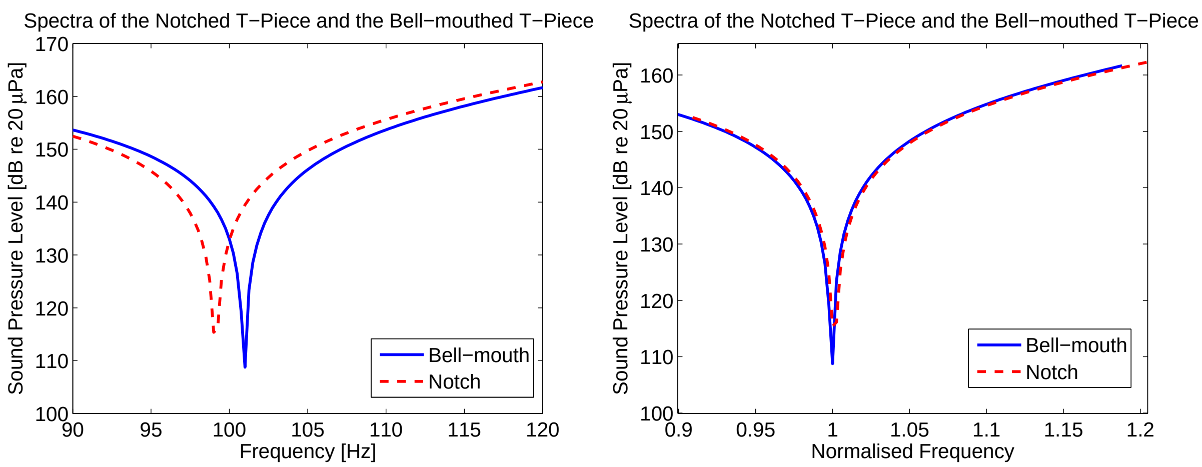
Inlets	Outlets	Walls
<u>Heaters</u> Temperature (° C)= 20, 70, 120, 200 Velocity (m/s)= 21.22 (100 LPM through a 10 mm diameter inlet) <u>Exhaust Inlet</u> Temperature (° C) = 600 Velocity (m/s) = 34.54 (From specified operating frequency, 2.5" pipe)	<u>Exhuast Outlet</u> Relative Pressure (Pa) = 0 (Ambient)	<u>QWT</u> $T_{ambient}$ (° C) = 20 Heat Transfer Coefficient (W/m^{2}K) = 0, 1.33, 1.86, 2.32 for each heater inlet temperature respectively <u>Exhaust Duct</u> $T_{ambient}$ (° C) = 20 Heat Transfer Coefficient (W/m^{2}K) = 8.88

From the CFD analysis it was shown that the gradient of the temperature distribution within the QWT from the top to the bottom was small. There was some recirculation within the QWT however there was little mixing and recirculation at the branch of the QWT. The air flow from the heaters on the QWT had minimal effect on the flow of the exhaust gases on the primary duct and was shown to reduce engine back pressure. The temperature distributions found on the midplane of the QWT are shown in figure 7.

3.2 Finite Element Analysis

Several Finite Element Analyses (FEAs) were conducted were conducted to assess the expected acoustic response of the QWT. These analyses used boundary conditions obtained from specification, initial testing and CFD to determine theoretical attenuation ranges and performance of the QWT.

The initial analysis focused on a constant temperature (600° C) harmonic analysis to determine the acoustic differences between the notched 90° and the bell-mouth QWT inlet geometry. It was found that there was no difference in the shape of the attenuation curve however with the same QWT length, the bell-mouth geometry provided a lower attenuation frequency as shown in Figure 3. This is due to an increase of the effective QWT length. The difference in the magnitude of the minimum SPL is due to the resolution of the analysis. The acoustic excitation method used was an acoustic normal surface velocity of 34.54 m/s. The model also used anechoic inlet and outlet terminations.



(a) Differences in T-piece geometry Performance (b) Comparison of normalised attenuation shape

Figure 3 – Notched vs bell-mouth T-piece

The final Finite Element Analysis used the temperature distributions calculated from the CFD analysis as boundary conditions for the FEA of the duct with the bell-mouth geometry. A harmonic analysis was conducted to determine the attenuation range of the system. When varying the air inlet temperature into the QWT from 20° C to 200° C a theoretical attenuation range of between 59 Hz to 70 Hz was shown. This theoretically corresponds to a speed range on the 6-cylinder engine used in this work of approximately 200 RPM.

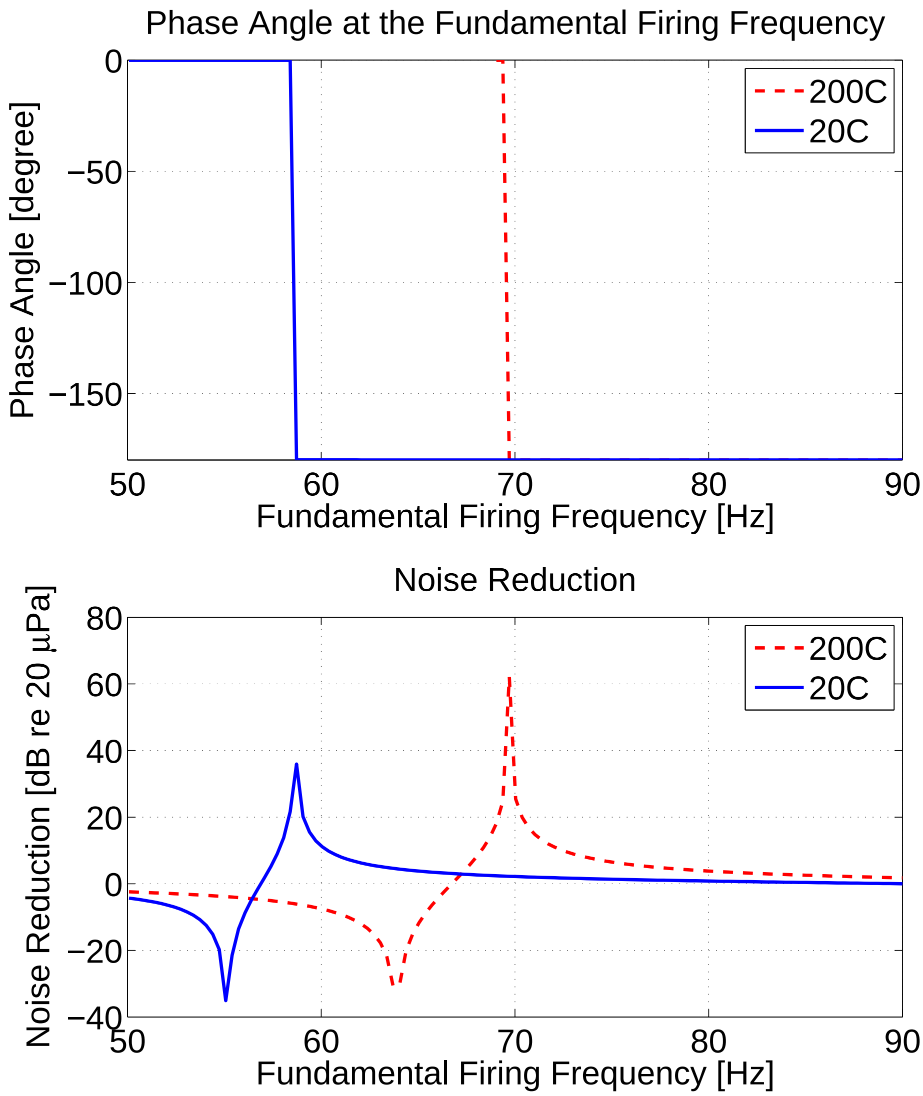


Figure 4 – Effects of varying heater inlet temperature on SPLs at the outlet of the main duct and the phase angle change

4. EXPERIMENTAL DEMONSTRATION

To demonstrate the attenuation capabilities of the QWT, an apparatus was setup as shown in Figure 5. A diagrammatic representation of the experimental setup can be seen in Figure 6. This used the notched 90° QWT with air injected along the QWT at temperatures from ambient to 200° C, which is the maximum air temperature that could be obtained with the electrical heaters. The AQWT was attached to the exhaust of a 3.5 L V6 Mitsubishi engine which was coupled to a dynamometer. The QWT was partially wrapped in fibreglass lagging to minimise thermal losses.

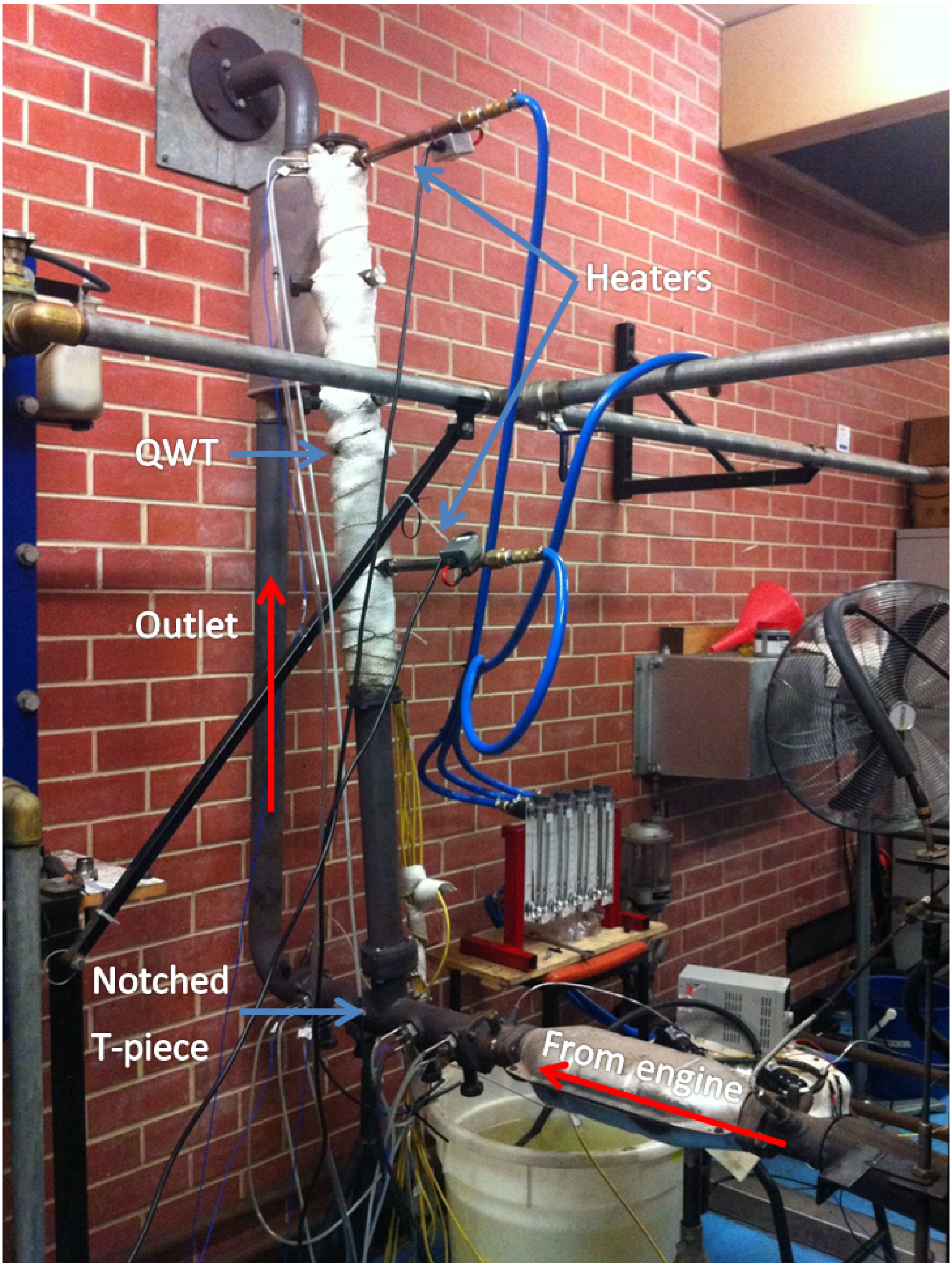


Figure 5 – Experimental setup

For testing, the heaters were used with an air flow of 100 LPM each, measured with variable area flow-meters. A total of four PCB106B microphones were used to record SPLs throughout, with microphone 1 being located upstream, microphone 2 and 3 being located downstream and microphone 4 being located at the top of the QWT. In addition three k-type thermocouples along the main duct and six along the length of the QWT were used to record temperatures to compare experimental results to simulations.

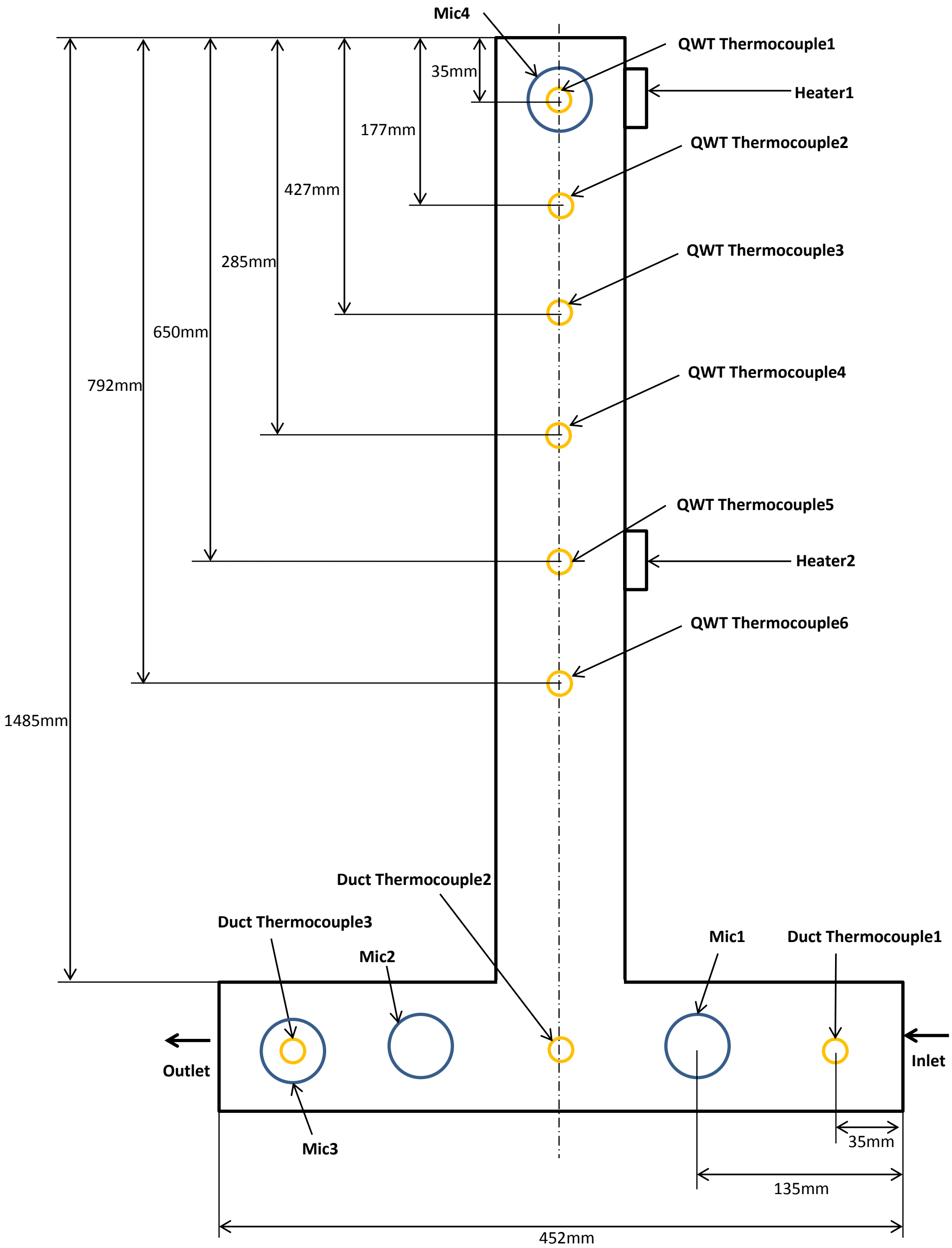
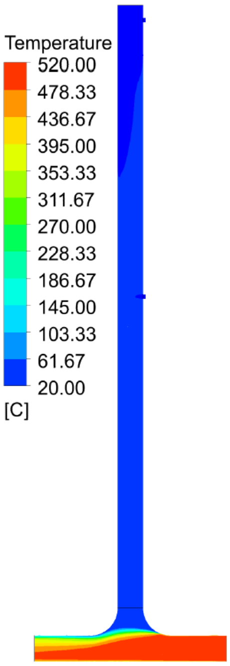


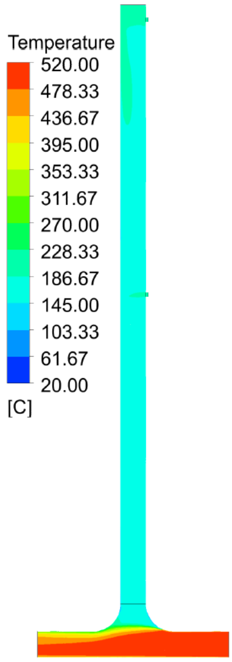
Figure 6 – Setup diagram

4.1 Results

The temperature of the gas within the exhaust duct and the QWT was measured throughout the experiment which was used to produced the temperature distribution plots in Figure 8. These plots were achieved by linearly interpolating the measured temperatures from the thermocouple positions shown in Figure 6. Comparing these plots to those obtained from the CFD analysis shows a lower temperature throughout the QWT which may be attributed to the experimental setup not reaching steady state.

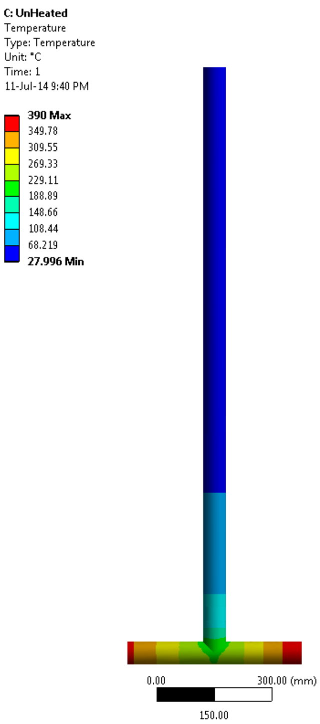


(a) 20° C heater inlet temperature

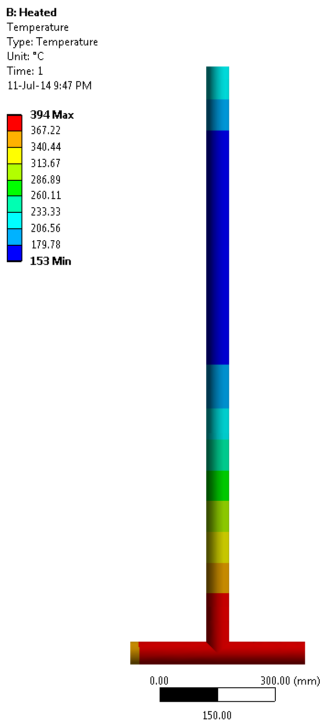


(b) 200° C heater inlet temperature

Figure 7 – Temperature within the exhaust duct system calculated using CFD



(a) 20° C heater inlet



(b) 200° C heater inlet

Figure 8 – Experimental temperature distributions at 1500 rpm

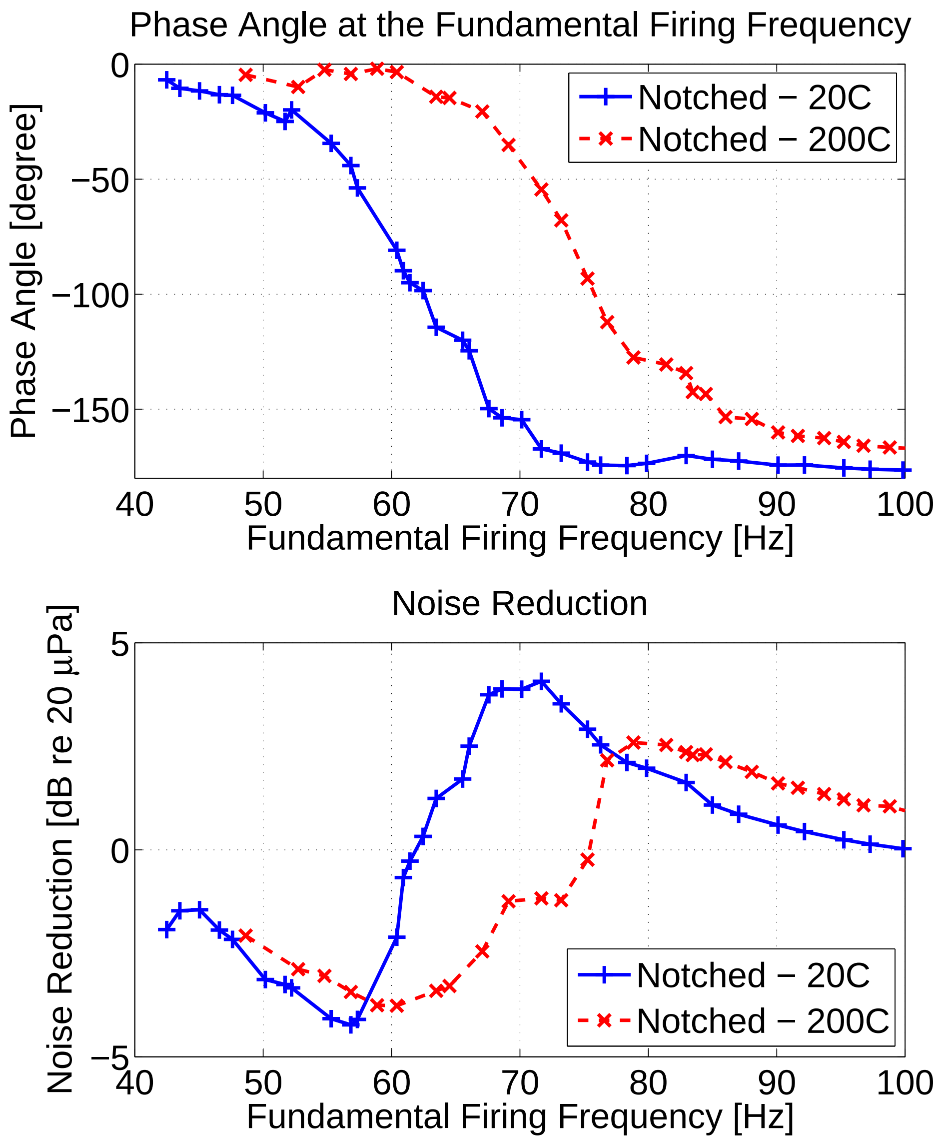


Figure 9 – Experimental noise reduction and phase angle vs firing frequency

The experimental acoustic results shown in Figure 9 show the noise reduction within the main duct as measured from upstream to downstream as well as the acoustic phase difference as measured from microphone 2 to microphone 4. The noise reduction was measured as the decrease in the average sound pressure level of the two downstream microphone measured from the upstream microphone. As the exhaust duct was highly reverberant it was impractical to measure insertion or transmission loss. This was a practical limitation of the current experimental setup. The maximum noise reduction occurred approximately 5 Hz after the acoustic phase angle was negative 90°. This was attributed to the positioning of microphone 2 which was downstream from the bottom of the QWT. The magnitude of the noise reduction obtained was much less than theoretically calculated. It was also demonstrated that by heating the QWT to 200° C the attenuating frequency could be shifted by approximately 10 Hz. This matches closely to the simulated attenuation range as seen in Figure 4. The frequency at which maximum noise reduction occurs from experimental results is slightly different to that obtained from simulations. The simulations showed maximum attenuation to occur at 60 Hz and 70 Hz for ambient and 200° C air being injected into the QWT respectively. The experimental results showed maximum attenuation frequencies of 68 Hz and 76 Hz respectively. This difference is attributed to the temperature of the QWT during the experiment being slightly higher than the QWT used in the simulations.

5. CONCLUSION

An Adaptive Quarter-Wavelength Tube to attenuate the noise at the fundamental firing frequency from an internal combustion engine was developed, which operated by varying the temperature of gas within the tube. The system was developed using CFD and FEA, and then tested experimentally. The simulations showed that no difference in performance was expected between a notched 90° branch and bell-mouth inlet geometry, however the bell-mouth did increase the effective length and therefore reduced the attenuation frequency. It was predicted using CFD and FEA that by varying the gas temperature within the QWT from 20° C to 200° C would cause a change in the attenuation frequency of the QWT from 60Hz to 70Hz – a 10Hz range, that corresponds to a 200 RPM speed variation in the 6-cylinder engine tested. This was comparable to that shown by experimental demonstration with an attenuation range of 8 Hz. The noise reduction achieved by the QWT as measured from upstream to downstream was less than that of simulations. The experimental results showed a maximum noise reduction of approximately 2.5 to 4.5 dB.

6. ACKNOWLEDGEMENTS

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