



Tonal noise attenuation in ducts by optimising adaptive Helmholtz resonators

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Dedicated to my parents, Sardar Jagmehar Singh and Sardarni Pawinder Kaur, and
my siblings, Arvinder and Gurwinder

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Abstract

Tonal noise propagating in ducts and radiating from their outlets is a common problem in situations where a fan or a blower is used to drive exhaust gases through the exhaust duct out to the environment. It is also a problem in the exhausts of large diesel engines such as those used to power large marine vessels. One way of attenuating tonal noise propagating in ducts is to use one or more side branch resonators, each of which is specifically designed for optimal performance at a particular frequency.

One of the major problems associated with the use of side branch resonators is that any slight change in excitation frequency decreases the effectiveness of the resonators. The change in excitation frequency can be caused by a change in the speed of the engine, fan or blower, or change in temperature in the duct, which changes the speed of sound, and hence the wavelength of the noise. Resonators incorporating a provision for altering their geometry in real-time in order to adapt to environmental or operating condition changes is one approach that has been used by previous researchers. In particular, adaptive Helmholtz resonators have received considerable attention in the literature.

Previous work has involved the use of one or more pressure sensors located in the duct downstream of the resonator to provide a cost function to be minimised by an electronic control system which alters the geometry of the resonator. However, in many cases, especially where the duct serves as a passage for exhaust gases to be driven out to the environment, it is not desirable to mount microphones in the duct. Also, microphones located remote from the resonator introduce wiring problems as well as the need to mount the microphones at the correct location in the duct, which will change as the wavelength of the tonal noise in the duct changes as a result of changes in operating or environmental conditions. It is highly desirable to have a completely self-contained Helmholtz resonator (HR) which can be attached to the duct and for which the only external wiring needed is the power supply.

The work described in this thesis is concerned with the development of a self-contained adaptive HR which can be optimally tuned by using signals from two mi-

crophones located in the cavity and neck of the resonator, respectively. The primary focus of the work is the development of a novel cost function, which can be used by an electronic controller to optimally tune the HR. The scope of the analysis has been restricted here to the ‘no mean flow’ condition.

The theoretical and numerical analysis of the duct-HR system is first conducted using the well known transfer matrix method and finite element analysis (FEA) software package ANSYS, respectively. The net acoustic power transmission in the duct downstream of the HR is estimated by using the two-microphone method. Analysing the duct-HR system with the transfer matrix method mandates the incorporation of three end-correction factors which are related to the unflanged open end of the duct, neck-cavity interface and neck-duct interface. However, because of the complexity in estimating the end-correction factor of the neck at the neck-duct interface due to the generation of a complex sound field in the vicinity of the neck opening, the transfer matrix method only approximates the in-duct net acoustic power transmission. This implies that changing the value of the neck-duct interface end-correction factor changes the calculated frequency at which the maximum reduction of in-duct net acoustic power transmission downstream of the HR occurs. On the other hand, ANSYS does not require the inclusion of any kind of end-correction factors apart from the actual physical dimensions of the system, and is thus much more accurate than the transfer matrix method.

To minimise the in-duct net acoustic power transmission downstream of the HR, a number of different cost functions that were related to the net acoustic power transmission were investigated theoretically, numerically and experimentally. These all involved either the acoustic pressure at the top of the closed end of the cavity of the HR or at the neck wall of the HR close to the neck-duct interface or the amplitude of the pressure transfer function between two microphones located in the resonator. The two potential cost functions which were initially considered to be maximised for indicating the minimisation of the in-duct net acoustic power transmission downstream of the resonator

were: *(a)* the pressure at the top of the closed end of the cavity, and *(b)* the amplitude of the pressure transfer function between the pressure at the top of the closed end of the cavity and the pressure at the neck wall close to the neck-duct interface. It was found that the location of the microphone in the neck was extremely important, with the best location being at the centre of the duct adjacent to the neck opening. However, this location was not considered practical because a microphone in the duct can obstruct the mean flow of gas in the duct. The best location for mounting the microphone in the neck was found to be at the neck wall as close as possible to the neck-duct interface.

The results are shown in two different ways: (1) *broadband analysis*, whereby the in-duct net acoustic power transmission downstream of the HR, the pressure at the top of the closed end of the cavity and the pressure transfer function between the pressure at the top of the closed end of the cavity and at the neck wall close to the neck-duct interface are plotted as a function of frequency, and (2) *single frequency analysis*, whereby all the aforementioned results are plotted as a function of the cylindrical cavity length (for a fixed cavity diameter) for a single, tonal frequency.

For broadband analysis, the numerical (ANSYS) results showed that the frequency at which the maximum reduction of in-duct net acoustic power transmission downstream of the HR occurs differs from the frequencies which correspond to the maximum responses of cost functions *(a)* and *(b)* described above. For single frequency analysis, when trying to optimise the performance of a duct-mounted HR at a particular frequency by altering its volume, the optimal dimensions of the HR required to attain the maximum reduction of in-duct net acoustic power transmission at that frequency differ from the dimensions of the HR which correspond to the maximised responses of the cost functions *(a)* and *(b)*. These results were validated experimentally using a 3 m long circular duct of 0.1555 m diameter with an attached cylindrical HR. During the experimental work, only plane waves were propagating down the duct and there was no mean flow in the duct.

Instead of only focusing on the amplitude of the pressure transfer function between the pressures at the top of the closed end of the cavity and the pressure at the neck wall close to the neck-duct interface, the phase difference between the same locations in the HR was also considered. It was found that the phase difference depends on the quality factor (or damping) of the entire acoustic system. Experiments were conducted with varying dimensions of the HR and two novel cost functions were empirically derived. Both cost functions, which does not include any kind of measurement remote from the HR, are based on the damping (or the quality factor) of the duct-HR system and the phase difference between the pressure at the top of the closed end of the cavity and the pressure at the neck wall close to the neck-duct interface. The effectiveness and performance of both cost functions were found to be excellent for minimising the in-duct net acoustic power transmission downstream of the HR. However, the second cost function is preferred because the procedure involved for measuring the system damping is more convenient from the practical point of view than the procedure for the first one.

The quality factor of the duct-mounted HR, at the frequency at which noise needs to be attenuated, was determined by tuning the length of the cavity of the HR so as to maximise the amplitude of the pressure transfer function of the HR. This estimated quality factor was found to be directly related to the transfer function phase which corresponds to the minimum in-duct net acoustic power transmission at the tonal frequency. Once this optimum transfer function phase is known, an active control system can be used to drive a motor to adjust the cavity length of the HR to achieve the optimum phase.

Statement of Originality

To the best of my knowledge and belief, all the material presented in this thesis, except where otherwise referenced, is my own original work, and has not been published previously for the award of any other degree or diploma in any university. If accepted for the award of the degree of Master of Engineering Science, I consent that this thesis be made available for loan and photocopying.

Sarabjeet Singh

Date:

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“Waheguru Ji Ka Khalsa, Waheguru Ji Ki Fateh”

(The Khalsa belongs to God, victory belongs to God)

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