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SUPPRESSION OF ACOUSTIC RESONANCE IN PIPELINES USING HELMHOLTZ RESONATORS

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ABSTRACT
The effectiveness of Helmholtz resonators (HRs) inserted in various configurations along a pipeline system is investigated under conditions of acoustic resonance. It is shown that the acoustic damping achieved by a single, large volume HR can be achieved using multiple, smaller HRs. The attenuation is found to be dependent upon the location of the HR along the standing wave, with maximum attenuation achieved at the acoustic pressure antinode and minimal attenuation at the node. The results show that the strategic placement of relatively small HRs can be used instead of a single, large HR where high magnitudes of damping are required. Mean flow introduced into the pipeline is shown to slightly reduce the effectiveness of the HRs. The results show the potential for using HRs in industrial systems, where mean flows are present and space may be limited.

NOMENCLATURE

HR	Helmholtz resonator
c	Speed of sound (m/s)
ρ	Density (m^3/s)
A	Cross-sectional area of HR (m^2)
V	Cavity volume of HR (m^3)
l_{eff}	Effective HR neck length (m)
S	Cross-sectional area of test pipe (m^2)
$T_{11}, T_{12}, T_{21}, T_{22}$	Transfer matrix coefficients
TL	Transmission loss
IL	Insertion loss

INTRODUCTION
Acoustic pressure pulsations in pipeline systems are generated by centrifugal or reciprocating turbomachinery, such as pumps or compressors (Hayashi and Kaneko [1]). These pulsations propagate into the piping system, where they may be amplified and reach sufficient amplitude to cause increased fretting wear or even fatigue failure of system components (Shaaban et al.[2]). In order to mitigate the effects of acoustic pressure pulsations, different damping techniques have been investigated in the literature. Passive damping devices (Sadek et al. [3]) are often preferred to active or hybrid solutions because of their simplicity and cost effectiveness, especially when adaptability to changing operating conditions is not required. However, the effects of industrial operating constraints, such as limited access to piping and high mean flow rates, make it difficult to incorporate well-established damping techniques into industrial systems. In this study, a passive damping device known as the Helmholtz resonator (HR) is used in various configurations to investigate the optimal use of HRs to damp acoustic resonance in pipelines.

The Helmholtz resonator consists of an enclosed volume with a protruding neck that connects to a system of interest as a sidebranch. Using the well-known lumped parameter model of an HR (Ingard[4], Abdelmwgoud et al. [5]), its resonant frequency is expressed as a function of its volume and neck dimensions, i.e.

$$f = \frac{c_0}{2\pi}\sqrt{\frac{A}{V \cdot l_{eff}}} \tag{1}$$

where c_0 is the speed of sound, A is the cross-sectional area of the neck, V is the cavity volume, and l_{eff} is the effective neck length. If the excitation in the pipeline, i.e. over the neck opening of the HR, matches the HR's resonant frequency, the mass of fluid in the neck oscillates while the volume of fluid in the cavity compresses and rarefies, acting as a stiffness. Therefore, an HR can be tuned to target a frequency so that some of the acoustic energy in the pipe at that frequency is dissipated via the viscothermal and radiation losses that occur within the resonator (Kinsler [6]).

HRs have been studied in some depth because of their geometric simplicity and ability to target low frequencies while maintaining relatively small physical dimensions (Cora et al. [7]). Early studies focused on improved methods for predicting the resonant frequencies of HRs (Ingard [3]), some of which considered the effects of different neck and cavity geometries without using the lumped-parameter model (Alster [8]). More recently, investigations have been carried out into the use of multiple HRs in order to increase the frequency band of attenuation (Wang and Mak [9], Zhao and Morgan [10]). The effects of mean flow have been noted to shift the resonant frequency of an HR (Anderson [11]), but little is said regarding the effect of mean flow on the magnitudes of damping. For the problem of acoustic pressure pulsations in pipeline systems, it is of interest to obtain significant damping at a discrete frequency in the presence of mean flow, with minimal impact on pipeline operation. There are often geometric restrictions in industrial systems, limiting the access for installation of HRs. Additionally, nearly all of the literature has focused on off-resonance conditions, and the effectiveness of HRs in resonant pipelines should be clarified. It is therefore of interest to investigate the use of compact damping devices, in this case HRs, and evaluate the damping achieved by various configurations under conditions of acoustic resonance.

EXPERIMENTAL SETUP AND METHODS

An open air loop test pipe was constructed so that its length corresponds to the fifth longitudinal acoustic mode of the 150 Hz frequency. The pipe diameter is 10 cm. Mean flow is driven by a centrifugal blower, which is acoustically isolated from the test pipe using an absorptive muffler. The test section is shown in Fig. 1. Multiple HRs in various configurations can be installed into the test section, and the acoustic performance of the devices is performed using both transmission loss and insertion loss measurements. The HRs used are circular concentric HRs.

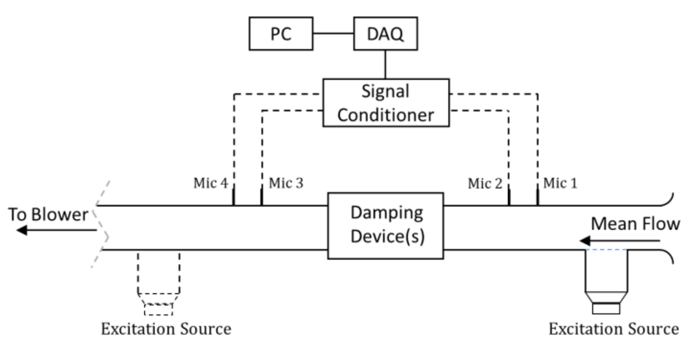

FIGURE 1: SCHEMATIC OF EXPERIMENTAL SETUP.

The transmission loss (TL) quantifies the acoustic attenuation of a damping device independent of the source or end termination characteristics. Transmission loss measurements were used to characterize the damping devices, ensuring that each HR obtained maximum attenuation at the 150 Hz frequency. In order to evaluate transmission loss, the two source-location method described by Munjal and Doige [12] was utilized. For a particular damping device configuration, measurements were first taken with the excitation source at one end of the test section, and then at the other end. Both measurements are analyzed to obtain the transfer matrix of the acoustic element, i.e. the damping device(s), from which the transmission loss is calculated using

$$TL = 10\log\left(\frac{1}{4}\left[T_{11} + \frac{S}{\rho c_0}T_{12} + \frac{\rho c_0}{S}T_{21} + T_{22}\right]^2\right) \qquad (2)$$

where T_{11}, T_{12}, T_{21}, and T_{22} are the transfer matrix coefficients, S is the cross-sectional area of the test pipe, ρ is the fluid density, and c_0 is the speed of sound.

Although transmission loss measurements are useful to quantify the attenuation achieved by devices independent of system characteristics, this also means that they are insufficient for measuring the effect of a damping device on a resonant system. Indeed, acoustic resonance is a property of the pipeline end terminations. Therefore, insertion loss (IL) measurements were taken to determine the effect of HRs on the resonant pipeline. Insertion loss measurements are calculated using:

$$IL = SPL_1 - SPL_2 \qquad (3)$$

where SPL_1 and SPL_2 denote the sound pressure level measurements taken before and after the damping device is inserted, respectively. Measurements are taken the same location acoustically downstream of where the damping device is to be inserted. Insertion loss measurements capture the effects that the HRs have on the resonant system.

RESULTS AND DISCUSSION

The transmission loss of HRs with different cavity volumes were evaluated to compare the relative magnitudes of damping. In order to tune the HRs, the cavity volumes were adjusted in conjunction with changes to the neck lengths, so that all HRs were tuned to target the 150 Hz frequency. The number of HRs was increased by placing additional HRs circumferentially around the test pipe, as shown in Figure 2. Multiple HRs were used to increase the damping at 150 Hz, in contrast to much of the existing literature which considered multiple devices in order to increase the bandwidth of attenuation.

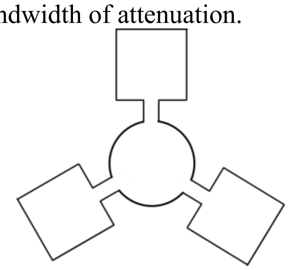

FIGURE 2: SCHEMATIC OF MULTIPLE HRS INSTALLED CIRCUMFERENTIALLY AROUND PIPE.

Figure 3 shows the transmission loss of 0.33 L and 1 L volume HRs extracted at the 150 Hz frequency. It can be seen that a single 0.33 L HR yields a TL of nearly 5.5 dB while a 1 L HR achieves a TL of approx. 11.5 dB. This shows that a single, relatively large-volume HR can achieve comparatively high magnitudes of damping. The transmission loss increases as HRs are added, showing a nearly linear trend. This finding shows that multiple HRs that are tuned to target the same frequency can be used to increase the magnitudes of damping. It is interesting to note that three 0.33L HRs achieve a TL of approx. 12.4 dB, which is slightly higher than that of a single 1 L HR, which yield a TL of 11.5 dB. In other words, multiple small-volume HRs can be used in place of a large-volume HR with equivalent total volume when large damping magnitudes are required. This is analogous to "splitting up" a single, relatively large HR into multiple smaller ones. In contrast to existing literature, the use of multiple HRs can increase the magnitudes of damping at a discrete frequency of interest, instead of increasing the frequency band of attenuation. This finding is also useful considering that the linear dimensions of a device are limited to a quarter wavelength to ensure that standing waves do not form within the device (de Bedout [13]).

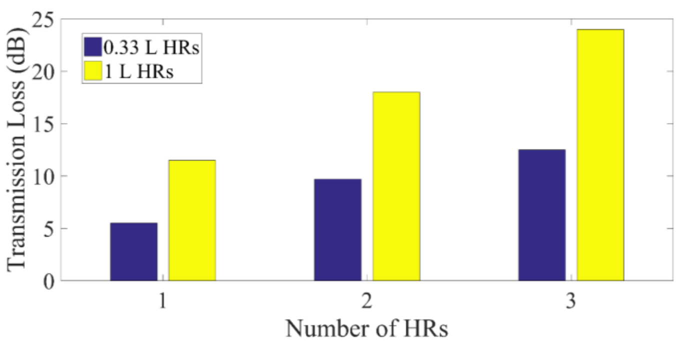

FIGURE 3: TRANSMISSION LOSS OF MULTIPLE HRS WITH DIFFERENT CAVITY VOLUMES.

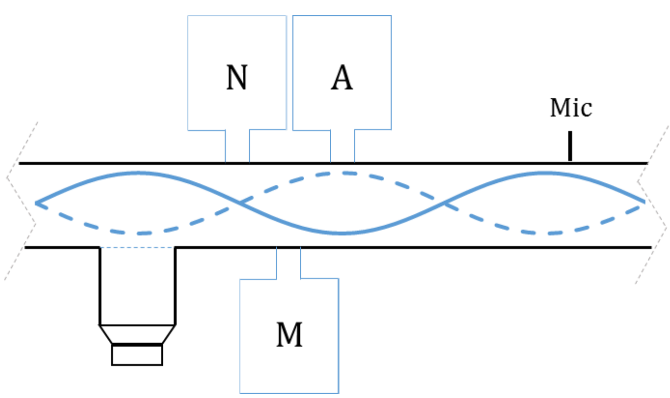

FIGURE 4: SCHEMATIC OF LOCATIONS INVESTIGATED FOR INSERTION LOSS MEASUREMENTS.

Transmission loss measurements for HRs at different locations along the test pipe yielded similar values to one another, showing that TL measurements are independent of the resonance in the main pipeline. Therefore, insertion loss was measured to capture the effects that various HR configurations had on the resonant system. Figure 4 shows a schematic of the locations along the standing wave that were considered, where 'N', 'A' and 'M' represent the acoustic pressure node, antinode and a midpoint between the node and antinode, respectively.

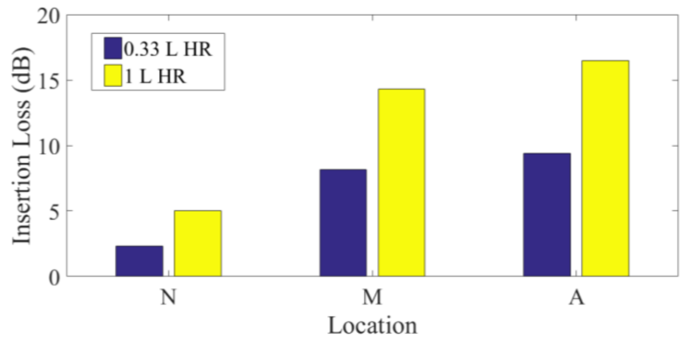

FIGURE 5: INSERTION LOSS MEASUREMENTS AT VARIOUS LOCATIONS ALONG THE STANDING WAVE.

Figure 5 shows the results for the insertion loss measurements for a single HR installed at the different locations along the standing wave. The results show that minimum attenuation is achieved when the device is placed at the node and maximal damping is achieved at the antinode. The IL also follows a curved trend, which seems to follow the shape of the standing waveform in the main pipe; the rate of change in IL is large near the node but small near the antinode, which is the peak of the sinusoid. Another finding from these results is that the smaller-volume 0.33 L HR, when placed at or near an antinode, achieves higher attenuation than the 1 L HR placed at a node. This shows that in a resonant system, the placement of a damping device is crucial. A well-placed device, even a small one with relatively low TL values, will achieve larger magnitudes of damping than a poorly-placed large device.

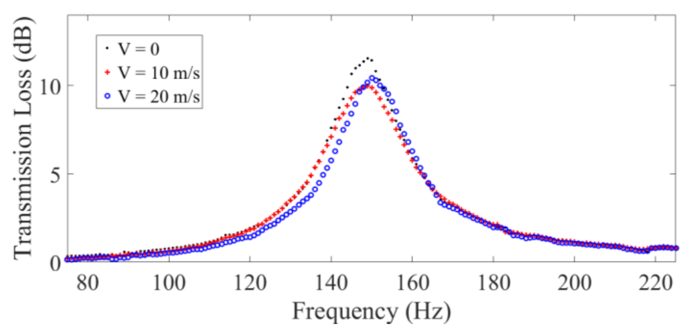

FIGURE 6: TRANSMISSION LOSS VALUES FOR 1 L HR WITH VARIOUS MEAN FLOW RATES.

The effects of mean flow on the TL were measured and the results are shown in Fig. 6. It can be seen that the presence of mean flow results in a slight reduction in TL, decreasing it from 11.5 dB to nearly 10 dB. Moreover, for a mean flow velocity of 20 m/s, a slight shift upwards in the resonant frequency was noted. This shift in resonant frequency is similar to that noted by Anderson [11]. Importantly, the effect of mean flow on the magnitudes of damping seems to be rather small, indicating that the use of HRs for systems with mean flow present is promising, so long as the HR dimensions are tuned to account for any shifts in its resonant frequency.

CONCLUSIONS

The effectiveness of HRs in various arrangements was experimentally investigated in a test pipe under conditions of acoustic resonance. Transmission loss measurements of multiple HRs placed at a single location along the length of the test section reveal that large-volume HRs achieve higher damping levels than smaller HRs, but multiple small HRs can achieve comparable levels of damping to a single HR of nearly equivalent volume. The use of multiple, smaller HRs can therefore be used to achieve high levels of damping at a particular frequency of interest without the need for a large device, which may be impractical. Insertion loss measurements to consider the effects of location along the standing wave show that maximum attenuation is achieved when the device is placed at the acoustic pressure antinode and minimal damping is achieved at the node. Moreover, a small-volume HR placed near an antinode is seen to yield more significant damping than a larger HR placed at a node. These results show promising trends regarding the use of compact HRs in resonant pipeline systems. The effect of mean flow is seen to only slightly reduce the magnitudes of damping, showing that HRs can achieve substantial damping in systems with mean flow present. These findings show the potential for utilizing strategically-placed compact devices instead of a single, large device for situations where high magnitudes of damping are required and space or access to the pipeline may be limited.

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