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Experimental characterisation of the acoustic properties of a residential ventilation valve

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Abstract
This paper introduces a novel indirect method to determine the acoustic properties of residential ventilation valves. Whereas conventional valve characterisation techniques use large-scale anechoic or reverberation rooms, the presented method uses a controlled low-cost compact environment in which the valve can be placed. To generalise the acoustic properties to different environments, the valve is represented by an equivalent piston model, and a calibration is carried out to obtain transfer functions between the equivalent piston velocity and pressure and the pressures measured inside the environment. The application of the equivalent piston model is verified by performing experimental characterisation of two different valves. Results indicate that some valves can be represented by an equivalent moving piston, but further fine-tuning of the calibration method is necessary in order to obtain a unique representation of the valve that is able to be extrapolated to different environments.

Keywords: residential ventilation systems; ventilation valve; indirect measurement method; radiation;

1 Introduction

In residential ventilation systems, an accurate characterisation of the noise radiated by end valves is important to make reliable predictions of the system's noise emission using network modelling approaches. As the valve is the last component of the network, it is not possible to take any significant noise mitigation measures after the valve. In addition, the aerodynamic mean flow through the valve generates a considerable amount of noise that is radiated directly to the connected room. Conventional end valve characterisation techniques employ power attenuation models such as those found in VDI or ASHRAE guidelines [1] [2], the properties of which are measured in large-scale anechoic or reverberation rooms [3]. However, these rooms are costly to construct and are often not available to the designers of end valves. An additional downside of these techniques is that they neglect the influence of the environment to which the valve radiates noise, even though the environment can have a significant influence on the reflection coefficient seen at the duct side and the generated sound power towards the environment.

As an alternative to conventional measurement techniques that require large-scale (semi-)anechoic or reverberation rooms, more compact measurement techniques have been investigated to determine the absorption properties of absorbing wall treatments [4] [5], and the insertion loss properties of acoustic insulation panels [6]. Several challenges are contained in the development of accurate measurement methodologies using compact rooms. For small rooms, the straightforward analytic models for free field radiation or diffuse field conditions are not valid, especially at lower frequencies as a result of the influence of the acoustic modes of the cavity. This makes the results of these measurement techniques not straightforward to extrapolate to different environments in which the valve is placed. To compensate for this behaviour, these compact measurement techniques often rely on calibration models of the measurement set-up and generic models of the object under study in order to be able to generalise the measured properties to different environments.

This paper introduces a novel indirect method to determine the acoustic properties of residential ventilation valves. The measurement set-up is a controlled low-cost environment consisting of a compact box equipped with microphones, connected to a duct with flush mounted microphones. To obtain a generic model of the valve that can be used in different environments, the valve is represented as an equivalent piston velocity at the duct end connected to the box. A calibration procedure of the measurement set-up without a valve is used to determine transfer functions between the plane wave particle velocity, representing the piston velocity, and the pressure at this duct end and the pressures measured in the box. These transfer functions are then used to determine equivalent piston velocities and pressures when a valve is placed in the set-up. A relationship can then be derived between the duct velocities and pressures when the valve inside the set-up and the equivalent velocities and pressures in order to obtain a generic valve model for different environments.

It is important that the measurement procedure leads to a unique representation of a valve which is able to be extrapolated to different environments. Therefore, the goal of this paper is to investigate the application of the equivalent piston model to two different valve geometries. An experimental characterization of both valves is carried out to investigate the sensitivity of the microphone positions to the corresponding equivalent piston velocities, after which possible improvements to the calibration procedure can be suggested.

The rest of this paper is structured as follows. The second section discusses the valve characterisation framework. First, acoustic theory related to the acoustic fields inside ducts is provided, followed by an overview of the measurement method, the calibration procedure and a short note on the generic valve model. The third section provides an experimental characterization of the equivalent velocities of two different valve geometries. Finally, the last section provides a conclusion and suggestions for future work.

2 Characterisation framework

2.1 Acoustic fields inside ducts

In order to provide a better understanding of the physical principles behind the measured method, first some acoustic theory on the modal pressure fields inside ducts is provided. At low frequencies, a fluctuating pressure p'_d inside a duct at a fixed axial position z can be expressed as a linear combination of propagating left- and right-running plane wave modes et every frequency f as a function of the modal pressures $p_d^{\pm}$ and axial wavenumbers $k^{\pm}$:

$$p'_d = p_d^+ e^{-jk^+z} + p_d^- e^{jk^-z} \tag{1}$$

Similar to the fluctuating pressure p'_d, the fluctuating particle velocity v'_d can be determined at an axial position z from:

$$v'_d = \frac{1}{Z_0}\left(p_d^+ e^{-jk^+z} - p_d^- e^{jk^-z}\right) \tag{2}$$

Where the characteristic impedance $Z_0 = \rho c_0$ is a property of the acoustic fluid dependant on the fluid mass density ρ and speed of sound $c_0 \approx 340\, m/s$. Due to the low mean flow speeds commonly encountered in ventilation systems, convective effects can be neglected and when no visco-thermal losses are taken into account, the axial wave numbers $k^{\pm}$ are equal to the acoustic wave number k_0 expressed as:

$$k^{\pm} = k_0 = \frac{2\pi f}{c_0} \tag{3}$$

The plane wave assumption is valid until the cut-on frequency of the first higher order mode f_c, which in a duct with a circular cross-section of a diameter D is given by:

$$f_c = \frac{1.84}{\pi}\frac{c_0}{D} \tag{4}$$

For a common ventilation duct diameter of 125mm this leads to a cut-on frequency f_c of approximately 1600 Hz. The modal pressure amplitudes $p^{\pm}$ can be determined by using microphones to measure the acoustic pressures $\boldsymbol{p}'_{\boldsymbol{mic}}$ using at least two distinct microphone positions by inverting the modal decomposition matrix $\boldsymbol{M}$, where the inverse is interpreted as the Moore-Penrose inverse when there are more than two microphones:

$$\begin{bmatrix} p_d^+ \\ p_d^- \end{bmatrix} = (\boldsymbol{M})^{-1}\boldsymbol{p}'_{\boldsymbol{mic}} \tag{5}$$

The rows of the modal decomposition matrix $\boldsymbol{M}$ express the wave propagation at a single reference position with respect to the axial position z_i of each microphone:

$$\boldsymbol{M} = \begin{bmatrix} e^{-jk^+z_1} & e^{jk^-z_1} \\ e^{-jk^+z_2} & e^{jk^-z_2} \\ \dots & \dots \\ e^{-jk^+z_N} & e^{jk^-z_N} \end{bmatrix} \tag{6}$$

Finally, an acoustic impedance Z can be defined as a relation between the pressure p'_d to the velocity v'_d across a certain surface:

$$Z = \frac{p'_d}{v'_d} \tag{7}$$

The acoustic impedance is a property of the environment and represents the opposition to acoustic flow when an acoustic pressure is applied to a system. In a duct where waves are propagating in both the positive and negative direction, the acoustic impedance varies along the duct axis due to standing wave effects. The real part of the impedance, the acoustic resistance, represents the net flow of energy to the medium ahead, whereas the imaginary part, the acoustic reactance, represents the temporary storage of energy in this medium.

2.2 Measurement method overview

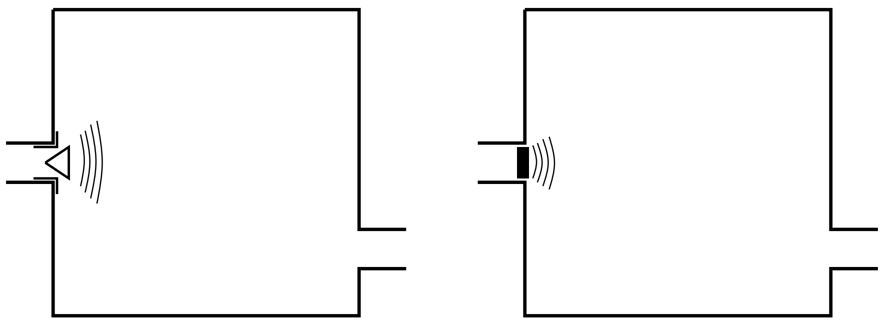

Figure 1: Compact measurement set-up schematic. Left: representation of valve inside set-up. Right: equivalent representation as moving piston inside set-up.

This paper describes a new measurement method to determine the acoustic properties of a residential ventilation valve, namely the sound that is transmitted from the duct to the environment characterized by the end reflection coefficient and the sound that is generated by flow through the valve. Whereas conventional valve measurement techniques employ large-scale (semi-)anechoic or reverberation rooms, the described measurement method uses a compact low-cost controlled environment of approximately 1m³, a schematic overview of which is shown in Figure 1. A downside of using a compact environment is that it exhibits severe modal behaviour in the frequency range of interest, affecting both the reflection coefficient of the valve and the sound power that is generated by the valve. Therefore, an indirect measurement procedure is carried out by relating the measured quantities to equivalent quantities of a generic model that is able to represent the radiation of the valve in different environments. Such a generic model should be simple enough in order to provide a straightforward calibration procedure of the set-up using conventional pressure microphones to keep costs low, but should be specific enough in order to account for the acoustic properties of the valve in different environments.

The acoustic radiation of a piston in a baffle or open ended pipe is a well-studied topic that has an analytic solution [7]. As a plane velocity waves in an empty duct can be regarded as a moving piston [8], it is straightforward to relate the piston velocity to the travelling wave pressures obtained from the modal decomposition inside the duct. In addition, such a method can even be extended to a higher-frequency range by including more cut-on pressure and velocity modes. An inverted method based on such a multi-modal framework has already been used to obtain the modal content of the waves inside a duct through far-field measurements inside an anechoic room [9]. Therefore, this paper will represent the valve as an equivalent velocity and pressure of a moving piston inside the duct end that is connected to the measurement set-up as modelled in Figure 1. Even though this assumption may not always hold in practice, at low frequencies the valve can potentially be represented as a compact source and such a method can represent the valve properties for different environments up to a reasonable accuracy.

To relate the measured properties of the valve inside the compact set-up, a calibration procedure is provided of the empty measurement set-up to investigate the radiation of an equivalent piston inside the environment. When the pressures in the box for the no-valve case $p'_{box,empty}$ are measured and the velocity at the duct end $v'_{d,empty}$ is determined through the modal decomposition procedure inside the duct, a transfer function H_{rad} relating the box pressure and duct velocity can be defined for each microphone:

$$H_{rad} = \frac{p'_{box,empty}}{v'_{d,empty}} \tag{8}$$

While it is straightforward to define a similar transfer function for the empty duct pressure $p'_{d,empty}$, the use of the acoustic impedance at the empty duct end Z_{empty} offers a more physical interpretation of acoustic properties of the environment to which the equivalent piston radiates, where this impedance is simply defined as:

$$Z_{empty} = \frac{p'_{d,empty}}{v'_{d,empty}} \tag{9}$$

Once the transfer functions and acoustic impedance of the empty duct end are defined, an inverse characterization can be carried out when the valve is placed inside the set-up. By measuring the pressures $p'_{box,valve}$ at the same positions as the ones used for the calibration procedure, an indirect method can be used to relate these pressures to an equivalent velocity v'_{eq} and equivalent pressure p'_{eq} that represent a piston moving in the duct end where the valve is located:

$$\begin{aligned} v'_{eq} &= \frac{p'_{box,valve}}{H_{rad}} \\ p'_{eq} &= Z_{empty} v'_{eq} \end{aligned} \tag{10}$$

The transfer functions include both the properties of the equivalent piston source strength, often characterized by the piston velocity or acoustic volume acceleration, and the directivity of the radiation as a function of the microphone positions. For a valve in the plane wave region, only one pressure has to be measured inside the box to obtain an equivalent velocity and pressure. However, if the radiation directivity of the valve differs greatly from the equivalent piston model obtained in the calibration procedure, the derived equivalent piston source strength may not be the same for different microphone positions. This can lead to ill-conditioning of the valve characterisation when trying to find a relationship between the in-duct quantities and the equivalent velocities for a general environment, as the influence of the microphone positions can depend on the environment itself.

2.3 Generic valve model

Although the equivalent velocity and pressures can be derived using the indirect measurement method when the valve is placed inside the compact set-up, the modal pressures inside the duct also depend on the environment in which the valve is placed. Therefore, network modelling tools require a generic model of the valve that can relate the in-duct quantities to the equivalent piston quantities for a general environment in order to make an accurate prediction of the sound field inside the network. As network modelling tools already exist that make use of two-port modelling methods [10], a possible approach is to represent the valve as a two-port model between the in-duct pressures and velocities and the equivalent pressures and velocities. Such an approach would lead to a matrix equation, where the $\boldsymbol{T}$ is the valve two-port matrix:

$$\begin{bmatrix} p'_d \\ v'_d \end{bmatrix} = \boldsymbol{T} \begin{bmatrix} p'_{eq} \\ v'_{eq} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p'_{eq} \\ v'_{eq} \end{bmatrix} \tag{11}$$

The two-port matrix $\boldsymbol{T}$ fullfils a similar role to that of the transfer matrix found in convential two-port modelling methods, with the main exception that it relates the physical pressure and velocities to a fictitious pressure and velocity at the same physical location. In essence, the matrix $\boldsymbol{T}$ describes the relative behaviour of the valve compared to a straight duct of infinitesimal length, where $\boldsymbol{T}$ equals the unity matrix for the empty duct case. Even though this two-port matrix might be difficult to physically interpret, it might provide a useful estimation of the reflected and radiated noise of a valve in a general environment. However, an accurate and robust determination of the two-port is highly dependant on the characterisation of a unique equivalent velocity corresponding to the in-duct pressures and velocities. For this reason, this paper will focus on the application of the equivalent piston velocity model to several valve geometries, and further discussion of the valve two-port model is considered out of scope.

3 Experimental characterisation

3.1 Experimental measurement set-up

As previously mentioned, it is important that the application of the equivalent piston model leads to a unique representation of the valve in order to obtain a generic valve model valid for multiple environments. Therefore, an experimental characterisation of the equivalent velocity for two different valves is carried out to investigate the sensitivity of the microphone location to the indirect determination of the equivalent velocity.

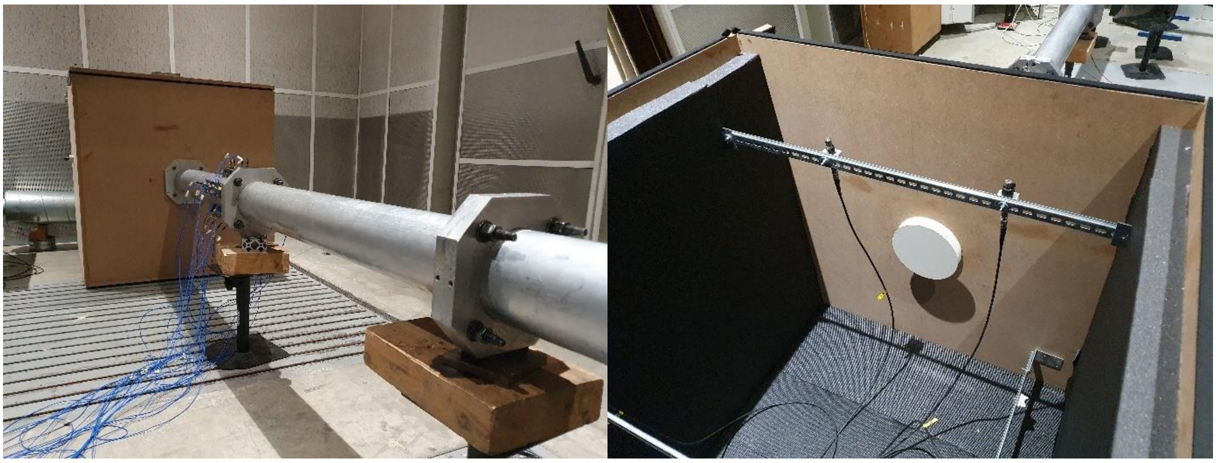

Figure 2: Experimental measurement set-up. Left: straight duct equipped with microphones connected to compact box. Right: Inside of box with Grada RLV valve mounted.

The experimental measurement set-up consists of a rigid aluminium straight duct of diameter 125mm connected to a cubic box constructed out of medium-density fiberboard panels with an inner edge of 0.98m and a volume of 0.96m³. The box is lined with sound absorbing polyurethane foam of 51mm thickness on all walls except for the wall connected to the straight duct. The duct is equipped with 20 PCB 376C10 flush-mounted pressure microphones, distributed in four groups along the axis, with five microphones per group mounted along the circumference of the duct. In the box, four PCB 378C20 random-incidence microphones labelled *BM1* to *BM4* are mounted at selected positions using thin bars fitted to the walls. A Siemens Simcenter SCADAS Mobile data-acquisition device and Siemens Simcenter Testlab 17 spectral testing software are used to obtain the microphone signals and process the time domain signals to the frequency domain with a frequency step size of 1Hz. A loudspeaker is used an external excitation driven by a white noise electric signal. This electrical signal is fed back to the SCADAS to serve as a clean reference signal. Custom MATLAB processing scripts implementing the methods described in this paper then use transfer functions between this reference and the microphone signals to filter out possible uncorrelated acoustic noise.

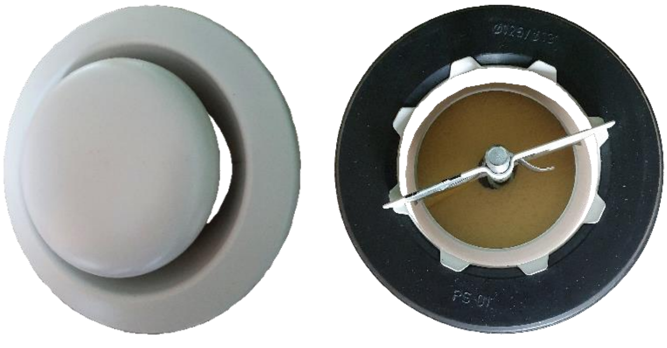

Figure 3: From left to right: Zehnder STB-1 front side and back side

Two different valves are studied in the set-up. The Zehnder STB-1 125mm shown in Figure 3 is an extraction valve featuring an axially-oriented annular opening. A hollow insert the middle of the valve is lined with porous absorber foam at the duct side and can move axially to regulate the flow opening. The Grada RLV ventilation valve depicted mounted inside the set-up in Figure 1 can be used as both a supply valve and an extraction valve. The valve consists out of a base which is inserted in the duct and that is covered with a flat circular top plate, leading to radially oriented inflow or outflow. Inside the valve, a bell-shaped insert is allowed to move axially on a threaded shaft to regulate the flow opening.

3.2 Valve equivalent velocities

First, a calibration of the measurement set-up is performed using the previously detailed methods, where the transfer functions for each microphone along with the acoustic impedance at the empty duct end are shown in Figure 4. It can be seen that the impedance of the box without a valve behaves comparably to the impedance of an empty infinite flange [8], but contains more wriggles due to the modal behaviour of the box. It can be argued that due to the symmetry of the box and the axial symmetry of the valve and equivalent piston, microphones that are placed on concentric circles at the same axial distance from the duct center inside the box see a similar radiation pattern. This is indicated by the pair of BM1 and BM2 and the pair of BM3 and BM4 having a more closely related transfer function, where the difference at higher frequencies is explained by the offset in distance from the vertical midplane of the box.

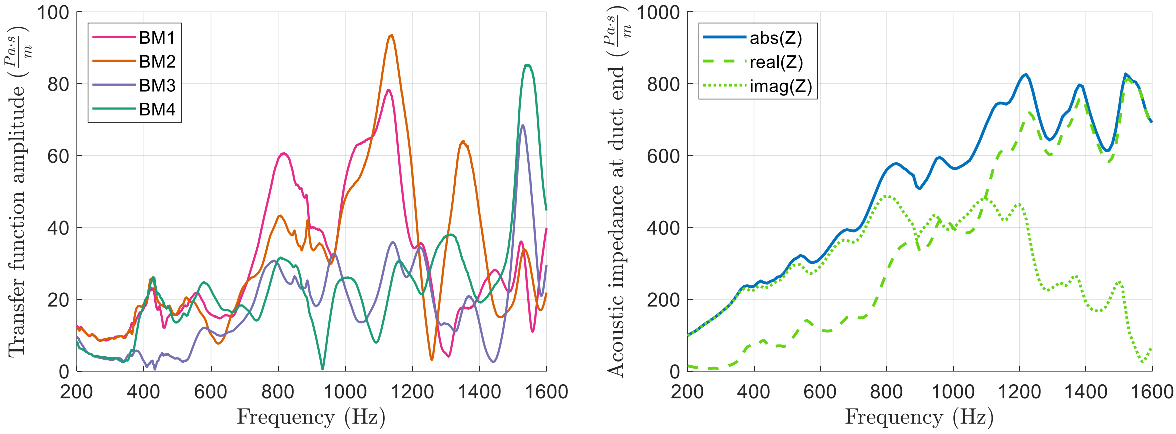

Figure 4: Left: Transfer functions H_{rad} between the box microphone pressure and the equivalent piston velocity for each microphone inside the box. Right: acoustic impedance of empty duct end.

After performing the calibration, the valves are placed consecutively inside the box and the equivalent velocity is determined based on each microphone separately. Due to the box and loudspeaker characteristics, the actual excitation level differs greatly for each frequency. For this reason, the equivalent velocities v'_{eq} are converted to a logarithmic equivalent Sound Velocity Level (SVL) $L_{v,eq}$ for a reference velocity $v'_{ref} = 5 \cdot 10^{-8}\ m/s$ through:

$$L_{v,eq} = 20 \log_{10} \frac{v'_{eq}}{v'_{ref}} \tag{12}$$

The equivalent SVLs of the Zehnder STB-1 valve are plotted in Figure 5. Some of the large peaks and dips in the equivalent SVL can be attributed to a pressure node in the calibration procedure leading to transfer function amplitudes near zero. When a valve is placed inside the set-up, it is possible that the node location shifts slightly, leading to greatly inflated or deflated equivalent SVL when measurement noise would be present. However, for most of the frequency range of 200 Hz to 1200 Hz, the derived equivalent SVLs are within 3 dB for each microphone, with occasional peaks to 6 dB. Above 1200 Hz, large deviations occur for all microphones with respect to the first microphone. This may indicate that the equivalent piston model does not hold well above this frequency. However, further investigation in this phenomena indicated that the coherence in this frequency range was lower, possibly as a result of the lower absolute radiation levels and a complication of the microphone mounting procedure. As mounting the microphone led to a partially blocked static vent port, higher than usual atmospheric measurement noise was introduced which impacted the signal to noise ratio for these lower levels of acoustic radiation. This makes it harder to draw definitive conclusions for the cause of the deviations.

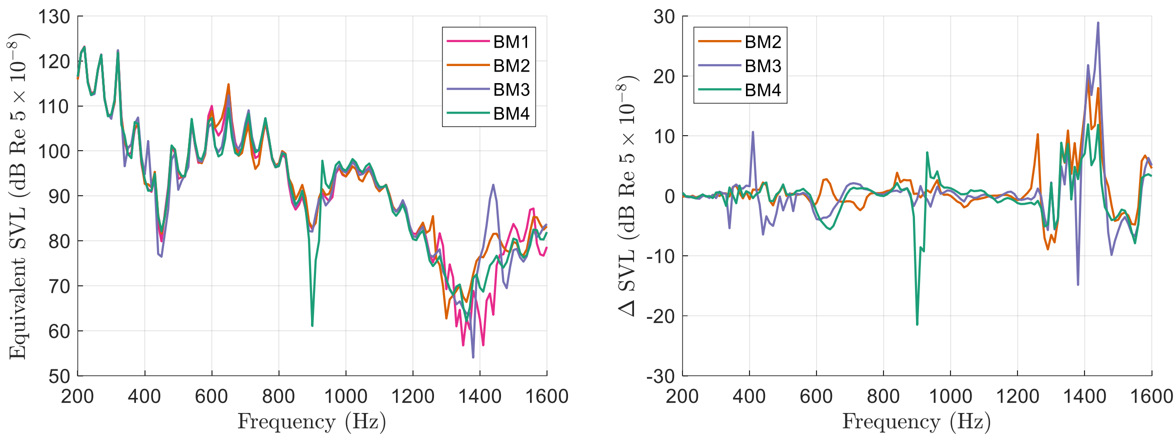

Figure 5: Zehnder STB-1 characterisation. Left: equivalent sound velocity level $L_{v,eq}$ for each microphone. Right: absolute difference in equivalent sound velocity level $\Delta L_{v,eq}$ with respect to BM1.

For the Grada RLV valve, the equivalent SVLs are provided in Figure 6. Similar peaks and dips can be found at comparable frequencies to those of the characterization of the Zehnder valve, indicating that the pressure nodes inside the box are a likely cause of this behaviour. At lower frequencies below 400 Hz, it can also be seen that the equivalent SVLs closely follow each other for the different microphones. However, at higher frequencies, both BM3 and BM4 start to deviate significantly from BM1 and BM2, with differences of 6 dB up to 10 dB. This could mean that the symmetry of the radiation pattern still holds, but that the radiation of the valve deviates from the equivalent piston model along the absolute distance from the valve. It is likely that the geometry of the valve with radially facing flow cannot be sufficiently approximated by an equivalent piston model. Above 1200 Hz, the results also start to deviate significantly from each other similar to the Zehnder STB-1 valve, but the cause can also be potentially attributed to the higher than usual measurement noise.

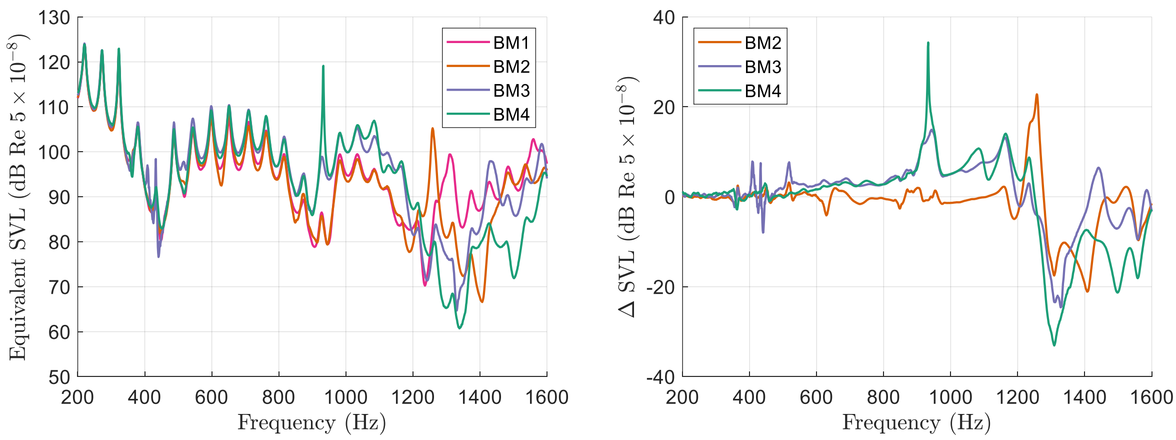

Figure 6: Grada RLV characterisation. Left: equivalent sound velocity level $L_{v,eq}$ for each microphone. Right: absolute difference in equivalent sound velocity level $\Delta L_{v,eq}$ with respect to BM1.

These results indicate that while the equivalent piston model offers potential in representing a valve inside a compact environment, further development of the radiation model and calibration procedure is necessary in order to obtain a model that is valid in a general environment. One possible approach may be found by combining several microphone measurements to solve for the piston velocity and for additional correction factors to the directivity separately, and by comparing the calibration model of the equivalent piston in the box to the analytic radiation model of a piston in an infinite flange to account for these correction factors. Another possible approach is to use calibration inserts of common valve shapes in order to more accurately account for the different radiation pattern valve geometries. If such a calibration insert would have a (semi-)analytic model available for the radiation behaviour in a general environment, it is possible to extrapolate the results obtained from the measurements inside the compact environment.

4 Conclusions

This paper introduced a novel indirect measurement method to obtain the acoustic properties of a residential ventilation end valve. This method uses a low-cost controlled measurement set-up consisting of a compact box equipped with microphones connected to a duct equipped with flush-mounted microphones. To be able to extrapolate the results to different environments, it is investigated whether the valve can be represented as an equivalent piston velocity. Experimental characterisation showed that the equivalent piston model lead to comparable equivalent velocities derived from different microphones positions for a valve with an annular opening. However, for a valve with a radially facing opening, larger relative differences between microphone positions are already observed at lower frequencies. This indicates that the simplified valve geometry will need to be taken into account in the calibration procedure to increase the quality of the results.

Future work will focus on finetuning the calibration procedure and the generic model in order to obtain a unique representation of the valve that is able to be extrapolated to a general environment. When such a model is available up to a reasonable accuracy, the measurement method can be augmented to determine the active flow noise generated by the valve. In addition, the presented measurement method can be straightforwardly extended to higher frequencies through the use of multi-modal modelling frameworks, but it will need to be verified whether such an extension will be valid for a general environment in which the valve is placed.

Acknowledgements

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