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Determination of radiated sound power from acoustic sources using the VBSP method and a mylar boundary

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The development of an "acoustic tent" for measuring the radiated sound power from devices with complex or hidden geometries using a vibration-based sound power (VBSP) method is presented. The VBSP method is based on spatially dense velocity measurements of the vibrating structure and has previously been validated for flat plates, cylindrical-shells, simple-curved panels, and arbitrarily curved panels. However, many acoustic sources, such as electric drone motors, kitchen appliances, and vehicles have sound power contributions from components where the velocity is difficult to measure. To overcome this challenge, a rectangular box with four high impedance walls, one rigid side, and one thin mylar side was used to enclose the noise source, forming an acoustic tent around the device. The acoustic tent was able to be calibrated to within 1-3 dB of the free-field sound power measurements for several different sources. Limitations of the VBSP acoustic tent are also presented and discussed.

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INTRODUCTION

The International Standard for Organization (ISO) indicates that the sound power level is an important parameter in product design as it characterizes the airborne noise emitted from acoustic sources. It is desirable for many applications and must be determined by measurement.[1] Furthermore, vibration-based measurements are becoming desirable when the background noise, testing environment, and application limit the current sound power methods.[2]

The vibration-based sound power (VBSP) method used in this paper relies on a 3D scanning laser Doppler vibrometer (SLDV) to obtain the components of the velocity at every location on a scan grid across the surface of a vibrating structure from which the complex normal velocities can be computed. From a discrete form of the Rayleigh integral, the sound power, Π, can be computed for a given frequency, ω, using a column vector of the surface normal velocities, $\boldsymbol{v_e}$, in conjunction with a radiation resistance matrix, $\boldsymbol{R}$, as:

$$\Pi(\omega) = \{\boldsymbol{v_e}(\omega)\}^H[\boldsymbol{R}(\omega)]\{\boldsymbol{v_e}(\omega)\} \tag{1}$$

where $(\cdot)^H$ denotes a Hermitian transpose.[3,4]

This method works well for vibrating structures such as flat plates, cylindrical shells, and simple-curved panels. Recent work has shown that this VBSP method can even obtain accurate sound power levels for arbitrarily curved panels by employing a known form of the radiation resistance matrix that approximates these structures.[2,4-8] A previous result of a curved aluminum panel with a 0.51 m radius of curvature is shown in Fig. 1 to illustrate the accuracy of the results that have been obtained with this VBSP method.

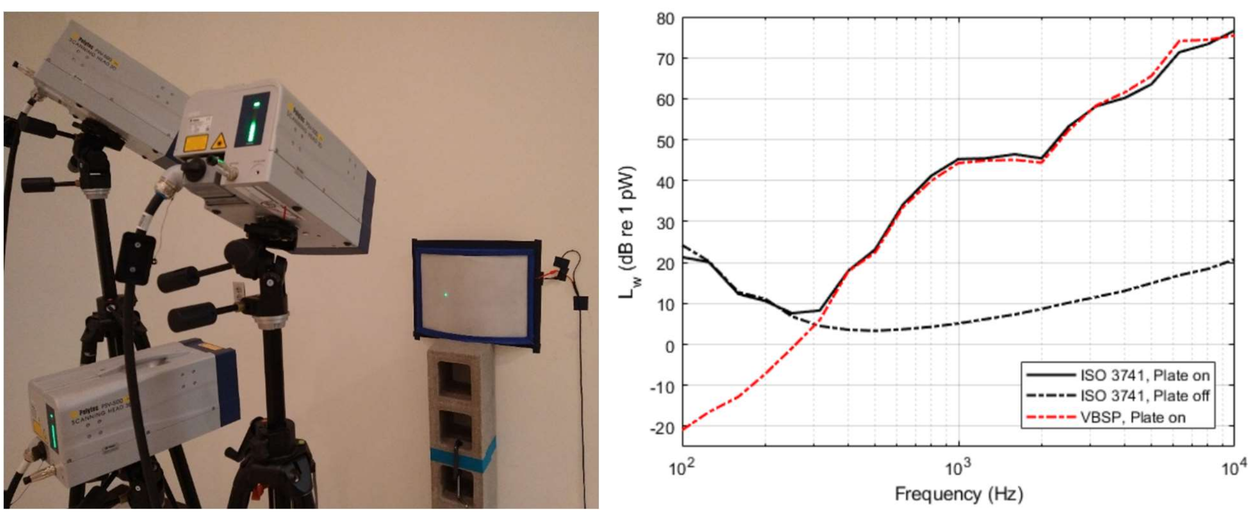


Figure 1. a) The 3D SLDV setup in a reverberation chamber prepared to scan a curved aluminum panel having a radius of curvature of 0.51 m mounted in a steel frame and sealed to the wall acting as a baffle. b) A result of this VBSP method applied to the simple-curved panel in (a) using Eq. (1). The sound power levels measured using the ISO 3741 standard (black curves) against the VBSP method (red) are compared.[5,8]

There are many sources of interest that radiate sound where the user cannot scan the source to obtain the sound power radiated from the vibration, so this raises the need to develop an extension of the VBSP method to determine the sound power for such sources. Examples include sources with internal fans, gears, etc. that have contributors to the sound power, but cannot be scanned properly. The purpose of this paper is to present an adapted VBSP method to accommodate these sources and lay out some of the challenges and potential solutions to the previously mentioned limitation.

ADAPTED VBSP METHOD

This section outlines an indirect way to extend the VBSP method to account for the numerous sources that cannot be scanned properly. For this to happen, the source radiation needs to produce something that vibrates that can be scanned properly. Placing the source inside an enclosure where all sides are acoustically transparent and vibrate would be ideal. However, such materials, like mylar, are transparent only for a limited range of low frequencies. This means that a correction will be needed to obtain the true sound power of these sources. To simplify the problem, a rectangular enclosure was fabricated, as seen in Fig. 2, where four sides on the perimeter are made up of 1 ½" thick MDF, the top face has a mylar membrane secured to the structure, and the base is open so that the rigid floor will seal off the bottom of the enclosure.

This enclosure is placed over the sources of interest, acting as an "acoustic tent." The rigid floor and four high impedance walls direct nearly all the acoustic energy from the source to excite the mylar membrane. Its vibration behaves as a flexible membrane, which can be scanned by an SLDV. Even though the mylar is acoustically transparent for a limited low-frequency band, the enclosure significantly affects the way each source radiates. Nevertheless, the sound power radiated from the enclosure can be measured and then calibrated to match the free-field sound power.

To better understand and calibrate the effect of the enclosure, the free-field sound power was measured for an individual source in a reverberation chamber using the ISO 3741 standard.[9] The source was then placed at nine distinct locations on the floor inside the enclosure, from which the sound power was measured for each location using the ISO 3741 standard. This process was repeated for multiple sources to see the potential variation between sources. By averaging the nine ISO measurements for each enclosed source and comparing these to their corresponding free-field results, a calibration curve was obtained to remove the influence of the enclosure to obtain each source's true radiated power. (See Fig. 5 for the calibration curve for several sources)

The adapted VBSP approach can be outlined as follows: first, the ISO 3741 standard is used in a reverberation chamber to obtain the sound power for multiple unique sources. Next, each source can be placed into the enclosure described above which has a mylar face that can be scanned using an SLDV. The ISO 3741 standard can be used to determine how much sound power the enclosure radiates into the larger space due to each source. Then, using the free-field ISO results, along with the enclosure ISO results, a calibration curve can be found to remove the radiation effects the enclosure has on the sources. Once this curve is established, the VBSP method can be used to obtain the sound power from the mylar face upon which the calibration can be applied to compare this method to the ISO standard. Finally, the adjusted VBSP results can be compared with the free-field ISO 3741 measurements of these sources to verify precision.

Figure 2. A visual of the enclosure used to simplify the problem. a) The mylar stretched across the MDF enclosure. b) A side view of the enclosure showing a developer spray used to make the mylar membrane easier to scan by the SLDV and the three ports drilled in the bottom left to feed the source cabling.

CALIBRATION

The purpose of this section is to verify that each of the tested sources leads to the same correction and to figure out if these sources can be moved internally on the floor without significantly impacting the radiated power. Kleiner and Tichy state "The sound radiation into a room depends on the source, its properties and location, and on the properties of the room such as its size, shape, and sound absorption."[10] Small enclosures have acoustic properties that are largely determined by the individual eigenfrequencies below the Schroeder frequency.[11] Due to the effect of the small enclosure on the radiation, it is desirable to obtain a calibration curve that could be used to hopefully remove the influence of the enclosure on the sources, including absorption, radiation impedance loading, and significant pressure differences that occur with resonances of the enclosure.

Initially, a class of sources will be used that should experience fewer effects on the way they radiate inside the enclosure. When a driving source is coupled with the acoustic waves present inside the enclosure, the radiation impedance can potentially be altered. The radiation impedance is defined as the ratio of the total force on the surface of a radiator that is needed to move the surrounding medium over the particle velocity of the radiator surface.[10,12] Therefore, nominally constant volume velocity sources will be considered for this method because they have a higher internal impedance and therefore the volume velocity of each source will be affected similarly. As a result, the sound power change due to the enclosure should be mostly attributable to the radiation impedance change and the absorption of the enclosure, both of which can be corrected for with an appropriate calibration curve.

Another consideration is to what extent these sources can be moved around within the enclosure without significantly altering the radiated sound power. This was done by performing an ISO 3741 measurement of each source in a reverberation chamber to obtain the free-field sound power result for every source. This was followed by placing each source within the enclosure at various locations on the floor as seen in Fig. 3a and then measuring the sound power using the ISO 3741 standard in a reverberation chamber. The result for a blender is shown in Fig. 3b.

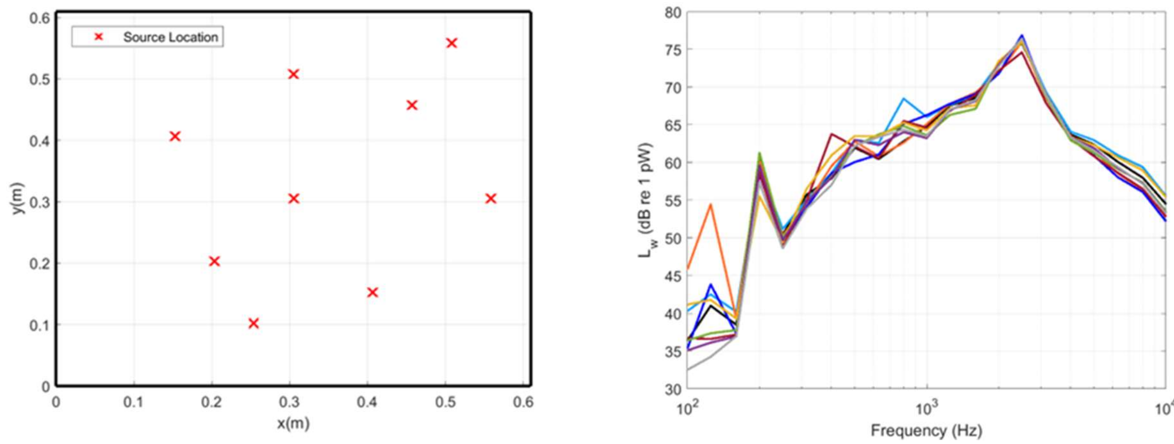


Figure 3. a) The floor map within the enclosure with the nine locations where each source was placed shown by a red "x." b) The nine sound power results obtained for a blender within the enclosure using ISO 3741 measurements.

Fig. 4 shows the average ISO 3741 curve from the data in Fig. 3b, and the blender's actual sound power measured using ISO 3741 without the enclosure present. The difference between these curves will identify a one-third octave (OTO) band correction for the blender.

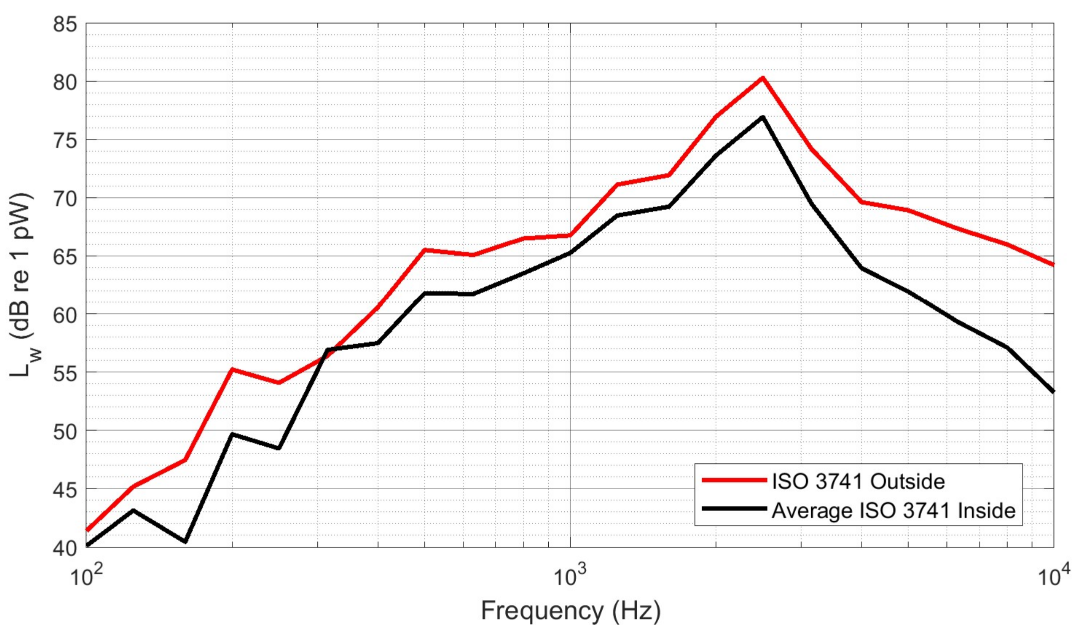
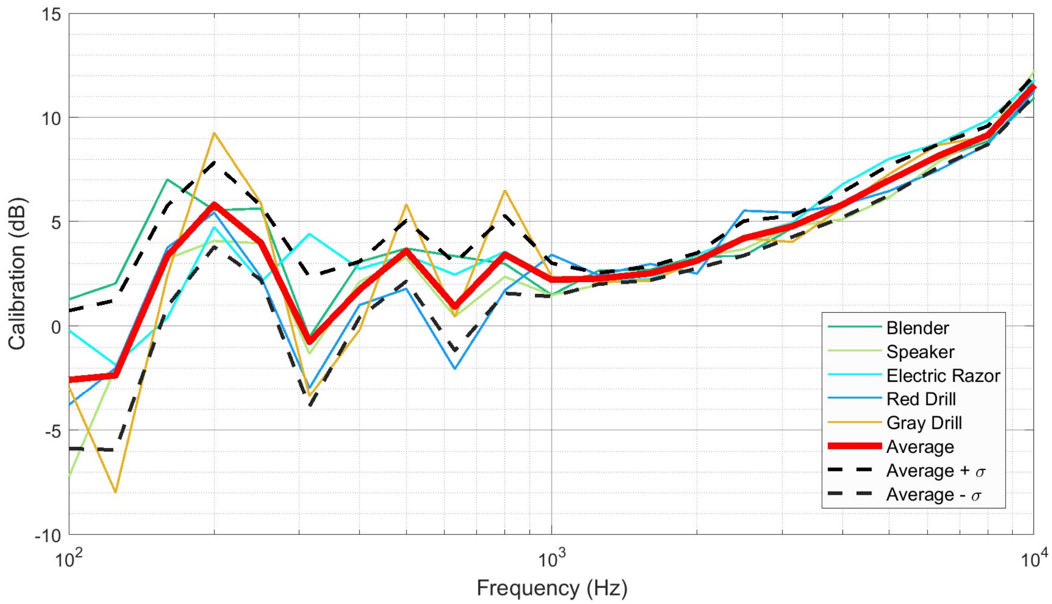


Figure 4. The free-field sound power result of a blender (red) is compared against the average of all nine ISO 3741 measurements of the blender within the enclosure (black).

Fig. 5 shows the OTO band correction curve that needs to be applied to the blender's sound power inside the enclosure to obtain the free-field sound power of the blender. The Schroeder frequency of the reverberation chamber used for testing is about 385 Hz so the ISO 3741 results below this frequency are not compliant with the standard's requirements and will not be considered. The energy is reduced across the bandwidth above the 400 Hz band due to the presence of the enclosure. This correction curve was obtained for multiple sources. For simplicity, five of them are shown in this figure. The average of these correction curves is shown in red. The calibration is within +/- 1 dB above the 1 kHz OTO band. Below that band the calibration is within +/- 2-3 dB in most areas. The acoustic field inside the enclosure is becoming diffuse above 1 kHz due to the reduced variation in sound power for each source over nine different areas within the enclosure. On the other hand, the modal region below 1 kHz significantly affects the pressure radiated from the sources due to the low modal density – leading to large pressure differences



throughout the enclosure depending on the source's location.

Figure 5. This OTO band calibration curve was obtained for multiple sources. The correction curves for five of the sources are shown here. The average of these correction curves is shown in red. A standard deviation is included to show that the average calibration is within +/- 1 dB above 1 kHz and within 2-3 dB below 1 kHz.

Recognizing that axial modes carry more energy than tangential and oblique modes, the frequencies of the enclosure's first couple of axial modes may significantly affect the output of the source, depending on its location.[10] This idea was investigated by identifying the significant resonances of the enclosure in the low frequency region to find better and poorer locations for each source within the enclosure that would lead to more consistency across ISO measurements.

Considering the modal behavior of the enclosure below 1 kHz, only modal indices up to 2 in each Cartesian direction are present. These are shown by the orange and blue lines in Fig. 6a. Strategically placing the blender in eight of these new locations and taking ISO 3741 measurements minimized much of the variation in the sound power obtained from the blender within the enclosure, as seen in Fig. 6b. This shows that the accuracy of the calibration developed previously can be improved below 1 kHz. In addition, these results support the findings in Fig. 5. Further work will be done to confirm this for multiple sources.

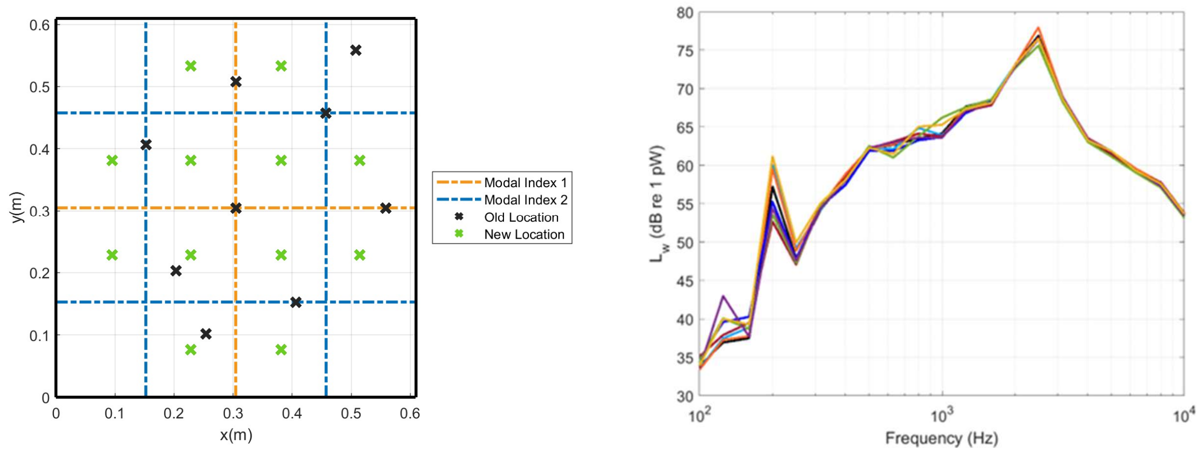


Figure 6. a) The pressure node lines for the first two mode indices of the enclosure in the x-, y-cartesian directions and the updated source locations (green 'x') against the earlier source locations (black 'x') relative to these node lines. b) Eight ISO 3741 measurements for the blender were made using the new source locations which tightened up all the curves better than before.

CONCLUSION

It has been shown that a high-impedance source can be placed into an enclosure with four high impedance walls and a mylar face, and the sound power results obtained can be corrected by a calibration process to obtain the free-field sound power. A calibration curve was developed to remove the radiation effects of the enclosure on each source to obtain the free-field radiated sound power of nominal constant velocity sources within +/- 1 dB above the 1 kHz OTO band and +/- 3 dB below that band. These results indicate that each source can be moved anywhere along the floor except directly in the corners of the enclosure to be within this uncertainty for the true free-field sound power result. In addition, locations were found that would lead to more consistent results for the sound power radiated from the enclosure and reduce the uncertainty associated with the calibration curve. Current efforts focus on obtaining an accurate calibration curve for a wide range of sources and then applying the VBSP method to confirm the radiated sound power can accurately be obtained by applying the calibration curve to the VBSP results. The current work shows promise in developing an extended VBSP method that can be used to obtain the sound power from structures that cannot be scanned effectively using vibration-based measurements.

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