Proceedings of Meetings on Acoustics

APRIL 07 2023

Developing an indirect vibration-based sound power method to determine the sound power radiated from acoustic sources

Ian C. Bacon; Scott D. Sommerfeldt ; Jonathan D. Blotter

Proc. Mtgs. Acoust. 50, 065003 (2022)
https://doi.org/10.1121/2.0001732

POMA Proceedings of Meetings on Acoustics

Volume 50 http://acousticalsociety.org/

183rd Meeting of the Acoustical Society of America

Nashville, Tennessee

5-9 December 2022

Structural Acoustics and Vibration: Paper 4aSAa3

Developing an indirect vibration-based sound power method to determine the sound power radiated from acoustic sources

Ian C. Bacon and Scott D. Sommerfeldt
Department of Physics & Astronomy, Brigham Young University College of Physical and Mathematical Sciences, Provo, UT, 84602; ianbacon24@gmail.com; scott_sommerfeldt@byu.edu

Jonathan D. Blotter
Department of Mechanical Engineering, Brigham Young University, Provo, UT, 84602; jblotter@byu.edu

An indirect vibration-based sound power (I-VBSP) method is in development to be used to measure noise from the numerous sources that radiate energy that cannot be captured effectively using surface vibration measurements. These sources are placed inside a rectangular enclosure with four high impedance sides, a single rigid side, and a single mylar side, inducing a vibration on the mylar membrane. A scanning laser Doppler vibrometer (SLDV) is used to scan the vibrating mylar to determine the sound power radiated through the mylar and this sound power result is then calibrated to obtain the free-field radiated sound power. A boundary element method (BEM) model showed that using the baffled flat plate form of the radiation resistance matrix approximates well the energy radiated from the enclosure above the 630 Hz one-third octave (OTO) band, enabling the indirect method to work above that frequency for this enclosure. The experimental sound power measurement of a blender obtained from the I-VBSP method agreed with the free-field sound power obtained in a reverberation chamber using the ISO 3741 standard within +/- 1 to 2 dB from 1.63-10 kHz. Other challenges are discussed that will be addressed in future research.

 https://doi.org/10.1121/2.0001732

1. INTRODUCTION

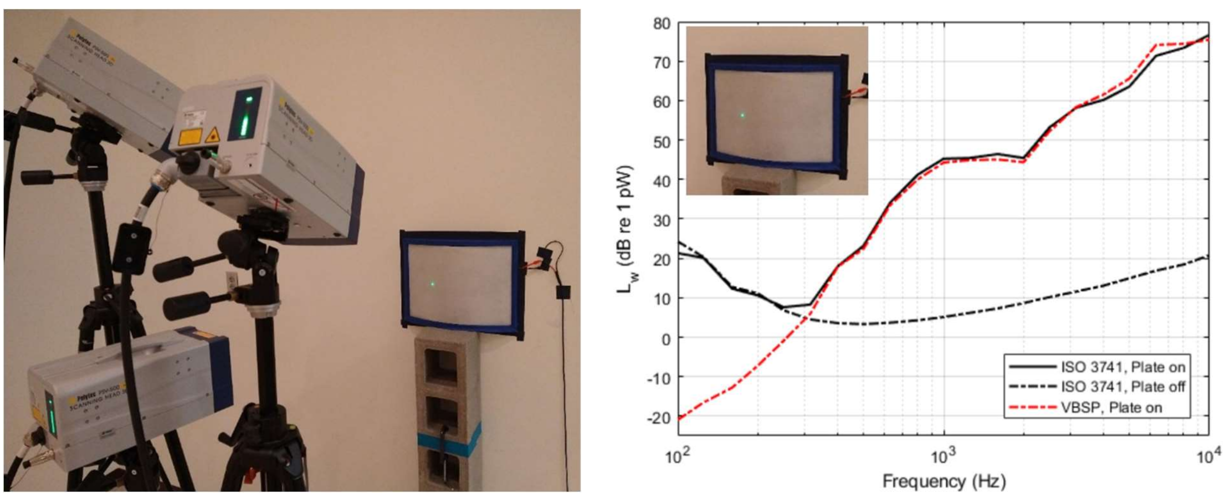
The sound power level characterizes airborne noise emitted from acoustic sources. It is an important parameter in product design, is desirable for many applications, and must be determined by measurement.[1] For some applications, the background noise or testing environment limits the current sound power methods, making an alternate method for determining this valuable quantity desirable. Recent work has shown that a vibration-based sound power (VBSP) method is finding success in overcoming these limitations while maintaining the same level of precision.[2-6]

The VBSP method relies on a 3D scanning laser Doppler vibrometer (SLDV) to measure the components of the velocity at every location spanning 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 connection with the radiation resistance matrix, $\boldsymbol{R}$, as:

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

where $(\cdot)^H$ denotes a Hermitian transpose.[6-8]

This method works well for vibrating structures such as flat plates, cylindrical shells, and simple-curved panels.[3-6] This VBSP method can even obtain accurate sound power levels for arbitrarily curved panels by employing a known form of the $\boldsymbol{R}$ matrix that approximates these structures.[2] 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 method.



a) ***b)***

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.[8] b) A result of the VBSP method applied to the simple-curved panel shown in the corner using Eq. (1). The sound power levels measured using the ISO 3741 standard (black curves) against the VBSP method (red) are compared.[3]

There are numerous products used on a daily basis with sound power levels that a user may want to quantify. Many of these sources, such as a blender, Bluetooth speaker, and electric drill, have internally generated noise that cannot be captured using surface velocity measurements. A new indirect method is being developed to extend the VBSP method to quantify many of these sources.[8] The purpose of this paper is to present further developments for this adapted VBSP method to measure these sources and lay out some of the challenges and potential solutions to the previously mentioned limitation.

2. INDIRECT VBSP METHOD

This section outlines an indirect method to extend the VBSP method to account for the numerous sources that cannot obtain the sound power from direct surface vibration measurements. For this method to work, the source radiation needs to vibrate something that can be scanned directly. A 0.61 m (2 ft) cube enclosure was fabricated for this purpose, as seen in Fig. 2. The four sides on the perimeter are made up of 1 ½" thick medium-density fiberboard (MDF), the top face has a mylar membrane that is stretched taut over the MDF enclosure, and the base is open so that the rigid floor will seal off the bottom of the enclosure. The mylar was glued to the MDF, adhered using gaff tape, and shrink-wrapped using a heat gun to increase surface tension of the membrane. Furthermore, the mylar is coated with a developer spray making it easier for the SLDV to scan.

This enclosure is placed over the sources of interest, acting as an "acoustic tent." During measurements, the ports and base are sealed off with putty and Gaff tape to reduce energy leaking through the bottom of the enclosure. 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 over most of the frequency range. Nevertheless, the sound power radiated from the enclosure can be measured and then calibrated to match the free-field sound power.[8]

The presence of the enclosure introduces absorption and can affect the radiation impedance of the internal sources. 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 to the particle velocity of the radiator surface.[9,10] Constant volume velocity sources have high internal impedances and therefore will experience little change to the volume velocity inside the enclosure. As a result, the change in sound power due to the enclosure will be attributed to the absorption and/or radiation impedance change, which can be corrected with a suitable calibration. It will be necessary to show that each of the sources will lead to the same calibration curve and that the sources can be moved internally in the enclosure without significantly affecting the radiated power. This will be the focus of the next section.

The I-VBSP method is outlined as follows: first, place the source into a small enclosure that ideally has five rigid sides and a single mylar face that can be scanned using an SLDV. Next, develop a calibration curve to remove the influence of the enclosure on the source using ISO 3741 measurements[11] to obtain the sound power for multiple sources to see how the enclosure radiates into the larger space. Then, obtain the sound power from the mylar face using the VBSP method. Apply the calibration to the VBSP results to obtain the free-field sound power of the source of interest. Finally, compare the free-field ISO 3741 result with the corrected VBSP result to verify accuracy and precision between measurements.

Figure 2. The mylar and MDF enclosure for I-VBSP measurements. There are three ports drilled in the bottom left to feed the source cabling. The bottom face is open so that the source can be enclosed on the floor where the source will then excite the mylar membrane acoustically. [8]

3. CALIBRATION

This section identifies a calibration curve for five tested sources (a blender, a speaker, an electric razor, and two different electric drills) and shows whether these nominally constant volume velocity sources can be moved within the enclosure without significantly impacting the radiated power. Kleiner and Tichy[9] 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." Small enclosures have acoustic properties that are largely determined by the individual eigenfrequencies below the Schroeder frequency.[12] It is desirable to obtain a calibration curve to remove the effects of the small enclosure on the source radiation. These effects are mostly attributable to absorption, enclosure resonances, radiation impedance loading, and significant pressure differences that occur internally.

ISO 3741 measurements were used to better understand these effects and calibrate the enclosure. The free-field sound power was measured for an individual source in a reverberation chamber following the ISO 3741 procedure.[11] The source was then placed at nine distinct locations on the floor inside the enclosure (see Fig. 5 for where those locations were chosen from), from which the sound power was measured for each location following the ISO 3741 procedure. Figure 3 shows the average of these nine enclosed ISO measurements for a blender and compares it against the blender's free-field ISO measurement. As expected, by enclosing the noise source with the constructed enclosure described above, the acoustic energy measured by the microphone-based standard is reduced. A one-third octave (OTO) band calibration curve for each source was obtained by taking the difference of the free-field ISO measurement and the average of the enclosed ISO measurements. This process was repeated for multiple sources to see the variation between sources (see Fig. 4 for the calibration curve for several sources). The calibration curve for each source was then averaged to obtain an effective calibration curve to remove the influence of this enclosure to obtain each source's true radiated power.

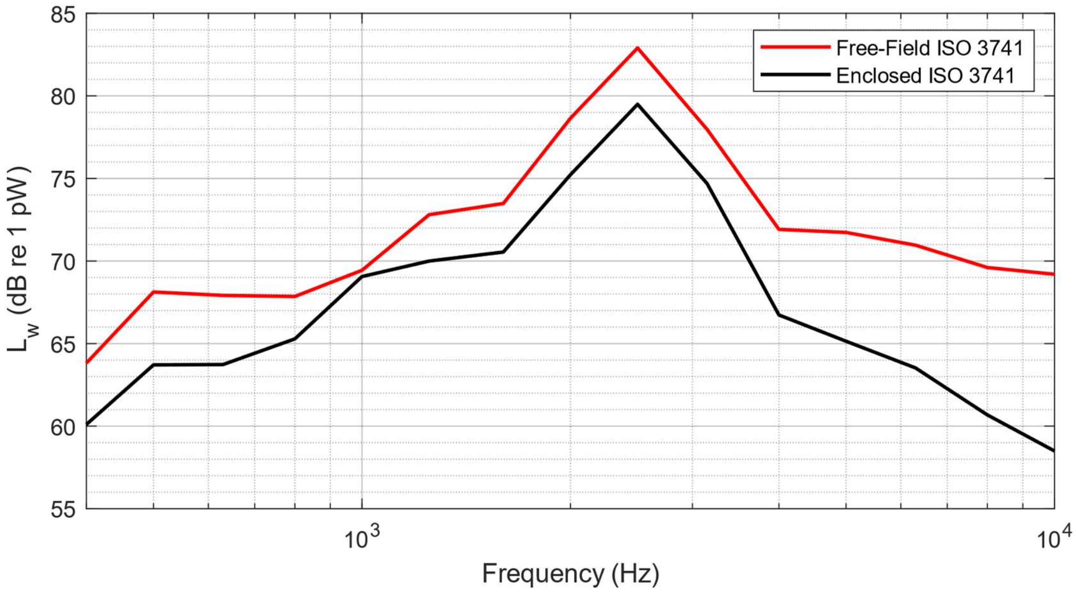


Figure 3. The free-field sound power level, L_w, spectrum of a blender (red) compared to the average of all nine ISO 3741 measurements of the blender within the enclosure (black). The difference between these two curves will identify an OTO band calibration curve for this source.[8]

Figure 4 shows an OTO band correction curve obtained using five sources, which were applied to the enclosed sound power of a blender to correct for the enclosure effects and obtain the free-field sound power of the blender. This calibration curve was obtained by averaging the individual calibration curves for the five sources. Above the 1 kHz OTO band, the calibration is about +/- 1 dB. Between the 400 Hz and 1 kHz OTO bands, the calibration is about +/- 2 to 3 dB. The reverberation chamber used for testing has a Schroeder frequency of 385 Hz, so the ISO 3741 results below this frequency do not meet the standard's requirements and will not be considered. The reduced variation in the sound power output above 1 kHz for each source over the nine different locations within the enclosure indicates that the acoustic field is becoming diffuse. On the other hand, below 1 kHz, the modal region significantly impacts the radiated pressure from the sources due to the low modal density. This leads to large pressure differences throughout the enclosure depending on the source location.

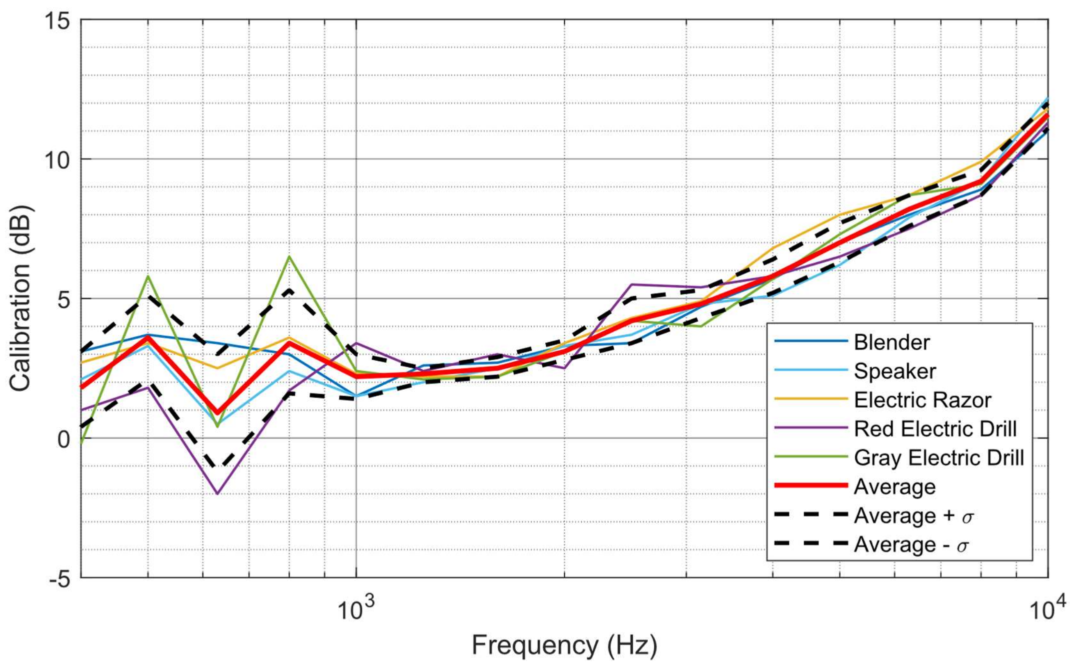


Figure 4. OTO band calibration curves obtained from multiple sources. The calibration curves for five of the sources are shown. The average of these calibration curves is shown in red. A standard deviation is included (black dashed) to show that the average calibration is within +/- 1 dB above 1 kHz and within 2 to 3 dB below 1 kHz. Note: The abscissa for this figure starts at 400 Hz – the usable bandwidth for the ISO 3741 standard measurements made.

Figure 4 reveals there is more source-to-source variation below 1 kHz and the resulting impact the enclosure will have on the radiated sound power depending on the source location. 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.[9] This was investigated to find better and poorer locations for each enclosed source that would lead to more consistent ISO 3741 measurements.

Considering the modal behavior of the enclosure below 1 kHz, only the first two modal indices in each Cartesian direction are present. Figure 5 shows the locations of the nodal planes for these modes, along with source locations tested in two rounds of testing. In Fig. 6a, the blender was placed in random locations within the enclosure on the floor, corresponding to "Random Locations" in Fig. 5, and the resulting ISO 3741 sound power measurements were averaged. Figure 6b shows specific locations within the enclosure on the floor, corresponding to "Specific Locations" in Fig. 5, from which eight of these were chosen for testing. Much of the variation in the sound power obtained from the blender within the enclosure is minimized by avoiding having the source located on a nodal plane for the low-order modes of the enclosure. Furthermore, this also shows that the accuracy of the calibration developed in Fig. 4 can be improved below 1 kHz by avoiding these nodal planes. Further work will be done to finalize a calibration curve for multiple sources with an improved enclosure.

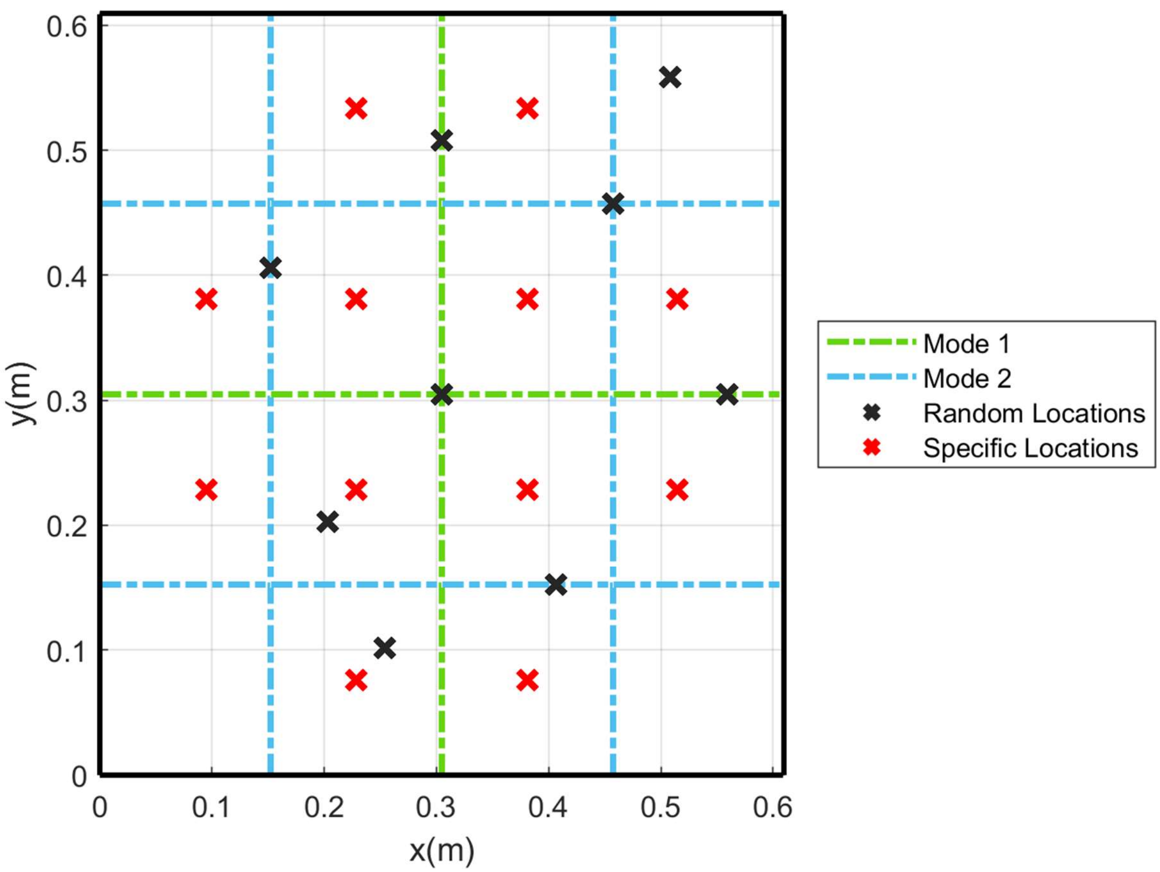
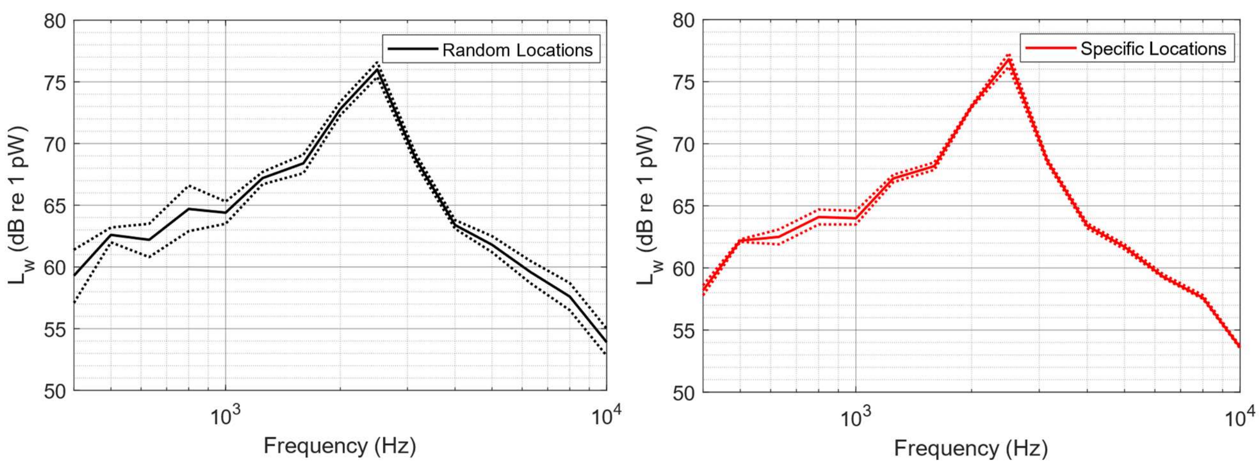


Figure 5. Top view schematic of the enclosure. The pressure node lines for the first two modes are shown as the dashed lines. Measurements were made with the blender placed on random locations (black 'x') and specific locations (green 'x') to assess the impact of the nodal planes.



a) ***b)***

Figure 6. The blender's sound power response, L_w, within the MDF enclosure. a) Average of nine enclosed ISO 3741 measurements of a blender at random locations (solid black) with standard deviation (dotted). b) Average of eight enclosed ISO 3741 measurements of a blender at specific locations (solid red) with standard deviation (dotted). By strategically placing the sources in the specific locations, the deviation between measurements tightened up. Note: The abscissa for these figures starts at 400 Hz – the usable bandwidth for the ISO 3741 standard measurements made.

4. COMPUTATIONAL MODEL

The sound power for this method depends on the normal surface velocities and the radiation resistance matrix, which depends on the vibrating surface geometry. The baffled flat plate form of the $\boldsymbol{R}$ matrix is well established in the literature.[2-7,13] However, the mylar face is a 0.61 m (2 ft) square raised off the ground by another 0.61 m, so it is possible that a modified $\boldsymbol{R}$ matrix could be needed when the mylar is no longer approximated well using a baffle.

A vibroacoustic model, shown in Fig. 7, was developed using the ESI software package VA One 2021 to identify the range of frequencies where the baffled flat plate form of the $\boldsymbol{R}$ matrix will approximate the radiation well for the mylar enclosure. This software inherently uses the correct form of the $\boldsymbol{R}$ matrix needed for the 0.61 m cube enclosure. The top face in the model is a very thin flexible panel to approximate the fixed mylar membrane, and the remaining sides are rigid.

The radiated power emitted from an enclosed acoustic source, with a pressure magnitude of 1 Pa for each OTO band, was quantified using the boundary element method (BEM). Then, the normal surface velocities from the top face were exported from VA One and processed through the VBSP method using the baffled flat plate form of the $\boldsymbol{R}$ matrix. Finally, the results were quantified in Table 1. These results show both methods agree within about 1 dB above 630 Hz, indicating that the baffled flat plate $\boldsymbol{R}$ matrix is a good approximation for obtaining the sound power of this enclosure above that frequency. If more error can be tolerated in the 400 and 500 Hz bands, this baffled flat plate $\boldsymbol{R}$ matrix can be used down to about 200 Hz.

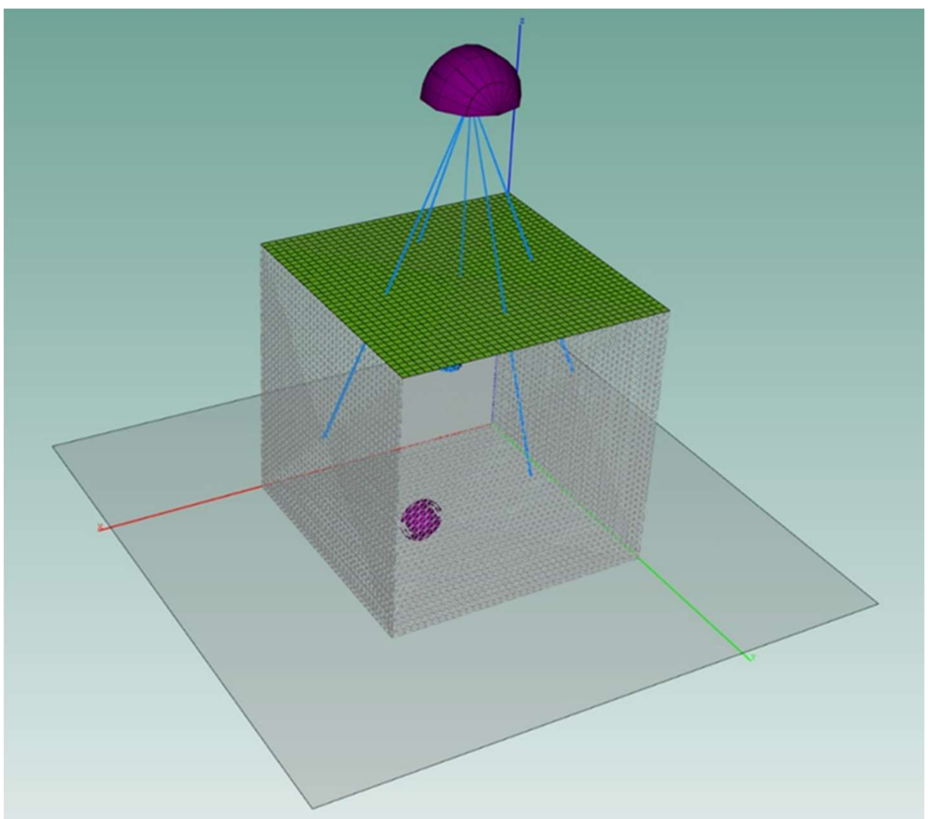


Figure 7. The VA One model of the enclosure with an ideal acoustic source. A BEM fluid (magenta hemisphere) is connected (blue lines) to the enclosure so that the BEM results can be obtained for this structural-acoustic system.

Table 1: The OTO band sound power of an ideal acoustic source computed with the VA One BEM model, the baffled flat plate form of the VBSP method, and the difference between the two methods (units are in dB re 1 pW).

OTO Freq (Hz)	BEM	VBSP	Difference (VBSP - BEM)
100	73.1	76.0	2.8
125	64.7	68.1	3.3
160	61.2	64.1	2.8
200	64.0	66.3	2.3
250	67.0	67.5	0.6
315	67.3	68.1	0.8
400	89.8	92.1	2.2
500	67.0	69.2	2.2
630	55.9	56.6	0.7
800	47.7	47.7	0.0
1000	44.1	44.5	0.4
1250	62.1	63.3	1.2
1600	57.1	57.4	0.3
2000	57.5	57.7	0.2
2500	64.6	65.1	0.5

5. RESULTS

Now that a calibration curve has been developed, and the current VBSP method for a flat plate is accurate from the 630 Hz OTO band upward, the next step was to scan the mylar face with the SLDV. Figure 8 compares the VBSP measurement of a blender inside the enclosure with the enclosed ISO 3741 sound power measurement. From 2-10 kHz, both methods agree to within about 1 dB. From 630 Hz to the 1,630 Hz OTO band, the measured sound power using the VBSP method is anywhere from 2-5 dB lower than the ISO 3741 measurement. This indicates that the mylar is not capturing all the radiated energy in its vibrations and that some of the energy from the noise source being measured is radiating through the MDF sides or leaking out of the enclosure via flanking path(s). After sealing off the mylar side to prevent radiation leak, the results indicated that there was still non-negligible radiation through the MDF walls. The MDF walls were not rigid enough to sufficiently inhibit energy from transmitting through them since the ports and floor were sealed with putty and Gaff tape.

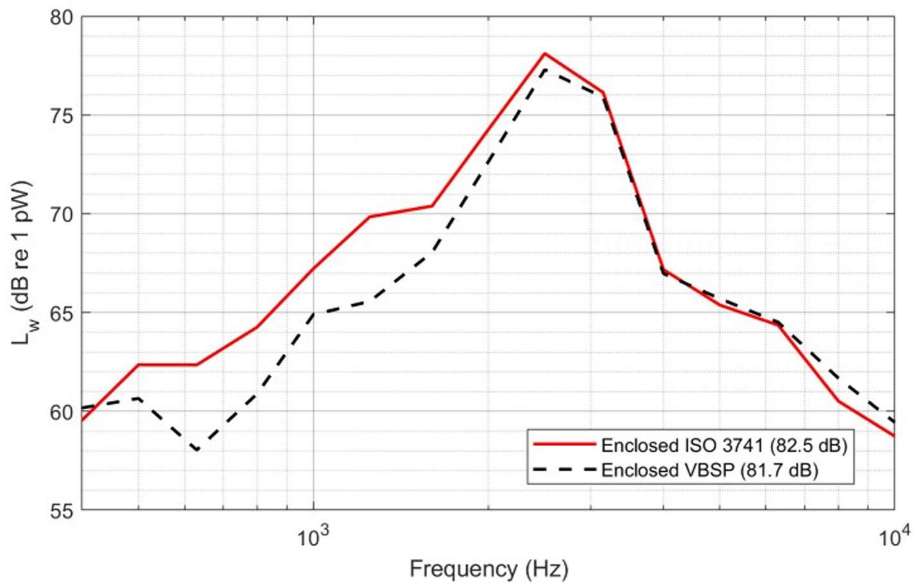


Figure 8. The ISO 3741 (red) and VBSP (black) sound power measurements of a blender inside the enclosure. Note: The abscissa for this figure starts at 400 Hz – the usable bandwidth for the ISO 3741 standard measurements made.

The calibration curve obtained previously was applied to the enclosed VBSP measurement and was compared to the free-field ISO 3741 measurement, as shown in Fig. 9. The I-VBSP method is within +/- 1 to 2 dB of the ISO 3741 method from 1.63-10 kHz. This result is encouraging, but the accuracy could still be improved. While investigating potential causes for this lack of desired accuracy, an updated reverberation time (T_{60}) is required for the ISO 3741 method to account for extra absorption within the reverberation chamber with the enclosure and measurement equipment present. This might explain why the vibrational energy is higher than the total energy present in the chamber at high frequencies and will be tested in future work.

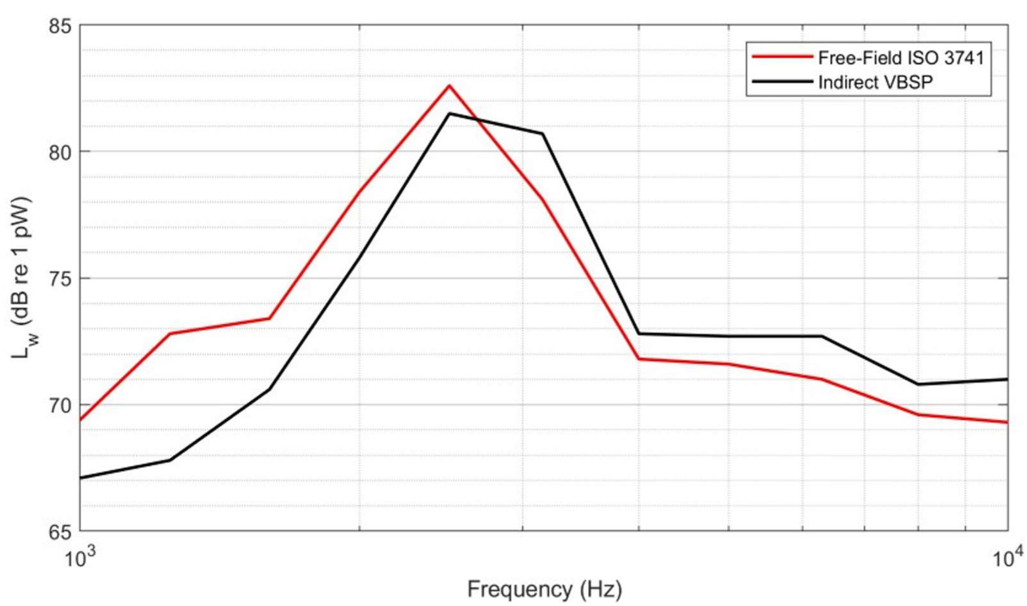


Figure 9. The I-VBSP blender measurement (black) compared to the free-field blender ISO 3741 measurement (red). Note: The abscissa for this figure is scaled to 1,000-10,000 Hz to visualize the sound power level increments between curves better.

6. CONCLUSION

It has been shown that there are source locations chosen that minimize the variance associated with the calibration curve used for the I-VBSP method. A BEM model predicted that the baffled flat plate radiation resistance matrix can be used to approximate the sound power radiated from the 0.61 m cube enclosure used in this work above the 630 Hz OTO band, enabling the indirect method to work above that frequency for this enclosure. Experimental analysis showed that the I-VBSP method is accurate to within +/- 1 to 2 dB of the free-field acoustic power above 1.63 kHz. This supports the hypothesis that the MDF sides are radiating significantly more than the sides of the enclosure in the VA One model below 1.63 kHz. Therefore, the transmission loss through the MDF sides of the enclosure need to be improved for future testing.

These results indicate that the I-VBSP method shows promise for obtaining the sound power of a noise source, although there is room for accuracy improvement. To improve the results, a new enclosure will need to be fabricated to improve the rigidity of the sides so that more of the source energy will radiate into the room through the membrane. This will ensure that the SLDV picks up the low frequency energy the ISO 3741 standard measures.

Future work will include improving the transmission loss of a new enclosure so that the scanned face captures a higher percentage of the acoustic energy radiating from the enclosed sources. Different material panels such as thin aluminum will be investigated to see if there may be a better choice than mylar for the I-VBSP method that will be more consistent between measurements. The new enclosure will also have unique dimensions to reduce the modal degeneracy of the acoustic field inside the enclosure simply to improve the diffuseness within the enclosure so that the sources can be moved around more freely without affecting the radiated power output. A new calibration curve for this enclosure will be obtained using the "Specific Locations" to improve accuracy. For the enclosed ISO 3741 measurements, an updated reverberation time will be obtained to account for the added absorption of the extensive measurement equipment within the reverberation chamber.

7. ACKNOWLEDGEMENTS

John C. Ebeling and Gibson H. Campbell contributed to the ISO 3741 measurements for many of the sources within the enclosure. Trent P. Bates simplified the figures for the average ISO 3741 measurements. Praveen Jayasheela provided VA One support to better understand the software. Additional support was provided by the BYU Department of Physics & Astronomy Wood Shop. This project was funded by the National Science Foundation, grant number 527136.

8. REFERENCES

[1] ISO 3740:2019. "Acoustics – Determination of sound power levels of noise sources – Guidelines for the use of basic standards" (International Organization for Standardization, Geneva, 2019).

[2] T. P. Bates, I. C. Bacon, J. D. Blotter, and S. D. Sommerfeldt, "Vibration-based sound power measurements of arbitrarily curved panels," J. Acoust. Soc. Am. **151**, 1171-1179 (2022), doi: 10.1121/10.0009581.

[3] T. P. Bates, *Experimental validation of a vibration-based sound power method*, Master's Thesis, Brigham Young University, Provo, UT (2022).

[4] P. Aslani, S. D. Sommerfeldt, and J. D. Blotter, "Analysis of external radiation from circular cylindrical shells," J. Sound Vib. **408**, 154-167 (2017), doi: 10.1016/j.jsv.2017.07.021.

[5] C. B. Goates, C. B. Jones, S. D. Sommerfeldt, and J. D. Blotter, "Sound power of vibrating cylinders using the radiation resistance matrix and a laser vibrometer," J. Acoust. Soc. Am, **148**, 3553–3561 (2020), doi: 10.1121/10.0002870.

[6] C. B. Jones, C. B. Goates, J. D. Blotter, and S. D. Sommerfeldt, "Experimental validation of determining sound power using acoustic radiation modes and a laser vibrometer," Applied Acoustics, **164**, Jul. 2020, doi: 10.1016/j.apacoust.2020.107254.

[7] F. Fahy and P. Gardonio, *Sound and Structural Vibration: Radiation, Transmission and Response*, 2nd ed. (Academic Press, Oxford, UK, 2007), pp. 165-175.

[8] I. Bacon, S. D. Sommerfeldt, and J. D. Blotter, "Determination of radiated sound power from acoustic sources using the VBSP method and a mylar boundary," Proc. Mtgs. Acoust. **46**, 065003 (2022), doi: 10.1121/2.0001663.

[9] M. Kleiner and J. Tichy, *Acoustics of Small Rooms*, (CRC, New York, 2017), pp. 28-32, 37-48, 64-71.

[10] L. E. Kinsler, A. R. Frey, A. B. Coppens, & J. V. Sanders, *Fundamentals of acoustics*, 4th ed., (John Wiley & Sons, New York, 2000), pp. 286-291.

[11] ISO 3741:2010. "Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Precision methods for reverberation test rooms" (International Organization for Standardization, Geneva, 2010).

[12] H. Kuttruff, *Room acoustics*, 5th ed. (CRC Press LLC, 2009), pp. 83-91.

[13] J. C. Ebeling, I. C. Bacon, T. P. Bates, S. D. Sommerfeldt, and J. D. Blotter, "Improved efficiency of vibration-based sound power computation through multi-layered radiation resistance matrix symmetry," JASA Express Lett. 2, 125601 (2022), doi: 10.1121/10.0015355.