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Experimental validation of determining sound power using acoustic radiation modes and a laser vibrometer

Cameron B. Jones [a], Caleb B. Goates [b], Jonathan D. Blotter [a,*], Scott D. Sommerfeldt [b]

[a] Department of Mechanical Engineering, Brigham Young University, Provo, UT 84602, United States
[b] Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602, United States

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ABSTRACT

The theoretical development for computing sound power using acoustic radiation modes is well documented. However, an experimental validation and comparison with other sound power measurement standards over a wide frequency range has not been presented. This paper compares experimental results from an acoustic-radiation-modes-based sound power measurement method to results obtained using ISO 3741 in two scenarios. First, sound power measurement results from a single simply-supported baffled panel are compared. A comparison of sound power measurements of two simply-supported baffled panels is then presented. Results between the two methods for the single panel show a maximum one-third octave band difference of 2.2 dB between 200 Hz and 4 kHz with an overall difference of 1.7 dB. For the two-panel system, the maximum one-third octave band difference is 1.6 dB with an overall difference of 0.7 dB. It is also shown that in the two-panel case, the sound power from each panel can be measured individually using the acoustic radiation modes approach and summed to obtain the overall sound power as measured using ISO 3741.

1. Introduction

Sound power is the standard measure used to quantify noise radiated from a source. It is considered a global metric because it measures the total radiated sound. Most of the literature addressing structural vibration sources has analyzed the response of the structure in terms of the vibration modes associated with the structure. When noise radiation is a concern, many of the papers in the literature have then formulated that acoustic radiation in terms of these structural modes. However, the structural vibration modes are not a natural basis set for describing acoustic radiation and as a result, this approach does not lead to an efficient solution for acoustic radiation. To address this limitation, an approach for describing the radiated sound power in terms of an acoustic basis set referred to as acoustic radiation modes has been previously formulated.

The theory behind computing radiated sound power from flat panels using the acoustic radiation modes approach and various applications have been presented in the literature [1–12]. Although the method of computing sound power using acoustic radiation modes has been widely used, an experimental validation and comparison with other standards over a wide frequency range has not been presented. One purpose of this paper is to present a detailed experimental validation of this approach by quantifying the differences between the experimental results and those from an accepted international standard. A second purpose is to provide a preliminary investigation of the potential for an acoustic radiation modes-based standard for measuring sound power that could overcome some of the limitations of current standards.

The International Organization for Standardization (ISO) currently has seven sound power standards based on pressure measurements. All but one of these require specified acoustic environments obtained with anechoic or reverberation chambers [13–24,26]. The one standard that does not require a known acoustic environment (ISO 3747) only provides survey grade results for narrowband measurements and engineering grade results for broadband [19].

There are three ISO sound power measurement standards based on intensity measurements [20–22]. These standards can provide precision grade results but require the measurement surface to completely surround the noise source, or, if placed on a hard/reflective surface, hemispherically surround the noise source. In practice, this makes the sound intensity approaches lose significant accuracy when the desire is to measure part of a built-up structure, such as the windshield or engine hood of an automobile. Intensity-based measurements also lose accuracy in windy conditions or conditions with varying background noise.

* Corresponding author.
E-mail address: jblotter@byu.edu (J.D. Blotter).

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The ISO provides two technical specifications based on structural vibration methods for computing sound power [23,24]. ISO/TS 7849-1:2009 provides survey grade results, while ISO/TS 7849-2:2009 provides engineering grade results.

In this paper, a validation of the method for computing sound power based on surface velocity measurements and acoustic radiation modes is presented. While a number of papers have been written that develop theoretical and computational results using this approach, the literature is lacking in experimental confirmation of the method. The long-term objective is that the method may be appropriate for a future new vibration-based standard for measuring sound power. This method, known as the vibration-based radiation modes (VBRM) method, removes or lessens the effects of many of the limitations of current methods, such as the need for a specific acoustic environment or limitations on background noise or wind conditions. It is also shown that the VBRM method will allow for truly in-situ measurements as well as the measurement of the contribution to sound power of different incoherent sources in a multiple source setup. Current limitations of the VBRM theory require the surface velocities of the source to be measurable, the vibration to be steady state, and the radiation resistance matrix to be known with sufficient accuracy. Limitations due to multiple coherent and coupling sources may exist as well, but need to be further investigated. Furthermore, the results presented in this paper are limited to baffled flat panels and extension to built-up geometries is not presented.

Experimental results will be compared to ISO 3741[13]. ISO 3741, titled "Acoustics – determination of sound power levels and sound energy levels of noise sources using sound pressure – Precision methods for reverberation test rooms", is a Precision (Grade 1) ISO standard that describes the methods for measuring sound power in a reverberation chamber. It details the reverberation time, temperature, air pressure, and humidity requirements to take sound power measurements. ISO 3741 methods are based on the sound power of the source under test being proportional to the mean-square sound pressure averaged in space and time. The standard requires sound pressure measurements to be taken using an array of at least six microphones. The minimum distance between a given microphone and any surface in the reverberation chamber is 1 m. The minimum required distance between the noise source and any microphone is given by $d_{s\_m} = 0.08\sqrt{V/T_{rev}}$ where V is the volume of the reverberation chamber and T_{rev} is the reverberation time of any given one-third octave band. Each microphone must be separated from other microphones by a minimum distance of $d_{m\_m} = \lambda/2$ where λ is the wavelength associated with the center-band frequency of the lowest one-third octave band in question. The reverberation chamber used in this work has a volume of 204 m^3 (4.96 m $\times$ 5.89 m $\times$ 6.98 m) which allows for measurements down to the 100 Hz one-third octave band so long as the noise floor is not within 10 dB of the sound power measurement for any given one-third octave band.

This paper will give a brief overview of the theory behind the VBRM method including acoustic radiation modes and their relationship to sound power measurements. The sound power from a single baffled panel will be measured using both the VBRM method and ISO 3741, and the results from the two methods will be compared. The sound power from two radiating flat panels in the same environment will be measured using both methods. The ability of the VBRM method to determine the individual contributions of the two panels during simultaneous vibration will be demonstrated.

2. The VBRM method

The VBRM method is based on spatially-dense surface velocity measurements and the acoustic radiation mode approach for computing sound power. The following derivation follows that given by Fahy and Gardonio in Ref. [1]. Acoustic radiation modes are derived from the radiation resistance matrix. For a baffled flat panel discretized into N elements of equal area, the radiation resistance matrix is given by

$$\mathbf{R}(\omega) = \frac{\omega^2\rho_0 A_e^2}{4\pi c}\begin{bmatrix} 1 & \frac{\sin(kd_{12})}{kd_{12}} & \cdots & \frac{\sin(kd_{1N})}{kd_{1N}} \\ \frac{\sin(kd_{21})}{kd_{21}} & 1 & \vdots & \\ \vdots & \ddots & & \\ \frac{\sin(kd_{N1})}{kd_{N1}} & \cdots & 1 & \end{bmatrix} \tag{1}$$

where ω is the angular frequency, ρ_0 is the density of the surrounding fluid, A_e is the area of a single discrete element, c is the speed of sound in the fluid, k is the acoustic wavenumber, and d_{ij} is the distance from the i^{th} to the j^{th} element. The eigenvectors of the radiation resistance matrix are the acoustic radiation modes, and the corresponding eigenvalues are related to the radiation efficiencies of the modes.

Using the radiation resistance matrix, sound power can be expressed as

$$\bar{P}(\omega) = \mathbf{v}_e^H(\omega)\mathbf{R}(\omega)\mathbf{v}_e(\omega), \tag{2}$$

where $\mathbf{v}_e$ is a vector containing the surface-normal velocity of each discrete element on the panel, and $(\cdot)^H$ signifies the Hermitian transpose. Using acoustic radiation modes, $\boldsymbol{q_r}$, and the eigenvalues, λ_r, the expression for sound power is

$$\bar{P} = \sum_{r=1}^{N}\lambda_r\left|\tilde{y}_r\right|^2 \tag{3}$$

where $\tilde{y}_r = q_r = \mathbf{v}_e$. Often the sum in Eq. (3) will be truncated at some $n < N$ because of the quick drop off of the eigenvalues at low frequencies. Because this work calculates power over a wide frequency range, all N radiation modes will be used. Eqs. (2) and (3) are mathematically equivalent as a result.

As noted, several articles present the theory of acoustic radiation modes for computing sound power. However, only one article was found that compares experimental results from the acoustic radiation modes approach and other established sound power measurement standards. This article was published by Bai et al. in 2002 [25]. Their research focused on the accuracy of the method using only the most efficient radiation modes to calculate sound power at low frequency. In their work, the vibration sampling of the structure was very sparse and experimental results only showed agreement with ISO 3745 up to 800 Hz. The VBRM method presented in this paper uses all radiation modes to calculate the sound power at a given frequency and the spatial sampling of the velocity field extends the frequency range up to 4 kHz.

It will also be noted that the acoustic radiation modes are frequency dependent. For this work, the radiation modes have been determined for each frequency across that frequency band of interest, in order to ensure maximum accuracy. However, the radiation modes are generally smoothly varying with frequency (and slowly varying at low frequencies). Thus, a future question to be explored is whether one can use values for the radiation modes at a limited number of frequencies to compute the sound power without degrading the results significantly.

3. Experimental setup and results

In this section, experimental results obtained using the VBRM method and ISO 3741 are presented and compared. The setup and results for a single baffled flat panel are first presented followed by the setup and results for a two panel system. ISO 3741 provides precision sound power results in one-third octave bands, while the VBRM method is a narrowband calculation. As such, the narrowband VBRM results will be converted to one-third octave band results using standardized one-third octave filter definitions [26].

3.1. Single panel

3.1.1. Setup and measurements of the single panel system

The single panel was setup to approximate an infinitely baffled panel in a way that both the VBRM and ISO 3742 measurements could be taken. The single, approximately simply-supported aluminum panel [27] of dimensions 48.5 cm × 42.0 cm × 0.16 cm was placed in a reverberation chamber with dimensions of approximately 5 m × 6 m × 7 m. The panel was mounted in a heavy steel frame and placed against one wall of the reverberation chamber, which was used to approximate an infinite baffle as shown in Fig. 1. Heavy black tape was used to help seal the panel to the wall as shown. It will be noted that the thickness of the frame results in the panel being approximately 2.54 cm (1 in.) off the wall. At 4 kHz, this is approximately 0.3 wavelengths away, and for frequencies at 4 kHz and below, it was found that this small offset did not significantly impact the panel in a rigid baffle assumption. A piezoelectric transducer was mounted in the upper left quadrant of the back of the panel and was excited with random noise between 0 and 20 kHz.

Measurements were taken both with a scanning laser Doppler vibrometer (SLDV) and according to ISO 3741. The SLDV was used to measure the surface velocities of the panel on an 11 × 13 point scan grid as shown in Fig. 2(a). The resulting surface normal velocity frequency response of a representative point on the panel is shown in Fig. 2(b). (The scan point shown corresponds to the point in the fifth row, fourth column of the scan grid.) The velocities obtained from the SLDV over the entire grid were expanded into the calculated radiation modes as described in Eq. (3) to calculate

Fig. 1. Setup of a single panel in a reverberation chamber with the wall of the reverberation chamber acting as a baffle.

Table 1
Sound power measurements from a single simply supported and baffled panel as calculated using ISO 3741 and the VBRM method, as well as the error between the two methods.

		Sound Power (dB)		
		ISO 3741	VBRM	Difference
Third octave band by center band frequency (Hz)	100	22.6	2.0	20.6
	125	22.8	2.0	20.8
	160	16.8	15.0	1.8
	200	14.8	16.0	(1.2)
	250	13.7	12.4	1.2
	315	30.1	29.6	0.5
	400	29.1	29.2	(0.1)
	500	31.8	32.3	(0.6)
	630	35.0	35.5	(0.5)
	800	41.6	42.1	(0.5)
	1000	35.6	36.6	(1.1)
	1250	43.0	44.0	(1.0)
	1600	48.8	49.1	(0.3)
	2000	46.0	47.2	(1.2)
	2500	50.5	51.4	(0.9)
	3150	57.9	55.9	2.0
	4000	62.8	60.6	2.2
	5000	66.8	67.7	(0.9)
	6300	67.9	70.1	(2.2)
	8000	70.5	74.8	(4.3)
	10,000	71.8	75.9	(4.1)

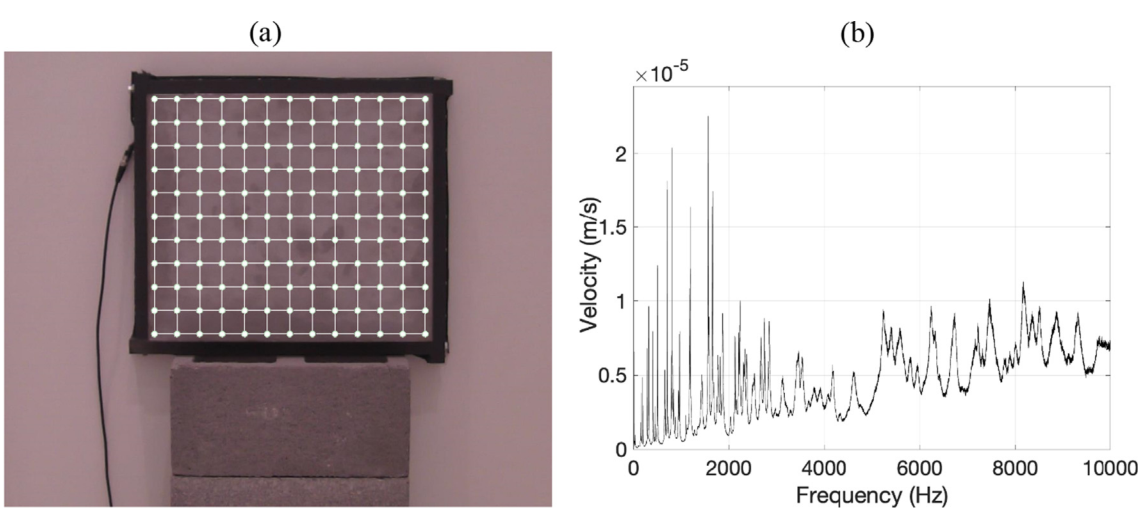

Fig. 2. (a) The 11 × 13 grid of scan points used to measure surface velocities of the panel; (b) the structural response of the panel as measured by the SLDV.

the sound power using all radiation modes. These results were compared to the sound power calculated from pressure measurements according to ISO 3741.

3.1.2. Results of the single panel system

The measured sound power resulting from ISO 3741 and the VBRM method are reported in one-third octave bands with center band frequencies between 0 and 10 kHz in Table 1, along with the differences between the two methods. A plot of these data is shown in Fig. 3.

Fig. 3 shows that between the one-third octave bands with center band frequencies of 200 Hz and 4 kHz there is good agreement between the two methods. The maximum difference was 2.2 dB at the 4 kHz one-third octave band (see Table 1). The mean one-third octave band difference between the methods in the 200 Hz to 4 kHz bands was −0.1 dB and the standard deviation of the errors was 1.1 dB. The total sound power in the 200 Hz to 4 kHz bands was 62.7 dB re 10^{-12} W using the VBRM method and 64.4 dB re 10^{-12} W using the ISO standard resulting in a total difference of 1.7 dB. Nearly all this difference comes from the 3.15 kHz and 4 kHz one-third octave bands.

At frequencies below 200 Hz there are discrepancies between the ISO 3741 results and the VBRM results. These differences arise due to limitations of the ISO 3741 measurements. The noise floor of the chamber was within 10 dB of the measured sound power below 200 Hz. According to ISO 3741, if the noise floor is within 10 dB of the measured sound power the results represent an upper bound on sound power. Due to the noise floor, errors were introduced at low frequencies using the ISO 3741 method. In this low frequency regime, the VBRM method may be a priori more accurate.

Above the 4 kHz one-third octave band, discrepancies between the two methods also appear. The 11 × 13 measurement grid used in this experiment resulted in a spatial sampling of one scan point every 3.73 cm in the horizontal direction and 3.82 cm in the vertical direction. The Nyquist frequency for the acoustic radiation modes, determined by the spatial sampling distance being half the acoustic wavelength, was 4.6 kHz. The VBRM method maps the vibration response onto the acoustic field, not the structural

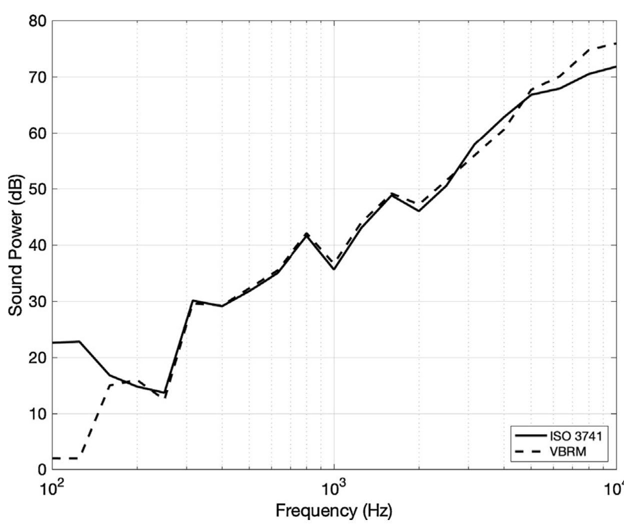

Fig. 3. The measured sound power of the single panel as calculated using ISO 3741 and the VBRM method.

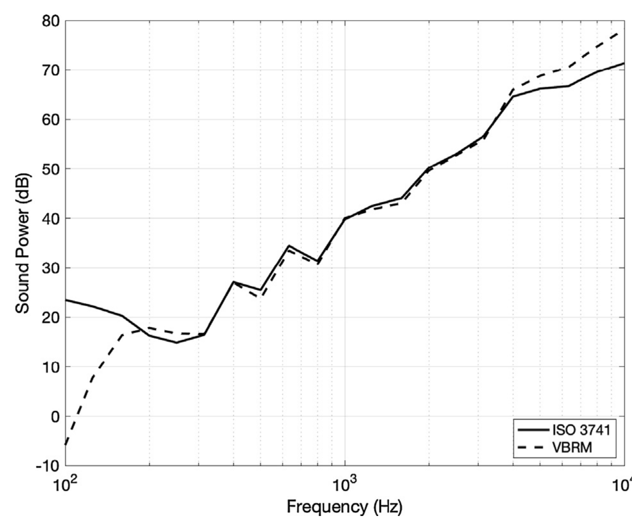

Fig. 5. The measured sound power of the second panel as calculated using ISO 3741 and the VBRM method.

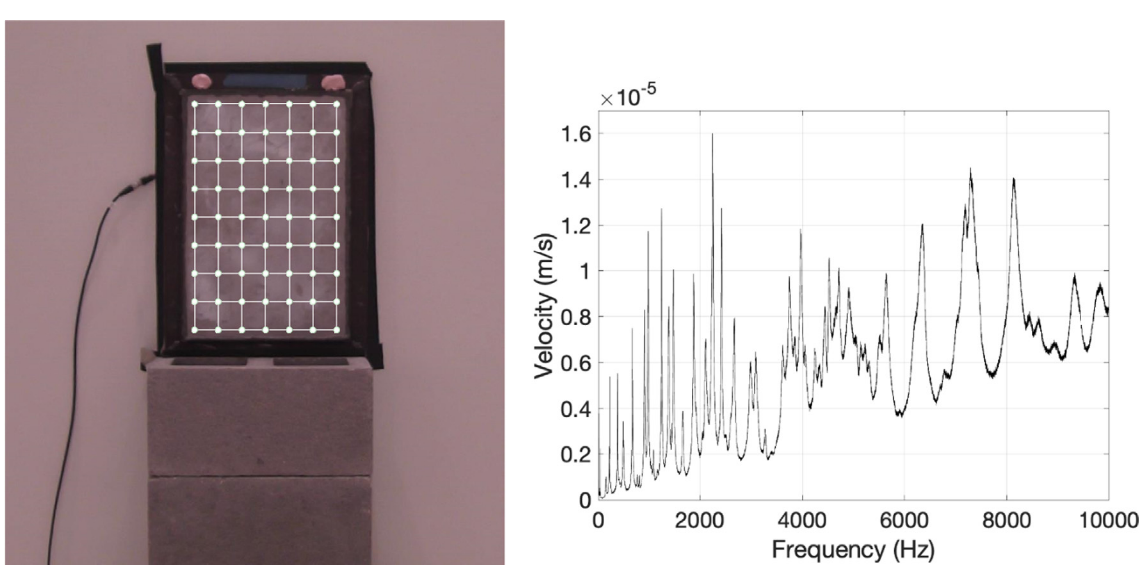

Fig. 4. (a) 7 × 13 grid of scan points used to measure the surface velocities of the second panel. (b) Structural response of the second panel as measured by the SLDV.

field. Thus, the spacing of the scan points dictates the smallest acoustic wavelength associated with the radiation modes that can be resolved. Due to the 5 kHz one-third octave band extending from 4454 Hz to 5612 Hz one would expect to see errors in and above the 5 kHz one-third octave band. Therefore, showing agreement between the two methods at and above the 5 kHz one-third octave band would require a finer spatial sampling mesh.

Using the VBRM method to measure the sound power for a single simply-supported panel requires a less restrictive setup when compared to current ISO standards. The ISO 3741 standard requires a reverberation chamber, while the VBRM does not require a specific acoustic environment; thus, the VBRM method allows for sound power measurements in-situ. The VBRM method would also allow for sound power measurements in windy conditions and conditions with varying background noise. Further advantages are gained when extended to scenarios where multiple incoherent sources contribute to sound power.

3.2. Multiple separated panels

3.2.1. Setup and measurements of the multiple panel system

Following the same procedures used for the single panel above, a second aluminum panel of dimensions 45.5 × 30.3 × 0.16 cm was added to the reverberation chamber on the opposite wall from the first panel. The second panel was also mounted in-plane with the wall of the reverberation chamber, with the wall approximating an infinite baffle. A piezoelectric transducer was mounted in the upper right quadrant of the second panel and was excited with random noise between 0 and 20 kHz. Using the SLDV, velocity scans of the second panel were taken using a 9 × 7 grid (see Fig. 4(a)) resulting in a spatial sampling of one scan point every 4.3 cm in the horizontal direction and 5.1 cm in the vertical direction. This combination of panel size and spatial sampling resulted in a Nyquist frequency of 3.6 kHz. The structural response curves of Panel 1 (Fig. 2(b)) and Panel 2 (Fig. 4(b)) illustrate the two panels have distinctive responses to the random noise inputs.

The sound power from the second panel was measured using the same procedure described in Section 3.1.1 and the results can be seen in Fig. 5. Due to the lower Nyquist frequency associated with Panel 2, discrepancies at higher frequencies begin to be seen in the 4 kHz one-third octave band. Panel 1 sound power results showed discrepancies starting in the 5 kHz one-third octave band.

After calculating the sound power of the second panel using the VBRM method, the panels were measured together. Both panels were simultaneously excited using uncorrelated random noise, new pressure measurements were taken, and the sound power of the multiple panel system was calculated according to ISO 3741.

3.2.2. Results of the multiple panel system

Using the additive property of sound power from uncorrelated sources, the total sound power of the two-panel system was calculated by summing the sound powers of the two panels individually calculated using the VBRM method. This summation is shown in Fig. 6. The sound power at each individual one-third octave band is most impacted by the panel which radiates the most energy in that band. The larger panel (Panel 1) dominates between 300 Hz and 800 Hz and the smaller panel (Panel 2) contributes more at frequencies between 1.9 kHz and 5 kHz.

The calculated total sound power using the VBRM method is compared to the sound power measured following ISO 3741 in Fig. 7 and in Table 2. The additive property was not used in the ISO 3741 data. Between the 250 Hz and 3,150 Hz one-third octave bands there is very good agreement between the two methods with the maximum difference being 1.6 dB at the 250 Hz one-third octave band. The mean one-third octave band difference between 250 Hz and 3150 Hz bands was −0.3 dB with a standard deviation of 0.7 dB. The total sound power difference between 250 Hz and 3150 Hz was 0.7 dB.

At frequencies lower than 200 Hz, the noise floor again caused discrepancies between the two methods, with the VBRM method possibly giving more accurate results in this regime. In the single-panel section there was very good alignment up to 4 kHz due to the Nyquist frequency being 5.5 kHz for the large panel. Due to the spatial sampling and the size of the smaller panel, the Nyquist frequency was 3.6 kHz and there began to be errors in the 4 kHz region and above. These results indicate that the VBRM method results compare well with the results from ISO 3741 up to the spatial sampling limitation, for all frequencies where the response is above the noise floor.

In this multiple panel scenario, the VBRM method exhibited the same advantages over current ISO standards as the single-panel scenario. Additionally, the VBRM method also showed the capability of measuring each panel's contribution to sound power, so long as the radiated waves are not correlated or coupled, without having to isolate and measure each panel individually as would be required by current ISO standards.

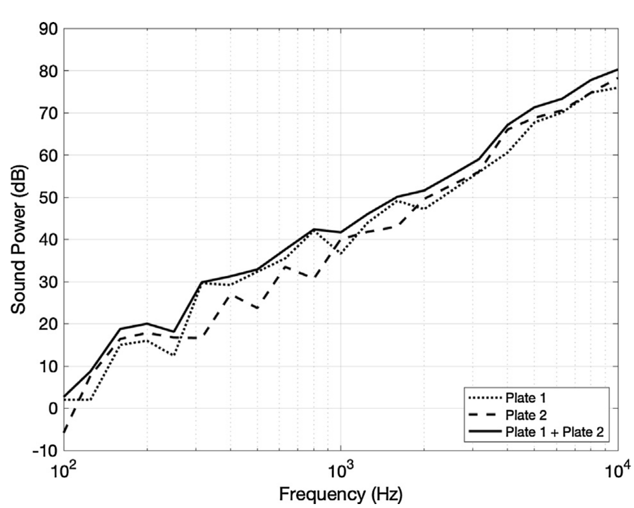

Fig. 6. The calculated sound power of panel 1 and panel 2 as well as the combined system using the VBRM method.

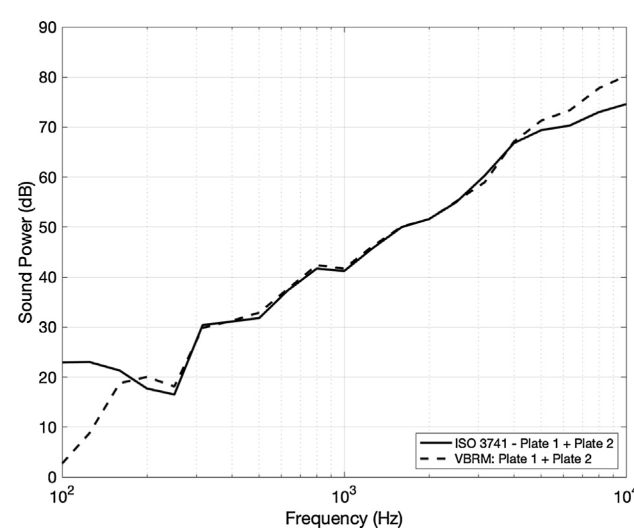

Fig. 7. Comparison of the calculated sound power of the multiple panel system using ISO 3741 and the VBRM method.

Table 2
Sound power measurements from the combined system of two simply supported and baffled panels driven by uncorrelated random noise.

		Sound Power (dB)		
		ISO 3741	VBRM	Difference
Third octave band by center band frequency (Hz)	100	22.9	2.7	20.2
	125	23.0	8.8	14.2
	160	21.3	18.8	2.6
	200	17.7	20.0	(2.3)
	250	16.5	18.1	(1.6)
	315	30.4	29.8	0.5
	400	31.1	31.3	(0.2)
	500	31.8	32.9	(1.0)
	630	37.3	37.6	(0.3)
	800	41.7	42.2	(0.7)
	1000	41.2	41.7	(0.5)
	1250	45.6	46.0	(0.4)
	1600	50.0	50.1	(0.1)
	2000	51.6	51.6	0.0
	2500	55.0	55.2	(0.2)
	3150	60.3	59.0	1.3
	4000	66.8	67.1	(0.4)
	5000	69.4	71.3	(1.9)
	6300	70.3	73.3	(3.1)
	8000	73.0	77.8	(4.7)
	10,000	74.6	80.3	(5.7)

4. Conclusions

This paper has focused on providing an experimental validation of the acoustic radiation modes approach for measuring sound power over a broad frequency range. Experimental results for single- and multi-panel systems using both ISO 3741 and the VBRM method have been presented and compared.

It was shown that for a single panel, sound power calculated using ISO 3741 and the VBRM method had a maximum one-third octave band difference of 2.2 dB between the 200 Hz and 4 kHz one-third octave bands and an overall sound power level difference of 1.7 dB in that frequency range.

It was then shown that for multiple panel systems driven with uncorrelated signals the VBRM method agreed with ISO 3741, with the maximum one-third octave band difference of the multiple panel system being 1.6 dB between the 250 Hz and 3.125 kHz one-third octave bands. The overall difference in sound power level was 0.7 dB in that frequency range.

The VBRM method allows for sound power measurements in a variety of situations made difficult by current ISO standards. These situations include but are not limited to scenarios where anechoic or reverberation chambers are not accessible or cannot fit a specified setup, windy conditions which prohibit the use of ISO standards, or the source of interest being part of a larger system. The VBRM method also allows the measurement of the contribution to total sound power of multiple incoherent sources in the same environment where coupling is negligible without requiring each source to be isolated and tested individually.

The current results have been limited to situations where the multiple sources are incoherent, and the frequency range of interest is below the Nyquist frequency as dictated by the spatial density of the surface velocity measurements. Future research will explore the extension of the VBRM method to more general situations, including the possibility of multiple coherent sources and curved structures.

CRediT authorship contribution statement

Cameron B. Jones: Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Caleb Goates:** Methodology, Formal analysis, Writing - review & editing. **Jonathan D. Blotter:** Conceptualization, Resources, Supervision. **Scott D. Sommerfeldt:** Conceptualization, Resources, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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