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Bandwidth extension of intensity-based sound power estimates

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Abstract: The traditional method for intensity-based sound power estimates often used in engineering applications is limited in bandwidth by microphone phase mismatch at low frequencies and by microphone spacing at high frequencies. To overcome these limitations, the Phase and Amplitude Gradient Estimator (PAGE) method [Gee, Neilsen, Sommerfeldt, Akamine, and Okamoto, J. Acoust. Soc. Am. **141**(4), EL357–EL362 (2017)] is applied to sound power for a reference sound source, a blender, and a vacuum cleaner. Sound power measurements taken according to ISO 3741:2010 (2010) are compared against traditional- and PAGE-processed intensity-based sound power estimates measured according to ANSI S12.12-1992 (R2017). While the traditional method underestimates the sound power at the spatial Nyquist frequency by 7–10 dB, the PAGE-based sound power is accurate up to the spatial Nyquist frequency, and above when phase unwrapping is successful.
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1. Introduction

In acoustical engineering, sound power is an important quantity for field and source characterization. Sound power can be estimated via numerical simulations[1] or standardized measurements.[2–4] One such standardized measurement method[2] finds sound power from acoustic intensity using multimicrophone probes. The traditional (TRAD) or p-p method for obtaining acoustic intensity from a multimicrophone probe, developed in the 1970s, uses a finite-differencing of complex pressures.[5–7] However, the TRAD method commonly used in engineering applications has a high-frequency bandwidth limitation determined by microphone spacing.[7–9] One solution to this problem has been the development of devices to directly measure acoustic particle velocity with heated wires, circumventing the need to estimate particle velocity from pressures in intensity calculations.[10] Unfortunately, such devices are inaccurate in extreme temperature and flow conditions.[11] In an effort to create a method robust enough for such conditions and powerful enough to overcome TRAD method bandwidth limitations, the Phase and Amplitude Gradient Estimator (PAGE) method has been developed.[12]

The PAGE method extends the bandwidth of reliable intensity estimates. One of the primary advantages of the PAGE method is that it has been shown to have zero bias error in estimating acoustic intensity up to the spatial Nyquist frequency, f_{Nyq}.[13] Additionally, for signals containing broadband content, the PAGE method's phase unwrapping capability allows accurate particle velocity estimates above f_{Nyq}.[14] The PAGE method has been applied to acoustic intensity in the context of near-field rocket noise,[15] supersonic jet noise,[11,14] plane wave tube environments,[14] broadband noise,[16] source localization,[17] and narrowband noise with low-level broadband noise.[18,19]

The work presented in this letter expands application of the PAGE method to intensity-based sound power. Specifically, we explore an engineering application of the PAGE method to *in situ* intensity-based sound power estimates. Also, this work seeks to validate the practicality and advantages of the bandwidth-extending capabilities of the PAGE method for industry professionals.

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2. Methodology

Sound power was obtained for the three sources depicted in Figs. 1(a)–1(c): a Norsonic Nor278 reference sound source, a handheld vacuum cleaner set to HIGH, and a household blender set to ICE CRUSH mode. Intensity-based sound power measurements were taken *in situ* using the free-field engineering-grade standard ANSI S12.12-1992 (R2017) with a two-microphone probe [see Fig. 1(e)].[2] The probe used a microphone spacing of 10.16 cm (4 in.), giving the probe a f_{Nyq} of 1.75 kHz. This large spacing was chosen as a proof of concept to illustrate the capability of the PAGE method to extend bandwidth. These measurements were processed with both the TRAD and PAGE methods for comparison purposes. Phase unwrapping was used in the PAGE processing.

To evaluate the accuracy of the TRAD and PAGE methods, the resulting intensity-based sound power estimates are compared with sound power obtained according to other standards. This includes sound power measurements of the same three sources taken in a reverberation chamber according to the diffuse-field scientific-grade standard, ISO 3741:2010.[3] Additionally, the reference sound source came with sound power documentation according to ISO 3745:2012, which is also used for comparison.[4]

For intensity-based sound power measurements *in situ*, each source was placed in the center of a 1 m^3 control surface [see Fig. 1(d)]. Each face of the virtual cubic surface was divided evenly into a 7×7 grid. A gantry system was used to maneuver the two-microphone probe to the center of each grid square on the four sides and top of the cube, making a total of 245 points. The line connecting the two microphones on the probe was kept orthogonal to the control surface.

By summing the intensity across all sampling points, the sound power (Π) can be estimated as

$$\Pi = \oint \boldsymbol{I} \cdot \boldsymbol{dS} \approx \sum_{i=1}^{245} I_i A_i \tag{1}$$

where $\boldsymbol{I}$ is the acoustic intensity vector, $\boldsymbol{dS}$ is the unit vector normal to the control surface, I_i is the magnitude of the acoustic intensity orthogonal to the surface at the ith position, and A_i is the area of the ith grid square. Within this formulation, the acoustic intensity was estimated using both TRAD and PAGE processing.

Active intensity ($\boldsymbol{I}_a$) depends on the complex pressure ($\tilde{p}$) and complex particle velocity ($\tilde{\boldsymbol{u}}$): $\boldsymbol{I}_a = 0.5\mathrm{Re}\{\tilde{p}^* \tilde{\boldsymbol{u}}\}$, where $*$ indicates complex conjugate. Using a multi-microphone probe, particle velocity can be estimated from the gradient of the pressure using Euler's equation, $\tilde{\boldsymbol{u}} = (j/\rho_0 \omega)\nabla \tilde{p}$, where j is the imaginary unit, ρ_0 is the air density, and ω is the angular frequency. The work of Fahy[7] and Whiting *et al.*[13] sets forth the formulation for estimating intensity with the TRAD and PAGE methods, respectively. For reference, their results are included herein.

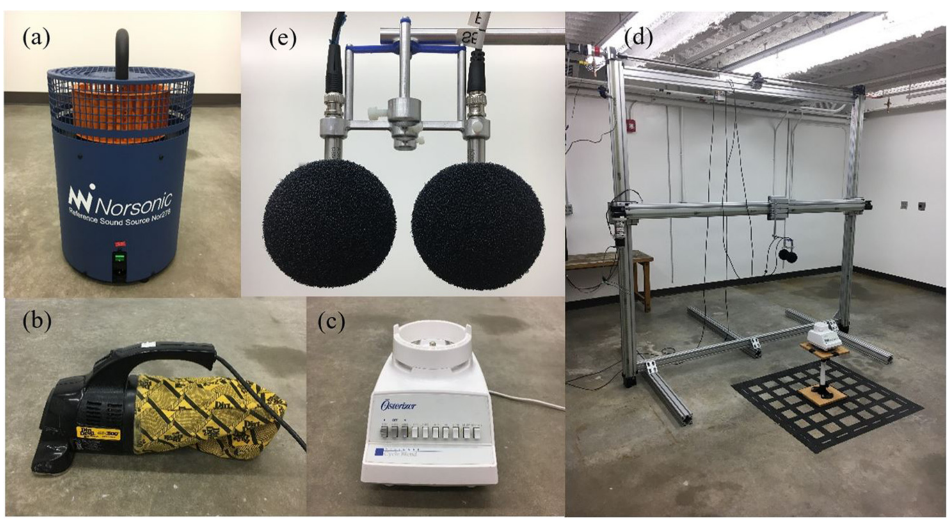

Fig. 1. (Color online) (a) Norsonic Nor278 reference sound source. (b) Handheld vacuum cleaner. (c) Household blender. (d) Experimental setup consisting of a 7×7 grid marking the location of the base of 1 m^3 control surface, a source in the center of the control surface cube, a gantry system, and a two-microphone probe. (e) Microphone probe with two phase-matched 1/2 in. G.R.A.S. 46AE microphones spaced 4 in. apart.

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For a two-microphone probe, the TRAD method uses the complex pressures from the two microphones ($\tilde{p}_1$ and $\tilde{p}_2$) to estimate the pressure and particle velocity at the center of the probe,

$$\tilde{p}^{\mathrm{TRAD}} = \frac{1}{2}(\tilde{p}_1 + \tilde{p}_2), \tag{2}$$

$$\tilde{\boldsymbol{u}}^{\mathrm{TRAD}} = \frac{j}{\rho_0 \omega}\left(\frac{\tilde{p}_2 - \tilde{p}_1}{d}\right), \tag{3}$$

where d is the microphone separation distance and the tilde is used to indicate complex quantities. Alternatively, the PAGE method, which builds on the work of Mann *et al.*,[20,21] uses a phasor representation for the pressure at microphone i: $\tilde{p}_i = P_i e^{j\phi_i}$, where P_i is the amplitude of the pressure and ϕ_i is the phase. The center pressure for a two-microphone probe is estimated as

$$\tilde{p}^{\mathrm{PAGE}} = \widehat{P} e^{-j\widehat{\phi}}, \tag{4}$$

where $\widehat{P} = (P_1 + P_2)/2$, and $\widehat{\phi} = (\phi_1 + \phi_2)/2$ is the center phase estimate. (Estimated quantities are denoted with an overhat.) Because $\widehat{\phi}$ is a relative phase between microphone locations, it can be ignored in intensity calculations since it cancels out in the $\tilde{p}^*\tilde{\boldsymbol{u}}$ calculation.[19] The particle velocity at the center of the probe can be estimated as

$$\tilde{\boldsymbol{u}}^{\mathrm{PAGE}} = \left(\frac{e^{-j\widehat{\phi}}}{\rho_0 \omega}\right)\left(\widehat{P}\widehat{\nabla\phi} + j\widehat{\nabla P}\right), \tag{5}$$

where $\widehat{\nabla P} = (P_2 - P_1)/d$ and $\widehat{\nabla\phi} = (\phi_2 - \phi_1)/d$. The PAGE formulation for active intensity can then be written as

$$\boldsymbol{I}_a^{\mathrm{PAGE}} = \frac{\widehat{\mathrm{P}}^2\,\widehat{\nabla\phi}}{2\rho_0\omega}. \tag{6}$$

For all PAGE processing in this study, phase unwrapping on $\widehat{\nabla\phi}$ was used to extend intensity estimates beyond f_{Nyq}.[11]

3. Results and analysis

First, the narrowband intensity-based sound power spectra are presented for the three sources to illustrate the difference between TRAD and PAGE processing. These spectra demonstrate similar features and are shown in Fig. 2. In each case, the TRAD method underestimates the sound power at frequencies greater than 70% of f_{Nyq}, and the difference between the PAGE and TRAD estimates is 7–10 dB at f_{Nyq}. The TRAD estimate continues to drop above f_{Nyq}. This result agrees

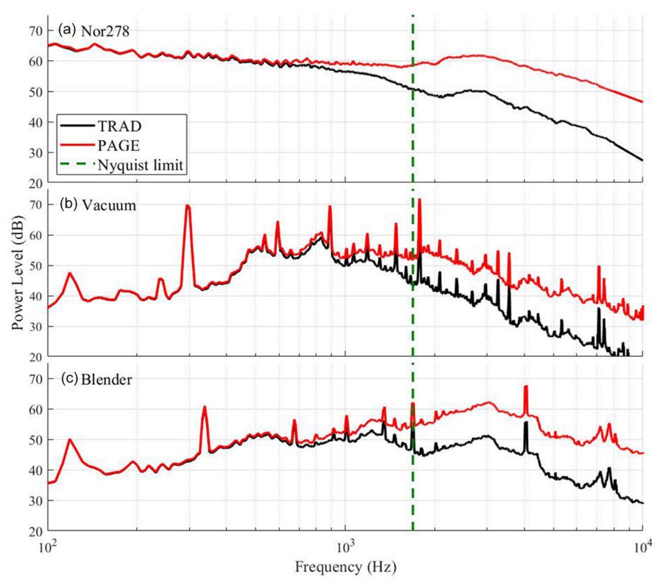

Fig. 2. (Color online) Narrowband intensity-based sound power spectra in dB re 10 pW for three sources with both TRAD and PAGE processing: (a) Nor278 reference sound source, (b) handheld vacuum cleaner, and (c) household blender. The spatial Nyquist frequency, f_{Nyq} is marked by a dashed vertical line.

with the two-microphone probe bias error analysis for intensity magnitude of a plane wave shown in Fig. 4 of Whiting *et al.*[13] They found the bias error is less than 5% for frequencies below 82% of f_{Nyq}. The PAGE method, on the other hand, was shown to have 0% bias error up to f_{Nyq}, and 0% bias error beyond the Nyquist frequency using phase unwrapping.[12] Errors from the spatial sampling,[22] summing discrete measurement locations versus integrating, have not been accounted for in this work. The maximum measurement uncertainty ranges from 1.5 to 3.0 dB, consistent with the cited sound power standards.

Although the narrowband sound power spectra indicate the two intensity-based processing methods (Fig. 2) follow expected trends, these spectra must be compared to a benchmark to evaluate their accuracy. To evaluate accuracy, therefore, the intensity-based sound power spectra for the three sources are compared against benchmark sound power spectra obtained from the diffuse-field method in ISO 3741:2010 for frequencies from 100 Hz to 10 kHz.[3] The Nor278 has a second benchmark in the calibration curve provided by the manufacturer obtained using ISO 3745:2003.[4] As both these benchmarks are one-third octave band spectra, the narrowband results in Fig. 2 are converted to one-third octave spectra for comparison.

The one-third octave spectra for all three sources are shown in Fig. 3. For the Nor278, the PAGE method intensity-based sound power estimate agrees with both benchmark measurements—the manufacturer's calibration curve and the diffuse-field reverberation chamber measurements, which are essentially the same—well above f_{Nyq} as shown in Fig. 3(a). The PAGE estimate stays within 2 dB of the calibration curve up to f_{Nyq}, while the TRAD estimate is already 8 dB below the curve at f_{Nyq}. With phase unwrapping, the PAGE estimate continues to follow the calibration curve closely, within 2 dB, up to the 8 kHz band while the TRAD estimate underestimates the sound power by 19 dB by the 8 kHz band. Low-frequency discrepancies are due to the influence of flow on the signal processing. Intensity-based sound power values above 10 kHz have a greater uncertainty due to the effects of the angle of incidence and windscreens. No free-field corrections were made because of different angles of incidence.

The sound power trends for the handheld vacuum cleaner and blender are similar to those of the Nor278, as shown in Figs. 3(b) and 3(c), respectively. The PAGE-processed sound power better matches the benchmark diffuse-field (reverberation chamber) sound power than the TRAD-processed sound power; the TRAD-processed sound power begins to drop off at about 70% of f_{Nyq} and continues to fall as frequency increases. There are, however, a few differences between the diffuse-field benchmark and the intensity-based estimates. The difference in the 125 Hz one-third octave band for both the vacuum and the blender is due to electrical noise during the intensity measurements. In addition, the vacuum exhibits strong tonal behavior in the 500–1000 Hz range, which complicates measurements for diffuse-field estimates when determining one-third octave intensity levels. In this frequency range, the intensity-based sound power method captured peak levels missed in the diffuse field method because of weaknesses in estimating the sound power from a diffuse field with a small number of microphones and the tendency for radiated power to be influenced by the normal modes of a room, as noted on page v. of ISO 3741.[3]

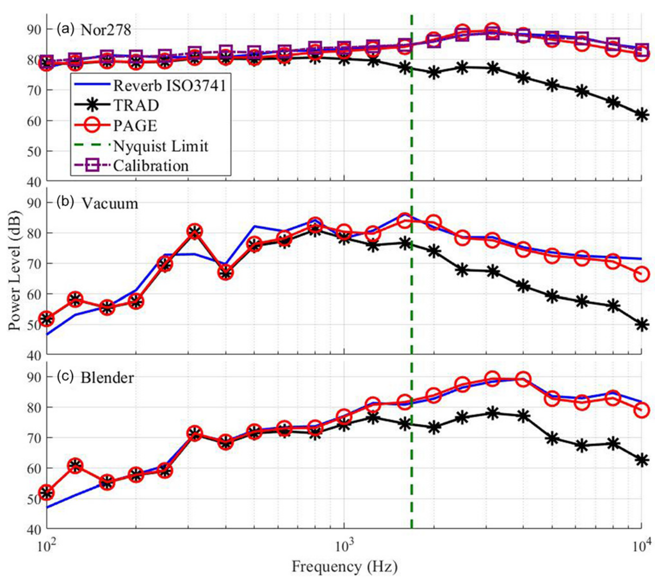

Fig. 3. (Color online) One-third octave sound power spectra in dB re 10 pW for (a) a Nor278 reference sound source, (b) a handheld vacuum cleaner, and (c) a household blender.

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For the 1–8 kHz range [Fig. 3(b)], the PAGE sound power estimate matches the diffuse-field benchmark within 1 dB while the TRAD method underestimates the power level by 10 dB at 2.5 kHz and 16 dB at 8 kHz. For the blender [Fig. 3(c)], the PAGE estimate of sound power matches the benchmark up to 8 kHz within 1.5 dB, well above f_{Nyq}, while the TRAD method estimate begins dropping off in the 630 Hz band. At the spatial Nyquist limit the TRAD method underestimates the benchmark by 7 dB, and by the 8 kHz band it underestimates the benchmark by 17 dB. Thus, the benchmark comparison confirms that the PAGE method increases the reliable bandwidth of sound power estimates.

4. Conclusion

This work demonstrates how the PAGE method can extend the usable bandwidth for multi-microphone probe intensity-based sound power estimations. The sound power spectra of three sources were obtained: a Norsonic Nor278 reference sound source, a handheld vacuum cleaner, and a household blender. Intensity-based sound power was taken according to ANSI S12.12-1992 (R2017)[2] with a two-microphone probe and compared against diffuse-field sound power measurements taken according to ISO 3741:2010 (Ref. 3) in a reverberation chamber. The intensity-based sound power was processed with both the TRAD method and the PAGE method for comparison.

For all three sources, the narrowband intensity-based sound power spectra showed that the TRAD and the PAGE estimates match closely until approximately 70% of the spatial Nyquist frequency, at which point the TRAD estimate begins to drop off. Above the spatial Nyquist frequency, the TRAD estimate continues to drop more rapidly. One-third octave band sound power spectra show that for all three sources the intensity-based sound power spectra estimated with the PAGE method agree better with the benchmark diffuse-field sound power measurements than the TRAD method intensity-based sound power results. While the TRAD method underestimates the sound power level as it approaches the spatial Nyquist limit, the PAGE method is accurate up to the spatial Nyquist limit. Additionally, for broadband noise sources where the phase can be unwrapped, the PAGE method extends the upper frequency limit well above the spatial Nyquist limit.

Since the PAGE method, as a signal processing method, is implemented computationally, engineers who use two-microphone probes to estimate intensity-based sound power can increase the bandwidth of their results without altering existing hardware. The PAGE method can use ordinary microphones, rather than phase-matched pairs, by using greater spacing to compensate for phase mismatch between microphones. Overall, the work presented here shows the practicality of applying the PAGE method to estimate intensity-based sound power spectra while extending the bandwidth of reliable levels up to the spatial Nyquist frequency and, where phase unwrapping can be employed, beyond the spatial Nyquist limit.

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