

Seeing the Pressure Behind the Noise: Ruthenium-Based Pressure-Sensitive Paint (PSP) Enables Noise Diagnostics of Axial Fans for Server Cooling

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ABSTRACT

This study presents the use of pressure-sensitive paint (PSP) measurements to diagnose potential noise sources on the blades of axial fans used for server cooling applications. Because the fan operates at high rotational speeds (3745-4392 rpm), time-resolved capture of surface-pressure fluctuations is achieved using a ruthenium-based PSP with enhanced sensitivity. The PSP measurements provide both mean pressure distributions and pressure fluctuations, revealing complex aerodynamics features associated with blade rotation and flow-structure interaction. To investigate the coupling between surface-pressure dynamics and acoustic emissions, proper orthogonal decomposition (POD) is applied to the pressure-fluctuation data. The resulting temporal coefficients exhibit spectral characteristics that closely match the measured fan noise spectra, indicating a strong correlation between blade-surface pressure fluctuations and noise generation. This correspondence enables qualitative identification of dominant pressure-driven noise sources and their spatial locations. Overall, the results demonstrate that PSP-based pressure visualization is a powerful diagnostic tool for linking aerodynamic pressure phenomena to noise generation mechanisms in axial fans. By revealing pressure features associated with acoustic signatures, the proposed approach offers valuable insights for identifying noise-critical regions and guiding targeted design modifications toward quieter and more efficient server cooling systems.

1. Introduction

Air cooling remains the dominant thermal management strategy for rack-based servers and compact electronic systems, where axial fans serve as the primary means of airflow generation. As power densities in modern data centers continue to increase, higher volumetric airflow rates are required to maintain acceptable operating temperatures. Consequently, axial fans are often driven at elevated rotational speeds, which inevitably leads to increased acoustic emissions. In practice, the allowable noise level has become a key constraint on server air-cooling performance, frequently limiting fan operation before aerodynamic or thermal limits are reached. This trend underscores

the growing demand for reliable diagnostic tools that can identify noise-generation mechanisms and support the development of quieter fan designs for server cooling applications.

Surface-pressure fluctuations on fan blades play a central role in aerodynamic noise generation (Roger & Moreau, 2004). Detailed knowledge of blade-surface pressure distributions and their temporal variations is therefore essential for understanding fan noise mechanisms. However, conventional pressure sensors provide only point-wise measurements and are difficult to integrate onto small-scale axial fan blades without disturbing the flow, particularly under the tight geometric constraints typical of server cooling fans. These limitations have hindered experimental investigations of pressure-driven noise sources in practical fan configurations.

To overcome these challenges, the present study employs pressure-sensitive paint (PSP) as a non-intrusive diagnostic tool for pressure-field visualization on rotating axial fan blades. PSPs are fluorescent paints that consist of oxygen-sensitive luminophores. While excited with ultraviolet or blue lights, the emission characteristics would vary with oxygen density, which can be related to air pressure by Henry's law. The luminescence is therefore captured with cameras or other optical measurement apparatuses. Visualization of the PSP comes in two ways: intensity-based and lifetime-based methods. Intensity-based method estimates the pressure from the emission intensity from PSP. The intensity shall be normalized and a reference condition with known pressure is required. Lifetime-based method on the other hand, measures the lifetime of the luminescence from PSP (Liu et al., 2021). For PSP imaging method for fast rotating surfaces, Peng & Liu (2020) noted 3 challenges: motion degradation, insufficient light intensity, and aerodynamic heating of the surface. In order to reduce motion blur due to sample movement during camera exposure, a short exposure time is desirable; however, it leads to insufficient incident light from the PSP, thereby forming a dilemma for motion degradation and image intensity. For high-speed flows, aerodynamic heating is also addressed since PSP fluorescence suffers from thermal quenching.

Juliano et al. (2011) introduced single-shot lifetime-based methods for PSP imaging on a propeller blade, then applied in other studies to other rotating surfaces (Peng et al., 2017; Li et al., 2022): the technique employs short, pulsed excitation and time-resolved detection to capture the luminescent decay of the paint within a single exposure. Instead of relying on intensity ratios, the pressure is inferred from the oxygen-dependent luminescence lifetime, typically obtained by gating the detector into two time windows following a single excitation pulse. Based on the single-shot lifetime-based method, Crafton & Komerath (2013) employed Wiener deconvolution to remove motion blur from the second exposure image obtained under relatively long exposure times. Their study examined the effects of image noise and the Wiener filter parameters on the quality of the reconstructed images. It was found that the deconvolution process amplifies noise present in the original images. Although stronger filtering can suppress noise amplification, it also reduces the reconstructed image intensity, which in turn affects the accuracy of the inferred pressure.

Though lifetime methods are largely independent of illumination non-uniformity, paint thickness,

and optical alignment, utilization of high-power pulse lasers makes them suffer from low acquisition rates, usually not more than 10 Hz, which even the rotational speed of the fan cannot be resolved. As a proof of concept, a ruthenium-based PSP is applied to a commercial axial fan used for server cooling, enabling acquisition of wind-on images at high frame rates suitable for time-resolved analysis. This approach allows for the simultaneous extraction of spatially resolved mean pressure and pressure fluctuations on the blade surfaces, providing a foundation for correlating pressure dynamics with acoustic emissions. By extending PSP techniques to high-speed axial fans, this work aims to establish a practical methodology for diagnosing noise-critical regions and advancing noise-aware fan design for next-generation server cooling systems.

2. Methods

Pressure-sensitive paint (PSP) measures surface pressure based on oxygen quenching of luminophore emission (Liu et al., 2021). Under constant temperature, as the local partial pressure of oxygen increases, the luminescent intensity decreases, allowing surface pressure P to be quantified through calibration using the Stern–Volmer relationship as shown in Eq. (1):

$$\frac{I_{\text{ref}}}{I} = A + B \frac{P}{P_{\text{ref}}} \quad (1)$$

where P_{ref} is the pressure under reference conditions, I and I_{ref} are the measured intensity under wind-on and reference condition, respectively, and A and B are calibration constants. In this study, Ru(dpp) is selected as the PSP luminophore due to its high absolute brightness, which enables shorter exposure times and minimizes motion-induced image degradation at high rotational speeds. The luminophore is mixed with nanoscale silica particles and RTV118 binder in toluene, then airbrushed onto the suction surfaces of the fan blades over a white base coat. The proportion of the paint is shown in Table. 1. All remaining fan surfaces are painted matte black to suppress reflections and improve signal quality.

Table 1. Components and proportions of ingredients for PSP used in this study

Component	Ru(dpp)	toluene	SiO ₂	RTV118
Proportion	1 mg	2 ml	40 mg	20 mg

The experimental setup is shown in Fig. 1 (a). The PSP-coated blades are illuminated using two blue LED PAR lamps, and the emitted luminescence is captured by a high-speed camera equipped with a 515 nm long-pass filter. After acquiring 64 wind-off reference images, 256 wind-on images are recorded at 3000 fps with an exposure time of 300 μs while the fan operates at full speed under a 12 V supply. Acoustic emissions from the fans, along with background noise, are measured under

the same configuration, using a calibrated commercial microphone. The sound pressure level (SPL) spectra are estimated using Welch's method, and background-noise correction is applied according to Eq. (2):

$$M_{\text{cor}} = M_0 + 10 \log(1 - 10^{(M_{\text{bg}} - M_0)/10}) \quad (2)$$

Following the aerodynamic experiments, the PSP-coated blades are calibrated in a vacuum chamber, as shown in Fig. 1 (b). For each 100 mmHg Pressure decrement, 64 images are recorded until the chamber pressure reached -600 mmHg. For a given pressure level P , the luminescent intensity I is obtained by spatially averaging over the blade surface and temporally averaging over the 64 frames. As the variation estimated from blade tip speed and the adiabatic wall temperature is minimal, the temperature effect is considered negligible and is not corrected.

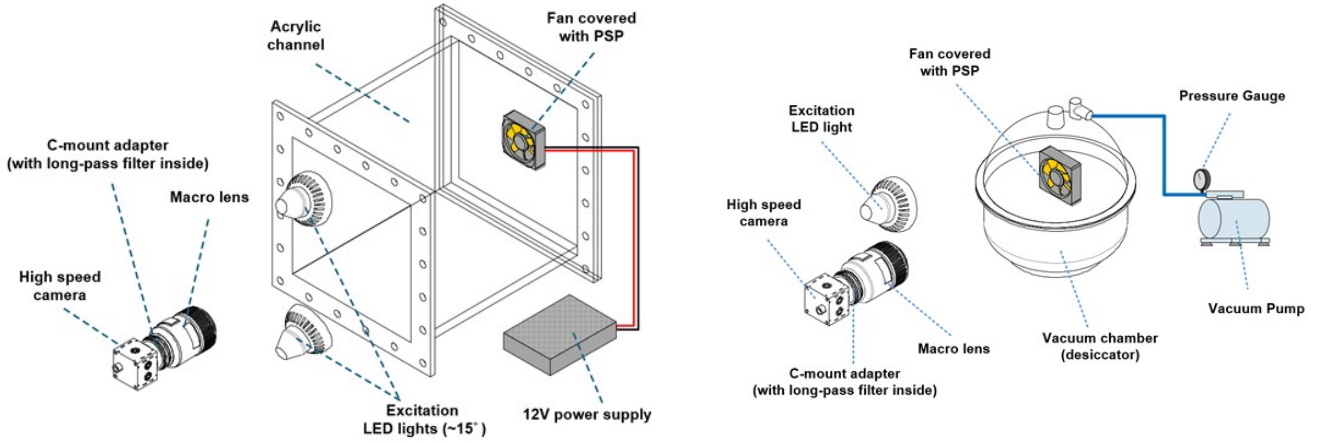


Figure 1. Schematics of (a) experimental setup and (b) calibration apparatus.

A set of 64 wind-off images is averaged to obtain the reference image. An illumination map is generated by averaging the raw wind-on images; this map is also used to determine the hub center and radius. To facilitate subsequent processing, both the reference image and 256 wind-on images are remapped from Cartesian to polar coordinates, spanning from the blade root to the tip. The mapping density is defined as three times the range of mapped radius and the arc length at the maximum radius in pixels. The primary advantage of this remapping is the transformation of circular motion in Cartesian coordinates into linear motion along the tangential direction in polar coordinates. This conversion significantly simplifies image alignment and enables more straightforward treatment of motion blur.

Prior to aligning the wind-on images with the reference image, motion-blur compensation is applied to ensure consistency of image features. Specifically, the reference image in polar coordinates is deliberately blurred via convolution with a point-spread function (PSF), to avoid bias and noises introduced from deconvolution algorithm. The process can be expressed in Eq. (3).

$$I_{\text{ref}} = I_{\text{ref},0} \otimes \text{PSF} \quad (3)$$

Under the polar mapping, rotational blur is transformed into linear motion, the point-spread function (PSF) can therefore be approximated as a straight line aligned with the blade motion. The corresponding blur length is determined from the product of the measured rotational speed and the camera exposure time, where the rotational speed is determined from the cross-correlation of two successive wind-on frames in polar coordinates. Following this, the wind-on images are aligned with the blurred reference image, after which illumination compensation is performed. This is achieved by computing the ratio between the original and the shifted illumination maps and applying this correction to the intensity ratios of the aligned images.

After pressure calibration and masking of non-blade regions, proper orthogonal decomposition (POD) is applied to the time-resolved pressure fields. The pressure data $\mathbf{X}$ are arranged into a matrix and decomposed as Eq. (4):

$$\mathbf{X} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^T \quad (4)$$

where $\mathbf{U}$ contains the spatial modes, $\mathbf{\Lambda}$ represents the modal energy, and $\mathbf{V}$ contains the temporal coefficients. The spatial modes describe the distribution of pressure fluctuations, while the temporal coefficients are analyzed using the Fast Fourier Transform (FFT) to identify the dominant frequencies associated with each mode and to enable comparison with the measured acoustic spectra.

Two commercial axial fans are investigated in this study; both have seven blades and four supporting struts. Fan A has a diameter of 80 mm, and operates at 4392 RPM. Fan B has a diameter of 92 mm, and operates at 3745 RPM during the experiments. Calibration results of PSP on 2 fan models are presented in Fig. 2.

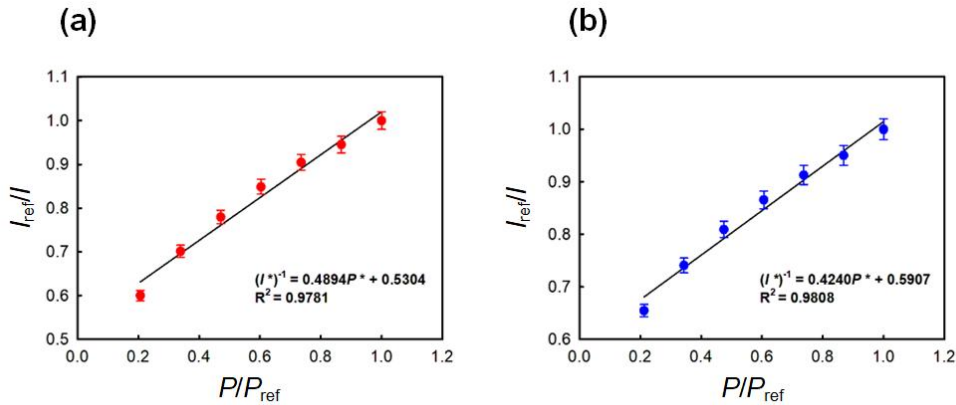


Figure 2. Calibration results of (a) Fan A (b) Fan b

3. Results

Fig. 3 presents the suction-side mean pressure and the standard deviation of pressure fluctuations for the two tested fans. The results are averaged over all seven blades and displayed in polar coordinates to highlight spanwise and chord-wise variations. As shown in Fig. 3 (a), Fan B exhibits a pronounced high-pressure region near the hub (left side of the plots). A similar hub-side pressure rise is also observed in Fan A, although it is less pronounced. In addition, as shown in Fig. 3 (b), both fans show a localized region of moderate pressure near the mid chord, while a negative-pressure zone appears near the trailing edge, indicating the likely presence of flow separation and reattachment.

The corresponding pressure-fluctuation distributions are shown in Fig. 3 (c). For both fans, large pressure fluctuations are concentrated near the trailing edge, consistent with wake formation and unsteady vortex shedding. Fan B additionally exhibits stronger pressure fluctuations near the blade tip. This behavior can be attributed to its larger tip clearance, which promotes the formation of stronger tip vortices and enhanced unsteady flow near the tip region.

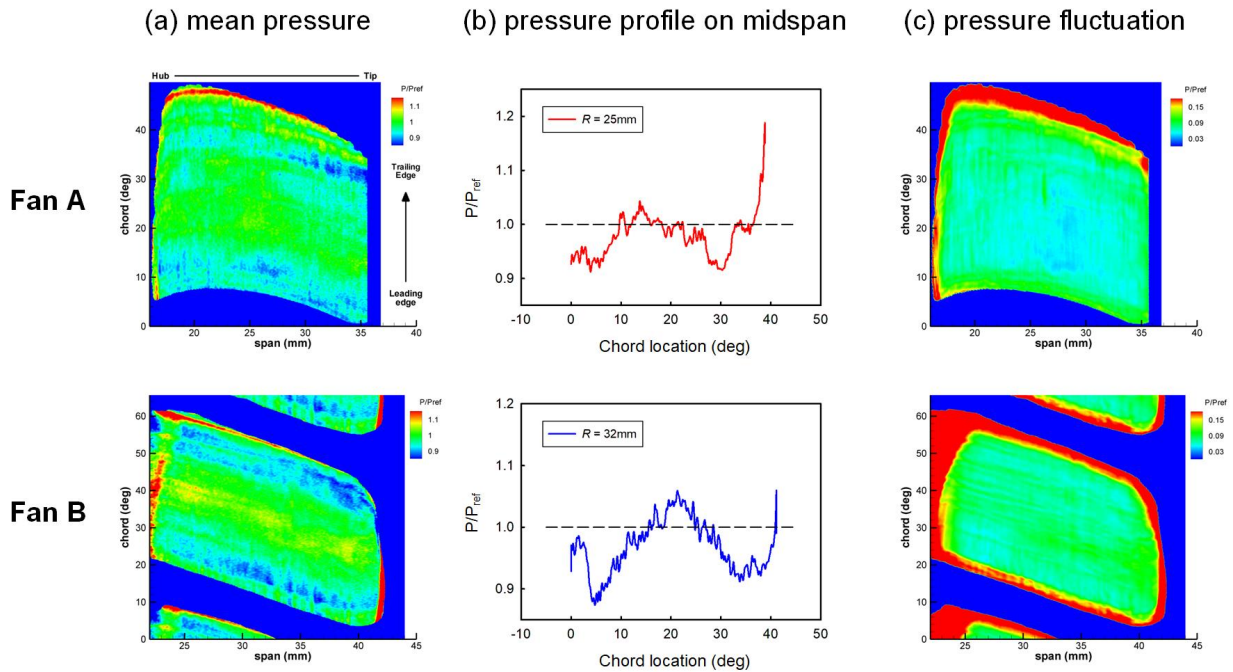


Figure 3. Comparison of suction-side (a) mean pressure (b) pressure profile on mid-span of the blade, and (c) standard deviation of pressure fluctuations for Fan A and Fan B. (a) and (c) are shown in polar coordinates.

To examine the relationship between surface-pressure dynamics and radiated noise, Fig. 4 compares the measured acoustic spectra with the power spectra of the temporal coefficients obtained from proper orthogonal decomposition (POD) of the pressure-fluctuation fields. The heatmaps display the frequency content of the first 100 POD modes, with the most energetic modes at the

top. The frequency axes of the acoustic and POD spectra are aligned to enable direct comparison.

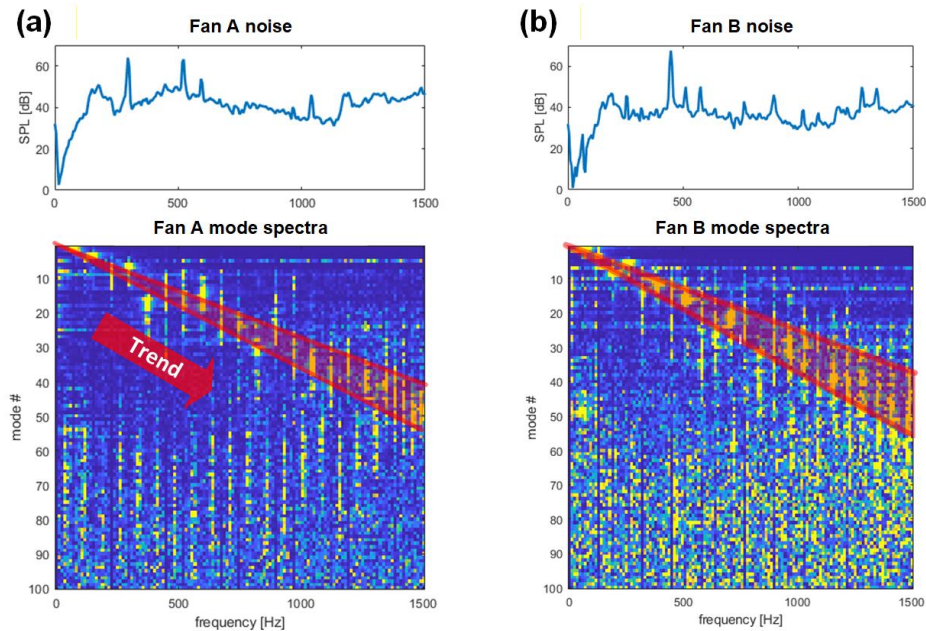


Figure 4. Comparison of measured acoustic spectra and POD temporal-coefficient spectra (first 100 modes) for (a) Fan A and (b) Fan B.

The dominant POD modes exhibit characteristic frequencies associated with the fan rotational speed, while higher frequencies appear in higher-order modes, forming a clear linear trend in the heatmaps. When compared with the acoustic spectra, the tonal noise components align closely with this mode-frequency relationship, although slight deviations are observed. Based on these observations, three indicators are proposed to identify pressure-driven noise contributions in the POD heatmaps: tonal peaks appearing in low-order modes above the rotational-frequency line, peaks occurring at neighboring frequencies, and spectral features spanning multiple POD modes at a given frequency. These patterns suggest a strong correlation between PSP-measured surface-pressure fluctuations and the radiated noise spectrum.

To further elucidate the dominant noise-related pressure structures, the first key POD mode, characterized by significant energy across a wide frequency range in Fig. 4, is selected for detailed analysis. Fig. 5 (a) shows the mode shape of this mode, while Fig. 5 (b) compares their temporal FFT spectra with the measured acoustic spectra. For Fan A, the first key POD mode exhibits strong pressure fluctuations concentrated near the trailing edge, whereas Fan B shows larger fluctuations in the mid-span region. In both cases, prominent peaks in the POD-mode spectra coincide with tonal components in the acoustic measurements, confirming that the PSP-derived pressure data capture key noise-generating mechanisms. Because these spectral peaks represent dominant noise sources, the associated spatial mode shapes provide clear guidance for blade-design modifications:

trailing-edge treatments for Fan A and mid-chord refinements for Fan B.

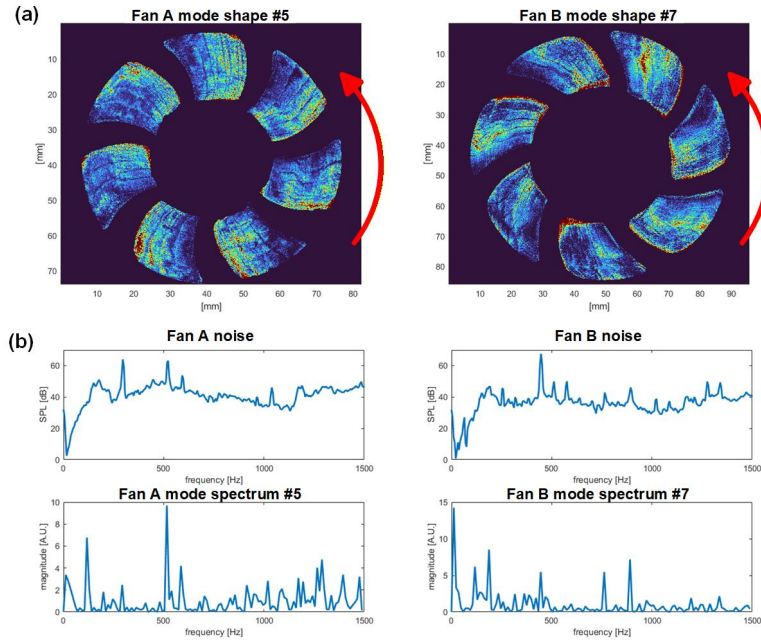


Figure 5. (a) Mode shape of the first key POD mode extracted from pressure fluctuation, and (b) comparison between the acoustic spectra and FFT of the corresponding POD temporal coefficients.

Fan rotational characteristics are also evident in Fig. 4 (b). With seven blades, the blade-passing frequencies are 511 Hz for Fan A and 434 Hz for Fan B, and these frequencies, as well as their harmonics, appear as distinct peaks in both the acoustic and POD spectra. This further validates the ability of PSP-based pressure measurements to resolve rotationally induced aerodynamics and acoustic features in axial cooling fans.

4. Conclusions

This study demonstrates the use of pressure-sensitive paint (PSP) as a non-intrusive diagnostic tool for identifying pressure-driven noise sources on axial fan blades used in server cooling applications. By employing a ruthenium-based PSP with high luminance, time-resolved surface-pressure measurements are successfully obtained on rotating blades operating at high rotational speeds. The combination of high-speed imaging, motion-blur compensation, and in-situ pressure calibration enables reliable extraction of both mean pressure distributions and pressure-fluctuation fields. The measured pressure fields reveal distinct aerodynamic features associated with blade rotation, including hub-side pressure buildup, mid-chord separation, and enhanced pressure fluctuations near the blade tip in fans with larger tip clearance. These spatial patterns provide direct insight into the flow structures responsible for unsteady loading and noise generation.

Proper orthogonal decomposition (POD) of pressure-fluctuation data establishes a clear link between surface-pressure dynamics and radiated acoustic emissions. The spectral content of the POD temporal coefficients closely matched the measured fan noise spectra, including tonal components associated with blade-passing frequencies and their harmonics. Analysis of dominant POD modes further enables localization of noise-critical regions on the blade surfaces, identifying the trailing edge as the primary contributor for Fan A and the mid-span region for Fan B.

Overall, the results confirm that PSP-based pressure visualization offers a powerful and practical approach for diagnosing aerodynamic noise mechanisms in small axial cooling fans. By providing spatially resolved pressure information directly correlated with acoustic signatures, the proposed methodology enables targeted blade-design modifications and supports the development of quieter and more efficient server cooling systems.

Acknowledgments

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Nomenclature

A, B	Calibration coefficients [1]
I	Luminescence intensity [a.u.]
M	Sound pressure level [dB]
P	Pressure [kPa]
R	Radial distance [mm]
U	Spatial modes [1]
V	Temporal coefficients [1]
X	Data matrices [a.u.]
Λ	Singular values [a.u.]
PSF	Point-spread function (PSF) [1]
RPM	Rotation per minute [s^{-1}]

Subscript

0	original
bg	background noise
ref	reference state, wind-off
T	transpose matrix
$\otimes$	convolution

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