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Experimental Validation of Unsteady Pressure-Sensitive Paint for Acoustic Applications

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Abstract

Investigation of acoustic pressures on a surface is traditionally performed using microphones either placed in discrete locations on the surface or with microphone arrays situated around the model. Pressure-Sensitive Paint (PSP) is an optical pressure measurement technique based on a photo-physical phenomenon of luminophores, where when exited with light with a certain wavelength the luminophores in the paint emit light with longer wavelength, Liu and Sullivan (2005). The intensity of the emitted light is directly related to the oxygen concentration around the luminophores and according to Henrey's law, the concentration of oxygen in the paint layer is proportional to the partial pressure of oxygen of the gas above the surface. With this, the surface pressure is a function of luminescent intensity of the PSP luminophore.

In order to measure acoustic phenomena a pressure sensitive paint designed for unsteady measurements (iPSP) featuring very short response time is used, Hilfer et al. (2017). The iPSP can be coated on many different surfaces regardless of geometry or material offering an advantage for measurements where a placement of a surface microphone is not possible. Furthermore, by using iPSP combined with a high definition camera each pixel in the image is a separate pressure sensor resulting in a high spacial resolution. A new test facility based on the design introduced by Ali et al. (2016) is build which allows evaluations of acoustic pressure distributions with frequencies up to 5 kHz and amplitudes between 0 and 400 Pa (or up to 146 dB). In this work frequencies and amplitudes comparable to the conditions found inside the Aeroacoustic Wind Tunnel (AWT) at Leibniz Universitt Hannover, Bartelt et al. (2013) are investigated to evaluate the capability of our iPSP system for acoustic measurements. Single mode acoustic excitation is performed to investigate the limits of our system showing a minimal detectable amplitude of 5 Pa (108 dB). Further, acoustic white noise signal was used to excite multiple modes to investigate the capabilities of our system to separate and detect specific modes. For post-processing phase averaging, proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD) are investigated showing a clear advantage of DMD for signal to noise ratio improvement and filtering of noise with specific frequencies such as camera noise. From white noise signal measurements using DMD, modes with amplitude above 5 Pa were identified and spatial distribution extracted.

1 Introduction

Using PSP to better understand the principals of flow phenomena is an established and widely used measurement technique, Liu and Sullivan (2005), Gregory et al. (2014). Acoustic measurements are particularly challenging due to the low signal amplitude compared to the high ambient pressure and PSP being generally an absolute pressure sensor. In this work an evaluation of fast response Pressure-Sensitive Paint for acoustic applications was investigated using iPSP developed at DLR. The iPSP measurement technique is tested during this evaluation with acoustic parameters similar to those found in an acoustic wind tunnel.

Intensity Method

There are two methods to measure pressure distribution with PSP; intensity and lifetime. In this work the intensity method is used for fast response measurements and requires a continuous illumination of the paint, with the pressure dependant intensity of the light emission measured by a high speed camera. In

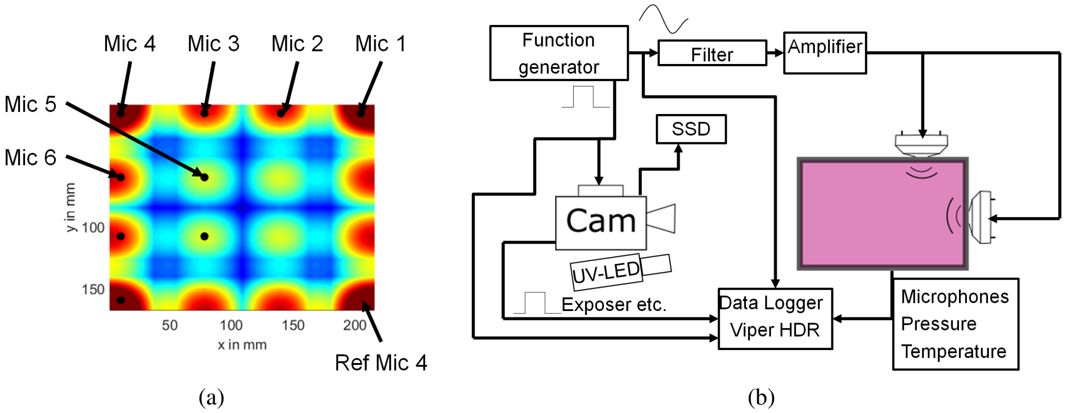

Figure 1: a) Microphone positions on the back wall. b) Acoustic measurement set-up.

order to determine the pressure, the Stern-Volmer relation (1) with predetermined temperature dependent coefficients A and B is used.

$$\frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \tag{1}$$

To measure high-frequency pressure fluctuations a high response time of the paint to sudden pressure changes is necessary. In preliminary tests in a shock tube at DLR Göttingen, our iPSP showed a pressure step response time of ca. 65 μs. In general such paint can be used for application with frequencies up to 30 kHz. The fast-response PSP developed at DLR consists of one base and active layer with the base layer mixed from a polymer, a ceramic particle (titanium silicon oxide TiSiO4), dispersant and water and applied to the cleaned surface of the back wall. The active layer is a mixture of Toluene and PtTFPP, the luminophore. The application of both layers is performed using an air brush resulting in a coat thickness between 24 μm and 34 μm.

Fast Response PSP in Acoustic and Low Pressure Amplitude Applications

Acoustic measurements are especially challenging because of the low pressure fluctuation compared to the high ambient pressure. In AWT sound pressure levels (SPL) of up to 136 dB, Bartelt et al. (2013) are generated, which corresponds to a maximal pressure level of 126 Pa. McGraw et al. (2003) performed an acoustic measurement with iPSP and a reference microphone in a resonant cylinder. The iPSP luminescense intensity was captured by a photomultiplier tube (PMT). Subsequently the data was averaged and Fast Fourier Transform (FFT) performed revealing lowest sound pressure level of 110 dB (6.32 Pa) with frequencies up to 3500 Hz. To measure spatial distribution of the sound pressure on a surface a PMT has to be replaced with a camera. This was done by Gregory et al. (2006) using a charge-coupled device (CCD) camera. The resulting iPSP data was phase averaged and compared to an analytic solution and a measurement of one fast response pressure sensor (Kulite). The measured data from iPSP matched well with the analytic solution with a minimum detectable pressure level of 115.8 dB (12.3 Pa). In order to investigate even lower pressure fluctuations or multi frequency phenomena, a more advanced noise reduction method has to be applied. Pastuhoff et al. (2016) used singular value decomposition (SVD) to enhance the SNR of iPSP data. Ali et al. (2016) used proper orthogonal decomposition (POD), a related technique to SVD, and dynamic mode decomposition (DMD) to reduce the noise and measure multi frequency phenomena. A POD mode is a left singular vector of the SVD and can be calculated with the known SVD algorithm. DMD calculation using flow field data is well described by Schmid (2010) and can be used in similar procedure for pressure field data. According to Ali et al. (2016), DMD is the more robust method in discriminating between the two modes and eliminating the noise of the CMOS sensor.

2 Experiment

The measurement of acoustic pressure distributions inside an acoustic wind tunnel requires a set-up which can detect pressure levels of up to 100 Pa with frequencies up to 4 kHz. Ali et al. (2016) already measured acoustic pressure distribution in a rectangular cavity, as described above, with frequencies up to 2200 Hz and pressure amplitudes above 600 Pa. The dimensions of test section, 216 mm x 168 mm x 102 mm, are the same as Ali et al. (2016) to have comparable results. Additionally, a second pressure measurement technique, condenser microphones, are included. The number of microphones and their position on the back wall is determined analytically to satisfy Nyquist-Shannon sampling theorem for modes with a mode number of four and lower. Two extra microphones are placed near the center on the left side to have additional reference signals inside the low pressure regions of mode (1 1 0). The microphones and their position are shown in Figure 1a. Due to the symmetry of the modes every microphone has a reference position on the back wall and can be correlated to iPSP results. The oxygen level in the air inside the box has also an effect on the calibration of iPSP, Liu and Sullivan (2005). By flushing the box with synthetic air with a known oxygen level, an oxygen meter is not required. This also ensures dry air conditions inside the cavity, which is part of the assumption for analytic calculations of the modes, Pierce (1981).

To excite the paint two UV-LEDs, HardSoft IL-106 UV, emitting light at a wavelength of 385 nm are used. The LEDs are equipped with 720 mm lenses and optical band-pass filters (ET385/70x, 385 nm ± 35 nm) fitted in front of the lenses. The LEDs are placed beside the camera and angled toward the acoustic box so that the whole back wall is illuminated. The camera is a Photron Fastcam SA-Z, equipped with a Nikon 85 mm lens and a bandpass filter (ET630/75m, 630 nm ± 37.5 nm) and is set to record 8192 images with an resolution of 768 x 768 pixel. The CMOS image sensor has 12 bit dynamic range. The camera is triggered and synchronized as shown in Figure 1b. The camera and LEDs are placed 500 mm away from the iPSP covered surface, which corresponds to a possible distance in a wind tunnel.

The included microphones are Brüel&Kjaer Type 4944 1/4” with a dynamic range of 46 to 170 dB and are able to detect frequencies between 4 Hz and 70 kHz. The microphones are mounted without the protection grid flush to the surface. The microphones are calibrated before and after all measurements.

An absolute pressure sensor is placed on the left side wall together with a Pt100 temperature sensor. The acoustic modes inside the box are excited with two BMS 4540ND - 8Ω speakers. The speakers can induce frequencies from 700 Hz to 30 kHz and are driven by a signal from a function generator Agilent 33522A. The signal from the generator is filtered and amplified.

All voltage signals are logged with a data logging system, Viper HDR, which is able of sampling with a maximal sampling rate of 250 kHz. It is logging the signals of the nine microphones, the absolute pressure sensor, the signal of the function generator and signals from the camera. The synchronisation of the measurement is shown in Figure 1b and consist of the function generator, generating two in phase signals. One sinusoidal signal is driving the speakers and the second signal is a square wave, which is synchronising the camera with the speakers. This is only done, when a specific single mode is excited. When the speakers are driven with a white noise signal, the camera is running independently. In both cases the output signals are logged and a post processing synchronisation can be carried out.

3 Data Analysis Methods

To obtain **spectral power density** (SPL) of a specific mode from microphone data, the PSD is calculated with the Welch’s estimation, and Hann window function. With the segment length of 2^{17}, a sample length of $5 \cdot 10^6$, and a segment overlap of 50%, the PSD is averaged 76 times.

Due to the small pressure fluctuations of acoustic phenomena, the emitted light from the paint is only exhibiting a small change corresponding to 0.7% of the dynamic range of an 12 bit (4096 counts) camera sensor or just 3 counts for 134 dB (100 Pa) signal at 105 kPa ambient pressure. This requires further image preparation and data analysis: To reduce the memory size required for post processing, the images are spatial binned averaging four pixels to one, which also increases SNR. This leads to a final resolution of 278 x 358 pixel. Since the back wall has a dimension of 168 mm x 216 mm, the pixel resolution in both direction is 1.65 pixel/mm. To obtain an reference image (I_{ref}, Eq. 1) an average of the whole images I are calculated.

Phase Averaging: During synchronised measurements only a specific mode with a specific frequency is excited. The speakers and the camera are running in phase. Therefore, phase averaging can be used. The camera is then set to take ten snapshots for each period of the mode, so every tenth image is averaged. Phase averaging can only be applied to a specific frequency.

Singular Value Decomposition: The mathematical principle is further described by Strang (2003). The modes obtained by SVD contain several frequencies and are sorted by energy.

Dynamic Mode Decomposition: The calculation of DMD is based in the first step on the results from SVD, but after application of DMD each mode represents a specific frequency. Further description of DMD by Kutz et al. (2016).

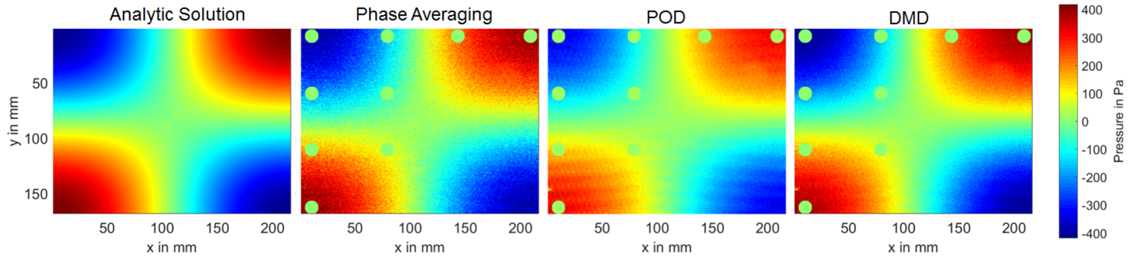

Figure 2: Mode (1 1 0), analytic and phase averaged solutions, POD and DMD modes scaled by mic. 4

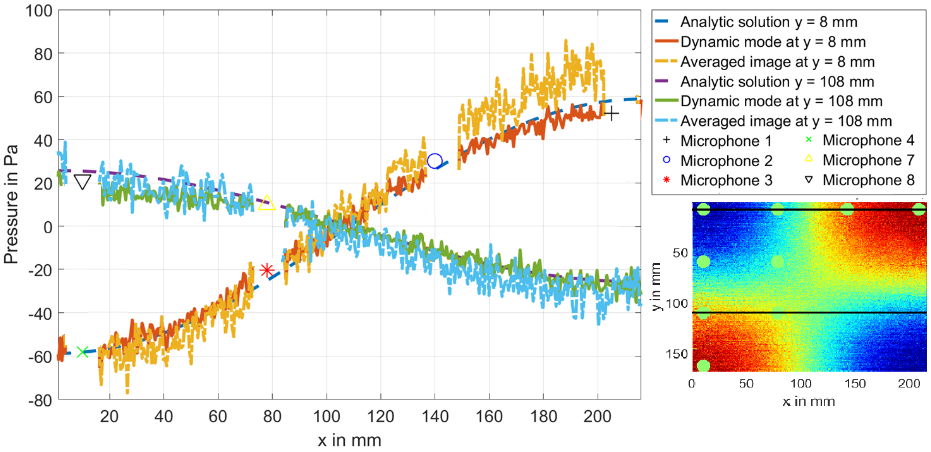

Figure 3: Horizontal cuts through analytic, dynamic mode and phase averaged result. Scaled with mic. 4.

Pressure Recalculation: The pressure of PSP is conventionally calculated with the Stern-Volmer equation. During this evaluation only the pressure of images from the phase averaged method can be recalculated with the given procedure. Calculation of the pressure of the SVD and DMD modes without information from additional pressure devices is more complex therefore, the pressures from microphones are used to scale the modes. The modes will be scaled with the amplitude of the power spectral density (PSD) of the microphones at the excitation frequency of the mode and a pressure reference region on the analysed iPSP images. The pressure reference region is chosen to be at a symmetric point to the microphone and therefore with the same pressure level as the microphone pressure. The investigated modes are either point symmetric or axis symmetric (x-axis or y-axis).

4 Measurement and Results

4.1 iPSP evaluation

In order to evaluate the performance of our iPSP, the mode (1 1 0) is excited and compared to results by Ali et al. (2016) (not shown here) displaying similar capabilities. The measured mode frequency of this mode is 1318 Hz with an uncertainty of ± 2 Hz. Two different pressure levels, 145.51 dB (377.50 Pa) and 128.28 dB (52 Pa), are measured with this set-up. In order to compare microphone and iPSP a corresponding reference position of microphone 4 is chosen from PSP data. To simulate the microphone a spatial 5 pixel square region is averaged to one value. In Figure 2 the results of the different data reduction methods are displayed. In DMD and more distinct in POD, horizontal lines caused by sensor read out noise are seen. Since in DMD only patterns with distinct frequency are extracted, the influence of the camera readout noise with a peak at 608 Hz is reduced. Lowest detectable pressure level with this set-up was 108 dB or 5 Pa and is defined by the systematic electronic camera noise. In Figure 3 the analytic and phase averaged results and DMD mode are cut horizontally at y = 8 mm and y = 108 mm showing a good agreement of the DMD mode with pressures from microphones and analytic results. The phase averaged result shows some asymmetric behaviour which

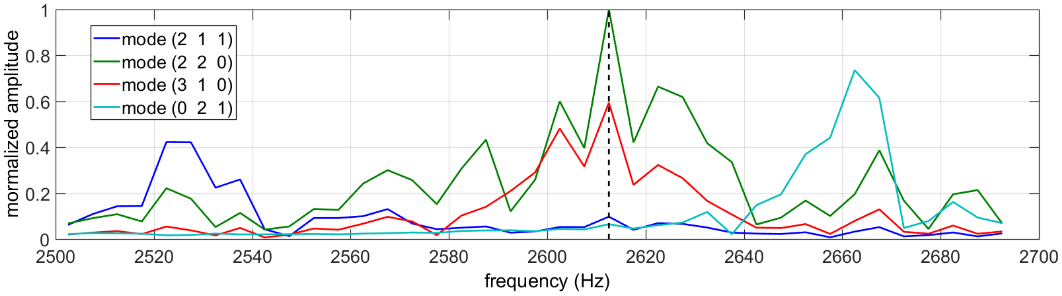

Figure 4: Solution of linear equations using microphones 1 - 9.

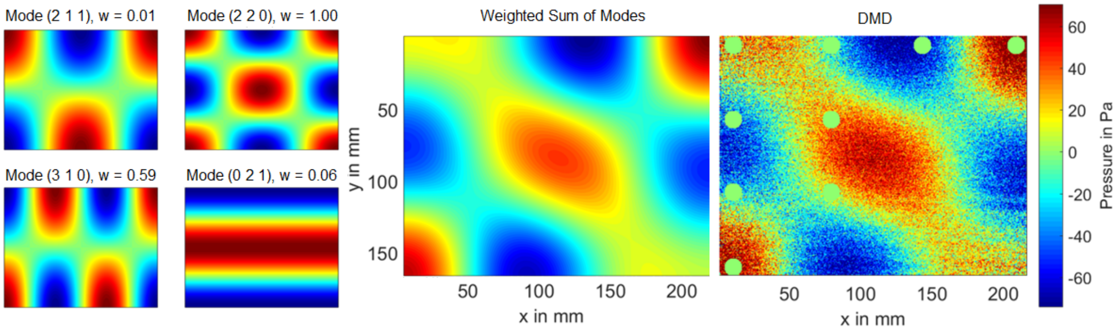

Figure 5: Comparison of reconstructed analytic solution and measured iPSP results.

could be caused by systematic inhomogeneous temperature distribution inside the acoustic box.

4.2 White Noise Excitation: Overlapping Modes at 2611 Hz

In this set-up the iPSP for acoustic phenomena with multiple mode appearance is evaluated. The speakers are driven with a white noise signal and due to the dimension of the acoustic box, several modes are induced each with a specific frequency. The phase averaging method can not be used for multi frequency phenomena. During the white noise excitation the acoustic box accommodates several modes within a close frequency range, including the modes (2 2 0) and (3 1 0) with theoretical excitation frequencies of 2607 Hz and 2614 Hz, respectively. The PSD of a microphone signal at this frequency range exhibits only one peak located at 2611 Hz (not shown here) indicating an overlap of the modes. The extracted dynamic mode from iPSP and the analytic solution of the modes (2 2 0) and (3 1 0) and the overlapping mode is shown in Figure 5. The analytic solution of the overlapped pattern is calculated by a sum of the basic modes multiplied by a weighting factor (w). To obtain the weighting factors a system of linear equations with the microphone signals is calculated and the first four most dominant modes are used where the modes (2 2 0) and (3 1 0) are most dominant, Figure 4. The resulting analytic solution as shown in Figure 5 is in good agreement with the measured iPSP distribution. These results show, that iPSP can be used to verify measurements performed by microphones. Further measurements with this set-up showed the capability of our iPSP to generate good results up to a Frequency of 5 kHz (not shown here).

5 Conclusion

In a typical application inside the Aeroacoustic Wind Tunnel in Hannover sound pressure levels up to 138.4 dB (166 Pa) with frequencies up to 4 kHz are expected. The results of the experimental evaluation presented in this work show that the iPSP is capable of detecting acoustic pressures in this range. The initial evaluation of our iPSP reveals, the data analysis methods; phase averaging, proper orthogonal decomposition, and dynamic mode decomposition are capable of increasing the SNR notably. During the post processing of the initial test the three different data analysis methods are compared to each other. The averaging method is simple to use and to implement. This method does not require a reference pressure device on the surface, however, multi frequency phenomena can not be investigated with the averaging method. Therefore, the averaging method is only recommended for single frequency phenomena evaluation. The POD, closely related to the SVD, is considered for white noise excitation. But since the POD modes contain several frequencies the camera read out pattern is included. Therefore, DMD is considered a preferable method capable of suppressing camera noise pattern and featuring associated frequencies. The used set-up together with DMD is capable of detecting pressure amplitudes as low as 5 Pa at a frequency of 1318 Hz. For the pressure recalculation a pressure reference device is needed, which must have a fast response time and able to detect low pressure levels. The white noise excitation proved the capability of the iPSP to detect multiple frequency phenomena even for pressure below 20 Pa and frequencies up to 5 kHz. Furthermore, the DMD is capable to extract modes of interest and increase the SNR significantly. The pressure of overlapping modes can be recalculated and modes, which are not overlapping but are close in frequency can be separated. Overall the iPSP together with the DMD is capable of measuring acoustic pressure phenomena similar to the acoustic phenomena appearing inside the AWT. Pressure amplitudes above 20 Pa are well observed and the minimal detectable pressure limit of 5 Pa at 1318 Hz is a good basis for future measurements. Based on the results shown in this work, a new acoustic iPSP measurement system is now being installed in the AWT.

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