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Investigation of potential benefits and functionality of a vibroacoustic camera by combining results of a common beamforming and nearfield holography acoustic camera and a high-speed camera, allowing to visualize structural vibration (optical flow tracking).

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ABSTRACT

In this paper potential benefits and functionality of a vibroacoustic camera are investigated by combining results of a common beamforming and nearfield holography acoustic camera using the software NoiseImage and a high-speed camera, allowing to visualize structural vibration (optical flow tracking) using the software WaveImage. Both results can be used to calculate color maps – mapped parameters are sound pressure, vibration displacement and its derivatives. The authors will investigate how the combination of methods might enhance understanding and interpretation of the vibroacoustic behavior of specimens in the overlapping frequency range. At low frequencies, the beamforming approach is limited due to main lobe width and array size. The limits for source localization can be offset employing nearfield acoustic holography. It was also previously shown that mode shapes of 2-dimensional structures can be reproduced using nearfield acoustic holography (SONAH). The high-speed camera results present a way to provide positions of local vibration maxima and operating deflection shapes without accessing the acoustic nearfield. Accordingly, the approach could be viewed as a potential extension of the frequency range in which meaningful visualization of vibroacoustic data can be achieved from a single far field measurement from 0 Hz to the ultrasound frequency regime.

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1. INTRODUCTION

Wherever there is airborne noise it has a root-cause that is either a vibrating surface like chords, speaker membranes or the surface of machinery or due to sudden pressure changes like explosions, lightning or gas relaxation. Any rotating or reciprocating machine or apparatus will therefore radiate airborne noise that is mostly adverse.

Common methods to localize noise sources include beamforming and acoustic holography. Sound power is typically quantified employing methods to measure sound intensity. In addition, vibration testing is often employed to trouble-shoot issues and perform detailed root-cause analysis. If the vibration velocity and size of a surface is known the radiated sound power can be calculated based on the radiation efficiency. This relationship also offers the possibility to predict acoustic radiation based on structural dynamic simulations.

A measurement approach that comprehensively allows to qualify noise and vibration properties in a single easy to set up and non-contact measurement would potentially allow to improve understanding of the vibroacoustic behavior of complex structures that are harder to control or yet cannot be simulated.

It is expected that a vibroacoustic camera will provide complementary insights and a bigger picture of the vibroacoustic behavior and facilitate derivation of manipulation potential. To obtain a general idea of potential benefits and redundancies, two tests will be conducted to compare results of the different measurement approaches, namely an impact test on a brake disc to investigate mode / deflection shapes as well as a conventional speaker including a tweeter and a woofer.

2. VIBROACOUSTIC ANALYSIS ON A BRAKE DISC

2.1. Test setup

A brake disc of a motor bike was rigidly mounted on a tripod (Figure 1, left). Acoustic measurements were taken using a gfai tech Mikado equipped with 96 MEMS microphones sampling with 48 kHz. The array was placed parallel at 8 centimeters from the brake disk as shown in Figure 1 (center). Optical testing was conducted using a Chronos 1.4 low-cost high-speed camera that was placed 1.5 meters to the brake disc at approximately 40° angle (Figure 1, right). The angle is important to ensure that main directions of vibration will be in plane of the recorded image. Aperture, lighting and framerate are the main factors to influence measurement quality. In this case 2.8 kfps were used. Results will be compared up to 1200 Hz. To improve contrast the background was covered with white material.

The structure was excited using a handheld impact hammer with a metal tip. As this paper is aiming to investigate a wireless, contactless and quick installation approach, the structural response will be analyzed without consideration of the impact force.

The specimen was chosen due to its 2-dimensionality and porous character as well as the reflective surface that complicate setup and constrain the utility for a Laser-Doppler-Vibrometer.

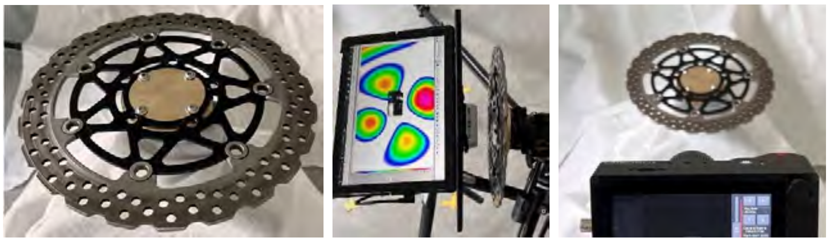


Figure 1: Rigidly mounted brake disc (left), Acoustic holography measurement (center), high-speed camera setup (right).

2.2. Results

A decay measured with the microphone array is shown in Figure 2.

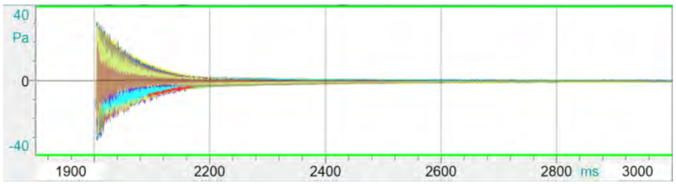


Figure 2: Acoustic response of the brake disc after single hit excitation with a metal tip.

The acoustic response spectrum (Δf = 0.73 Hz) in Figure 3 shows that there are four prominent peaks in the spectrum indicating natural frequencies.

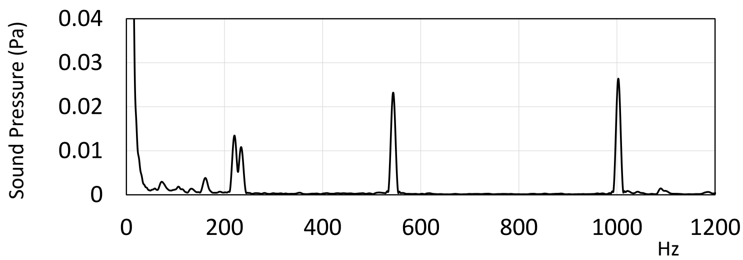
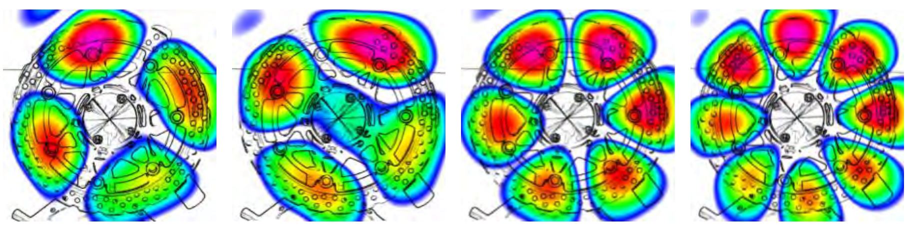


Figure 3: Acoustic response spectrum of the brake disc after single hit excitation with a metal tip.

Using the gfai tech software NoiseImage 4.13.2 acoustic maps were calculated for these narrow bands using the nearfield module. As indicated by Puhle et al [1] the statistically optimzed near-field acoustical holography (SONAH) was giving the best results over the range of investigated frequencies. Results were plotted on a total view image of the brake disc shown in Figure 4. For the investigated frequency range, the found mode shapes are plausible.



220 Hz 235 Hz 560 Hz 1000 Hz

Figure 4: Mode shapes based on acoustic holography (SONAH, 20 dB dynamic, particle velocity).

An impact test recorded with the high-speed camera was analysed with the WaveCam module of the gfai tech software WaveImage 22.1. No preparation of the test specimen, such as the use of a speckle pattern, is required for the analysis. The video was cut to exclude any visibility of the impact hammer movement. The time data was obtained from the video sequences of the high-speed camera by the optical flow. This is calculated on a pair of two temporally consecutive images and includes the assignment of the pixels from the first image to their associated correspondences in the second image. The resulting vector field is called optical flow. In general, a distinction is made between sparse and dense optical flow. In sparse optical flow, only certain points are selected for further processing. In this case, corners [2] are often used, since they can be easily tracked and assigned over several temporal progressions and the associated image changes. However, other more complex features [3], [4] are also used for sparse optical flow. In contrast, in dense optical flow, the correspondences are determined for each pixel, resulting in the computation of a complete flow field. The goal of dense optical flow is a gapless calculation, so no interpolation is necessary.

A spectrum was calculated for a reference position ($\Delta f = 0.75$ Hz) in the image as presented in Figure 5. Even the first modes, found to occur in two rotations at 220 Hz and 235 Hz are separated.

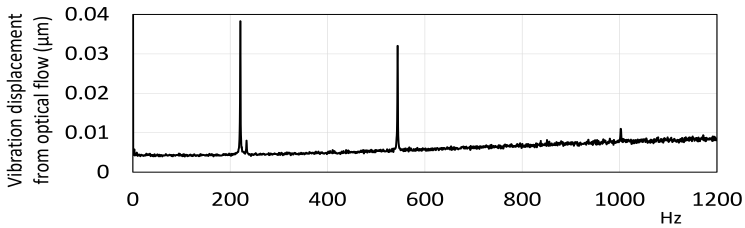
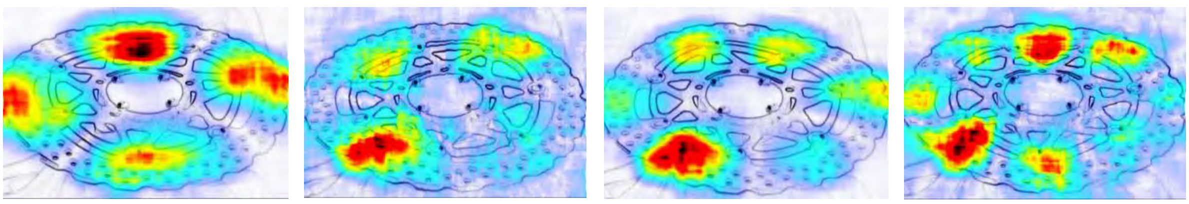


Figure 5: Optical response spectrum of the brake disc after single hit excitation with a metal tip.

Operating deflection shapes were calculated as shown in Figure 6 clearly validate the findings of the acoustic measurements.



220 Hz | 235 Hz | 560 Hz | 1000 Hz

Figure 6: Frequency operating deflection shapes (ODS) based on high-speed camera recordings.

Although the analysis of the optical data was limited to operating deflection shapes, it is consistent with the mode shapes and natural frequencies identified using SONAH. An advantage of the approach is that the data allows to animate the deflection which facilitates interpretation.

Both approaches have very different limitations. The acoustic holography requires access to the near-field and accurate alignment. Additional factors are the acoustic environment including background noise, reflective surfaces and limited value to investigate 3-dimensional structures. In addition a high microphone density close to the specimen is required which limits the applicability for one specific array in regards to various test bodies. In the farfield beamforming provides highly reliable results.

The high-speed camera approach is not limited by the noise but the vibration environment. The camera needs to be mounted isolated from the tested structure. Its applicabilty depends on the light conditions, which degrade with higher framerates and lower exposure times respectively. Vibration perfectly perpendicular to the image plane are not sufficiently resolved, which can mostly be compensated by a change of camera angle. Vibration displacements need to be sufficiently high to be detected. Besides the lighting that can be improved using flicker-free artificial light sources, high frequency applications are constrained to limited recording time and filesize respectively.
The direct comparison in Figure 7 shows the same frequency content for both methods. All four modes in the investigated frequency range are present in the spectra although at different relative magnitudes.

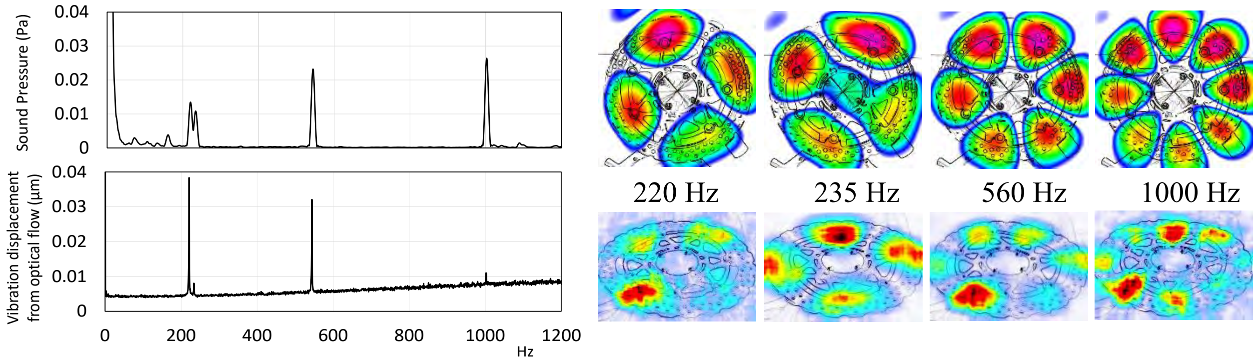


Figure 7: Comparison of spectral content and vibration shapes.

The presented data is based on a single impact test. Both tests were set up and conducted in under five minutes, as no setting of individual measurement positions is required. Results are obtained in under one hour including processing.

The combination of methods provides cross-validation for the results. Due to the different strength and weaknesses of the methods, the range of applications is increased. While in this case there is limited knowledge gain, it is expected that more complex applications will reveal more complementing information.

3. VIBROACOUSTIC ANALYSIS OF A SPEAKER

3.1. Test setup

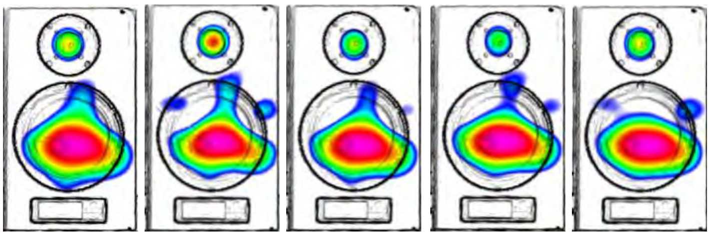
In order to simulate acoustic emissions based on dynamic structural behaviour, it is expected to be beneficial to characterize and validate acoustical and vibrational behaviour independently. Additional testing was carried out on a speaker using a setup comparable to the brake disk (Figure 8).

Figure 8: Speaker (left), Acoustic measurements (center), high-speed camera setup (right).

Acoustic measurements were carried out parallel to the speaker at 6 centimetres as well as from 1.5 metres. The camera was set up at 1.5 metres with a speaker rotation angle of 30°. Five frequencies (different to multiples of power line frequency) below 500 Hz were examined playing pink noise.

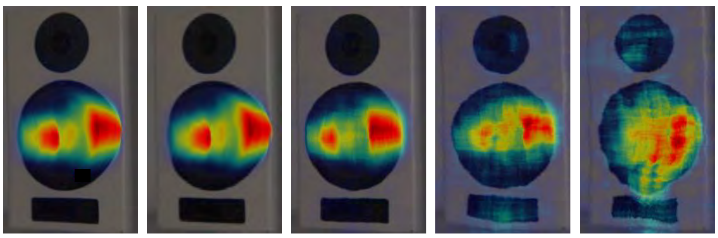
3.2. Results

The results of the near-field acoustical holography measurements are shown in Figure 9, the equivalent high-speed camera recordings are shown in Figure 10.



60 Hz 90 Hz 80 Hz 320 Hz 470 Hz

Figure 9: Acoustic holography (SONAH, 12 dB dynamic, particle velocity)



60 Hz 90 Hz 80 Hz 320 Hz 470 Hz

Figure 10: Frequency ODS based on high-speed camera recordings.

Low frequency noise emissions from the tweeter could be due to airborne noise leakage from the speaker casing or forced vibration excited by the woofer. That could explain the absence of the tweeter in the optical flow image. It could also be due to the metal grid cover of the tweeter, preventing optical information to be recorded. The woofer movement appears to be characterized consistently with the acoustic measurements. No significant differences in mode or deflection shapes are apparent between the examined frequencies in both methods, which is expected in this case.

In case of applications that are not suitable for acoustic holography but offer a direct line of sight towards to emitting surfaces the camera images allow analysis of low frequency and infrasound. The high-speed camera approach allows to examine vibration frequencies way lower than acoustic waves down to 0 Hz using motion magnification. Figure 11 below shows how a baby's breathing rate at 0.5 Hz can be visualized. The video was first used to demonstrate motion amplification by Rubinstein [5]. In the motion enhancement method, the brightness changes for each pixel are used over the entire duration of the video sequence. The progression reflects the oscillation characteristics of a structure under consideration. In this process, the magnitudes of the brightness variations are filtered and amplified in the frequency domain. Since this data is subject to enormous noise and other sources of error, there are various approaches, as presented by Wadhwa et al [6], to obtain the best possible results minimizing artifacts.

Figure 11: Baby breathing at 0.5 Hz, video downloaded from http://people.csail.mit.edu/mrub/evm/ and processed with WaveImage.

While low frequency acoustic waves can be investigated with near-field holography (Figure 12), the frequency range 2 – 20 kHz is best investigated using beamforming (Figure 13). Using the MIKADO, the recommended frequency limit for beamforming is about 500 Hz. Above that accurate localization is possible in the whole acoustic range.

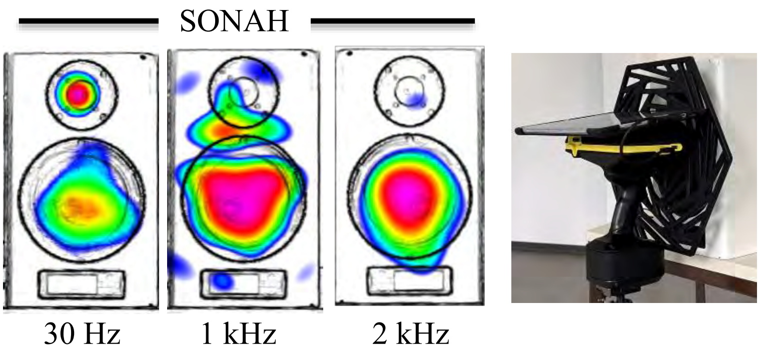


Figure 12: Acoustic holography (SONAH, 12 dB dynamic, Particle Velocity)

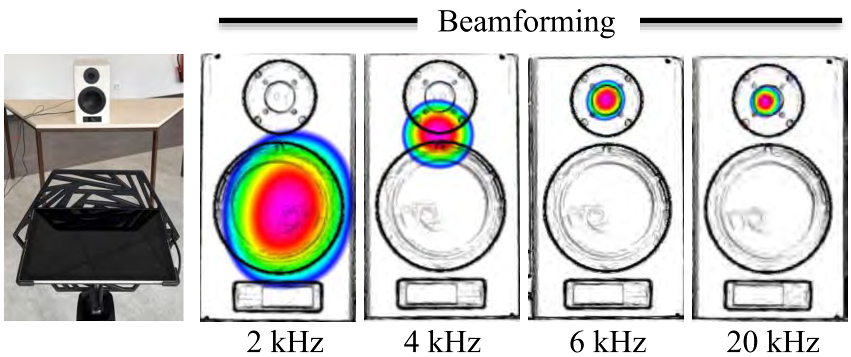


Figure 13: Beamforming (Power Beamforming [7], functional 16, 1 dB dynamic, Sound Pressure)

4. CONCLUSIONS

Two simple tests were carried out to compare measurement results of an acoustic array (processed using beamforming and acoustical holography) and high-speed camera videos (processed using optical flow tracking and motion amplification). An impact test was carried out on a brake disc. A speaker was investigated playing pink noise.

Both methods were found produce valid mode shapes and operating deflection shapes respectively at the correct frequencies. A comparison of results obtained with SONAH and optical flow tracking are mainly cross validating results. Complementing benefits are the creation of animated deflection shapes and the option to carry out low frequency vibration measurements from the far field.

Due to the high disparity and difference in deviating limitations of approaches the field of application is increased with the combination. Potential benefits of an approach comparison at higher frequencies will require further investigation.

It appears that there are great potential benefits in employing both methods, in one measurement device. The combination carries the potential to widen the frequency range allowing to obtain spatially-resolved vibroacoustic information from a single measurement. In this paper this has been demonstrated from 0.5 Hz – 20 kHz.

The total view measurements reduce setup times by a large margin compared to single channel approaches using microphones, accelerometers and Laser Doppler Vibrometry (LDV).

The time savings would be even more significant if speed-variable processes are monitored as e.g., a run-up or coast down can be recorded in one measurement.
The results could also be employed to calibrate models that predict sound emissions from structural dynamic behavior.

5. ACKNOWLEDGEMENTS

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