

## Measurements of sound-flow interaction at a bias flow liner

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**Abstract** In order to optimize the noise reduction of perforated liners with bias flow that are applied in jet engines and gas turbines, a better understanding of the inherent aeroacoustic sound damping mechanisms is necessary. For that purpose, the interaction between sound and flow that is responsible for the damping process needs to be localized, analyzed and balanced. To this aim, laser optical measurements are needed that both acquire the complex sound field and flow field contactlessly. Acoustic particle image velocimetry (A-PIV) and Doppler global velocimetry with sinusoidal frequency modulation (FM-DGV) are applied for this measurement task in comparison. The results show that both methods are advantageous due to their ability for multipoint measurement. In particular, A-PIV offers a wide overview of multiple perforation orifices, whereas FM-DGV satisfies with a high measurement rate of up to 100 kHz allowing the spectral analysis of the velocity field.

Both methods were applied at a generic bias flow liner, showing acoustically induced flow velocity oscillations near the rim of the perforation orifices. The spatially resolved oscillation magnitude shows a correlation to the dissipation coefficient and indicates an acoustically induced flow vortex generation and collapse in the vicinity of the liner perforation, respectively, which depends on the relative position to the orifice. As shown in this paper, the measurement methods have the potential to enhance current knowledge about the aeroacoustic interaction at liners, especially in the scenario with both grazing and bias flow. In order to fully understand these interaction phenomena an expansion to volumetric measurements is needed in the future.

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### 1. Introduction

A deeper understanding of the sound damping mechanisms at bias flow liners is required for their optimization regarding maximum damping performance for their application in aircraft engines or gas turbines [9]. Acoustic liners consist of a perforated sheet with a cavity behind, which leads to the damping of the propagating sound wave due to acoustic resonance effects. If an additional air flow through the perforation (the bias flow) is applied, like e.g. for cooling in combustion chambers, the magnitude and the bandwidth of the damping increases, which is based on interaction between the acoustic field and the flow field [3]. However, this interaction has not yet been understood completely, especially if a grazing flow is applied over the perforation, which is typically the case for the engine and the turbine. Therefore, aeroacoustic measurements are needed [11]. For this purpose, both the acoustic particle velocity (oscillation velocity associated with the sound) and the flow velocity at a bias flow liner have to be measured. To capture the complex sound-flow interaction phenomena, multi-component and multi-dimensional velocity measurements are necessary. Since the acoustic particle velocity is typically in the range of a few mm/s, a low measurement uncertainty (< 10 mm/s) is demanded. In addition, velocity spectra with a Nyquist frequency up to 20 kHz are needed to analyze the energy transfer from the sound field to the flow field in order to enhance the understanding of the aeroacoustic damping mechanisms.

In this paper, we present the validation, characterization and application of two laser optical measurement methods for the aeroacoustic investigations. First, the measurement methods and the experimental setup at the test facility are described in section 2. Then, the validation results of

the APV measurement are presented in section 3, followed by an application example, the measurements of the sound-flow interaction at a generic bias flow liner. Finally, the main results and in outlook are given in section 4.

## 2. Experimental methods and setup

### Methods

For the aeroacoustic investigations, two laser optical measurement methods were applied, both evaluating the light scattered by seeding particles.

First, the Doppler global velocimetry with sinusoidal laser frequency modulation (FM-DGV) was applied. The measurement principle is based on spectroscopic evaluation of the velocity dependent Doppler frequency shift of the scattered light. The detailed explanation of the measurement principle and the currently used measurement system can be found in, e.g. in [4]. Finally, the mean flow velocity and velocity oscillation are determined using a Fourier transform of the measured velocity time series.

Second, the acoustic particle image velocimetry (A-PIV) was used, where two-dimensional correlation of subsequently recorded particle images yields the velocity vector in the image plane. Applying a phase-locking technique for a given acoustic frequency finally yields the velocity oscillation as well as the mean flow velocity [8]. Whereas the measurement rate of A-PIV is less than for FM-DGV (some Hz), the number of simultaneously recorded measurement points is much higher than for FM-DGV (some thousands).

### Setup

The aeroacoustic measurements were conducted at the “DUCT-R” (duct acoustic test rig with rectangular cross section) of the German Aerospace Center (DLR) in Berlin, see Fig. 1. The size of the duct is 60 mm x 80 mm x 3.34 m and the walls are made of aluminum having a thickness of 10 mm. Notwithstanding, one section is equipped with glass windows to enable optical access for the laser optical measurements. An (grazing) air flow (fluid temperature about 20 °C) through the duct is provided by a radial compressor. The resulting Mach number is about 0.3 at maximum. Seeding particles of diethylhexyl sebacate with a diameter of about 1 μm were inserted into the flow. Up to two speakers with sinusoidal excitation were used to generate the sound in the duct. In order to avoid undesired reflections of the sound wave, an anechoic termination was installed at the upstream end of the duct. At the downstream end, the anechoic termination was refrained because it could have been contaminated by the seeding particles.

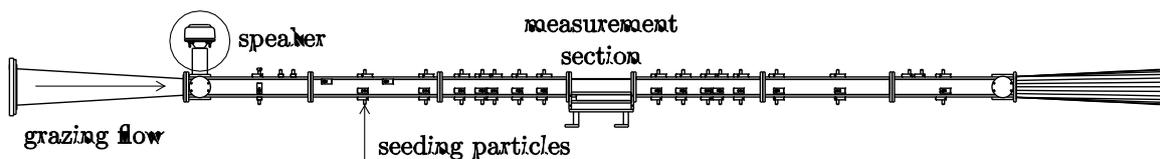


Fig. 1 Sketch of the test rig “DUCT-R” with optically accessible measurement section [5]

### 3. Measurement results

#### Validation

Firstly, the measurement of the acoustic particle velocity in a flow using FM-DGV and A-PIV is successfully validated. Therefore, the measurement section in DUCT-R employed only acoustically hard surfaces. Here, acoustic plane waves with a frequency of about 1 kHz and a maximum sound pressure level of approximately 130 dB have been applied. In addition, a flow has been superposed using different Mach numbers. Due to the plane wave assumption, which is valid for frequencies below about 2.2 kHz for the DUCT-R, the APV is directed in the axial direction. Consequently, this axial component was measured and compared with reference data obtained with a well-proven microphone measurement method [7]. The resulting APV amplitude profile is depicted for all the measurement methods together with the 95% confidence intervals in Fig. 2. Thereby, a good agreement of the results for the optical measurement methods with the results of the microphone method was achieved. Assuming random deviations only, the uncertainty for the measured APV amplitude is limited by flow turbulence and depends on the temporal and spatial resolution of the measurements. As an example for Fig. 2b, the uncertainty for the measured APV amplitude amounts to about 5 mm/s for FM-DGV and 11 mm/s for A-PIV. These uncertainty values are similar for both optical measurement methods and fulfil the requirements. For further validation examples, it is referred to [5].

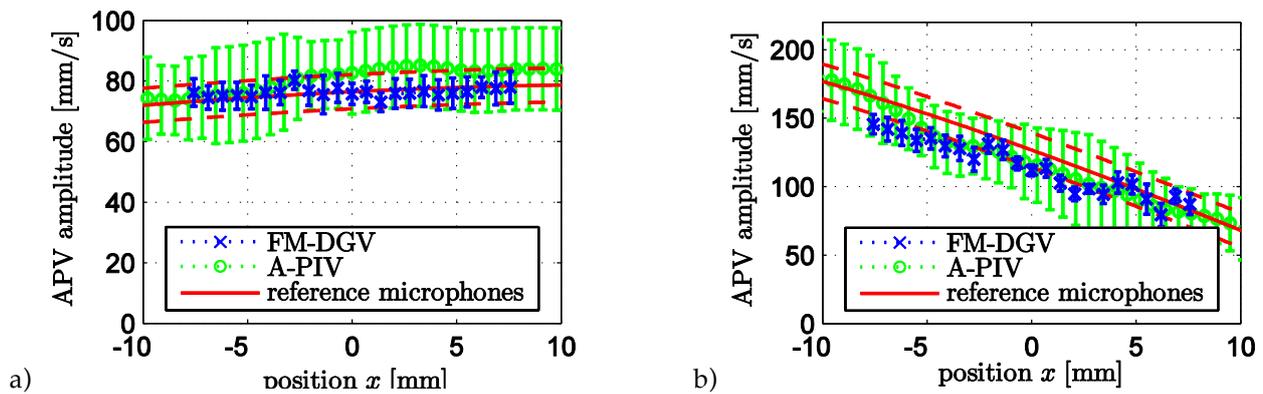
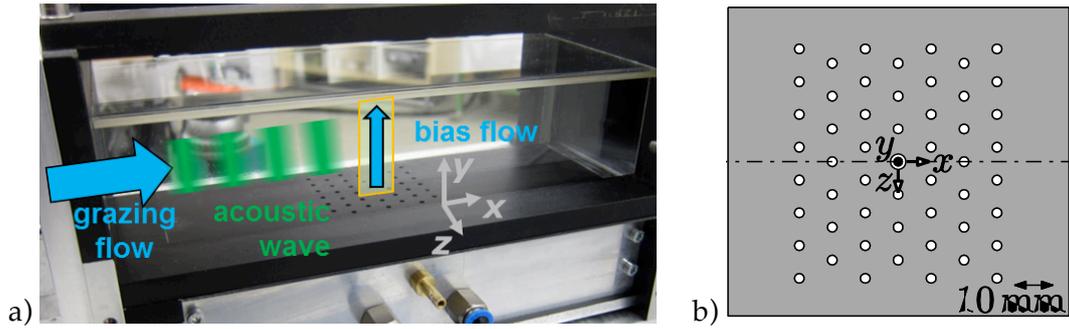


Fig. 2 Comparison of the amplitude profile of the acoustic particle velocity (APV) along the axial position  $x$  in the duct using a superposed flow with a) Mach 0.02 and b) Mach 0.1, measured with the laser optical methods FM-DGV and A-PIV and a microphone method as a reference

#### Application

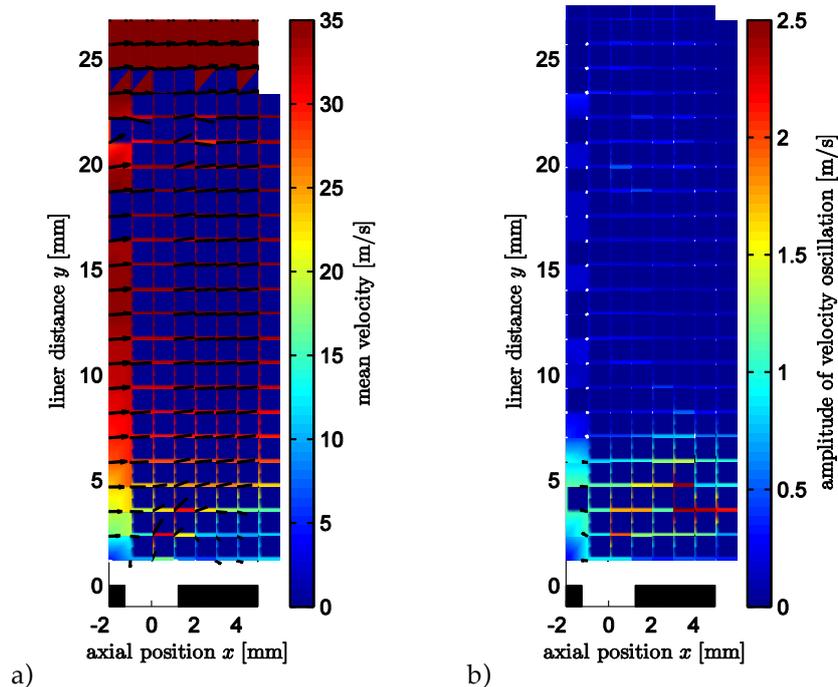
Secondly, an aeroacoustic measurement at a generic bias flow liner with grazing flow and sinusoidal acoustic excitation was conducted to study the inherent sound-flow interaction. Now the measurement section was equipped with a liner surface, see Fig. 3. The liner was designed using the perforation parameters (53 orifices with a diameter of 2.5 mm, perforation coefficient 6.8 % and single-volume backing cavity) from to the one used in former experiments [7], but having a rectangular cross section in order to fit into DUCT-R. Again, acoustic plane waves were excited with a frequency of about 1 kHz and a sound pressure level of about 130 dB.



**Fig. 3** a) Photograph of the measurement section with bias flow liner at DUCT-R and measurement plane (origin of the coordinate system is at center of the central orifice) and b) perforation geometry of the liner [6]

The FM-DGV measurements results for the mean flow velocity field and the amplitude of the velocity oscillation at the acoustic frequency are depicted in Fig. 4 for the  $x$ - $y$  plane in the vicinity of the central orifice of the liner perforation at  $z=0$ . The in-plane velocity components were extracted from a measurement of three oblique-angled components using a coordinate transform according to [1].

The mean flow velocity field in Fig. 4a reveals both the bias flow jet and the grazing flow, each with about Mach 0.1. The flow velocity oscillation field in Fig. 4b shows high amplitudes up to 2.5 m/s especially in the vicinity of the orifice. This oscillation does not only comprise the APV but also an acoustically induced hydrodynamic velocity oscillation (typically for flow vortices), which is in accordance with [7]. To separate the APV and the acoustically induced flow velocity oscillation, it is aspired to apply the Helmholtz Hodge decomposition [2] to the measurement data in the future, which requires an extension to volumetric measurements.



**Fig. 4** a) Mean velocity and b) amplitude of the velocity oscillation at the acoustic excitation frequency, measured at a bias flow liner with grazing flow using FM-DGV at the central orifice [5]

For comparison of the potential of the measurement techniques FM-DGV and A-PIV for aeroacoustic applications, the phase-resolved results for the velocity oscillation at the acoustic excitation frequency are depicted in Fig. 5. The advantage of A-PIV measurement is the larger size of the measured field, which is 45 mm x 30 mm here, see Fig. 5a. This size is given by the camera chip, whereas the size of the FM-DGV field is currently given by the linear arrangement of 23 fiber-coupled avalanche photodiodes in  $y$ -direction and sequentially traversing in  $x$ -direction,

cf. Fig. 5b. In the future, the application of a high speed camera with 1 megapixel is aspired to increase the number of measurement points. The A-PIV measurement field in Fig. 5a shows the increase of the maximum oscillation magnitude at the downstream rim of each orifice along the grazing flow direction  $x$ . Within the common measurement field at the central orifice of the liner, the resolved structures agree concerning shape, size and magnitude. This again cross-validates the aeroacoustic measurements of the laser optical methods.

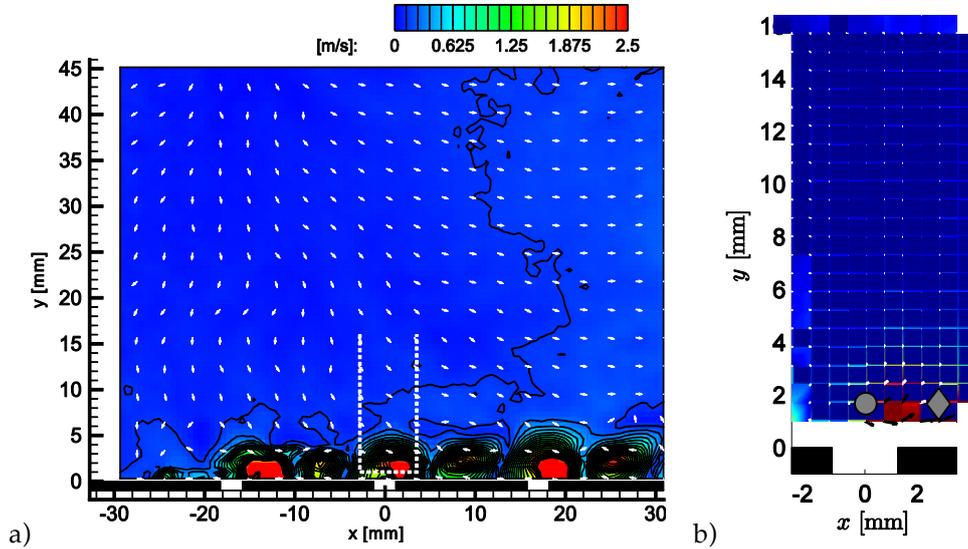
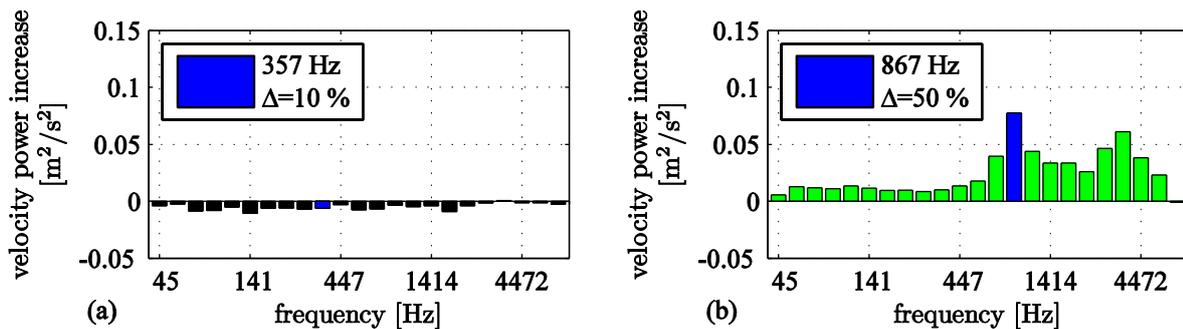


Fig. 5 Comparison of the amplitude of the velocity oscillation at the acoustic excitation frequency, measured at a bias flow liner with grazing flow using a) A-PIV and b) FM-DGV [10]

The advantage of FM-DGV is the high measurement rate of up to 100 kHz, which is possible due to the high detector bandwidth. This allows a spectral analysis of the measured velocity field up to 50 kHz (according to the sampling theorem) which enables the analysis of the energy transfer from the sound field to the flow field. As a first step, the locally resolved increase of the fluid velocity power shall be discussed. Therefore, the power spectral density (PSD) of the velocity was evaluated for a measurement with and one without the acoustic excitation. Then, the difference of the PSD between the cases with and without the excitation was evaluated. Finally, a summation of the PSD over the frequencies was applied, which yields the spectral power. The summation was done within third octave bands, which is typical for acoustical analysis. However, the PSD at the acoustical excitation frequency itself was excluded to omit the pure acoustic energy and obtain the broadband flow velocity power increase that results from the sound-flow interaction.

The resulting velocity power increase is depicted in Fig. 6 as an example for a position downstream of the orifice at  $x = 2.8$  mm,  $y = 1.7$  mm,  $z = 0$  for one measured velocity component in the direction of the unit vector  $(x, y, z) = (0.41, 0.71, -0.58)$ , according to the current optical setup [5]. The figure shows the results for different excitation frequencies, which were chosen such that the liner exhibits different values for the dissipation coefficient  $\Delta$  (= ratio of acoustic energy that is dissipated into heat).



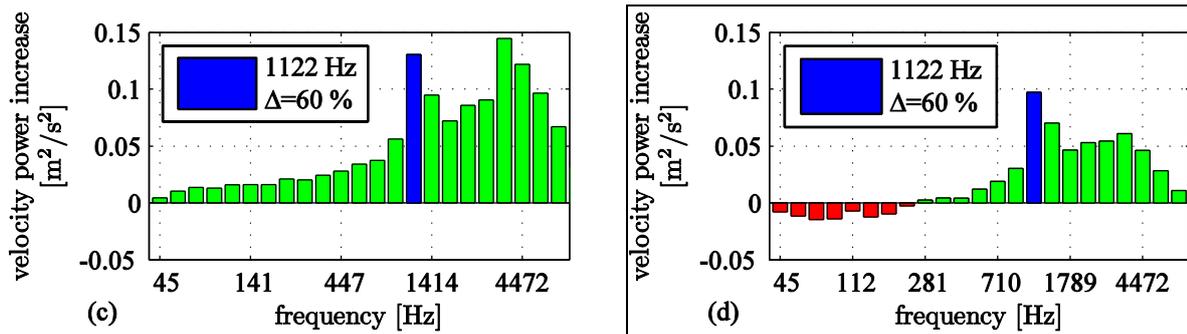


Fig. 6 Increase (green) and decrease (red) of spectral velocity power for (a) - (c) at the downstream position  $\square$  and for (d) at the position  $\bullet$  above the central orifice of the liner when acoustic excitation with a tone frequency is turned on (position markers according to Fig. 5) [6]

As a result, there is no spectral power increase of the velocity if the dissipation coefficient  $\Delta$  is low, like in Fig. 6a for an acoustic excitation frequency of 357 Hz. However, there is a broadband power increase of the flow velocity, if the dissipation coefficient of the liner is high (Fig. 6b-d), especially for high frequencies. This supports the assumption of acoustically induced small scale vortex generation.

Note that there are also positions, where a velocity power decrease exists, e.g. directly above the orifice at  $x = 0$ ,  $y = 1.7$  mm,  $z = 0$  in the low frequency range (see in Fig. 6d). It is assumed, that either there is an augmented collapse of large vortices (small frequencies) which is caused by the sound-flow interaction or the vortex generation is suppressed due to a stabilizing effect in the flow field. Future investigations are required to explain these interaction phenomena better in order to gain a deeper understanding of the damping mechanisms at bias flow liners.

#### 4. Conclusion

We presented the application and comparison of the laser optical measurements FM-DGV and A-PIV to aeroacoustic measurements in order to investigate the sound-flow interaction at perforated liners with both bias and grazing flow. At first, a successful validation of the laser optical measurements for measurement of the acoustic particle velocity was performed at acoustic plane waves in a flow duct using reference data from microphone measurements. Finally, both systems were used for measurements at a generic bias flow liner. While the A-PIV system allows gaining an overview of the interaction phenomena simultaneously at multiple orifices, the potential of FM-DGV for analyzing flow velocity spectra due to its high measurement rate of up to 100 kHz was revealed. As a result, acoustically induced flow velocity fluctuations at the liner perforation were captured. It was shown, that there is an increase of flow vortices due to a sound-flow interaction which is correlated to the dissipation factor. In order to enhance the understanding of the damping phenomena at bias flow liners, the energy transfer from the sound field to the flow field has to be further identified and completely quantified. Therefore, the separation of the complex three dimensional velocity oscillation field into acoustic particle velocity and acoustically induced flow velocity oscillation has to be done. For that purpose, volumetric measurements are obligatory in the future.

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