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Aeroakustische Nahfeldmessung mit Mikrometerauflösung

Aeroacoustic near-field measurement with micrometer resolution

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Laser-Doppler-Profilsensor, Schallschnelle, perforierte Schalldämpfer mit Durchströmung
laser Doppler profile sensor, acoustic particle velocity, bias flow liner

Abstract

For the investigation of sound-flow interaction in near-fields, like aeroacoustic damping or acoustic streaming, measurements of the acoustic particle velocity (APV) and the flow velocity field with a micrometer resolution are required. In addition, a high working distance is needed for contactless measurement. For this task, the laser Doppler velocity profile sensor is shown to be a predestined tool. First, the APV measurement is successfully validated in an aeroacoustic duct using a microphone-based measurement method as a reference. Here, a minimum APV amplitude of 4 mm/s was resolved in agreement with the reference measurements. Then, the profile sensor was applied for measurements at a perforated acoustic liner with bias flow. Acoustically induced flow vortex structures were resolved with a spatial resolution of 10 µm with a minimum distance of 350 µm to the liner perforation. A comparison to frequency modulated Doppler global velocimetry (FM-DGV) demonstrated the advantage of the profile sensor for spatially resolved measurements of small scale structures. In contrast, FM-DGV is beneficial due to its high measurement rate which enables the spectral analysis of the velocity in order to better understand the energy transfer from sound to flow.

Introduction

In order to investigate aeroacoustic near-field phenomena in boundary layers e.g. acoustic streaming (Campbell et al. 2000), contactless field measurements of the acoustic particle velocity and the flow velocity are required. To resolve even small structures, i.e. turbulent vortices within the Kolmogorov scales, a high spatial resolution in the micrometer range is demanded. Whereas laser Doppler anemometry or particle image velocimetry can be applied for this task, these measurements are limited to a short working distance. In contrast, the laser Doppler velocity profile sensor offers a high spatial resolution in the micrometer range at a working distance of some centimetres, according to Czarske et al. 2002.

However, the profile sensor has not been used for aeroacoustic measurements, yet. Therefore, this paper deals with the setup and the required signal processing of a profile sensor system for measurements of the acoustic particle velocity (APV) first. Next, a successful validation of the APV measurement in a superposed flow with conventional microphones is performed. Furthermore, the application of the sensor for aeroacoustic measurements at the near-field of a perforated acoustic liner with bias flow is demonstrated. Finally, the measurement properties (e.g. spatial resolution, measurement rate) of the profile sensor for that measurement task are compared to frequency modulated Doppler global velocimetry, which has been recently used for measurements at bias flow liners by Haufe et al. (2013). The paper closes with an outlook where future perspectives and application fields of the profile sensor for aeroacoustic measurements are discussed.

Sensor setup and signal processing

For the experiments, a profile sensor using wavelength division multiplexing was used, see Fig. 1. The sensor employs laser light of two different wavelengths which are multiplexed by a dichroic mirror. Using a diffraction grating for beam splitting and achromatic lenses for focussing of the beams, two interference fringe systems are formed in the measurement volume at a working distance of 80 mm. The resulting fringe spacings for the two wavelengths are a function of the axial position z, one is monotonically increasing and the other decreasing with z, respectively. By evaluating the Doppler frequency of the scattered light signal (burst signal) of a moving particle within the measurement volume separately for both wavelengths, the quotient of both fringe spacing values can be determined. Applying a calibration function (obtained by measurements at a scattering object with known velocity and variably given position), the profile sensor finally yields both the y component of the velocity and the position z. For more details on the general setup, the principle and calibration of the profile sensor it is referred to Czarske et al. 2002.

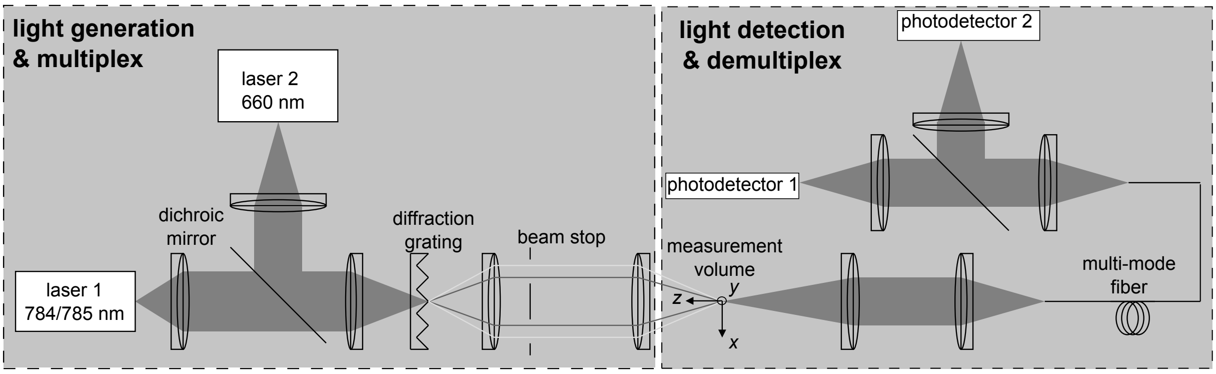


Fig. 1: Schematic of the laser Doppler velocity profile using wavelength division multiplexing

In order to determine the (oscillatory) APV in a flow, it is necessary to evaluate the velocity time series $v(t)$. For that purpose, the velocity v of multiple particle bursts at distinct times t has to be measured. Here, a velocity oscillation with a single frequency f_{osc} and a superposed mean flow velocity v_0 as well as additive noise $n(t)$ is assumed:

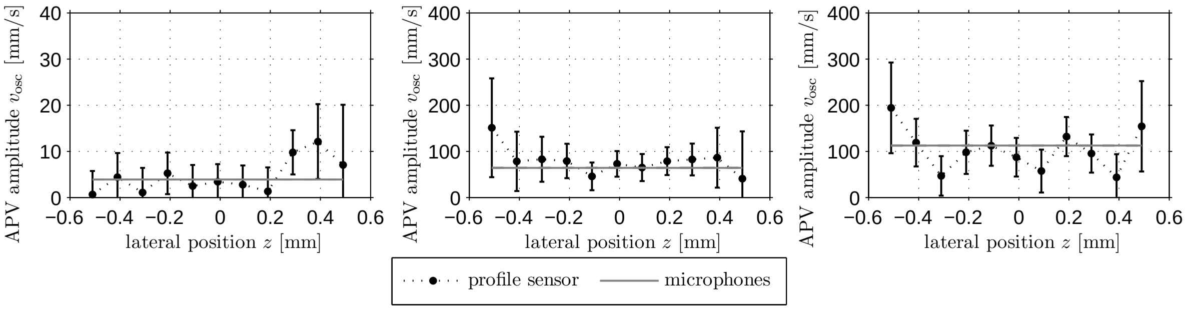
$$v(t) = v_0 + v_{\mathrm{osc}} \cos\left(2\pi f_{\mathrm{osc}} t + \varphi_{\mathrm{osc}}\right) + n(t). \quad (1)$$

From equation 1, the estimation of the amplitude v_{osc} and phase φ_{osc} of the oscillation as well as the estimation of the mean velocity value can be achieved using an efficient least squares method by Simon et al. 2008 for a given velocity-time-signal model. This estimation has to be performed for each location z within the measured profile. Hereby, a spatial discretization of the measurement volume along the z-axis in sectors of a given length δ_z is applied. Hence, velocity values of bursts from particles that are within the same spatial sector (i.e. nearly having the same position) are used for each estimation. Consequently, δ_z represents the spatial resolution in axial direction. Note that the choice of the spatial resolution δ_z affects the effective measurement rate of each measurement location which is given by the particle burst rate divided by the number N_z of spatial sectors.

Sensor validation

In order to validate the profile sensor and the signal processing for the measurement of the APV, an experimental validation was performed. The experiments were conducted at the DUCT-R (duct acoustic test rig with rectangular cross section: 60 mm x 80 mm) of the German Aerospace Center in Berlin, cf. Haufe et al. 2013. An approximately uniform flow, seeded with particles made of diethylhexyl sebacate (diameter about 1 µm), was provided by a radial compressor. Acoustic plane waves were generated in the acoustically hard-walled duct with a loudspeaker at an arbitrarily chosen frequency of 683 Hz, which is below the cut-off frequency of high order modes (2.2 kHz here). Then, the APV is in axial direction, consequently, the axial velocity was measured, which was done in the vicinity of the centre of the cross section for a profile along a lateral coordinate z being perpendicular to the axis of the duct (cf. Fig. 3, but with acoustically hard wall). Due to the plane wave assumption, a constant APV is expected along z. Reference values for the measured APV were obtained using a wave field decomposition technique using multiple microphones along the axis of the duct, see Heuwinkel et al. 2010.

For comparison, the resulting APV amplitudes from the profile sensor and the microphone measurement are depicted in Fig. 2 for different Mach numbers of the flow. The results agree within the 95 % confidence intervals. For the first example in Fig. 2a, a minimum APV amplitude of 4 mm could be resolved. The standard uncertainty of the APV amplitude, according to the Guide to the Expression of Uncertainty in Measurement (ISO 1993), is about 2 mm/s at a measurement duration of 81 s and a spatial resolution of $\delta_z = 100\,\mu\mathrm{m}$, excluding systematic deviations. Note that the measurement uncertainty, represented by the size of the confidence intervals, is higher for outer sectors. This is due to a smaller number of particle bursts (lower particle burst probability because of thinner measurement volume at the margins) used for the



(a) Ma 0.02, 99 dB

(b) Ma 0.19, 125 dB

(c) Ma 0.25, 126 dB

Fig. 2: Validation of the measurement of the acoustic particle velocity with the laser Doppler velocity profile sensor in an aeroacoustic flow duct using microphones as reference technique, 95 % confidence intervals have been added, but are imperceptible for the microphone results

estimation of the oscillation amplitude. Furthermore, the uncertainty is increasing for higher Mach numbers from Fig. 2a to 2c. This is caused by the higher flow turbulence (higher standard deviation of the flow velocity), which coincides with Haufe et al. 2013. As a result, the validation of the profile sensor for APV measurement was successful.

Sensor application and characterization

The profile sensor was applied for aeroacoustic measurements at a perforated acoustic liner with bias flow. Although the basic principle of those liners was thoroughly discussed e.g. in Eldredge et al. 2003, details of the damping mechanism are still subject of current aeroacoustic research, for instance by Rupp et al. 2010; Zhong et al. 2012. In the following experiment, profile sensor measurements were performed as a very first approach at a generic liner (similar to the one in Heuwinkel et al. 2010) with 53 regularly arranged orifices having a diameter of 2.5 mm. The liner was mounted in the flow duct, see Fig. 3. An acoustic excitation frequency of $f_{\text{osc}} = 1073$ Hz was chosen, where the liner has a high damping performance (dissipation coefficient of almost 60 %). The resulting sound pressure level maximum in the duct was 122 dB. Furthermore, the injected bias flow had an approximate mass flow rate of 5 kg/h and a grazing flow of 3 m/s was applied. The measurement was performed for the y component in a plane slightly downstream of the central perforation orifice at $x = 1$ mm, whereas the origin of the coordinate system is located at the centre of that orifice. In order to enable a measurement close to the perforation, the laser beams of the sensor were aligned to the perforation surface accordingly to avoid shadowing as well as reflections of the laser beams. As a result, a minimum distance of $y = 350$ µm was achieved. A measurement field was obtained using the measured profiles along the z axis and traversing the sensor in y direction. The mean flow velocity v_0 and the velocity amplitude v_{osc} at the excitation frequency were estimated from the time series in equation (1).

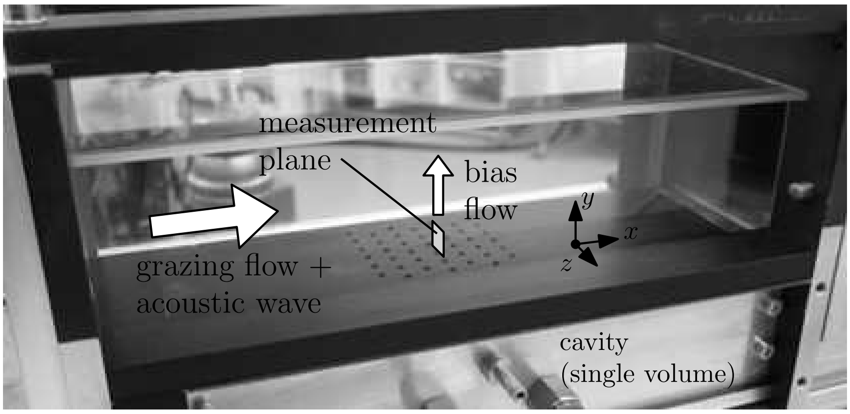
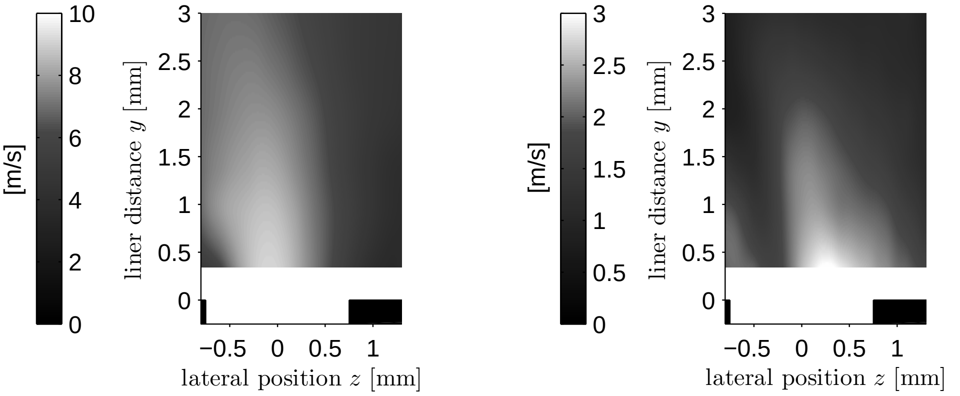


Fig. 3: Photograph of the generic bias flow liner mounted in the aeroacoustic flow duct

The resulting fields for the measured velocities are given in Fig. 4 for a spatial resolution of $\delta_z = 100$ µm. Note that all measured fields show a certain asymmetry regarding $z = 0$, which is because the feeding of the bias flow into the liner cavity is asymmetric (from positive z direction only, cf. Fig 3). In Figure 4a the bias flow is clearly visible, the velocity is maximum near the perforation, where the average velocity within the jet cross section amounts to 7 m/s. The oscillation amplitude in Fig. 4b is also maximum near the perforation amounting to 3 m/s. This oscillation value also comprises hydrodynamic fluctuations from flow vortices, see e.g. Heuwinkel et al. 2010. The minimum standard uncertainty of both the APV amplitude and the mean flow velocity was about 1 mm/s for a measurement duration of 300 s.

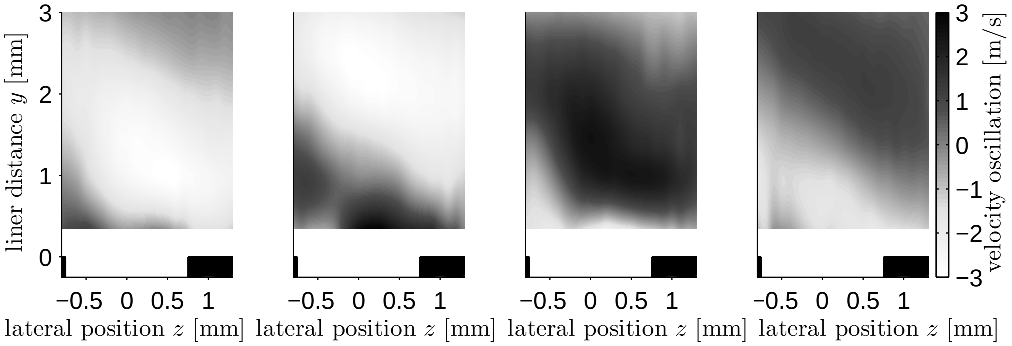


(a) mean flow velocity v_0

(b) amplitude v_{osc} of the velocity oscillation at the acoustic excitation frequency $f_{\text{osc}} = 1073\,\text{Hz}$

Fig. 4: Results of the aeroacoustic near-field measurement (y components) at a generic bias flow liner in the vicinity of the central orifice at $x = 1\,\text{mm}$, using the laser Doppler velocity profile sensor

For a better visualization of the velocity oscillation, it is depicted in Fig. 5 for four different phases, showing the movement of fluid structures for increasing phase. The results indicate that there are flow vortices being shed from the perforation orifice. This vortex shedding must be initiated by an aeroacoustic interaction, since the velocity oscillation vanishes when no sound excitation is present (not depicted here). In order to analyse the dissipation of the vortices into heat it is necessary to resolve small scale structures down to the Kolmogorov scale, which is estimated to about $20\,\mu\text{m}$, according to Pope (2000). For that purpose, the results are compared in Fig. 6 for two spatial resolution of $\delta_z = 100\,\mu\text{m}$ and $10\,\mu\text{m}$ for a profile at a distance of $y = 2\,\text{mm}$ to the liner perforation. Both profiles agree well within the $95\,\%$ confidence intervals. In the profile for $\delta_z = 10\,\mu\text{m}$ no smaller structures are visible than for $\delta_z = 100\,\mu\text{m}$. Obviously, the needed spatial resolution for this experiment is lower than provided by the profile sensor. Hence, the profile sensor has the potential for the application at micro-perforated liners with smaller orifices having a diameters below $1\,\text{mm}$ like in Tayong et al. 2013, where smaller flow structures are expected.



(a) arbitrary phase φ_v

(b) $\varphi_v + 90°$

(c) $\varphi_v + 180°$

(d) $\varphi_v + 270°$

Fig. 5: Phase-resolved velocity oscillation (y component) at the acoustic excitation frequency $f_{\text{osc}} = 1073\,\text{Hz}$ for $x = 1\,\text{mm}$

Finally, the capabilities of the profile sensor for aeroacoustic measurements are compared with the frequency modulated Doppler global velocimetry (FM-DGV) which has been recently

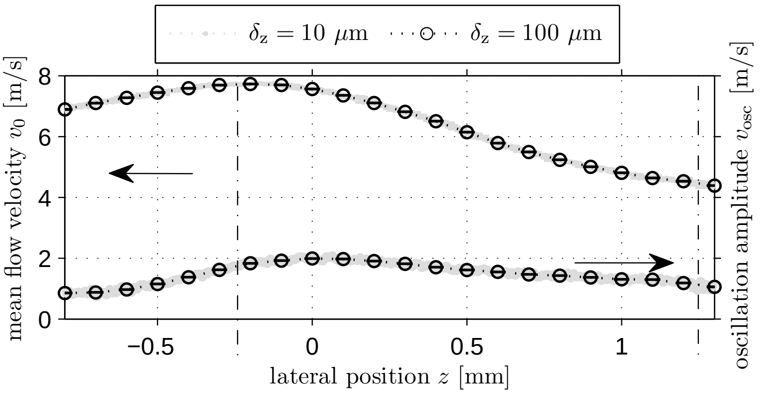


Fig. 6: Comparison of measured profiles (y components) at $x = 1$ mm, $y = 2$ mm with micrometer spatial resolution, both measurements agree within the 95 % confidence intervals

used by Haufe et al. 2013 for the same bias flow liner. The overview in Tab. 1 shows that the profile sensor is advantageous for the near-field measurement concerning the spatial resolution and liner distance. However, FM-DGV satisfies with the higher measurement rate. A high measurement rate allows to analyse the velocity spectrum, especially for the investigation of energy transfer from the sound to the flow with the aim to get a deeper understanding of the damping phenomena here, see Haufe et al. 2014.

measurement parameter	profile sensor	FM-DGV
best spatial resolution	10 µm	600 µm
measurement rate	some kHz/N_z	100 kHz
minimum liner distance	350 µm	1000 µm

Tab. 1: Comparison of measurement properties for the profile sensor and for FM-DGV from Haufe et al. 2013

Conclusion and Outlook

The capabilities and the application of the profile sensor for near-field aeroacoustic measurements were demonstrated. First, the sensor setup and the corresponding signal processing for the measurement task were presented. Then, the measurement of the acoustic particle velocity in a flow was successfully validated in an aeroacoustic duct with a maximum Mach number of 0.25. The minimum resolved velocity amplitude was about 4 mm/s in agreement with reference measurements using common microphones.

In addition, a measurement of the velocity mean and oscillation field at a perforated acoustic liner with bias flow was performed. Here, a minimum distance of 350 µm to the perforation was achieved with a minimum velocity uncertainty of about 1 mm/s for a measurement duration of 300 s. The results show an acoustically induced velocity oscillation which indicates flow vortex shedding from the perforation orifice. For the measurement at the liner, a surpassing spatial resolution of 10 µm was illustrated. This capability of the profile sensor exceeded the requirements for the given geometry parameters, but offers perspectives for investigations at liners with micro-perforation. The comparison to frequency modulated Doppler global velocimetry revealed that the latter has benefits for the spectral analysis of the sound-flow interaction at bias flow liners due to the higher measurement rate.

Acknowledgements

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