Experimental investigations on the fluid-structure-acoustic interaction of the flow past a thin flexible structure

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Abstract  In the present paper the fluid-structure-acoustic interaction of a thin flexible structure in the wake of a wall-mounted square cylinder is investigated experimentally. The experiments are performed in an acoustics wind tunnel employing microphone measurements of the sound pressure level. Detailed flow measurements are carried out using laser-Doppler anemometry and 3D-hot-wire anemometry. The flow induced vibration of the flexible structure is measured with a laser scanning vibrometer. Experimental results characterizing the flow field, the structural vibration and the generated sound are presented.

1. Introduction

In many technical applications, the flow of a fluid past a flexible plate-like structure leads to structural vibrations and thereby to the generation of vibrational sound. Coverings and panelings of cars and airplanes are important examples of this kind of fluid-structure-acoustic interaction. Usually the sound generated by the flow-induced vibrations is considered as noise and its reduction is a topic of major interest.

The emission of noise due to flow-induced vibrations of a flexible plate has received much attention in the literature. One of the early investigations in this direction was the work of Davies [1], where the excitation of a thin flexible panel by wall-pressure fluctuations of a turbulent boundary layer was studied using modal analysis. The boundary layer excitation of flexible plates and the resulting emission of noise has also been investigated by, e.g., Howe and Shah [2].

In the present work, the interaction of a fluid flow with a thin flexible structure and the resulting acoustic field were studied in detail. For this purpose, a test case was developed which represents a simplified model of a car underbody.

A description of the test case is given in the following section. The experiments were mainly performed in a low-noise wind tunnel using microphone measurements, laser Doppler anemometry (LDA) and three-component hot-wire anemometry. Flow-induced structural vibrations were measured with a laser-scanning vibrometer. Finally, the results of the study concerning the flow field, the vibration of the flexible plate and the generated sound are presented.

2. Experimental Setup

The investigation was based on a simplified geometric model, which is nevertheless complex enough to represent all important features of relevant technical application cases. The basic setup
consisted of a flexible plate-like structure which is part of an otherwise rigid wall (Figure 1). In order to study the influence of geometric flow disturbances on the resulting acoustic field, different configurations were investigated: one case with a square cylinder obstacle in front of the flexible plate as shown in Figure 1a and the other without an obstacle (Figure 1b). In the remainder of the presentation, the two basic configurations are referred to as case A and case B, respectively.

![Diagram of setup (Case A)](image)

**Fig. 1 Setup of the test cases A and B**

The plate was made of stainless steel with a thickness of 40 μm. The density was $\rho_s = 7850 \text{ kg/m}^3$, the modulus of elasticity was $E = 2\cdot10^{11} \text{ kg/ms}^2$, and Poisson's ratio equalled 0.3. The plate was prestressed in the main flow direction at a value of $7\cdot10^6 \text{ N/m}^2$. In case A, the edge length of the square cylinder was $D = 0.02 \text{ m}$.

A sketch of the general setup is depicted in Figure 2. The spanwise extension of the plate was 33D. The plate was mounted on a massive aluminum construct to avoid coupling between plate and mounting. The streamwise extension of the flexible plate amounted to 7.5D in both configurations. Because of the prestressing, the plate was clamped over a length of 0.5D both the upstream and downstream edges.

![Diagram of experimental setup](image)

**Fig. 2 Schematic drawing of the experimental setup**
A flow of air at ambient conditions was considered. Different freestream velocities $U_\infty$ ranging from 10 to 40 m/s were studied experimentally.

3. Experimental Methods

The acoustics measurements were performed in the acoustic wind tunnel of the University of Erlangen-Nuremberg, which is equipped with sound absorbers (anechoic chamber condition). A description of the acoustic wind tunnel was given by Becker et al. [3]. Additional flow measurements were carried out in the wind tunnel of the Institute of Fluid Mechanics.

The velocity field of the flow was measured using LDA. To avoid contamination of the aeroacoustic wind-tunnel absorbers due to the particle seeding necessary in the LDA measurement technique, this part of the experiment was carried out in a classical aerodynamic wind tunnel. The LDA measurement technique allowed reliable measurements in the recirculation region behind the obstacle and in the flow field close to the vibrating surface of the flexible plate. The LDA system employed was specially designed for application in low-speed wind tunnels. For the measurement of turbulent velocity fluctuations at high sample rates, hot-wire anemometry (HWA) using a three-component hot-wire probe (Dantec StreamLine System) was applied. A microphone at a 1 m distance perpendicular to the plate was used for the sound measurements.

Phase-resolved measurements with a scanning vibrometer were carried out to identify the vibration modes of the flexible plate. For this purpose, a single-point Polytec vibrometer was used together with a scanning vibrometer to observe the flexural modes of the plate at different frequencies. The single-point vibrometer constantly detected the vibrations of one point on the plate while the surface of the plate was scanned with the scanning vibrometer. To investigate the structure-acoustic interaction, correlation measurements with the scanning vibrometer and the microphone were performed.

Phase-resolved LDA measurements were made by coupling the LDA system with the single-point vibrometer which acquired the plate vibration. The setup in the wind tunnel is depicted in Figure 3. The vibrometer signal was monitored with a tracker expecting the first eigenfrequency and dynamically detecting the modulation of the frequency in a range of $\pm 30$ Hz. The current frequency was transmitted to the LDA system, in which the incoming signals were matched with the period length, so allowing for a time-dependent visualization of the flow field at a certain frequency.
4. Results

The normalized average velocity field obtained by LDA measurements at $U_{\infty}=20$ m/s is depicted in Figure 4a. The most prominent flow structure is a large region of recirculation which is located behind the square cylinder.
b) Distribution of turbulent kinetic energy

**Fig. 4** Measured average flow field at $U_\infty=20$ m/s (case A)

The distribution of the measured turbulent kinetic energy normalized to the maximum achieved value is shown in Figure 4b. It shows that the turbulence develops in the shear layer between the main flow and the region of flow separation. This means that the flow in front of the obstacle is already transitional in the experiment.

Figure 5 shows the velocity distribution close to the plate structure at $U_\infty=20$ m/s. Each picture corresponds to a certain phase angle. Obviously, one can identify almost no difference between the vector plots. This indicates that there is neither an influence of the plate vibration on the flow field near the flexible plate nor, consequently, on the global flow field. The flow patterns are dominated by the presence of the obstacle. This leads to unsteady three-dimensional structures with an averaged flow field as depicted in Figure 4.
Frequency spectra of the measured sound pressure level at $U_\infty=20$ m/s are plotted in Figure 6. Spectra obtained for the empty test section, for the flexible plate without obstacle (case B) and for the flexible plate with square cylinder (case A) are provided. In comparison with the empty test section, the sound radiation of the flexible plate with obstacle shows a prominent peak at about 140 Hz, which is very close to the first numerical eigenfrequency at 142 Hz. Additionally, at higher frequencies a large increase in broadband noise is observed. The tonal peak between 500 and 600 Hz is not relevant since it is also present in the measurement of the empty test section. The results of the vibrometer measurements indicate that the first low-frequency peak is due to the structural vibration of the flexible plate, whereas the high-frequency broadband noise is due to flow induced sound. This is also supported by measurements of the correlation between the acoustic pressure at the microphone position and the velocity of the vibrating plate. The corresponding coherence spectrum is shown in Figure 7. A strong correlation is found between 100 and 200 Hz, which is in good agreement with the spectrum of the sound pressure level in Figure 5.

**Fig. 6** Sound pressure level at a 1 m distance perpendicular to the plate (cases A and B, $U_\infty=20$ m/s)

**Fig. 5** Velocity distribution corresponding to different phase angles above the plate structure at $U_\infty=20$ m/s (case A)
Frequency spectra of the measured sound pressure level for case B are also plotted in Figure 6 as mentioned. The spectrum shows several peaks in the range between 100 and 200 Hz. In the higher frequency range, there is only a small difference from the reference case with the empty test section.

The sound pressure level of the tonal noise component in Figure 6 is much lower in the case without the obstacle than in the case with the square cylinder. However, this finding cannot be generalized. In the measurements a strong influence of the free-stream velocity $U_\infty$ on the acoustic field was observed. Experimental results for $U_\infty=40$ m/s are depicted in Figure 8. The sound pressure levels are significantly higher than for $U_\infty=20$ m/s. The difference of 17.65 dB in the total sound pressure level for case A corresponds very well with the value of 18 dB of a Ma$^4$ law for the acoustic power. A difference of 13.79 dB for case B is close to a Ma$^5$ dependency.

In case of a free stream velocity of $U_\infty=40$ m/s, the presence of the obstacle leads to a peak which is lower and wider than without the obstacle. To understand this phenomenon, three-component hot-wire measurements were made in two lines 10 and 20 mm above the plate. Figure 9 shows the measured data plotted in an anisotropy invariant map [4]. In contrast to the case without the obstacle, the case with the obstacle can be found in the lower middle of the invariant map, i.e. the turbulence generated by the obstacle in the region behind the square cylinder is much closer to isotropic turbulence than in the flow field without the obstacle. Since isotropic turbulence is normally located in highly three-dimensional flow fields, the correlation length of turbulent patterns is very short. This leads to an uncorrelated excitation of the plate and consequently to a reduction in the peak of the tonal frequency and to more broadband noise than in the better correlated flow without the obstacle.
5. Conclusion

Experimental investigations on the noise produced by the flow over a thin flexible plate have been presented. Two different configurations were considered: one case with a square cylinder obstacle located in front of the flexible plate and the other without an obstacle.

The experiments were performed in an acoustic wind tunnel employing microphone measurements, LDA and three-component hot-wire anemometry. The flow-induced vibration of the flexible structure was measured with a laser-scanning vibrometer.

In the experiments, a strong influence of the freestream velocity \( U_\infty \) on the radiated sound field was found. For low freestream velocity (\( U_\infty = 20 \) m/s) the introduction of the square cylinder obstacle led
to a significant increase in sound pressure level compared to the case without an obstacle. However, at higher velocity ($U_\infty=40$ m/s), a decrease in the tonal noise component was observed. This was attributed to the stronger isotropy of the turbulent fluctuations in the wake of the square cylinder in comparison to the flow without the obstacle, leading to a less correlated excitation of the flexible plate.

References