7.5 FSI investigations of an air-inflated membranous hemisphere in turbulent flow

This section discusses the complementary fluid and structure measurements carried out on the flexible hemisphere in turbulent flow at Re = 50,000, 75,000 and 100,000 as published in [379]. It is organized in the following manner: First, the inflow condition at the entrance to the test section is presented in Section 7.5.1.1. Due to the expanded Re number range, the arrangement of the turbulence generators is slightly modified in order to optimize the comparability between the velocity profile. After this, the unsteady and time-averaged flow field in the symmetry plane around the flexible hemisphere is discussed in Sections 7.5.1.2 and 7.5.1.3. In order to highlight the effects of the flexible structure on the flow, the results obtained are compared with the flow around the rigid hemisphere. Afterwards the instantaneous and time-averaged deformations of the membranous structure are outlined in Section 7.5.2. The response of the flexible hemisphere to the turbulent flow is analyzed in detail by linking the gathered PIV, DIC and CTA data.

7.5.1 Flow field characteristics

7.5.1.1 Inflow conditions of the turbulent boundary layer for the FSI case

The inlet TBL for the FSI studies considers a modified setup of the turbulence generators discussed in Section 5.2.4 and shown in Fig. 5.8(b). This is necessary to keep the time-averaged velocity and turbulence intensity distributions comparable at each Reynolds number. The measured profiles of the TBL are depicted in Fig. 7.19.

Figure 7.19: Time-averaged velocity and turbulence intensity in streamwise direction measured at the inlet of the test section by CTA for the three Reynolds numbers Re = 50,000, 75,000 and 100,000 [379].
In this study, the characteristics of the turbulent boundary layer are solely measured by CTA using the TBL hot-film probe designed for this purpose. The advantages of this technique are the near-wall resolution of the flow in combination with the high sampling rates. However, for the higher Reynolds numbers 75,000 and 100,000, an estimation of the friction velocity \( u_\tau \) based on the measurement at \( \text{Re} = 50,000 \) is necessary, since the associated laminar sublayers for the higher Reynolds numbers cannot be resolved by the hot-film probe adequately. This circumstance is shown in Fig. 7.19(b), where the near-wall values for \( \text{Re} = 75,000 \) and 100,000 begin in the log-law region. The estimation procedure is detailed below.

All profiles are measured in the symmetry plane of the hemisphere at the location \( x/D = -1.5 \). As before, there is no model of the hemisphere placed inside the test section to receive the undisturbed characteristics of the approaching flow. The time-averaged velocity profiles and the turbulence intensity of the streamwise flow component at each Reynolds number are presented in Fig. 7.19(a). The comparison between the measured velocity profiles shows a very good agreement. Compared to the 1/7 power law (reference profile) some deviations are visible in the region \( 0.2 \leq z/D \leq 0.4 \). The occurring “belly” indicates a not fully developed boundary layer. However, the desired thickness of the TBL is found at about \( \delta \approx D/2 \). The shape of the turbulence intensity profiles is similar for each Re number showing minor deviations in the amount of turbulence in the region between \( 0.05 \leq z/D \leq 0.15 \). The upper part of the turbulence profiles also indicates a thickness of \( \delta \approx D/2 \) since the turbulence levels possess a nearly constant value beyond \( z/D \geq 0.5 \).

A closer view at the velocity distribution is given in Fig. 7.19(b) showing the \( z^+ - u^+ \) graph for each Re. First, the near-wall region, i.e., where \( z^+ = u^+ \), is used to determine the spatial resolution of the applied CTA probe at the wall. The measurements at \( \text{Re} = 50,000 \) correspond to a non-dimensional wall distance of \( z^+ = (\Delta z u_\tau)/\nu = 3 \) translating to a minimum physical distance of \( z_{\min} = 0.2 \) mm between the probe wire and the flat plate. In the previous LDA measurements of the rigid hemisphere at \( \text{Re} = 50,000 \) a similar value was measured. Following the approach of this former study, the friction velocity is estimated to \( u_\tau^{\text{Re1}} = 0.225 \) m/s. This value is taken as the reference to approximate the friction velocity \( u_\tau \) for the higher Reynolds numbers based on the theory of a fully developed turbulent boundary layer. For this purpose, the relation between the friction coefficient \( C_f \sim \text{Re}^{-1/5} \) and the friction velocity \( u_\tau = \sqrt{C_f \text{U}_\infty^2}/2 \) is used (see Appendix A.2). The resulting values of the two higher Reynolds numbers are \( u_\tau^{\text{Re2}} = 0.324 \) m/s (\( \text{Re}_2 = 75,000 \)) and \( u_\tau^{\text{Re3}} = 0.421 \) m/s (\( \text{Re}_3 = 100,000 \)). The second interesting region of the TBL is the log-law range. Here, all three profiles collapse to a single line with a best fit curve described by \( u^+ = 1/0.42 \ln(z^+) + 5.5 \) with the von Kármán constant evaluated to \( \kappa = 0.42 \). All relevant parameters of each TBL are summarized in Table 7.1.

In addition to the determination of the classical TBL parameters, the CTA measurements are used to approximate the Kolmogorov length scale \( \eta \) defined by \( \eta = \nu^{3/4}/\epsilon^{1/4} \), where \( \nu \) is the kinematic viscosity and \( \epsilon \) the turbulent dissipation rate. This parameter relates to the size of the smallest vortical structures appearing in a flow depending on the Reynolds
Table 7.1: Characteristics of the turbulent boundary layer at the examined Reynolds numbers [379].

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>50,000</th>
<th>75,000</th>
<th>100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>free-stream velocity $U_\infty$</td>
<td>5.14 m/s</td>
<td>7.64 m/s</td>
<td>10.24 m/s</td>
</tr>
<tr>
<td>friction velocity $u_{*}^{Re}$</td>
<td>0.225 m/s</td>
<td>0.324 m/s</td>
<td>0.421 m/s</td>
</tr>
<tr>
<td>max. turbulence level in boundary layer</td>
<td>11.5 %</td>
<td>10.8 %</td>
<td>10.1 %</td>
</tr>
<tr>
<td>$\delta_1/\delta$ (displacement thickness)</td>
<td>1/8</td>
<td>1/10</td>
<td>13/100</td>
</tr>
<tr>
<td>$\delta_2/\delta$ (momentum thickness)</td>
<td>1/10</td>
<td>7/8</td>
<td>21/200</td>
</tr>
<tr>
<td>$H = \delta_1/\delta_2$ (shape factor)</td>
<td>1.24</td>
<td>1.27</td>
<td>1.24</td>
</tr>
<tr>
<td>$Re_\delta_2$ (Reynolds number based on $\delta_2$)</td>
<td>2530</td>
<td>3281</td>
<td>5115</td>
</tr>
</tbody>
</table>

number. It is utilized to evaluate the spatial resolution necessary for the PIV system in order to resolve smaller structures appropriately. Lavoie et al. [187] uses a hot-wire sensor to determine the Kolmogorov length scale and to formulate a “best practice approach” for the resolution of a PIV system with regard to its appropriate distance to the laser light sheet. Especially for a sufficient resolution of the small-scale turbulence, it is necessary to adjust the size of the interrogation window in the PIV processing to less than $5 \eta$. However, a direct measurement of the turbulent dissipation rate $\epsilon$ is a challenging task, since all nine components of the fluctuating velocity gradient tensor are needed. In the present study, a very rough approximation of $\epsilon$ based on a single wire hot-film probe measurement is used. In this case only the first component $\partial u'/\partial x$ can be measured directly. Consequently, the estimated value of $\epsilon$ has to be considered with care. For this purpose, reasonable approach using $\epsilon = -(\bar{u}_i/2)(\Delta \langle u'\rangle^2/\Delta z)$ proposed in [187] is applied to the TBL measurement leading to a rough approximation of the Kolmogorov length scale $\eta$. In this approximation, $\bar{u}$ is the mean velocity and $\langle u'\rangle^2$ denotes a measure for the turbulent kinetic energy leading to the value of $\eta \approx 0.3$ mm at $Re = 100,000$. Similar results are achieved by the common relationship $\epsilon_{iso} = (15\nu/U_c^2)(\partial u/\partial t)^2$ for example found in [170]. Here, Taylor’s “frozen eddy” hypothesis is applied using the local convection velocity $U_c$, which is equal to the local time-averaged velocity $\bar{u}_i$. Furthermore, it is assumed that the turbulent flow is statistically isotropic. In this case a smaller Kolmogorov length of $\eta \approx 0.16$ mm is found. With regard to the utilized interrogation window of $24 \times 24$ pixels ($1.518 \text{ mm} \times 1.518 \text{ mm}$) and following the recommendations made in [187] this translates to about $5 \eta \times 5 \eta$. However, these calculations have to be considered as crude approximations of $\epsilon$ and seem to overestimate the Kolmogorov length $\eta$ since the determined values lead to smallest eddies corresponding to a non-dimensional wall-distance of about $z^+ = 8.5$. Moreover, the measurements are restricted to the approaching TBL. The Kolmogorov length in the wake of the hemisphere is not considered where even smaller scales are expected connected to a broader decay process.

The next section discusses the unsteady flow field around the rigid and the flexible hemisphere.
7. Experimental results

7.5.1.2 Unsteady flow field

A comparison of the unsteady flow field around the rigid and the flexible hemisphere at each Reynolds number measured by PIV is depicted in Fig. 7.20. The snapshots of the flow field are visualized by the velocity magnitude \( |u| = \sqrt{u^2 + w^2} \) normalized by the free-stream velocity \( U_\infty \) focusing on the symmetry plane of the hemisphere. Furthermore, the color plots are superimposed by unsteady streamlines based on the streamwise and wall-normal velocity component.

Figure 7.20: Comparison of the unsteady flow field of the rigid (left) and the flexible (right) hemisphere visualized by the non-dimensional velocity magnitude \( |u| = \sqrt{u^2 + w^2}/U_\infty \) in the symmetry plane at each Reynolds number.

The instantaneous flow field is mainly used for a qualitative characterization of the flow around the wall-mounted obstacle. In contrast to the time-averaged flow field the instantaneous flow is useful to visualize the true turbulent nature of the examined problem in form of snapshots. Since the PIV measurements are spatially divided into two measurement areas (see Fig. 5.19) the upstream flow ranging between \(-1.5 \leq x/D \leq 0\) is connected to the “measurement area 1”, whereas the rest of the flow field \(0 \leq x/D \leq 2\) corresponds to
FSI investigations of an air-inflated membranous hemisphere in turbulent flow

“measurement area 2”. Thus, the subsequently merged images do not represent the same instant in time. Nevertheless, the location \( x/D = 0 \) seems the optimum position to join both images with minimal optical distortion. In the following comparison, the pictures on the left show the flow around the rigid hemisphere, while the ones on the right illustrate the flexible hemisphere indicated by the white surface with superimposed speckle pattern. Figures 7.20(a) and 7.20(b) depict the flow field at \( Re = 50,000 \). In both images a large recirculating region is visible in the wake which is characteristic for the \( Re \) number. The development of the free shear layer reaches a height of about \( z/D \approx 0.7 \) which can be determined by viewing the turbulent/non-turbulent interface (TNTI) (see also Fig. 2.21). A slight change in the flow characteristics in the wake is visible at \( Re = 75,000 \). In case of the rigid hemisphere in Fig. 7.20(c) the recirculation region seems to move closer to the lee-side. In contrast to this, the flow in the wake region of the flexible hemisphere in Fig. 7.20(d) stretches further downstream than at \( Re = 50,000 \). In both cases the size of the recirculation area is smaller for the flexible case. Also the height of the free shear-layer is slightly decreased to about \( z/D \approx 0.6 \). The observed trend for the wake region continues at \( Re = 100,000 \). The flow field in the wake of the rigid hemisphere in Fig. 7.20(e) shows a significantly smaller recirculation region which is located close to the lower lee-side of the hemispherical obstacle. This is connected to the separation line which is located at a position further downstream clearly visible in the image. The higher velocity in the region of the apex connected to the suction of the flow is reaching to a position further downstream. Here, the flow remains longer attached to the surface of the hemisphere. This has also an effect on the development of the free shear layer since the location of the flow separation is shifted towards the lee-side. The orientation of the shear layer visualized by the streamlines is pointing more downwards instead of parallel to the bottom wall. This leads to a shear layer height of about \( z/D \approx 0.5 \). A similar behavior is observed in case of the flexible hemisphere in Fig. 7.20(f). The direction of the shear layer is also pointing slightly downward. However, the separation of the flow is now driven by the unsteady deformation of the flexible structure. The suction of the flow in the vicinity of the apex causes an upward deflection of the flexible surface. The updated shape of the membranous structure leads to an altered separation line which is located closer to the apex. Moreover, it is assumed that the strong vorticity of the detaching shear layer has an impact on the oscillating structure in the wake associated with the FSI mechanism IIE discussed in the following sections.

The upstream flow region is not as sensitive to the inflow velocity showing similar results at each \( Re \) number. Only the size of the main vortex of the horseshoe vortex (HSV) in front of the hemisphere is highly dynamic obviously resulting from the instantaneous character of the flow.

In addition, the images of the unsteady flow field are used to illustrate the quality of the achieved PIV setup. For this purpose, the post-processing step is disabled in the software which typically fills up cells containing an inaccurate measurement by a correctly correlated neighbor cell. These uncorrelated cells are without this correction step visible as red dots in the flow field. Fortunately, the amount of erroneous cell values is small resulting in
a low degree of post-processing for the time-averaged data. A larger error appears at about \( x/D \approx -1.45 \). This is especially visible in case of the flexible hemisphere where a prominent blue stripe is visible at \( Re = 100,000 \). This is connected to a background reflection of the nozzle outlet which is amplified by further reflections of the white surface of the flexible hemisphere. Due to this systematic error source, the measurements in this region are of no physical relevance.

7.5.1.3 Time-averaged flow field

This section focuses on the time-averaged flow around the rigid and the flexible hemisphere. For this purpose, the streamwise \( \overline{u}/U_\infty \) and the wall-normal \( \overline{w}/U_\infty \) velocity components and the corresponding Reynolds stresses (\( \overline{u'w'}/U_\infty^2 \), \( \overline{w'w'}/U_\infty^2 \) and \( \overline{u'w'}/U_\infty^2 \)) of the PIV measurements are investigated at each Reynolds number. The results are presented by two-dimensional contour plots supplemented by profile lines. Furthermore, a detailed view at the streamlines is used to allocate the differences in the flow field between both hemispherical models.

Case \( Re = 50,000 \)

Figure 7.21 depicts the contour plots of the PIV measurement at \( Re = 50,000 \). The results of the rigid hemisphere are given on the left, while the measurements of the flexible case are displayed on the right. All characteristic flow regions described in Section 7.2.2.1 are visible in the streamwise velocity component in Figs. 7.21(a) and 7.21(b). Especially at this Reynolds number only marginal differences in the flow field between the rigid and the flexible hemisphere are recognizable. The largest deviations are visible in the normal Reynolds stresses \( \overline{w'w'}/U_\infty^2 \) connected to the wall-normal velocity (Figs. 7.21(g) and 7.21(h)) and the Reynolds shear stresses \( \overline{u'w'}/U_\infty^2 \) (Figs. 7.21(i) and 7.21(j)). The Reynolds stresses are slightly lower in the wake of the flexible hemisphere compared to the rigid case. The overall minor differences in the flow field are related to the moderate flow velocity (\( U_\infty = 5.14 \) m/s). The corresponding viscous and pressure forces acting on the membranous structure cause only very small deformations in the order of magnitude of \( 10^{-4} \) m. Thus, the flow field at \( Re = 50,000 \) has only a weak impact on the flexible structure.

The profiles are extracted from the time-averaged data focusing on the streamwise positions \( x/D = -0.9, -0.6, -0.3, 0, 0.3, 0.6, 0.9, 1.2, 1.5 \) and 1.8 depicted in Fig. 7.22. The graphs are used for a quantitative comparison between the rigid (blue line) and the flexible case (red line), since profile lines are more suitable to highlight differences in the flow field compared to the color plots. As described for the two-dimensional contour plots, the flow field is very similar for the rigid and the flexible case. There are only marginal differences visible at the apex and in the near-wake region of the Reynolds stresses in Figs. 7.22(c) to 7.22(e).

This observation also holds true for the time-averaged streamlines given in Fig. 7.23. The size of the HSV as well as the recirculation area are nearly identical. The reattachment
Figure 7.21: Comparison of the time-averaged velocities and the Reynolds stresses between the rigid and the flexible hemisphere in the symmetry plane at Re = 50,000 [379].
Figure 7.22: Comparison of the time-averaged velocities and Reynolds stress profiles between the rigid and the flexible hemisphere measured by PIV in the symmetry plane at specific locations at Re = 50,000 [379].

point in the wake is found at about \( x/D \approx 1.05 \) for both cases. A minor deviation is found in the position of the center point of the recirculation spiral. In the rigid case the center point is found at about \( x/D = 0.59 \), whereas it is slightly further downstream in the flexible case at \( x/D = 0.63 \). In both images a saddle point is detected at \( x/D = 1 \) and \( z/D = 0.2 \) connected to the downstream boarder of the recirculating spiral pattern.
Figure 7.23: Comparison between the rigid and the flexible hemisphere based on the time-averaged streamlines in the symmetry plane at Re = 50,000 [379].
7. Experimental results

Case \( Re = 75,000 \)

At \( Re = 75,000 \) \((U_\infty = 7.64 \text{ m/s})\) the differences in the time-averaged flow field between the solid and the deformable hemisphere are more pronounced than in the former case. The results for the two-dimensional contour plots are shown in Fig. 7.24.

In this case deviations are visible for all components. The largest differences appear in the wake region, whereas the upstream flow field does not reveal significant changes between both configurations. First, the streamwise velocity component is discussed. Here, a subtle difference is visible in the shape of the recirculation region interface (RRI) for the rigid hemisphere displayed in Fig. 7.24(a). It is slightly smaller compared with the flexible case in Fig. 7.24(b) which has a pronounced “belly shape” visible at the streamwise location \( x/D = 0.85 \). The shape of the RRI in the flexible case is similar to the former results discussed for \( Re = 50,000 \). The characteristic size of the recirculation region strongly depends on the position of the separation line. In case of the rigid hemisphere, the flow detaches at a position further downstream compared to the flexible hemisphere. This difference arises from the slight deformation of the flexible structure due to the suction of the flow in the apex region. The acceleration of the fluid starting at the stagnation point and continuing along the front side of the hemisphere is connected to a decrease in the pressure. This suction effect causes an upward deflection of the flexible structure leading to an overall updated shape of the flexible hemisphere. This slight deformation causes a more oval shape of the flexible structure in the region of the apex. As a result the separation line is shifted towards a position further upstream.

This characteristic feature of the flexible hemisphere is visible in the wall-normal velocity component in Fig. 7.24(d). The vertical component in the wake is much less pronounced showing smaller velocity values in the core region at \( 0.75 \leq x/D \leq 1.05 \) than for the rigid case in Fig. 7.24(c). Furthermore, the distribution of the wall-normal velocity in the wake of the rigid hemisphere suggests stronger downward momentum of the fluid. This fits to the slightly truncated shape of the RRI in case of the streamwise component discussed above. Moreover, the deformable surface of the flexible hemisphere adapts constantly to the unsteady flow conditions. As a consequence, the position of the separation line also adapts to the instantaneous deformation of the membranous structure, which is not the case for the rigid hemisphere.

The differences observed for the time-averaged velocity field are also influencing the Reynolds stresses. These show a slightly attenuated development of the shear layer in the wake of the flexible hemisphere compared to the rigid case. This is visible in the maximum intensities of the streamwise Reynolds stresses \( \overline{u'\nu'}/U_\infty^2 \) (Figs. 7.24(e) and 7.24(f)) forming a narrower region at around \( x/D = 0.75 \) compared to the rigid case. The observed downward flow in the wake of the rigid hemisphere is also visible in larger fluctuations associated with the wall-normal Reynolds stress component \( \overline{w'\nu'}/U_\infty^2 \) depicted in Fig. 7.24(g). Shortly after the developing shear layer the separation of the flow reveals significantly larger Reynolds stresses in the range \( 0.25 \leq x/D \leq 0.7 \) compared to the membranous structure in Fig. 7.24(h). A similar results is found for the Reynolds shear

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Figure 7.24: Comparison of the time-averaged velocities and the Reynolds stresses between the rigid and the flexible hemisphere in the symmetry plane at Re = 75,000 [379].
stress $\bar{u}w'/U^2_\infty$ in Figs. 7.24(i) and 7.24(j). As observed before, the values of the Reynolds shear stresses are remarkably lower in the wake in case of the flexible hemisphere. Based on these results it is suggested that the flexibility of the structure leads to an altered distribution of the flow in the wake regime.

The comparison of the profiles at $Re = 75,000$ is depicted in Fig. 7.25. The characteristics of the profile lines follow the previous discussion of the color plots. Major differences between the rigid and the flexible case are especially visible for the wall-normal velocity component (Fig. 7.25(b)) and the Reynolds stresses (Figs. 7.25(c) - 7.25(d)). An interesting feature of the flow around the flexible hemisphere is visible at $x/D = 0$ for the streamwise normal Reynolds stresses. The sharp spike near the surface of the hemisphere is an indicator for the developing shear layer connected to the separated flow. This is not visible for the rigid hemisphere which leads to the conclusion that the flow is separated at a location further downstream in case of the solid body altering the flow in the wake.

![Figure 7.25: Comparison of the time-averaged velocities and Reynolds stress profiles between the rigid and the flexible hemisphere measured by PIV in the symmetry plane at specific locations at $Re = 75,000$ [379].](image-url)
The comparison of the streamlines at Re = 75,000 in Fig. 7.26 shows a significantly different distribution between the rigid body and the air-inflated flexible structure. The largest changes are visible in the recirculation area. Behind the rigid hemisphere, the recirculation area is located close to the lee-side and overall smaller compared to the flexible case. Furthermore, the center point of the recirculating spiral in the wake of the solid body is shifted to the streamwise position $x/D = 0.55$ at a height of $z/D = 0.3$. Moreover, the former saddle point observed at Re = 50,000 at the downstream border of the spiral pattern has vanished. In contrast to this, the recirculation area of the membranous hemisphere is following the characteristic features of the previous case at Re = 50,000. The center point of the recirculation spiral is slightly shifted downstream to $x/D = 0.61$ with a height of $z/D = 0.35$. Furthermore, the saddle point in the wake is still clearly visible. The reattachment point in both cases is at a similar position at about $x/D \approx 0.93$. No significant deviations are found in the upstream region. The size of the main vortex of the horseshoe vortex system is more or less identical in both cases and seems to be mainly driven by the characteristics of the approaching TBL.

![Streamlines Comparison](image)

Figure 7.26: Comparison between the rigid and the flexible hemisphere based on the time-averaged streamlines in the symmetry plane at Re = 75,000 [379].
7. Experimental results

Case Re = 100,000

The time-averaged velocity field at Re = 100,000 ($U_\infty = 10.24$ m/s) is depicted in Fig. 7.27. In both cases all components follow qualitatively the trend discussed for Re = 75,000. First, a significant difference of the shape of the recirculation area is visible in the plots of the streamwise velocity component in Figs. 7.27(a) and 7.27(b). In case of the rigid hemisphere the RRI reveals a more compressed boarder. The actual backflow region is located closer to the lower lee-side. Different to this, the wake region of the flexible hemisphere is similar to the one for Re = 75,000 although decreased in size. The “belly” shape is still clearly visible in the region $0.8 \leq x/D \leq 0.95$. Both cases reveal a significant decrease in the size of the recirculation area compared with the other Reynolds numbers indicating that the flow separates at a position further downstream. The largest deviations between the rigid and the deformable hemisphere are visible in the wall-normal velocity component given in Figs. 7.27(c) and 7.27(d). Following the discussion of Re = 75,000: At the given free-stream velocity $U_\infty = 10.24$ m/s the accelerated fluid traveling along the front side of the rigid hemisphere is capable to longer resist the increasing pressure gradient (see also Fig. 2.17) before it separates from the surface. Since the position of the separation line is shifted towards the lee-side of the solid hemisphere, the flow is still attached. This leads to a strong downward momentum when the flow separates from the surface of the hemisphere. In summary, the ideally hemispherical shape of the solid body guides the oncoming fluid along its smooth and solid surface. With increasing Reynolds number the detachment point shifts to the back of the hemisphere leading to a smaller recirculation area accompanied with a strong downward directed velocity. This behavior is not present for the flexible hemisphere. The wall-normal velocity is remarkably less pronounced in the wake compared to the rigid hemisphere due to the altered detachment behavior of the flow from the membranous surface. Here, the separation of the flow strongly depends on the adapted shape of the flexible body which is no longer comparable to a perfect hemisphere, since the suction of the apex region leads to a large deformation. Thus, at least partially the shape of the deformed membranous structure is responsible for altering the separation behavior of the flow. Furthermore, the separation characteristics are also depending on the unsteady oscillations of the structure associated to FSI phenomena, such as IIE and MIE. As observed for Re = 75,000 the separation of the flow from the surface of the flexible hemisphere is shifted to a position further upstream compared to the rigid case. Moreover, altered Reynolds stress distributions are observed in the wake shown in Figs 7.27(e) to 7.27(j). In all graphs, the fluctuations are lower in case of the flexible hemisphere. The identification of the driving mechanisms causing the reduction of the Reynolds stresses in the wake of the membranous structure are challenging by solely analyzing the PIV data.

The same flow characteristics are also observed in the profiles at Re = 100,000 depicted in Fig. 7.28. These display the largest deviations in the flow fields between the solid and the flexible structure for all Re. An interesting feature is detected in all profile lines at $x/D = 0$. In case of the flexible structure the values close to the hemisphere are not
FSI investigations of an air-inflated membranous hemisphere in turbulent flow

Figure 7.27: Comparison of the time-averaged velocities and the Reynolds stresses between the rigid and the flexible hemisphere in the symmetry plane at Re = 100,000 \[379\].
7. Experimental results

starting directly at the surface. This is due to the large deformation of the membranous structure in the region of the apex. The idealized hemisphere sketched in the graphs does not represent this deformation. Furthermore, the streamwise Reynolds stresses in Fig. 7.28(c) show larger values at the apex of the hemisphere supporting the hypothesis of the flow separating further upstream compared to the rigid case.

Figure 7.28: Comparison of the time-averaged velocities and Reynolds stress profiles between the rigid and the flexible hemisphere measured by PIV in the symmetry plane at specific locations at Re = 100,000 [379].

Finally, the streamlines at Re = 100,000 are presented in Fig. 7.29. As mentioned before, the previously seen trend at Re = 75,000 continues for both setups. The recirculation region in case of the rigid hemisphere is located closer to the lee-side of the structure with the center of the spiral at $x/D = 0.56$ and at a height of $z/D = 0.27$. The flow reattaches at around $x/D \approx 0.87$. The streamlines of the flexible case reveal a similar pattern as detected at the lower Re numbers. The saddle point at the downstream border of the recirculation is still present. Furthermore, the center point of the spiral pattern is located further downstream at $x/D = 0.63$ and $z/D = 0.32$. The reattachment point is found at $x/D \approx 0.87$ for both configurations. An outstanding detail is the development of the
FSI investigations of an air-inflated membranous hemisphere in turbulent flow

dividing streamline in the wake region. In case of the solid structure the flow passes the obstacle and moves towards the bottom wall. This reattachment behavior of the flow behind the rigid hemisphere is even more pronounced at higher Reynolds numbers. In contrast to this, the position of the dividing streamline for the deformable case is oriented parallel to the ground throughout the entire wake without changes in height. Once again, the upstream region including the horseshoe vortex in front of the hemisphere shows no larger variation for either case or Reynolds number. All discussed characteristic locations of the flow as well as the position of the flow separation are summarized in Table 7.2.

![Streamline comparison](image)

Figure 7.29: Comparison between the rigid and the flexible hemisphere based on the time-averaged streamlines in the symmetry plane at Re = 100,000 [379].

Table 7.2: Comparison between the rigid and the flexible case based on characteristic flow field positions [379].

<table>
<thead>
<tr>
<th>Flow Characteristics</th>
<th>Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50,000</td>
</tr>
<tr>
<td></td>
<td>rigid</td>
</tr>
<tr>
<td>center of recirculation $x/D$</td>
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</tr>
<tr>
<td>separation from body $\varphi_{sep}$</td>
<td>88°</td>
</tr>
<tr>
<td>reattachment point $x/D$</td>
<td>1.05</td>
</tr>
</tbody>
</table>
7. Experimental results

From the PIV measurements, the following assumptions are made to explain the underlying FSI of the current case:

- The global deformation of the structure leads to an altered velocity distribution in the wake of the flexible hemisphere associated with different Reynolds stresses.

- The reduction of the Reynolds stresses is connected to a partial energy transfer from the flow field to the flexible structure. The strain of the silicone material leads to the dissipation of energy due to internal friction which is acting as resisting force when the flexible structure is undergoing deformation.

- The flexible structure has an impact on the development of the free shear layer leading to reduced velocity fluctuations.

- The vortex shedding is altered in case of the flexible hemisphere leading to lesser pronounced vortical structure which are associated with decreased velocity fluctuations.

These points are further addressed in the following section. For this purpose, complementary CTA measurements are carried out close to the surface of both hemispheres in order to gain deeper understanding of the influence of the flexible structure on the flow.

7.5.1.4 Complementary CTA measurements in the wake of rigid and flexible hemisphere

The PIV measurements reveal significantly lower Reynolds stresses in the wake of the flexible hemisphere at Re = 100,000. One thesis is that the kinetic energy from the fluid is partially transferred to the flexible structure and dissipated due to internal friction occurring in the silicone material. It is assumed that this effect leads to a reduction of the velocity fluctuations. To investigate this idea more closely, a comparison of the velocity spectra of the rigid and the flexible model close to the wall is considered to quantify this effect by comparing the power content of the signal for both cases at the same location. A frequency band-width analysis is used to characterize the flow in the vicinity of the structural monitoring points E75, E60, E45 and E30 at Re = 100,000 (also see Fig. 5.13(b)). Due to measurement restrictions of the setup, CTA data at point E15 are not attainable. During the measurements the wire of the CTA probe is placed at about 2 mm away from the surface of the hemisphere. The measured velocity signal is directly converted to a power spectral density (PSD) plot. These data are used to extract the information given in Fig. 7.30.

Bar plots are applied to visualize the differences of the amplitudes in the PSD in the frequency range $2 \text{ Hz} \leq f \leq 125 \text{ Hz}$. The data of the rigid hemisphere are plotted behind the ones of the flexible model. This is necessary since the amplitudes of the rigid hemisphere are generally larger. In order to analyze quantitative data in more detail, the spectra are divided into four frequency bands ($j = k$). Each $\text{band}_j$ is analyzed by cumulating its power content by the Signal Power $j = \sum_i (\text{PSD}_i \cdot \Delta f_i), \ f_i \in \text{band}_j$. The subdivision of the entire
Figure 7.30: Comparison of the velocity spectra measured by CTA in the close vicinity of the structural monitoring points E75, E60, E45 and E30. A frequency band analysis reveals the differences between the rigid and the flexible hemisphere at $Re = 100,000$ [379].
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data set into four bands is considered to reveal the power content connected to certain frequencies. Furthermore, splitting the data into bands avoids biasing effects towards the largest amplitudes which are typically found at the lower end of the spectrum. The procedure allows to characterize the velocity fluctuations in specific frequency ranges. The gained cumulative results of each band are plotted in Fig. 7.30(e). As expected the largest amount of the signal power is found in “band 1” with a continuous decrease observed at each higher band. The points E60, E45 and E30 indicate an identical behavior: The power content of the signal of the rigid hemisphere is generally larger than for the flexible case. In other words: The velocity fluctuations in the wake of the flexible hemisphere are lower compared to the solid case confirming the observations made in the PIV measurements. This supports the idea that the kinetic energy of the fluid may be partially transferred to the structure lowering the velocity fluctuations on the lee-side of the object.

However, this effect has to be analyzed in more detail in the future since the sparse literature on this subject is contradictory: Similar effects are observed in a direct numerical simulation carried out by Shen et al. [302] investigating the turbulent flow along a smooth wavy wall undergoing transverse motion in the form of streamwise traveling waves. Close to the wall a significant reduction of the turbulence intensity and turbulent shear stresses is observed compared to a solid wall. In contrary to this study, Rosti and Brandt [278] detect an increase of the Reynolds stresses in the near-wall region of a numerically simulated hyper-elastic viscous wall. Following this observation, Rojratsirikul et al. [273, 274] compare a rigid and a membranous wing in a Reynolds number range between Re = 53,100 and 106,000 based on the camber length of the wing section. The membrane is made of silicone material to emulate the flexible characteristics of a bat wing. A comparison with the rigid model shows that the oscillating membrane increases the Reynolds stresses on the upper side of the flexible wing. This characteristic property of the membranous wing leads to a delayed flow separation at higher angles of attack since the flexible structure adapts quickly to the unsteady flow. These contrary findings indicate a dependency related to the flow problem considered. In case of the air-inflated flexible hemisphere investigated here it is clearly seen that the velocity fluctuations in the wake region are reduced except for the flow close to the surface point E75. At this location the power content of band 1, 2 and 4 is larger than for the rigid case. This is explained by the different separation characteristics of each hemisphere: For the flexible hemisphere the separation line is located further upstream due to its deformed shape as discussed for the PIV measurements. At this position the CTA probe is already recording larger fluctuations due to the developing shear layer after the detachment of the flow from the surface. The flow around the rigid hemisphere separates at a location further downstream. Thus, the shear layer is at an earlier development stage consequently measuring lower fluctuations.

With the exception of the point E75 all monitoring points of the flexible structure indicate a reduction of the velocity fluctuations in the wake visible in the cumulative power spectra in Fig. 7.30(e). This finding can be transferred to the Reynolds stresses in the wake regime which are also reduced in case of the flexible structure.

Closely considering the findings and conclusions of the flow field measurements, the
next section focuses on the unsteady and time-averaged structure deformations of the membranous hemisphere induced by the turbulent flow.

### 7.5.2 Structural response characteristics to fluid loads

This section concentrates on the structural response characteristics of the flexible hemisphere excited by the turbulent flow. The corresponding measurements are attained by the DIC method. Figure 7.31 presents the actual camera view mainly focusing on the lee-side of the hemisphere connected to the setup described in Section 5.3.4.1.

![Figure 7.31: Illustration of the DIC measurement data including the raw image and the achieved correlation area, the spatial resolution of the DIC grid and an example of the three-dimensional displacement field.](image)

The achieved correlation area (1) is highlighted as a light blue area including the line element (red line) in the symmetry plane of the hemisphere with the main monitoring points E15, E30, E45, E60, E75 and the apex. Additionally, the red dashed extension line is used for an extended view at the unsteady deformation and strain characteristics. A view of the raw camera image of the correlation area is given in the upper mid picture (2). In this view the larger perceived dots are connected to the position of the monitoring points which are used as a visual guide to identify the location in the raw and processed images more easily. The corresponding correlation grid is indicated in the upper right image (3). The correlation area is composed of about 6500 cells. The amount of evaluation cells is not constant due to the moving structure of the flexible hemisphere. Especially the cells at the boarder of the correlation area are sensitive to this effect, which is connected to the overlapping area where both cameras view at the same speckle pattern. Larger movements of the flexible structure lead to a reduced camera overlap as parts of the boarder are pushed out of view in one camera image. This can also cause erroneous correlations visible
in the displacement field data in the image (4) as deep blue values at the upper left side of the correlation area. A three-dimensional view at the DIC area is presented in picture (5). Based on this brief introduction, the following paragraph discusses the unsteady structure oscillations of the air-inflated membranous hemisphere.

### 7.5.2.1 Unsteady structure excitations

The instantaneous excitations of the highly flexible silicone membrane exhibit very complex deformation patterns especially in the turbulent wake of the hemisphere. In order to present these complicated three-dimensional characteristics, a step by step approach is taking in the following, beginning with a brief view at the time-dependent signals gathered by the DIC system. For this purpose, an example of the unsteady structure excitation at the monitoring point E75 is depicted in Fig. 7.32. This particular monitoring point is chosen because of its location close to the separated shear layer, where high velocity fluctuations are expected due to the formation of vortices. In this graph all three displacement components $\Delta x$, $\Delta y$ and $\Delta z$ are compared at each Reynolds number within the complete time interval of the associated DIC measurements.

It is clearly visible that the amplitude of the oscillating membrane increases at higher Reynolds numbers. The unsteady streamwise displacements $\Delta x$ in Fig. 7.32(a) show a random character related to a chaotic motion. Interestingly, a more distinctive signal is visible for the displacement $\Delta y$ in Fig. 7.32(b), which is associated with the spanwise direction. In this case the movement of the monitoring point reveals a more alternating excitation characteristic especially visible at $Re = 100,000$ in the time span $8 \leq t \leq 22$ seconds. This spanwise motion is triggered by large vortices that are detaching from the hemisphere associated to the IIE mechanism. The largest mean deformations are observed for the vertical displacement $\Delta z$.

In the next step, the displacements are shown in the phase plane in order to observe the instantaneous oscillations at each monitoring point in more detail for all Re numbers. Figures 7.33 and 7.34 show the $\Delta x$–$\Delta z$- and $\Delta y$–$\Delta z$-phase planes. The graphs represent the spatial area which a monitoring point occupies or “passes through” during the DIC measurement. These patterns are useful to detect characteristic oscillation patterns of the structure which can be linked to certain FSI phenomena.

A closer view at the $\Delta x$–$\Delta z$-phase plane illustrates the excitation characteristics of the observed monitoring points at each Re number. As previously seen in Fig. 7.32, the mean deformation and the amplitude of the oscillations increase with growing Re number. First, the deformations at the apex point are observed: At $Re = 50,000$ (red symbols) the mean streamwise deformation is more or less located at $\overline{\Delta x} = 0$ mm. The mean vertical deformation $\overline{\Delta z} = -0.1$ mm is slightly below the reference configuration. Moreover, the oscillations of the flexible structure are more pronounced in wall-normal direction. The overall shape of the motion pattern can be described as a thin oval area. At $Re = 75,000$ (green symbols) the deformations at the apex are all positive with a mean vertical displacement $\overline{\Delta z} = 0.75$ mm and a horizontal displacement $\overline{\Delta x} = 0.17$ mm
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Figure 7.32: Example of the time-dependent displacements $\Delta x$, $\Delta y$ and $\Delta z$ taken at the monitoring point E75 for each Reynolds number.

in streamwise direction. The occupied area of the apex is significantly larger than at $Re = 50,000$ with stronger excitations in streamwise direction widening the overall shape more into a circular area. This trend continuous at $Re = 100,000$ (blue symbols) exhibiting the largest mean deformations ($\bar{\Delta x} = 0.34 \text{ mm}$, $\bar{\Delta z} = 2.7 \text{ mm}$) and amplitudes of the oscillations. Moreover, the oval motion pattern is tilted towards the streamwise direction. Next, the monitoring point E75 depicted in Fig. 7.33(b) is examined. This position is considered to be strongly subjected to the velocity fluctuations of the separated shear layer. An indication of the influence of the shear layer on the flexible structure is found in the large wall-normal excitations which are present at all Re. In contrast to the apex,
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Figure 7.33: Phase planes of the displacements $\Delta x$ and $\Delta z$ at all monitoring points recorded by DIC.

the structure at E75 oscillates around the mean position $\overline{\Delta x} = 0$. The oval shapes are similar to those observed at apex point at each flow velocity. Again, a motion pattern at $Re = 100,000$ is tilted towards the streamwise direction due to its location on the hemisphere. A global trend is visible when observing the characteristic motion shapes of the remaining monitoring points. When moving from E60 to E15 (Figs. 7.33(c) - 7.33(f)) the mean deformations shift towards negative streamwise values and decreasing excitations in vertical direction. As observed before, the major excitation direction depends on the position of each point. At the lowest position E15 (Fig. 7.33(f)), the flexible structure
is mainly oscillating in streamwise direction visible as a truncated oval pattern. Here, the streamwise movement of the flexible structure is far more dominant than the vertical deformations. This is mainly caused by three effects: As the largest velocity component the streamwise flow has a significant impact on the global structural motion. Furthermore, the normal direction of the residual displacement at this location of the hemisphere is pointing mainly in streamwise direction. Finally, the lower fluctuations in vertical direction are influenced by the clamping of the membrane onto the flat plate at positions close to the bottom.

Another view at the motion behavior of the monitoring points is given for $\Delta y - \Delta z$-phase plane in Fig. 7.34. This illustration is used to discuss the characteristics of the spanwise displacements $\Delta y$. The vertical displacements $\Delta z$ have not changed as the view at the phase plane is only rotated by $90^\circ$ around the $z$-axis. As before a schematic representation of the actually displayed point is sketched above each diagram now with the view in streamwise direction. In general, the amplitudes of the excitations in spanwise direction are smaller than in the other directions. An interesting motion pattern in the shape of a heart is visible for the apex, E75, E60 and E45 at Re = 100,000. This gives evidence for a periodic motion in spanwise direction related to alternating vortex shedding. Although small, the mean displacements in spanwise direction at Re = 100,000 have a positive value with $\Delta y = 0.2$ mm. Presently, the reason for this observation can only be speculated. It is possible that the resulting mean pressure distribution on the flexible hemisphere at Re = 100,000 is acting in a way that the mean deformation is tending towards minor positive spanwise values. This may be due to the inhomogeneous wall thickness resulting from the manufacturing process of the flexible model (see Section 6.3). Furthermore, the clamping ring holding the model in place may be slightly out of position at Re = 100,000.

This first overview of the structure excitation is useful to receive an impression of the general movement of a single point in space depending on the Re number. In the next step, the temporal data is analyzed in the frequency domain in order to examine the response characteristics of the flexible structure to the turbulent fluid load. For this analysis, the power spectral density (PSD) of all three displacement components $\Delta x$, $\Delta y$ and $\Delta z$ at each monitoring point is considered and shown in Fig. 7.35. For the sake of clarity, the discussion of the frequency spectra is given for each Reynolds number separately [379].

**Case Re = 50,000**

Figures 7.35(a) – 7.35(c) depict the power spectra at Re = 50,000 revealing relatively low amplitudes due to the small displacements as previously shown in the time-dependent data and phase plane diagrams. Large amounts of the spectral power are visible in the $\Delta x$ (streamwise) and $\Delta z$ (vertical) displacements at higher frequencies. The strongest streamwise and wall-normal oscillations are present at E60 at a frequency of 35 Hz associated with the natural frequency $f_n^1$ of the flexible hemisphere. The distribution of the PSD for the streamwise displacements $\Delta x$ is similar at all points except for the
Figure 7.34: Phase planes of the displacements $\Delta y$ and $\Delta z$ at all monitoring points recorded by DIC.

A broad peak is observable around 9.5 Hz. Translating this structure frequency into a Strouhal number yields $St = fD/U_\infty = 0.27$ associated with the arc-type symmetric vortex shedding process (type 1) also detected by [208, 329, 380]. In addition, a distinctive peak is found at 40 Hz which is followed by a frequency attenuation until a second large peak at 102 Hz is observable. The lateral displacements $\Delta y$ connected to the spanwise flow component indicate a peak at 5.5 Hz. This frequency corresponds to a Strouhal number of $St = 0.16$ associated with the asymmetric von Kármán shedding process (type 2) occurring...
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Figure 7.35: Power spectra generated from the unsteady displacements $\Delta x$, $\Delta y$ and $\Delta z$ measured at the lee-side monitoring points and at the apex of the flexible hemisphere [379].

at the lateral sides of the hemisphere. This shedding type is also present in the CTA measurements of the rigid hemisphere [380] discussed in the first section of this chapter. Similar Strouhal numbers are found in the other publications on hemisphere flow [208, 329]. Furthermore, a frequency of 13.7 Hz (St = 0.40) is present in all displacement components with larger amplitudes found for the apex, E75 and E60. These monitoring points are located close to the separated shear layer. The study of Tamai et al. [326] presents similar Strouhal numbers in the wake of a wall-mounted rigid hemisphere. It is stated that these St numbers correspond to the formation and shedding of vortices within the recirculation area. Tamai et al. [326] use the term "formation" for the merging process of smaller vortices arising from the Kelvin-Helmholtz instability close to the separation line leading
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to larger structures in the recirculation area (see also Fig. 2.24). According to [326], this formation process ends when sufficiently large vortical structure leave the recirculation area associated with the term “shedding”. Manhart [208] finds a wide range of Strouhal numbers $0.2 \leq St \leq 0.5$ supporting the existence of this wake effect. The second natural frequency $f_n^2 = 42 \text{ Hz}$ of the membranous structure is clearly visible in the streamwise $\Delta x$ and lateral $\Delta y$ displacements. At this frequency the PSD shows a large amplification of the spectrum at all monitoring points. This corresponds well with the dynamic response characteristics of the flexible hemisphere described in Section 6.6.2 revealing a dominant natural frequency in $x$- and $y$-direction. A noticeable feature of the PSD is visible for the spectrum of the vertical component $\Delta z$. The monitoring points E75 and E60, located close to the separated shear layer, indicate a nearly constant distribution over the investigated frequency range with a significant peak at 35 Hz connected to the natural frequency $f_n^1$. Additionally, the increase of the PSD in the higher frequency range $60 \text{ Hz} \leq f \leq 100 \text{ Hz}$ at E45 is interesting visible for the $\Delta x$ and $\Delta z$ component. Seemingly, the higher frequencies contain a significant amount of energy around 100 Hz.

**Case Re = 75,000**

The spectra of each monitoring point for the streamwise displacements $\Delta x$ at Re = 75,000 is depicted in Fig. 7.35(d). The lower frequency range of the PSD exhibits an almost constant distribution at each point until about 50 Hz. After exceeding this frequency an attenuation of the spectral power is visible for the apex and E75. In contrast to this, the PSD amplitude at the remaining monitoring points does not decrease significantly showing a wide peak in the range $50 \text{ Hz} \leq f \leq 125 \text{ Hz}$. As in case of Re = 50,000, several peaks are detectable in the Strouhal number range $0.21 \leq St \leq 0.33$. Again, these St numbers are associated with the symmetric vortex shedding (type 1). The lateral movement $\Delta y$ in Fig. 7.35(e) shows a similar trend as for the lower Re number with overall higher PSD amplitudes throughout the whole frequency range. As before, a Strouhal number of $St = 0.16$ caused by the asymmetric von Kármán vortex shedding is visible in the spectra. A distinctive peak is found at a frequency of 19 Hz corresponding to $St = 0.37$. It is considered that this frequency is connected to the formation and shedding of larger vortical structures from the recirculation area due to the vortex merging process observed by Tamai et al. [326] also reported for Re = 50,000. Moreover, larger peaks are found in the frequency range $30 \text{ Hz} \leq f \leq 100 \text{ Hz}$. These are mostly related to the natural frequency response of the flexible structure. An interesting feature of the spectrum is found in the vertical excitations $\Delta z$ in Fig. 7.35(f). The signal of the apex shows a significant amplification of the spectrum at about 40 Hz and 70 Hz as well as amplified peaks at about 35 Hz connected to $f_n^1$ and around 50 Hz fitting well to $f_n^*_n$ (see Section 6.6.2.3). The monitoring point E60 shows remarkably large and constantly distributed PSD values in the complete frequency range. Similar spectra are found at the points E75 and E45. An interesting characteristic of the frequency spectrum is visible at the monitoring point E15. A sudden amplification of the spectrum is present in the range $60 \text{ Hz} \leq f \leq 125 \text{ Hz}$ with
a peak at about 98 Hz. This frequency range is related to the natural frequencies $f_{n}^{8-13}$ of the flexible structure, where especially the wall-normal component $\Delta z$ reveals large amplitudes in the dynamic response measurements.

*Case Re = 100,000*

The power spectra at Re = 100,000 are given in Figs. 7.35(g) – 7.35(i). For the streamwise component $\Delta x$ a significant increase of the PSD values in the frequency range $30 \text{ Hz} \leq f \leq 50 \text{ Hz}$ with the maximum peak at 30 Hz is observed. The frequency of the peak corresponds to a Strouhal number of $\text{St} = 0.44$. As shown for both lower Re numbers, this Strouhal number fits well to the observations of Tamai et al.\[326\] connected to the vortex formation in the recirculation area. The impact of this phenomenon is observable at every monitoring point with almost identical amplitudes. This excitation behavior of the flexible hemisphere is connected to structural waves that are generated when merging vortical structures separate from the membranous surface. In general, these waves travel from the apex to the bottom without significant loss of amplitude. The impact of these structure waves on the PSD is especially visible in the streamwise displacements. Here, considerably larger peaks are found in a frequency band $34 \text{ Hz} \leq f \leq 42 \text{ Hz}$. Within this frequency band the amplitudes of each PSD merge to a single line with identical characteristics. Besides the influence of the structure wave, it is assumed that the vortex formation and shedding frequencies of the fluid approach the natural frequencies of the flexible structure ($f_{n}^{1} = 35 \text{ Hz}$ and $f_{n}^{2} = 42 \text{ Hz}$). A strong response of the excited natural frequencies will also cause the merging of the PSD values. As for the other Re numbers, large amplitudes at higher frequencies are found at the points E15, E30 and E45. A remarkable peak at 70 Hz is visible for E15 which is connected to $f_{n}^{5}$. Generally, the large excitations at this monitoring point are mainly in streamwise direction as discussed for the phase planes (see Fig. 7.33(f)). Similar to this observation, the lateral component $\Delta y$ shows a wide peak in the frequency range $30 \text{ Hz} \leq f \leq 42 \text{ Hz}$ with a maximum amplitude at about 38 Hz. Once again, alternating von Kármán (St = 0.16) and symmetric vortex sheddings ($0.27 \leq \text{St} \leq 0.31$) are detected. The vertical displacement component reveals qualitatively the same distribution as seen at Re = 75,000 with a sharp peak at 30 Hz for the apex, E75 and E60. As mentioned before, these are closely related to the fluctuations of the separated shear layer. Furthermore, dominant peaks in the PSD at the apex can be linked to the natural frequencies $f_{n}^{1} = 35 \text{ Hz}$, $f_{n}^{**} = 55 \text{ Hz}$ and $f_{n}^{5} = 73 \text{ Hz}$.

The main observations of the frequency analysis of the structural response to the fluid loads are summarized as follows:

- The asymmetric von Kármán vortex shedding (St = 0.16) and the symmetric shedding ($0.21 \leq \text{St} \leq 0.33$) are present at each Reynolds number. Consequently, the associated frequencies can be attributed to the fluid.

- A characteristic range $0.37 \leq \text{St} \leq 0.44$ is found in all Re numbers. Considering the
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observations made in [326] these Strouhal numbers are connected to complex vortex formation and shedding processes caused by the separated shear layer. Since the corresponding frequencies reveal similar Strouhal numbers at each Re, they cannot be related to any natural frequencies of the structure and therefore they are attributed again to the fluid.

- The dominant natural frequencies $f_{1n}, f_{2n}, f_{5n}$ and $f_{n}^{*}$ of the flexible structure are clearly found in all PSD plots.

- At higher Reynolds numbers, the frequencies of the vortex formation and shedding increase. At approximately $\text{Re} \approx 100,000$, the vortex formation frequency starts to overlap with the lower natural frequencies of the structure causing an amplification of the structural deformations.

- Larger amplitudes at higher frequencies are especially found at the monitoring points located closer to the bottom wall.

The results from the structure measurements are now compared to the CTA measurements of the flow in the near-wall region close to the hemisphere in order to investigate the fluid-structure interaction more detailed. This method is considered to build a link between the non-synchronized PIV and DIC measurements. It is assumed that dominant natural frequencies of the structure have an impact on the near-wall flow in the wake of the hemisphere and should be detectable in the velocity fluctuations. The results of this investigation are presented in the following.

7.5.2.2 Link between velocity fluctuations and structure oscillations

In order to correlate the DIC measurements with the fluid domain, additional experiments using CTA are carried out according to the setup described in Section 5.3.1.1. The previously discussed PIV and CTA data display a significant difference of the Reynolds stresses in the wake between the rigid and the flexible hemisphere, especially close to the surface of each hemisphere. The deviations are largest at $\text{Re} = 100,000$.

For this purpose, the link between the structural movement and the fluid field is discussed as presented in [379]. This is achieved by comparing the previously presented PSD spectra based on the DIC measurements with the velocity spectra recorded by the CTA probe schematically shown in Fig. 7.36.

The flow measurements are carried out close to each monitoring point at a distance of about 2 mm from the surface as depicted in Fig. 5.13(b). A position closer to the flexible structure bears the risk of damaging the fragile CTA probe due to collisions with the oscillating membrane. It is assumed to find distinctive frequencies in the CTA signal which can be matched to the frequencies observed in the DIC measurements. The approach is conceived as a complementary validation procedure.

The results of this measurement campaign are depicted in Fig. 7.37. Each graph presents the velocity spectrum (CTA) as a black line while the spectra of the structure oscillations
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Figure 7.36: Schematic representation of the comparison of the spectra between DIC and CTA [377].

(DIC) are colored in red ($\Delta x$), green ($\Delta y$) and blue ($\Delta z$).

The plots are used to identify similarities in the spectra between the near-wall fluid velocities and the oscillation characteristics of the flexible wall. Furthermore, the data are applied to examine the physical source of possible FSI mechanisms of interesting frequencies, such as vortex shedding (IIE) or natural frequencies of the membrane (MIE).

Figure 7.37(a) presents the power spectra at the monitoring point E75. The CTA measurements record a peak at about 11.5 Hz. This frequency is also detected in the DIC measurements, especially in the $\Delta y$-component. It corresponds well to the quasi-periodic asymmetric von Kármán vortex shedding occurring at the lateral sides of the hemisphere. This frequency translates to a Strouhal number of about $St \approx 0.17$ and is in good agreement with previous studies of a rigid hemisphere [380]. This observation confirms the presence of an instability-induced excitation (IIE) caused by the von Kármán vortices. Moreover, a strong connection between the fluctuations of the fluid and the excitation of the membranous structure is observed at a frequency of 30 Hz ($St = 0.44$). As discussed above, this effect is driven by the merging of smaller vortices arising from the separated flow, especially visible for the monitoring points close to the shear layer (E75 and E60).

Furthermore, several natural frequencies of the flexible hemisphere are seemingly influencing the flow field at the measuring points of the CTA probe, which are also present as strong membrane excitations in the DIC measurements. Similar spectra are found for the monitoring point E60 as presented in Fig. 7.37(b). In contrast to this, the PSD values of the velocity spectra at E45 and E30 are rather small. Thus, peaks associated with the von Kármán vortex shedding ($St = 0.16$), the symmetric vortex shedding ($0.21 \leq St \leq 0.33$) and the vortex merging arising from the shear layer separation ($St = 0.44$) are not clearly distinctive at these monitoring points in the CTA data. Nevertheless, it is possible to link prominent velocity fluctuations to the structural response since significant frequencies of both spectra (CTA and DIC) match well.

Some implications on the FSI phenomena of the flexible hemisphere at $Re = 100,000$ can be drawn from the additional CTA measurements: First, the vortex formation and shedding processes are clearly detectable in the CTA data for the monitoring points close to the apex.
Figure 7.37: Frequency spectra of the displacements and the velocity fluctuations close to the surface at the monitoring points E75, E60, E45 and E30 at Re = 100,000 [379].
These processes are connected to an IIE mechanism which is driven by the fluid. Second, a distinctive dynamic response of the flexible hemisphere to the fluid loads is observed. Several natural frequencies, which are connected to their respective eigenmodes, are detected in the measurements. However, the overall excitations of the flexible hemisphere do not reveal any characteristics of a MIE mechanisms (see Section 2.4.4.3) such as wake breathing or mode coupling. It is assumed that an MIE mechanism is occurring at higher Re numbers and/or that the development of a stable motion connected to this FSI phenomenon is prohibited partly by the high turbulence intensity of the approaching flow. The small turbulent vortices of the TBL act as an external excitation source. Thus, a closer view at the spectra of the artificially generated TBL is taken to determine its role in the FSI. This is presented in the next section.

7.5.2.3 Influence of the approaching TBL on the structure excitations

The impingement of small turbulent vortices on the flexible structure of the hemisphere form a constant excitation source. In this case the TBL can be characterized as the external source independent from the presence of the hemisphere. The associated FSI mechanism presented in Section 2.4.4.1 is denoted as extraneously-induced excitation (EIE). Furthermore, the artificially generated TBL may contain undesired turbulent structures arising from the vortex generator. In order to investigate this issue, further velocity spectra are measured by CTA. The recorded data are used for a comparison between the approaching TBL and the corresponding velocity spectra in the wake of the hemisphere. The spectra of the TBL are measured at the inlet of the empty test section at $x/D = -1.5$. The results are depicted in Fig. 7.38.

![Figure 7.38: Comparison of the frequency spectra of the approaching TBL of the empty test section with the measurements made for the rigid and the flexible hemisphere at the locations E30 and E45.](image)

The results are depicted in Fig. 7.38.
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The velocity spectra of the TBL are taken at wall-normal distances comparable in height with the monitoring points E30 (\(z_{E30}/D = 0.25\)) and E45 (\(z_{E45}/D = 0.35\)) at Re = 100,000. These two points are chosen under the assumption that significant frequencies corresponding to turbulent structures are primarily found in the log-law region of the TBL. As a result, the plots do not indicate any dominant frequencies comparable to the spectra of the actual hemisphere measurements. In both cases the spectra of the rigid and the flexible hemisphere do not reveal global effects resulting directly from the turbulent boundary layer. Usually, the turbulence of the oncoming flow is visible as small local deformations on the flexible structure caused by energetic vortices with strong vorticity. However, these transient events usually have no direct effect on the global oscillating behavior of the membranous structure. From these observation, the EIE mechanism does not contribute significantly to the FSI of the flexible hemisphere.

Until this point, the analysis of the structure excitations are based on the local measurements at the monitoring points. The following paragraph discusses the two- and three-dimensional structure oscillations of the flexible hemisphere.

7.5.2.4 Unsteady 2D/3D deformations of the flexible hemisphere

The previous sections focused on the point-wise characterization of the dynamic behavior of the structure. These are now expanded to two-dimensional line elements and three-dimensional areal measurements which are taking the complete correlation area (see Fig. 7.31) into account. All presented results correspond to measurements carried out at Re = 100,000. First, a qualitative view at the instantaneous excitation patterns associated with the symmetry wake line are given. Afterwards, the three-dimensional deformations and the corresponding maximum Lagrangian strains \(\varepsilon_{\text{max}}\) are discussed.

Lee-side structural wave patterns in the symmetry plane

Two characteristic wave patterns are observed on the lee-side of the flexible hemisphere depicted in Fig. 7.39. These data are captured by the DIC system set to a frame rate of 500 fps. From this measurement 30 successive images are extracted covering a time span of \(\Delta t = 0.06\) seconds. These are used to illustrate the qualitative behavior of the FSI mechanisms occurring during the wind tunnel experiments. The unsteady deformations on the lee-side line are magnified by a factor of \(a = 5\). In order to visualize the instantaneous characteristics, each time step \(t_i\) is shifted by an offset of \(\Delta x/D = 0.1\). The analysis of the data reveals two periodically repeating patterns:

- Rapidly developing small waves are visible within the time steps \(t_1 - t_{15}\). These patterns are usually observed and are linked to constantly detaching smaller vortices related to the development of the free shear layer.

- Eventually the smaller oscillations are followed by subsequently appearing larger structural waves visible within the time steps \(t_{16} - t_{30}\). These patterns sporadically
occur and are linked to large vortical structures that are generated by the merging of smaller vortices to larger ones. These excitations are visible as long waves forming at about the location of E75 and then traveling towards the ground.

- A temporally alternating behavior between both patterns is observed, where one bigger excitation is following after several smaller waves occurred.

This first approach towards the complex structural response characteristics is strongly simplified by the fact that only the wake line in the symmetry plane of the structure is reviewed. Thus, the drawn conclusions are restricted to the two-dimensional view at the much more complex three-dimensional deformation patterns taking place in the wake region. In order to visualize the latter, the unsteady deformations of the complete correlation area associated with the three-dimensional surface of the hemisphere are presented in the following. The observations focus mainly on the development of the large structural waves.

**Three-dimensional deformation patterns**

The three-dimensional characteristics of the larger wave formation pattern on the lee-side of the flexible hemisphere at Re = 100,000 are depicted in Figs. 7.40 and 7.41. The three-dimensional contour plots are used to visualize the unsteady development of large structural waves on the wake side of the hemisphere. A series of nine successive measurements...