Dependence of the aeroelastic stability of a slender U-beam on the realized flow pattern

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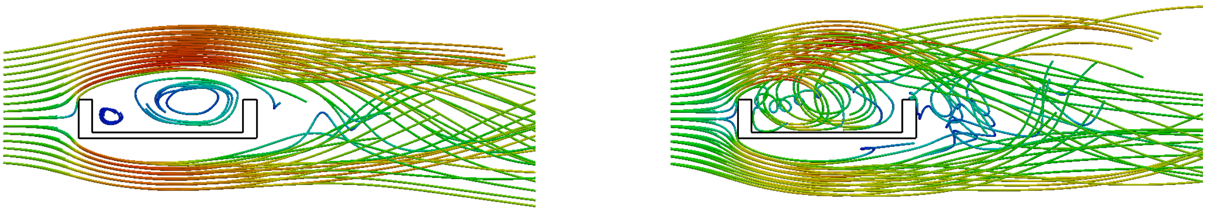
We investigate the aeroelastic behaviour of a slender U-beam in cross-flow. Two distinct, time periodic flow patterns are observed in simulations of the flow around this beam. Its aeroelastic properties depend on the realized flow pattern, especially so for low reduced velocities: One flow pattern leads to pronounced torsional vortex-induced vibrations. No such vibrations could be observed under the other flow pattern.

We investigate the aero-elastic behaviour of a slender U-beam with an aspect ratio (width over height) of $B/H = 4.62$ in cross-flow at high Reynolds numbers, $\mathrm{Re} = u_\infty B/\nu_{\mathrm{air}} \sim 10^5$. For the investigation of the flow-pattern the U-beam is considered stationary. The aeroelastic behaviour is analyzed for the case of two-degree of freedom (2DOF) vibrations for the case of equal heave (vertical translation y) and pitch (rotation about the long axis φ) eigenfrequencies f_0. We consider low reduced velocities $U^* = u_\infty/(Hf_0)$ in our investigation: $U^* > 1/\mathrm{St} = Hf_{\mathrm{vs}}/u_\infty$, where f_{vs} is the vortex shedding frequency, used in the Strouhal number St. The proprietary CFD software package ANSYS Fluent 14.5 is used. All simulations were carried out in a two-dimensional computational domain and were using the $k\omega$-SST turbulence model.

1 Flow Patterns

The two distinct flow patterns are discerned by the behaviour of the free shear layer above the cavity of the U-beam. In case of the so-called R-flow pattern the shear layer is curved weakly and reaches over the cavity and into the wake where a von Kármán vortex street forms. Particles in the flow would travel over the beam and not into its cavity. An almost stationary vortex rests there (see Fig. 1**a**).

In case of the so-called U-flow pattern the shear layer rolls up quickly behind the windward sidewall and forms an instationary vortex that moves through the cavity of the profile. Thus, particles travel into the cavity of the profile (see Fig. 1**b**).



a) b)

Fig. 1: Particle paths coloured by the velocity magnitude, simulation at $\mathrm{Re} = 2.45\cdot 10^5$. **a** R-flow pattern, **b** U-flow pattern.

A similar behaviour of free shear layers can be found in the flow around a short rectangular prism. Intermittent change between weak and strong shear layer roll-up was observed in simulations, [1]. Reportedly, this is related to the small and large fluctuations of the lift force acting on a short prism in cross flow, [2]. The intermittent change between the flow patterns was not observed at the flow around the U-beam.

The U-beam is more similar to a rectangular prism or an H-beam than to a short rectangular prism. The U-flow and R-flow pattern correspond to so-called Leading Edge Vortex-shedding (LEV) and Impinging Leading Edge Vortex-shedding (ILEV) modes of rectangular or H-shaped prisms, respectively (see [3]). For ratios $4 < B/H < 5$ the Strouhal number, calculated with the fundamental frequency of the aerodynamic forces is in the range $0.1 < \mathrm{St} < 0.15$, [3]. The vortices travel with a velocity of about $0.6u_\infty$ along the surface of the rectangular prism (also see [4]).

The vortex formation under the U-flow pattern is asymmetric: Impinging vortices were only observed at the cavity-side of the beam and not on its smooth side. The vortices located in the cavity of the beam travel at a velocity of $0.2u_\infty$ in the wake of the windward sidewall of the beam. The fundamental frequency of the lift force is about half of the R-flow vortex shedding frequency, and also lower than reported ILEV vortex shedding frequencies for a rectangular prism of comparable aspect ratio. Therefore, we will not use the fundamental frequency of the aerodynamic forces under the U-flow pattern in the Strouhal number St.

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The angle of inclination of the U-beam can decide which flow-pattern forms: When the smooth, lower side is oriented towards the oncoming flow (negative angle of inclination) the R-flow pattern is favoured. When the cavity is oriented towards the oncoming flow (positive angle of inclination) the U-flow pattern is favoured. At an inclination around $\varphi \approx 1^\circ$ both flow patterns can be realized.

2 Vibrations

The aeroelastic properties of the U-beam depend on the flow-pattern. Only very small vibrations could be observed at low reduced velocities under the R-flow pattern. Vortex-induced vibrations were expected, but could not be observed, below $U^* < 15$ (see Fig. 2**b**). Increasing the reduced velocity to $U^* \approx 30$ results in pronounced 2DOF vibrations. These vibrations are not related to the vortex shedding behind the U-beam. Simulations of 2DOF vibrations under the R-flow pattern agree well with wind tunnel experiments (see Fig. 2**a**, where experimental results are shown). Thus, we assume that the R-flow pattern was realized in the wind tunnel experiments.

Contrasting this, pronounced pitch vibrations could be observed under the U-flow pattern at low reduced velocities $U^* \approx 14$. The heave vibration plays only a minor role (see Fig. 2**b**, where simulation results are shown). These vibrations are related to the instationary vortex moving through the cavity of the U-beam. The U-beam is in resonance with the fundamental frequency of the aerodynamic forces under the U-flow. Unfortunately, experimental evidence for the U-flow has yet to be obtained.

Simulations above $U^* = 14$ show an interesting behaviour: Initially the U-flow pattern is present. The motion of the profile seems to be incompatible with the U-flow. After an initial increase of vibration amplitudes the R-flow pattern forms and replaces the U-flow pattern. At reduced velocities below $U^* \approx 30$ the initial vibrations die out. Above this reduced velocity the U-flow pattern itself can give rise to vibrations, as observed in the experiments.

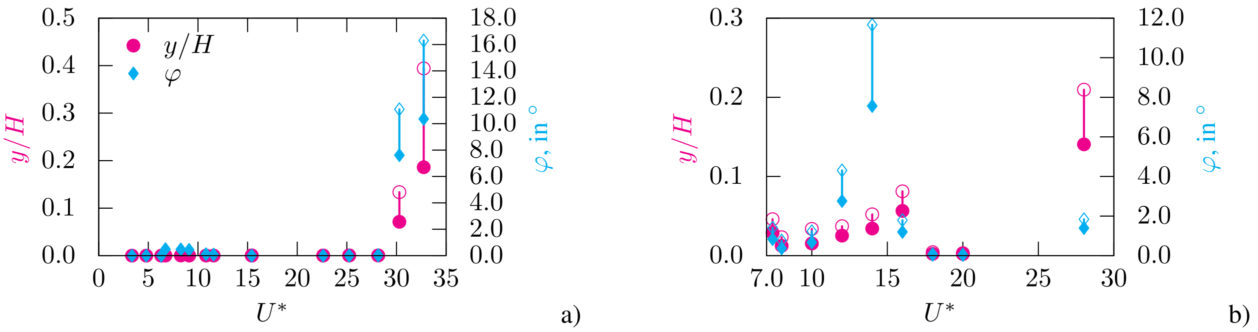

Fig. 2: Dimensionless heave and pitch amplitudes: R.M.S value (full symbol) and maximum value (open symbol) of a suitable time-interval: **a** Wind tunnel experiments, $4.1 \cdot 10^4 < \mathrm{Re} < 8.2 \cdot 10^4$, **b** Simulation results $\mathrm{Re} = 2.45 \cdot 10^5$.

3 Conclusions

The asymmetry of the U-beam introduces additional interesting aspects: The R-flow pattern seems to suppress vortex induced vibrations in the investigated reduced velocity range. The U-flow pattern does not only yield a totally different fundamental frequency of the aerodynamic forces. In the resonance case vortex-induced pitch vibration with large amplitudes were observed! Statically inclining the U-beam can favour one or the other flow-pattern. Flow-pattern changes were also observed during free vibration of the beam, but only from the U-flow to the R-flow pattern.

We are aware that scale-resolving turbulence treatment should be part of future simulation campaigns. 2D URANS methods were chosen to achieve feasibility of parametric studies by simulation. The observations form a promising base for future research.

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