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Utilizing CFD-Simulations to Assess Flow-Induced Vibrations of Slender Beams in Cross-Flow

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Flow-induced vibrations of a slender U-beam in cross-flow are assessed, using the proprietary CFD-solver ANSYS-CFX. The U-beam has two degrees of freedom: heaving motion and rotation. The flow- and motion-governing equations are solved together, using an iterative coupling method. We find, that using this iterative coupling does not ensure a valid long-time behaviour of the solution. The results of free vibration simulations would allow investigation of the excitation mechanisms. But for determining possibility of large amplitude vibrations, methods relying on forced motion are deemed more promising.

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1 Introduction

Since the collapse of the Tacoma-Narrows bridge in 1940, flow-induced vibrations of slender, beam-like structures are being widely discussed by various communities. We consider a slender U-beam of along-wind length B and frontal height H where the aspect ratio $B/H = 4.65$. Since the Tacoma-Narrows incident, such shapes are no longer used for bridge decks. However, they are used in a special kind of conveyor belt. This gives rise to our current research.

Typically, the dimensions and eigenfrequencies of bridge decks are such, that the shedding-frequency of the von Kármán vortices is much larger, than the structural eigenfrequency of the most dangerous vibrational modes. Differently, the focus of our research is the range of flow-velocities where the vortex shedding frequency is equal to, or not much larger than the structural eigenfrequency. We chose CFD simulations over wind tunnel experiments for the prospect of obtaining the complete flow-field, and to determine and understand the excitation mechanism of vibrations.

In order to reach a manageable level of computational effort, we simulate the unsteady, two-dimensional flow around a cross-section of the U-beam. The $k\omega$-SST turbulence model is employed, to model the turbulent aspects of the flow. This choice is based on the results of numerous benchmark simulations.

1.1 Definitions

The oncoming flow has the velocity u_∞. The aerodynamic lift L and drag D act on the beam. Additionally, these forces may induce the aerodynamic moment M around the center of gravity of the structure. This is shown in figure 1. Behind the beam, von Kármán vortices are shed with the frequency $f_{0,\mathrm{vs}}$, where the subscript zero indicates that this frequency was determined from simulations when the beam was held in place. Using these quantities we form the Reynolds number $Re = u_\infty B/\nu$ and the Strouhal number $Sr = H f_{0,\mathrm{vs}}/u_\infty$.

The beam has two degrees of freedom. The vertical displacement y of its center of gravity, and rotation about the longitudinal axis through its center of gravity, by an angle φ. This is shown in figure 2. Let the beam have the mass m and the mass moment of inertia I_T. It is supported by a linear and a torsional spring with stiffness k and k_T, respectively. In this paper we consider specific combinations of these parameters. Namely, such combinations, that the eigenfrequencies pertaining to vertical and rotational motion $f_{0,\mathrm{y}} = f_{0,\varphi} = f_0$. Finally, we form the reduced velocity $U^* = u_\infty/(H f_0)$. Note, that we do not consider mechanical damping here.

In the following, we will consider the reduced vibrational energy $E_\mathrm{vib} = \left(ky^2 + m\dot{y}^2 + k_\mathrm{T}\varphi^2 + I_\mathrm{T}\dot{\varphi}^2\right)/(\rho l B H u_\infty^2)$, where l is the depth of the calculation domain. It is the sum of the kinetic and potential energy of the beam section, made dimensionless by the kinetic energy of a characteristic air volume.

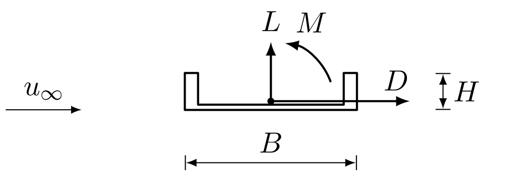

Fig. 1: The aerodynamic lift L, drag D and torsional moment M acting on the U-beam.

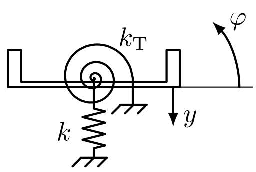

Fig. 2: The U-beam with two degrees of freedom y and φ, supported by springs with stiffness k and k_T.

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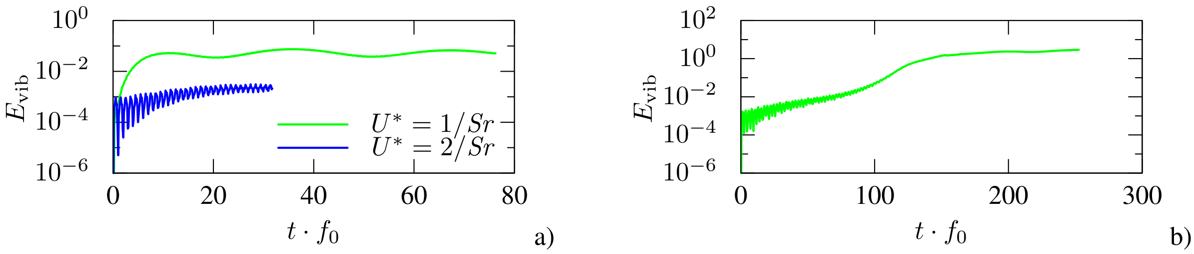

Fig. 3: Time series of the vibrational energy for $Re = 4.45 \cdot 10^5$, $U^* = 1/Sr$ and $Re = 4.45 \cdot 10^5$, $2/Sr$ (a) and $U^* = 1.43/Sr$ (b).

2 Results

We consider the results of four simulations characterized by distinct reduced velocities. The choice of the reduced velocities was motivated by [1]. In case $U^* = 1/Sr$, the structure is in resonance with the von Kármán vortices. In case $U^* = 2/Sr$, the vortex shedding frequency equals twice the structural eigenfrequency. The time-series of the reduced vibrational energy is shown in figure 3, a. Interestingly, only vibrations at a very low energy level are excited in both cases. However, the time-step size and iterative coupling between flow and motion solution had to be chosen carefully in order to obtain valid solutions. The findings discussed here represent our current best knowledge.

For $1/Sr < U^* < 2/Sr$ (figure 3, b) and $U^* = 8.88/Sr$ (figure 4, a) two degree of freedom flutter can be observed. These results correspond to the similar case of single-degree of freedom vibration of a rectangular prism with similar aspect ratio, reported by M. Matsumoto in [1].

The influence of the von Kármán vortices decreases with increasing reduced velocity. M. Matsumoto conjectures, that the von Kármán vortices damp vibrations for some reduced velocities around $1/Sr$ and $2/Sr$. Given the result of the simulation where $U^* = 8.88$, this might also be applicable for the U-beam. In this spirit, the case $U^* = 2/Sr$ was simulated with a splitter-plate mounted behind the beam. Interestingly, vibrations could be observed. The time-series of the vibrational energy for this case is shown in figure 4.

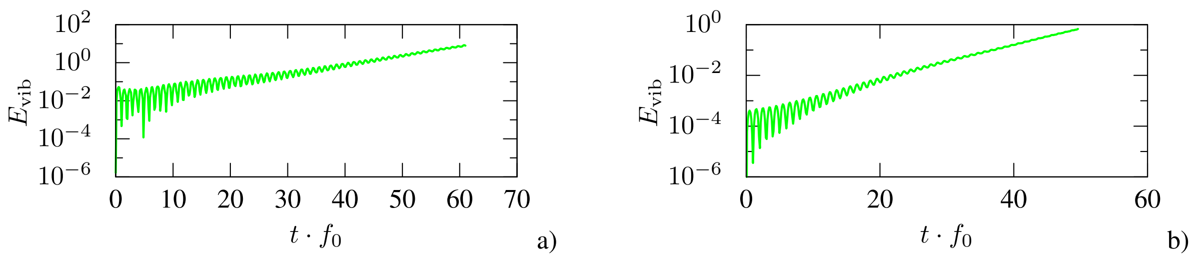

Fig. 4: Time series of the vibrational energy for $Re = 2.5 \cdot 10^4$, $U^* = 8.88/Sr$ (a) and $Re = 2.45 \cdot 10^5$, $U^* = 2/Sr$ with attached splitter-plate (b).

3 Conclusions

The two-degree of freedom flutter of the beam was simulated. For the cases $U^* = 1/Sr$ and $U^* = 2/Sr$ only vibrations at a very low energy level could be observed. On the contrary, in case of $U^* = 1.43/Sr$ and $U^* = 8.88/Sr$, the energy levels were considerably higher.

Depending on the type of iterative coupling, too large time-steps lead to numerical instabilities. In some cases (see figure 3, b), a very large flow time has to be simulated, until the final amplitudes of the vibration can be estimated. To obtain reliable results, computation times of several days or even weeks have to be taken into account.

It is important to simulate free vibrations, in order to understand the excitation mechanisms. But, given the time-consuming nature of these simulations, they are not convenient when the possibility of large amplitude vibrations should be assessed. For this, we aim to employ simulations with forced motion of the beam. Linear methods, as the method of aerodynamic derivatives, or non-linear variants thereof, can then be used to assess stability and estimate amplitudes. The adaption of these methods for the range of reduced velocities around $1/Sr$ to $2/Sr$, where the von Kármán vortices play an important role, the is our current work in progress.

References

[1] M. Matsumoto, T. Yagi, H. Tamaki, and T. Tsubota, J. Wind Eng. **volume 96**, pp 971-983 (2008).

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