Journal of Fluids and Structures 82 (2018) 577–609

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Numerical studies on the instantaneous fluid–structure interaction of an air-inflated flexible membrane in turbulent flow

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ARTICLE INFO

Article history:
Received 24 March 2018
Received in revised form 5 June 2018
Accepted 16 August 2018

Keywords:
Fluid–structure interaction (FSI)
Hemisphere
Membrane
Turbulent flow
Large-eddy simulation (LES)
Inflow generator

ABSTRACT

The present paper is the numerical counterpart of a recently published experimental investigation by Wood et al. (2018). Both studies aim at the investigation of instantaneous fluid–structure interaction (FSI) phenomena observed for an air-inflated flexible membrane exposed to a turbulent boundary layer, but looking at the coupled system based on different methodologies. The objective of the numerical studies is to supplement the experimental investigations by additional insights, which were impossible to achieve in the experiments. Relying on the large-eddy simulation technique for the predictions of the turbulent flow, non-linear membrane elements for the structure and a partitioned algorithm for the FSI coupling, three cases with different Reynolds numbers ($Re = 50{,}000$, 75,000 and 100,000) are simulated. The time-averaged first and second-order moments of the flow are presented as well as the time-averaged deformations and standard deviations. The predictions are compared with the experimental references data solely available for 2D planes. In order to better comprehend the three-dimensionality of the problem, the data analysis of the predictions is extended to 3D time-averaged flow and structure data. Despite minor discrepancies an overall satisfying agreement concerning the time-averaged data is reached between experimental data in the symmetry plane and the simulations. Thus for an in-depth analysis, the numerical results are used to characterize the transient FSI phenomena of the present cases either related to the flow or to the structure. Particular attention is paid to depict the different vortex shedding types occurring at the top, on the side and in the wake of the flexible hemispherical membrane. Since the fluid flow plays a significant role in the FSI phenomena, but at the same the flexible membrane with its eigenmodes also impacts the deformations, the analysis is based on the frequencies and Strouhal numbers found allowing to categorize the different observations accordingly.

1. Introduction

Light-weight thin-walled membranous structures are common in modern civil engineering and design. They are flexible, transportable and fast and easy to shape due to the non-existence of bending stiffness. To induce a form and to maintain a tensile state, a pre-stress has to be applied. Two major types of pre-stresses can be pointed out: The mechanically induced

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https://doi.org/10.1016/j.jfluidstructs.2018.08.005
0889-9746/

tension by specific boundary conditions and the pre-stress due to internal pressure. When the structure is exposed to a fluid flow and undergoes fluid–structure interactions (FSI), the pre-stress plays an important role in the stabilization of the whole construction. In order to optimize such buildings or avoid the damage of the material caused by FSI, experimental and numerical investigations are necessary. Wood et al. (2018) recently gave an overview on experimental FSI-related studies involving membranes with application in civil engineering and other aeroelastic phenomena. In the current work a brief literature survey concentrates on corresponding numerical FSI research investigations with pre-stressed membrane models.

Glück et al. (2001) carried out numerical FSI investigations on a real-life structure, i.e., a tent roof under constant turbulent wind load. The equilibrium shape of the pre-stressed membrane was obtained by a form-finding technique before starting the simulation. To solve the FSI problem, a partitioned approach based on an in-house finite-volume (FV) fluid code and a commercial finite-element (FE) program combined by the arbitrary Lagrangian–Eulerian (ALE) method was applied. The CFD code solved the unsteady Reynolds-averaged Navier–Stokes (URANS) equations combined with the classical k-ε turbulence model. The setup led to steady deformations. In Glück et al. (2003) the inflow conditions were modified to take a gust-like laminar inflow into account resulting in an unsteady behavior of the construction. In both studies pressure distributions and deformations of the FSI interface were presented. However, there was no discussion on the physics or comparison with experimental measurements. The cases were basically used to demonstrate the stability and the robustness of the FSI coupling scheme.

A complementary experimental and numerical investigation was conducted by Rank et al. (2003) on a big mobile membranous umbrella. A 1:50 model was put into a wind tunnel. The forces in the retention cables and the deformation of the thin structure were measured. For the simulation the same FSI environment as in Glück et al. (2001) was applied. Despite some discrepancies, the predicted deformed shape and the forces in the cables matched quite well with the experimental data.

Wüchner et al. (2007) presented two studies on real-life civil engineering constructions: A hanging roof and a four-point tent. The pre-stresses in the membranes were fixed and the respective equilibrium shapes were determined by separate form-finding procedures before the FSI simulations (Wüchner and Bletzinger, 2005). A gust-like wind load was imposed to mimic the time-dependence in the natural environment. A commercial FV fluid solver based on the URANS equations with the SST turbulence model and an in-house FE structure code were coupled. Weak and strong FSI schemes were successively taken into account. Both cases led to an unsteady behavior. However, as in the simulations mentioned above, no deep discussion on the physics or comparison with measurements were presented. Again, the goal was to test the FSI coupling schemes and to assess the computational FSI framework.

In Kupzok (2009) the same FSI code as used in Wüchner et al. (2007) was applied on the ARIES[1] structure. Different wind loads and directions were examined in steady-state computations. The effect of the wind on the back and front sides of the structure were discussed in detail. Additionally, transient simulations were carried out using gust-like inflow conditions. Studying the resulting deformations of the membrane, the author made recommendations to the designers to adjust the pre-stress of the membrane.

Hojjat et al. (2010) used a similar FSI framework and extended it to realize shape optimization in the context of wind engineering. Several optimization strategies were successfully tested on a light slender membranous roof exposed to a turbulent boundary layer. The equilibrium shape for a defined pre-stress distribution within the initial structure was determined by a form-finding computation. Then, for each specified state of the membranous construction, the problem was solved as a steady problem. After optimization a strong improvement of the objective function was observed. The final form and the pressure distribution on the FSI interface were presented.

Due to their low weight and costs, thin-walled membranes fit perfectly for temporary or emergency buildings. As an example the "uLites" research program[2] develops the technology to enable a fast assembly of light-weight structures with integrated solar cells. Wind-tunnel experiments were performed to estimate forces and deformations. In order to minimize the development costs, the numerical counterpart was carried out by Rossi (2013) based on an embedded and partitioned FSI approach using FE solvers. No data was published yet for comparison.

Recently, Michalski et al. (2011, 2015) carried out transient simulations on big umbrellas in turbulent wind flows. The applied commercial software environment was based on FE solvers and the ALE method. The turbulent flow was predicted by the large-eddy simulation (LES) technique. In both investigations particular attention was laid on a consistent structural modeling of the pre-stressed membrane subjected to wind flow, i.e., the proper inclusion of shape-finding techniques in the overall simulation approach besides the pure FSI analysis. Furthermore, the authors ensured to synthetically mimic an atmospheric boundary layer. Information about the flow, the forces and the structural deformations predicted by the simulations were provided. Moreover, in order to enable a comparison with experimental data, strain gauges and cameras were put in and around the umbrellas to measure forces and moments of the structures as well as their deformations. Overall a good agreement between simulations and measurements was achieved. That demonstrates the applicability of numerical methods in modern civil engineering applications. However, because of the real scale of the investigated test cases, no fully controlled flow conditions could be guaranteed and therefore comparisons with the numerical results are extremely difficult.

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[1] http://www.tensinet.com/index.php/component/tensinet/?view=project{&}id=4171.

[2] http://www.cimne.com/websasp/ulites/default.asp.