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

J.N. Wood, M. Breuer *, G. De Nayer

Professur für Strömungsmechanik, Helmut-Schmidt-Universität Hamburg, D-22043 Hamburg, Germany

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ABSTRACT

The present paper investigates the interaction between a turbulent fluid flow and a flexible membrane structure. Such flexible structures are of increasing interest for modern engineering applications due to their adaptable utilization. Highly flexible membranes under turbulent flow conditions still bare fundamental challenges such as the structural response to fluid loads leading to the motivation of the present study. It investigates the fluid–structure interaction of a flexible membranous structure in the shape of a hemisphere. The air-inflated structure is placed in the test section of a wind tunnel and is exposed to a turbulent boundary layer flow. The properties of the turbulent boundary layer are clearly defined so that the test case is reproducible by numerical simulations. Three Reynolds numbers (50,000, 75,000 and 100,000) are chosen to examine the interaction between the turbulent flow and the pressurized membrane. Special emphasis is put on the instantaneous effects. Furthermore, the flow field around an equally sized rigid hemisphere is measured under identical conditions serving as a reference for the flexible case. The experiments are conducted by combining particle-image-velocimetry for the flow field and high-speed digital-image correlation measurements for the deformation of the oscillating membrane. Furthermore, a constant-temperature anemometer is used for evaluating the velocity spectra at locations close to the wall to connect the independently performed fluid and structure measurements. A thorough analysis of the comprehensive data sets for the fluid flow and the displacements of the structure leads to the characterization of the behavior of the flexible structure under changing flow conditions.

1. Introduction

Flexible structures interacting with fluid flows are fundamental physical phenomena omnipresent in nature and technical applications. A deeper understanding of the general characteristics of coupled systems is of common interest. Thus, multi-physical approaches are developed and applied to investigate fluid–structure interaction (FSI) problems in various fields of science.

In modern engineering thin flexible structures are essential construction elements. Thin and shapeable materials are often taken into account when weight reduction, space-saving and individualized design are major objectives of a project. These requirements are often satisfied by membrane structures that feature a cost-efficient solution for various applications . As an example Fig. 1(a) illustrates typical shapes of membranes used as main structural components for light-weight buildings. A few examples of membrane applications are selected from the literature to outline their operation spectrum.

* Corresponding author.
E-mail address: breuer@hsu-hh.de (M. Breuer).

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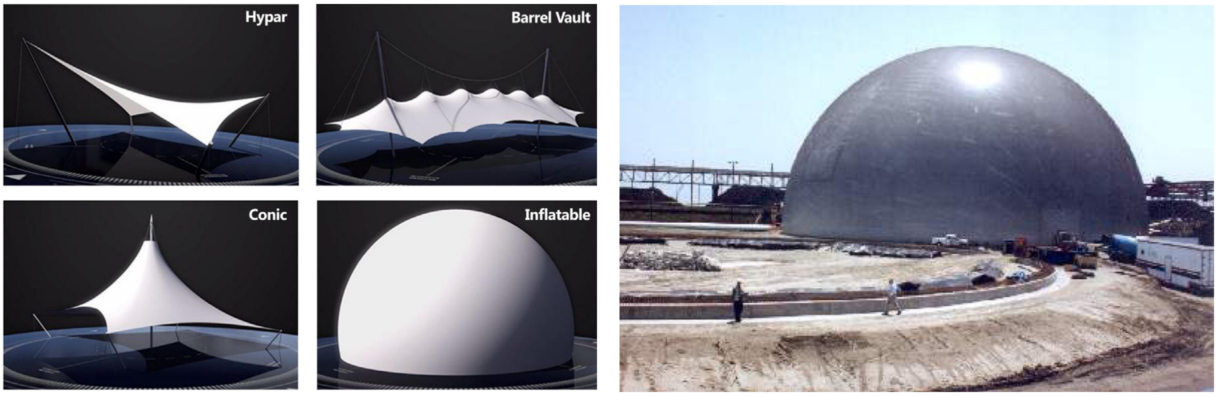

(a) Possible shapes of membranous structures.[2] (b) Air-inflated hemisphere (Los Angeles).[3]

Fig. 1. Examples of flexible membranous structures.

First fundamental studies on inflated spherically shaped structures under wind loads were carried out by Newman et al. (1984). The study targeted at a proposal on the safe operation of air-inflated buildings exposed to wind. A critical parameter for this is the gauge pressure inside such buildings keeping the inflated structure stable. The research was divided into two sections: First, the flow around three rigid domes with different height-to-base-radius ratios ($h/(D/2) = 0.5$, 0.37 and 0.25) made of Plexiglas were measured in a boundary layer wind tunnel mainly focusing on the surface pressure distribution and smoke visualization of the flow patterns at $Re = 50{,}800$, based on the base diameter of the domed structure. The results of the pressure measurements were afterwards transferred to a numerical simulation based on a finite-element solver in order to obtain the stresses in the plane of the membrane. The simulation was used to predict the position and orientation of first buckling onset while reducing the gauge pressure step-wise. To evaluate the numerical results obtained, the rigid models were exchanged by inflatable models made of impervious, effectively unstretchable light cloth. After reducing the inner pressure during wind tunnel operation, it was possible to observe the deformations on each flexible model. Based on this experiment, the critical gauge pressure was estimated to be about 0.65 times the dynamic pressure measured at the apex of the dome. Dynamic effects of the wind load excitations of the flexible structure were not taken into account.

Gong et al. (2010) presented the further utilization of the China National Stadium which was built for the 29th Olympic Games in Beijing. An air-inflated membrane is suggested to cover the open roof construction of the stadium in order to protect the inside from external factors like rain or extensive sun. In general, inflated membranous structures can be used as permanent or temporary installations. A model at a scale of 1:20 was manufactured to validate analytic results by experimental measurements. After testing the mechanical behavior of the inflatable structure by different static loads, the overall construction seems to be suitable for the intended purpose. However, unsteady wind loads are not taken into account because the overall size of the model (9.12 m × 6.2 m × 1.362 m) is difficult to transfer to a suitable test facility.

Another inflatable application is a portable ultra light-weight emergency shelter conducted by the "uLites" research program.[1] The main design feature focuses on the fast assembly of temporary housings in regions that are exposed to natural disasters, where a quick deployment of adequate first supply is mandatory. The construction consists of air-inflatable arc-shaped membranous tubes that can be connected to a conjoint module of desired length. For the fast accessibility, the hangar-like building is open at both sides. This makes it vulnerable to unsteady wind loads that can cause high lift forces. To estimate this load, wind tunnel experiments with down-scaled models were conducted by Larese et al. (2014a, b). In parallel, a virtual wind tunnel for advanced coupled simulations of membrane systems was implemented by Rossi (2013) to validate the experimental data and to reduce the costs of large-scale tests.

Similarly, Ligaro and Barsotti (2013) presented a numerical study of a thin hemispherical dome which is composed of a lattice of interacting inflatable beams and panels. The internal pressure of the inflated beams induce a pre-stress in the panels stabilizing the dome. This case differs from an ordinary inflated structure, where the whole inner domain of the building is pressurized. One advantage of inflated beams is the weight reduction in comparison to standard metallic elements. Several load cases, such as a static wind load approximated by the guidelines of the Italian NTC2008 norm (Norm Tecniche Costruzioni 2008), were applied to examine the mechanical behavior of the structure. It is claimed that the composite of inflated beams and panels is less vulnerable to incidental damage than standard fully inflated structures.

1 http://www.cimne.com/websasp/ulites/default.asp.
2 http://www.architen.com/wp-content/uploads/2009/03/basic-theories-image-2.jpg.
3 http://www.ketchum.org/shellpix.html.