Journal of Fluids and Structures 57 (2015) 159–169

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Flapping dynamics of an inverted flag in a uniform flow

Jaeha Ryu, Sung Goon Park, Boyoung Kim, Hyung Jin Sung*

Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 17 November 2014
Accepted 10 June 2015
Available online 17 July 2015

Keywords:
Inverted flag
Immersed boundary method
Energy harvesting system
Vortical structures

ABSTRACT

The flapping motions of an inverted flag in a uniform flow were simulated using the immersed boundary method. The strain energy of the inverted flag was used as an indicator of the energy harvesting system efficiency. The flapping dynamics of and vortical structures around the inverted flag were examined in terms of the bending rigidity (γ) and the Reynolds number (Re). Three flapping motion modes were observed: a deflected mode, a flapping mode, and a straight mode. A mode intermediate between the flapping mode and the straight mode was identified, the biased mode. The vortical structures in the wake were characterized by three modes: a vortex pair; a vortex pair with a single vortex, and two vortex pairs, during half of the flapping period. The maximum mean strain energy (E_S) was obtained when the vortical structures behind the inverted flag formed a vortex pair during the flapping mode.

1. Introduction

Much research in recent years has focused on the flow dynamics of flexible structures in a uniform flow and particularly on the flow dynamics related to energy harvesting systems. An energy harvesting system comprising piezoelectric patches attached to the surface of a flexible structure can convert the energy stored in solid deformations into an electric current that powers a purely resistive output circuit. Systems that can be exploited for energy harvesting are ubiquitous in nature, for example, rivers and straits, which can be used as the basis for an eco-friendly approach to generating energy without contaminating the surroundings.

Allen and Smits (2001) and Taylor et al. (2001) devised energy harvesting systems using the flapping of a flexible structure with a piezoelectric material attached to the structure's surface. Several researchers have suggested the design of energy harvesting systems based on a flexible flag that undergoes self-sustained oscillations. Such systems may be useful in a variety of fields, including oceanography and atmospheric sciences (Dunnmon et al., 2011; Giacomello and Porfiri, 2011). Energy harvesting systems based on piezoelectric patches attached to flexible structures operate through two energy transfer processes. First, the kinetic energy of a uniform flow is converted into strain energy within the flexible structure via interactions between the uniform flow and the flexible structure. Second, the electrical energy is harvested by the piezoelectric materials attached to the flexible structures (Michelin and Doare, 2013). The mechanisms through which the kinetic energy in a surrounding fluid is converted into strain energy in a flexible structure have been investigated in an effort to improve the energy harvesting efficiency (Ottman et al., 2003). Large deformations in flexible structures benefit the energy harvesting processes. Instabilities induced by large deformations in the flexible structures can significantly improve the energy harvesting system operation. Michelin and Doare (2013) increased the flow velocity to destabilize the flexible structures. Allen and Smits

* Corresponding author. Tel.: +82 42 350 3027; fax: +82 42 350 5027.
E-mail address: hjsung@kaist.ac.kr (H.J. Sung).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.06.006
0889-9746/

(2001) and Taylor et al. (2001) positioned bluff bodies ahead of the flexible structures to increase the instabilities of the structures. Recently, Kim et al. (2013) suggested the use of an inverted flag, in which the leading edge was free to move and the trailing edge was clamped. The inverted flag improved the amount of strain energy that was converted into the flag deformations from the surrounding fluid. The fluttering motions of the inverted flag were classified as a deflected mode, a flapping mode, and a straight mode. Many researchers have focused on developing piezoelectric devices to improve the energy harvesting efficiency (Loreto and Francesc, 2005; Shashank, 2007; Akaydin et al., 2010; Akcabay and Young, 2012). Michelin and Doare (2013) investigated the electrical and mechanical properties of piezoelectric patches. Sodano et al. (2004) focused on optimizing electric circuits that convert the solid deformations into an electric current.

Vortex structures generated in a wake represent the hydrodynamic footprint of the fluid interactions with the immersed structures. The vortex structures were analyzed quantitatively by Gharib et al. (1998), who defined the vortex formation time as the ratio between the length and the diameter of the ejected fluid column. The formation time provided an indicator of the vortex ring growth from the trailing jet. Kim et al. (2013) re-defined the formation time based on the peak-to-peak amplitude ratio (A/L), the velocity at the tip of the inverted flag and the fluid velocity, to investigate the vortex dynamics generated in the wake of the fluttering inverted flag.

The immersed boundary method was adopted to handle the interaction between a uniform flow and flexible structures. In the method, the structures were imaginarily decomposed into the massive part and the massless part. The massive part is the only part on which the elastic force was exerted. The massless part interacted with the local fluid velocity. Both parts were united strongly by a stiff spring with damping between the two parts. Through this mechanism, the fluid equations and the solid governing equations were independently calculated with the momentum forcing which was the force of the stiff spring with damping (Peskin, 2002; Zhu and Peskin, 2002; Kim and Peskin, 2007). The improved version of the immersed boundary was proposed to handle the mass of a flag, in which the momentum forcing was added to induce the fluid velocity equivalent to the velocity on the immersed boundary (Huang et al., 2007; Huang and Sung, 2009).

In this study, we simulated the dynamics of an inverted flag in a uniform flow using the immersed boundary method. We focused on the mechanism by which the kinetic energy of the surrounding fluid was converted into strain energy in the inverted flag. The main purpose of the present study was to investigate the flow dynamics of the inverted flag as a function of the Reynolds number (Re) and the bending rigidity (γ). The numerical results were compared with experimental data reported by Kim et al. (2013). We examined the flapping shapes, the vortical structures, and the flapping dynamics in relation to the formation time and strain energy conversion. The next section describes the formulation used to simulate an inverted flag in a uniform flow and the numerical method derivation. In Section 3, the numerical results and discussion are presented. Finally, a summary is provided in Section 4.

2. Problem formulation

A schematic diagram of the inverted flag and coordinate system is shown in Fig. 1. An inverted flag with a free leading edge and a clamped trailing edge was subjected to a uniform flow. The interactions between the inverted flag and the surrounding fluid were modeled using the immersed boundary method, in which the momentum forcing was added to the Navier–Stokes equations. The fluid was governed by the continuity equation and the incompressible Navier–Stokes equations,

$$\rho_0\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right) = -\nabla p+\mu\nabla^2 u+f, \tag{1}$$

$$\nabla\cdot\boldsymbol{u}=0, \tag{2}$$

where $\boldsymbol{u}$ is the velocity vector, p is the pressure, ρ_0 is the flow density, μ is the dynamic viscosity, and $\boldsymbol{f}$ is the momentum forcing used to enforce the no-slip boundary conditions along the immersed boundary.

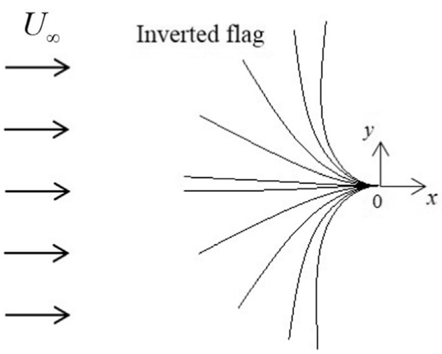

Fig. 1. Schematic diagram of the elastic inverted flag.