Journal of Fluids and Structures 40 (2013) 127–147

Contents lists available at SciVerse ScienceDirect

Journal of Fluids and Structures

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

Fluid–structure interaction of quasi-one-dimensional potential flow along channel bounded by symmetric cantilever beams

Gang-Won Jang [a], Se-Myong Chang [b,*], Gyun-Ho Gim [b]

[a] Faculty of Mechanical and Aerospace Engineering, Sejong University, 98 Gunja-dong, Gwangjin-gu, Seoul 143-747, Republic of Korea
[b] School of Mechanical and Automotive Engineering, Kunsan National University, 558 Daehak-ro, Kunsan-shi, Jeonbuk 573-701, Republic of Korea

ARTICLE INFO

Article history:
Received 20 November 2011
Accepted 23 February 2013
Available online 15 May 2013

Keywords:
Fluid–structure interaction
Potential flow
Inviscid flow
Incompressible flow
Channel
Cantilever beam

ABSTRACT

An analysis of fluid–structure interaction is presented for incompressible and inviscid flow in a channel bounded by symmetric cantilever beams. Small deflections of the beams and no flows normal to the beams are assumed, thus allowing the governing equations to be defined using quasi-one-dimensional pressure and flow velocity distribution; pressure and velocity are assumed to be uniform across the cross section of the channel. The steady-state solution of the present problem is analytically derived by the linearization of the governing equations. The solution is shown to consist of infinite modes, which is verified by comparing with numerical solutions obtained by the finite element method. The nonlinear effect in the steady-state solution is modeled by numerical method to estimate the error due to linearization. However, only a few leading modes are physically significant owing to the effects of flow compressibility and viscosity. The analytic solutions of the fluid–structure interaction are also presented for dynamic problems assuming harmonic vibration. The steady-state and stationary initial conditions are used, and the equilibrium frequency is determined to minimize the residual error of Euler equation. The fluid–structure interaction is characterized by a phase difference and distortion of waveform shape in the time history of the boundary velocity.

1. Introduction

The fluid–structure interaction between incompressible flow and a cantilever beam has been studied widely (e.g. Wang et al., 2001). One of its possible applications can be found in the reed valve, a pressure-driven flow stopper for systems such as two-stroke engines, compressors, and shock absorbers (Baudille and Biancolini, 2005). The analysis of interaction between internal flow and a cylindrical cantilever pipe is also important for cardiovascular fluid dynamics (Van de Vosse et al., 2003). Biomedical applications require sensors to be stable for the excitation of external biofluids where fluid–structure interaction is dominant for very small-scale dynamics problems (Gupta et al., 2006). The main rotor of a helicopter can also be considered as an interaction problem between inviscid, incompressible flow and elastic cantilever

* Corresponding author. Tel.: +82 63 469 4724; fax: +82 63 469 4727.
E-mail address: smchang@kunsan.ac.kr (S.-M. Chang).

0889-9746/$ - see front matter
http://dx.doi.org/10.1016/j.jfluidstructs.2013.02.021

beams (Yam, 2008). Among musical instruments, the fluid–structure interaction can be found in a harmonica where the reed plates are cantilevers that vibrate to create sounds through interaction with inviscid flow.

Previous literatures have dealt with the fluid–structure interactions in cantilever-beam channels or pipes by applying a simple analytic approach (Koh et al., 1993) or using a three-dimensional numerical analysis (Mittal and Tezduyar, 1995). The flexible wall model of the flow inside a channel or a pipe has been studied extensively for vessels in the cardiovascular system by Shin (1996). Numerical studies based on finite element methods have even been widely applied to interaction problems such as flexible shell problems in Bathe and Zhang (2004). An artificial traveling wave controlled at the wall of a channel can transfer fluid similar to a pump, and these waves can be induced by the fluid–structure interaction in a passive manner (Min et al., 2006; Oruc, 2012). Currently, many studies are being published on the nonlinear structural model (e.g., Kaya et al., 2009) and a new finite difference method to effectively analyze the flow component combined with a suitable linearized model (Gallinger and Bletzinger, 2010).

In this research, we derive analytic solutions for fluid–structure interactions between inviscid, incompressible flow and a channel bounded by cantilever beams using a simplified quasi-one-dimensional model. By eliminating the viscous diffusion term in the momentum equation, very thin boundary layers are assumed with respect to the geometric scale of the model. In many practical applications, this potential flow model is valid because it contains the flow physics concerning the convective transport terms that are dominant over the diffusion terms in the regime of a high Reynolds number without turbulence (Doare et al., 2011). The cantilever beams are modeled as Euler beams so that their shear effect is not considered.

For the steady-state solution, both a purely analytic approach with linearization and a finite element method (see Appendix A) are used to verify the effectiveness of the present method. In the sequence, harmonic vibration is considered to determine the flow–structure interaction under two initial conditions: steady-state and stationary conditions.

2. Quasi-one-dimensional governing equations

The flow in the unit-depth channel in Fig. 1 is assumed to be inviscid, incompressible, and quasi-one-dimensional; the cross-sectional fluid speed is uniform along the vertical line at a given arbitrary position. This assumption is valid in the case of a thin viscous boundary layer. The channel wall consists of elastic beams that are clamped at the outlet. As there is no effect of viscosity under the assumption of inviscid flow, this problem is essentially the same as the rigid wall at the centerline.

For the flow inside the channel, a control-volume element is defined, where the conservation of mass and momentum are considered. If the flow is steady and incompressible, the volume flow rate per unit depth should be constant (see Fig. 2(a)):

$$\left(u+\frac{du}{dx}dx\right)\left\{h+2\left(\delta+\frac{d\delta}{dx}dx\right)\right\}-u(h+2\delta)=0, \tag{1}$$

where u is the fluid velocity and δ is the beam deflection. Neglecting higher order terms, Eq. (1) is simplified as

$$(h+2\delta)\frac{du}{dx}+2u\frac{d\delta}{dx}=0, \tag{2}$$

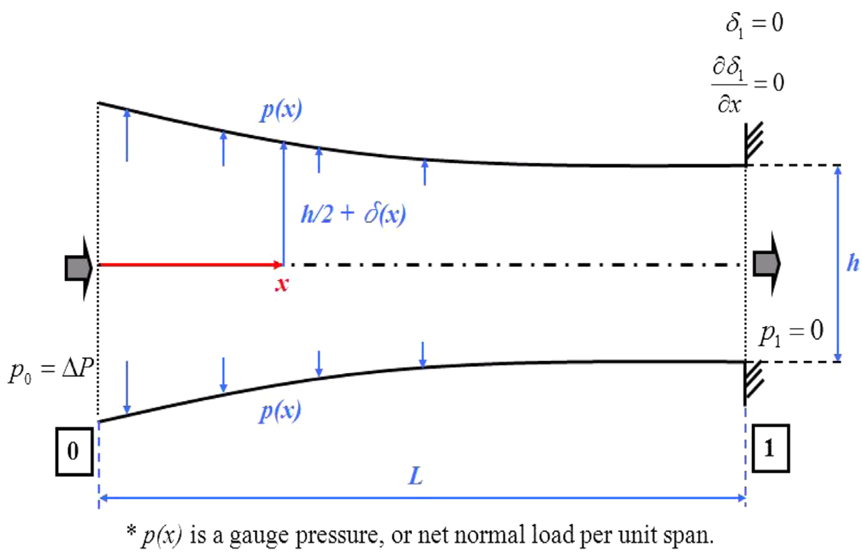

Fig. 1. Quasi-one-dimensional fluid–structure interaction.