J. Wind Eng. Ind. Aerodyn. 98 (2010) 65–72

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Fluid–structure interaction of a two-dimensional membrane in a flow with a pressure gradient with application to convertible car roofs

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ARTICLE INFO

Article history:
Received 14 September 2006
Received in revised form
26 November 2008
Accepted 4 September 2009

Keywords:
Aeroelasticity
Membrane
Fluid–structure interaction
Coupling methodology
Flexible surface
Roof

ABSTRACT

The flow-induced deformation of a membrane in a flow with a pressure gradient is studied. The investigation focuses on the deformation of aerodynamically loaded convertible car roofs. A computational methodology is developed with a line-element structural model that incorporates initial slackness of the flexible roof material. The computed flow–structure interaction yields stable solutions, the flexible roof settling into static equilibrium. The interaction converges to a static deformation within 1% difference in the displacement variable after three iterations between fluid and structural codes. Reasonably accurate predictions, to within 7%, are possible using only a single iteration between the fluid and the structural codes for the model problem studied herein. However, the deformation results are shown to be highly dependent on the physical parameters that are used in the calculation. Accurate representation of initial geometry, material properties and slackness should be found before the predictive benefits of the fluid–structure computations are sought. The iterative methodology overcomplicates the computation of deformation for the relatively small displacements encountered for the model problem studied herein. Such an approach would be better suited to applications with large amplitude displacements such as those encountered in sail design or deployment of a parachute.

1. Introduction

With the increase in computational power, computer aided engineering approaches (including the coupling of multi-disciplinary approaches) are becoming viable for engineering analyses. Most of the development of fluid–structure interaction has used potential flow theory to account for the forces due to fluid motion. This work has been undertaken for flexible surfaces in a pressure field of zero mean-flow streamwise pressure gradient. This paper reports work that has been performed for a flexible surface in an imposed pressure gradient such as that experienced by a convertible roof of a car.

Much of the development of fluid–structure interaction began with the motion of a simplified thin flexible plate. Kornecki (1978) analysed an infinitely long flat plate on which flapping or flutter type motions were possible. Potential flow was used to determine the pressure, which drives/imbalances the system. These analyses were performed in a zero pressure gradient. Likewise, Carpenter and Garrad (1986) and Crighton (1989) used simple flexible-wall models and small-amplitude deformations to predict the unsteady aero-elastic behaviour of a system using potential flow in a zero pressure gradient. Guruswamy (1990) used the Euler equations to study the aeroelasticity of wings. This work has been extended to incorporate the Navier–Stokes equations (Guruswamy and Byun, 1993, 1996). Balint and Lucey (2005) also solved the Navier–Stokes equations in the fluid–structure interaction of a cantilevered flexible plate in a channel. The response of a ship rudder behind a propeller has been investigated by Turnock and Wright (2000).

For a membrane, the problem usually becomes non-linear, due to the induced tension term, which is a function of displacement. These non-linear effects have been modelled for flexible surfaces in a flow that has zero mean-flow pressure gradient (Newman and Goland, 1982). A potential-flow solution is used to determine the local pressure field on the deformed surface. This work was extended by Greenhalgh et al. (1984) and Newman (1984, 1987) whereby comparisons with experimental data are made. Smith and Shyy (1995) used the Navier–Stokes equations to model the flow over a two-dimensional flexible surface. Substantial differences were realised over the potential flow theory as expected, due to the incorporation of viscous effects including separation from the curved surface.

Flexible surface modelling of membrane structures is similar to that encountered in sail design in that deformations have low

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0167-6105/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jweia.2009.09.003

wavenumbers, typically that of the fundamental mode. The application also entails the effects of flow separation, which cannot be addressed by a potential flow solution. However, approximate means of simulating the separation over yacht sails using potential flow calculations have been developed (Cyr and Newman, 1996). Fiddes and Gaydon (1996) used a vortex lattice method to calculate the flow past yacht sails. The calculation of viscous flow about yacht sails in two dimensions has been performed by Jackson and Fiddes (1999). A commercial CFD code has also been employed in sail design to study the interaction between combinations of sails (Hedges et al., 1996). Here, the mesh employed was of fixed geometry, so avoiding the complexity of having to calculate the flow over a surface that deforms.

In a statically stable equilibrium, the pressure difference between the upper and lower surface balances the structural restorative forces of pre- and induced tension. For a two-dimensional membrane, the tension is constant along its length and the effect of curvature balances the local pressure coefficient (Newman and Goland, 1982). For a three-dimensional membrane, at any given point, the combination of curvatures in the two directions with their associated tensions must balance the pressure force.

This paper is laid out as follows. A representative formulation of the current problem is first presented. Thereafter, the computational approach is described beginning with the computed flow about the model. A structural solver that is capable of modelling slackness is used in our approach, which is detailed and validated. The coupling of this to the commercial computational fluid mechanics code and source panel method codes is presented including the software interfacing strategy. The results of the computational methodology are presented for various configurations. Finally, some conclusions are offered.

2. Problem formulation

Consider the deformation of a two-dimensional flexible surface subjected to a forcing pressure as shown in Fig. 1. According to Lucey et al. (1997), the governing equation for this thin flexible surface is

$$\rho_m h \frac{\partial^2 w}{\partial t^2} + D\frac{\partial w}{\partial t} + B\frac{\partial^4 w}{\partial x^4} - (T_0 + T_I)\frac{\partial^2 w}{\partial x^2} = \Delta P \qquad (1)$$

where $w(x,t)$ is the wall displacement perpendicular to the x direction, t is the elapsed time, ρ_m and h are the material density and thickness. D is a dashpot-type damping constant, B is the flexural rigidity, T_0 and T_I are the pre-tension and induced tension terms respectively, whilst ΔP is the fluid pressure difference between the upper and lower surfaces of the flexible wall. Eq. (1) assumes one-dimensional motions of the flexible surface, which is a line in two-dimensional space. A full model would include geometric nonlinearity and a second equation relating horizontal motion of a material point with the fluid shear-stress. This is omitted in the current work as shear stresses are at least an order of magnitude smaller than normal stresses in the present problem, wherein a pressure distribution across the membrane is present.

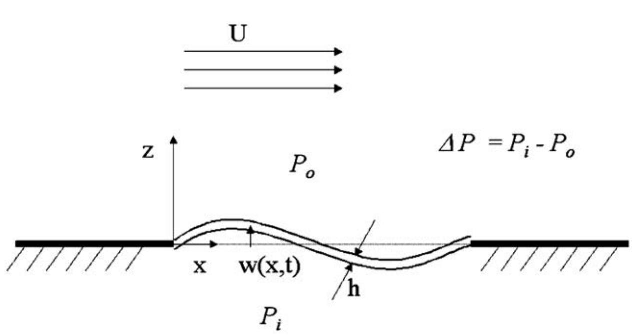

Fig. 1. Schematic of the underlying principles used in the problem formulation.

In the present investigation we are interested in deformations with large (non-linear) amplitudes and the effects of pressure gradients including boundary-layer separation. To make the problem tractable, we follow the approach typical of sail design, for example see Cyr and Newman (1996), and omit the time-dependence in Eq. (1). We also omit the flexural rigidity term from Eq. (1) so that the objective is then to solve

$$-(T_0 + T_I)\frac{\partial^2 w}{\partial x^2} = \Delta P \qquad (2)$$

using a procedure which iterates towards a deformed static equilibrium. The induced tension, T_I is a function of displacement, w, so that Eq. (2) is non-linear. By using a membrane, the motion of the flexible wall can be characterised solely by the consideration of surface points and thus $w(x)$ defines the boundary of the fluid flow relative to the undeformed membrane surface. The present work is aimed at modelling the fluid–structure interaction of convertible car roofs with the surrounding air flow. In simplifying from Eqs. (1)–(2), the study of flutter instability about the deformed state is precluded. Other wave disturbances could be expected to be quickly damped out by the high levels of structural damping present in real padded flexible roofs. There is also the possibility that unsteady large-amplitude solutions about the undeformed state might exist. However, this outcome would be indicated by the failure of our fixed-point algorithm to converge. Thence, the solution is assumed to be steady-state settling to static equilibrium after a certain period of time, so that the structural restorative forces balance the transmural pressure force applied. Other related aspects of the problem beyond the scope of the research are unsteady effects within the wake and those due to changes in forward speed in the case of a car.

3. Computational methods

3.1. Flow field computation

Initially, the computation of the flow field about a model with a rigid roof is validated as a first step, the results from which can then be used with confidence in the computational methodology using a flexible roof. The commercial CFD code StarCD (Computational Dynamics Ltd., 1997) is used in this work with MARS discretisation (Computational Dynamics Ltd., 1997), the SIMPLE algorithm (Patankar and Spalding, 1972) and the standard k–ε turbulence model (Jones and Launder, 1972) for all of the calculations presented herein. A quarter-scale version of the top half of MIRA reference vehicle (Carr, 1992) was used in this work. This was chosen as it is a simplified shape featuring most of the common flow characteristics around the top of a typical car. This facilitates the validation of our methodology by negating certain geometric complexities such as those of the hood that will affect the development of the flow as it approaches the front windscreen. Thus, the flow around the roof of real cars will not be identical to that in our model. However, both model and real car will experience a broadly similar characteristic pressure field. The geometry of the model and characteristic dimensions are shown in Fig. 2a. The distribution of cells to achieve a mesh independent