FLUTTER INSTABILITY OF CANTILEVER BEAMS IN VISCOUS FLOW

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Summary: Identification of flutter boundary is important for many engineering and energy harvesting applications. This work adds to the existing (potential flow based) flutter boundary studies through solving the full Navier-Stokes equations. Results are compared with available experimental results and the importance of the non-dimensional parameters is discussed and parametric relations are developed.

BACKGROUND AND OBJECTIVE

Flutter, a self-excited dynamic instability of elastic structures in otherwise uniform, steady flow, has been extensively studied; a recent review article on the topic can be found in [1]. Most of the theoretical studies have used potential flow models, as mentioned in [1]. A common feature of these results is that they tend to predict over-conservative flutter boundary compared to the experimental results [2].

The objective of this study is to determine the flutter boundary of cantilever beams by solving the full Navier-Stokes equations coupled with a nonlinear elastic beam model, derive parametric relations for the flutter boundary, and compare the results with the available experimental and theoretical results.

NUMERICAL APPROACH

The two-dimensional unsteady Navier-Stokes equations are solved with a fractional-step based solver. The solid is modeled with a large-deformation thin beam model and the fluid and structure interaction is achieved through a modified Peskin's Immersed boundary method. Detailed descriptions are in [3, 4].

PROBLEM SET UP AND NON-DIMENSIONAL PARAMETERS

The problem set-up is given in Fig. 1. The dimensional variables are the uniform incoming flow speed U_o', fluid density ρ_f', fluid viscosity μ', beam length L', beam density times thickness $\rho_s'q'$, and beam bending stiffness K_b'. According to Buckingham-Pi theorem, there should be 3 independent dimensionless variables, which can be expressed as:

$$U = \left(\frac{\rho_f' U_o'^2 L'^3}{K_b'} \right)^{1/2}, \quad \rho q = \frac{\rho_s' q'}{\rho_f' L'}, \quad Re = \frac{\rho_f' U_o' L'}{\mu'}$$

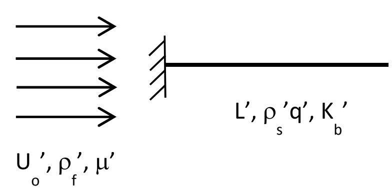

Figure 1: Problem set-up.

U is the ratio of the fluid inertial forces to the solid bending restoring force, ρq is the ratio of the solid to fluid inertial force, and Re is the ratio of the fluid inertial forces to the fluid viscous forces – the Reynolds number.

RESULTS

The computed flutter boundary is plotted in Fig. 2 with various experimental and computational data. The computed results show that for heavy beams in light fluid (high ρq), the flutter boundary could be described by a U=constant line – in particular U~5 and the results are independent of Re. On the other hand, for light beams in heavy fluid (low ρq), U depends on both Re and ρq through a non-linear relation:

$$U = \rho q^{-8000\,Re^{-1.8} - 1.4} + 5.5$$

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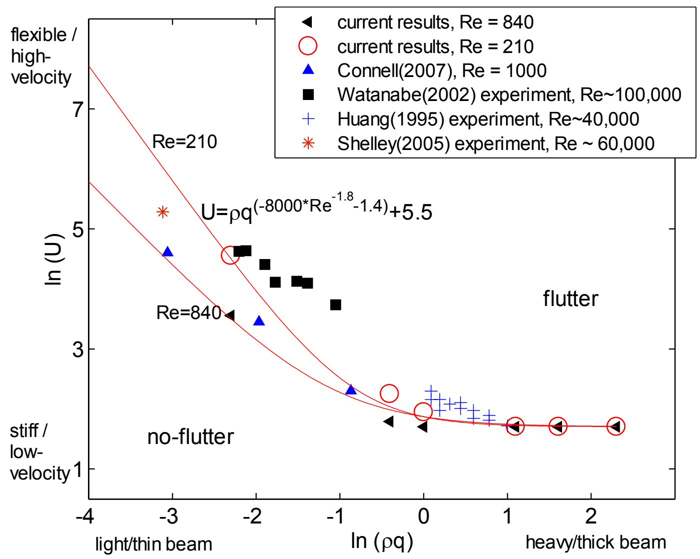

Figure 2: Flutter boundary data

The lighter the beam (with respect to the fluid), the more pronounced is the effect of the Re on the flutter boundary. In general, the current results and the fitted relation are in good agreement with previous experimental and numerical data. It should be noted that Watanabe's results have a higher critical speed than the current results, but this might be due to the effect of the structural damping, which is not considered in the current results. The derived equation shows that the Reynolds number needs to be higher than 1500 or 5600 to make a less than, respectively, 1% and 0.1% in the exponent of ρq.

Order of magnitude analysis shows that the ratio of the viscous to bending restoring forces is proportional to (U^2/(Re.q)) and since the critical U decreases with higher ρq (as shown in Fig. 1), so is the effect of the viscous forces in comparison with the bending restoring forces. Similarly, the ratio of the viscous to inertial forces is proportional to 1/(Re.q.(ρq+1)), so this ratio decreases with a higher ρq.

CONCLUSIONS

In this work the flutter boundary of a cantilever beam was observed to exhibit two different regimes. In the first regime, the heavy beam in light fluid – e.g. metal/plastic in air, the flutter boundary was observed to remain insensitive to ρq and Re and could be described by a constant U line. In the second zone, light beams in heavy fluids – e.g. water, the viscous forces were observed to have a significant effect.

Also the results show, in general – when the viscous forces are low – the critical speed of the fluid flow increases with higher fluid density, viscosity, beam stiffness and thickness, but decreases with higher beam length, and solid density.

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