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A study on the energy transfer of a square prism under fluid-elastic galloping

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ABSTRACT

In this paper, power transfer of an elastically mounted body under the influence of fluid-elastic galloping is analysed.

The quasi-steady state model equations are first analysed to find suitable governing parameters. It is shown that, as well as Re, the system is a function of three dimensionless groups: a combined mass-stiffness parameter, Π_1; a combined mass-damping parameter, Π_2; and mass ratio, m^*.

Data obtained by numerically integrating the quasi-steady state equations show that for high values of Π_1, the power extracted from the flow is a function of Π_2 only. For low values of Π_1, the power extracted is still a strong function of Π_2, but is also a weak function of Π_1. For all the cases tested, the power extracted was independent of the value of m^*.

These results are then compared to results of direct numerical simulations. It is found that Π_1 has a much stronger impact on the power extracted than predicted by the quasi-steady state model. The error is shown to be an inverse function of Π_1. The failure of the quasi-steady state model at low Π_1 is hypothesised to be due to the stronger influence of vortex shedding, which is not accounted for in the quasi-steady model. Spectral analysis of the DNS cases at low Π_1 shows a significant response at the vortex shedding frequency. The strength of the vortex shedding response is also shown to be an inverse function of Π_1.

Even though the quasi-steady state model does not accurately predict the power extracted, it does predict the parameter values at which maximum power transfer occurs reasonably well, and both the quasi-steady model and the direct numerical simulations show that this value is basically independent of Π_1.

1. Introduction

Transverse fluid-elastic galloping is one phenomenon in the broader class of phenomena of fluid structure interactions. This area has been of interest due to the vibrations created by galloping on transmission lines (Parkinson and Smith, 1964) and other civil structures, leading to failure either through high peak loads or the cumulative effect of fatigue. Therefore understanding this phenomenon in order to suppress these vibrations has been an important research task. However, the search for alternate energy sources with minimal environmental impact has become an important area of research in the modern world. Therefore researchers are moving towards investigating the possibility of extracting useful energy from

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Nomenclature

a_1, a_3, a_5, a_7 coefficients of the polynomial to determine C_y
A displacement amplitude
c damping constant
D characteristic length (side length) of the cross section of the body
$f = \sqrt{k/m}/2\pi$ natural frequency of the system
f_g frequency of galloping
f_s frequency of vortex shedding
F_y instantaneous force normal to the flow
F_0 amplitude of the oscillatory force due to vortex shedding
$\mathcal{F}$ Fourier transform of velocity
k spring constant
m mass of the body
m_a added mass
P_d power dissipated due to mechanical damping
$P_{in} = \rho U^3 D/2$ energy flux of the approaching flow
P_m dimensionless mean power
P_t power transferred to the body by the fluid
t time
U freestream velocity
U_i induced velocity
$y, \dot{y}, \ddot{y}$ transverse displacement, velocity and acceleration of the body
$\mathcal{A} = DL$ frontal area of the body
λ inverse time scale of a galloping dominated flow
$\lambda_{1,2}$ eigenvalues of linearised equation of motion
ρ fluid density
$\omega_n = 2\pi f$ natural angular frequency of the system
ω_s vortex shedding angular frequency
$c^* = cD/mU$ non-dimensionalised damping factor
$C_y = F_y/0.5\rho U^2 DL$ normal (lift) force coefficient
$m^* = m/\rho D^2 L$ mass ratio
Re Reynolds number
$U^* = U/fD$ reduced velocity
$Y = y/D$ non-dimensional transverse displacement
$\dot{Y} = m^* \dot{y}/a_1 U$ non-dimensional transverse velocity
$\ddot{Y} = m^{*2} D\ddot{y}/a_1^2 U^2$ non-dimensional transverse acceleration
$\Gamma_1 = 4\pi^2 m^{*2}/U^{*2} a_1^2$ first dimensionless group arising from linearised, non-dimensionalised equation of motion
$\Gamma_2 = c^* m^*/a_1$ second dimensionless group arising from linearised, non-dimensionalised equation of motion
$\zeta = c/2m\omega_n$ damping ratio
$\theta = \tan^{-1}(\dot{y}/U)$ instantaneous angle of incidence (angle of attack)
$\Pi_1 = 4\pi^2 m^{*2}/U^{*2}$ combined mass-stiffness parameter
$\Pi_2 = c^* m^*$ combined mass-damping parameter

these vibrations by encouraging rather than suppressing them (Barrero-Gil et al., 2010). Hence, in this paper the power transfer from the fluid to the body and the governing parameters influencing it are investigated, with a focus on identifying conditions that lead to optimum power transfer.

According to Païdoussis et al. (2010) and Glauert (1919) provided a criterion for the onset of galloping by considering the auto-rotation of an aerofoil. DenHartog (1956) provided a theoretical explanation for galloping for iced electric transmission lines. A weakly non-linear theoretical aeroelastic model to predict the response of galloping was developed by Parkinson and Smith (1964) based on a quasi-steady state (QSS) hypothesis. This hypothesis simply claims that only the time-mean lift on the body (averaged over a time much longer than any vortex shedding period) contributes to the dynamics. Lift forces measured experimentally on a static square prism at different angles of attack were used as an input for the theoretical model. This relatively simple model achieved a remarkably good agreement with galloping experiments conducted in a wind tunnel, where the vortex shedding frequency was much higher than the eventual body oscillation frequency, due to the body being relatively heavy.

However, the QSS model equation, when solved analytically assuming a sinusoidal solution, is not as accurate for cases where the body is relatively light and is the setup in some fluid-dynamic applications. Joly et al. (2012) observed that finite element simulations show a sudden change in amplitude below a critical value of the mass ratio m^*. The QSS model derived in Parkinson and Smith (1964) was altered to account for the vortex shedding and solved numerically to predict the reduced displacement amplitude at low mass ratios to the point where galloping is no longer present. While a reasonable agreement could be found, the model still required a parameter to be tuned to find the best match.

Most of the literature on galloping using the QSS model has been focused on predicting the displacement amplitude (Parkinson and Smith, 1964; Joly et al., 2012; Luo et al., 2003). However, it is quite important to analyse the behaviour of the velocity when studying the power transfer from the fluid to the body. This is because instantaneous power from the fluid flow to the system is the product of the fluid dynamic force and the velocity of the system while instantaneous power out of the system is the product of the damping and the velocity of the system. The fluid dynamic force is also modelled to be only dependent on the velocity of the system. This study also focuses on how well the QSS model performs at high damping at low Reynolds numbers.

Here, the modified QSS model is integrated numerically and the power transfer from the fluid to the body is investigated, similar to the study of Barrero-Gil et al. (2010). Two different values of Re are tested: Re = 200, a case that should remain laminar and closer to two-dimensional behaviour; Re = 22 300, a case where the flow is expected to be turbulent and three-dimensional. The QSS model requires the lift or transverse force coefficient, C_y as a function of angle of attack θ for a fixed