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Critical and post-critical behaviour of two-degree-of-freedom flutter-based generators

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A B S T R A C T

Energy harvesting from flow-induced vibrations is a recent research field, which considers a diverse range of systems, among which two-degree-of-freedom flutter-based solutions were individuated as good candidates to obtain high energy performance. In the present work, numerical linear analyses and wind-tunnel tests were conducted on a flat-plate sectional model. The aim is to identify some design guidelines for generators exploiting the classical-flutter instability, through the investigation of the critical condition and the response during the post-critical regime. Many sets of governing parameters of interest from the energy-harvesting point of view were considered, including high levels of heaving damping to simulate the operation of a conversion apparatus. In particular, eccentricity of the elastic centre and small downstream mass unbalance can be introduced as solutions aiming at optimal operative ranges. The collected results suggest the high potentiality of flutter-based generators, and a significant enhancement of performance can be envisaged. Moreover, they contribute to improve the knowledge of the flutter excitation mechanism and to widen the dataset of measurements in the post-critical regime.

1. Introduction

The research on alternative renewable energy sources is a crucial issue for modern society, and is receiving increasing attention from the scientific community. Regarding air and water flows, devices that convert the kinetic energy due to flow-induced vibrations into electricity is rapidly evolving. Contrary to the common practice in wind/aeronautical engineering, a peculiarity of the energy-harvesting field is that systems are specifically designed to be prone to aero-/hydro-elastic phenomena. Therefore, several specific state-of-the-art solutions can be found, depending on the different type of excitation mechanism. The present work focuses on the energy harvesting from the oscillations of a two-degree-of-freedom (2-DoF) system, which are produced by the classical-flutter instability. The reason for such a study is clear after a careful analysis of the literature.

At the end of the '70s, Ahmadi [1] explored torsional galloping (or torsional flutter) oscillations of H-shaped cross sections from both the analytical and experimental point of view. This concept has also recently been re-examined for a wing section oscillating about its leading edge with a nonlinear elastic restoring force [2]. The idea of exploiting vortex-

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Nomenclature

Acronyms

CE Centre of stiffness
CM Centre of mass
CFD Computational fluid dynamics
DoF/s Degree/s of freedom
LCO/s Limit-cycle oscillation/s
VIV Vortex-induced vibrations

Symbols

A_i^* Dimensionless flutter derivatives for the pitching DoF (i=1, 2, 3, 4). The subscript '0' ($A_{i,0}^*$) is used to refer to the flutter derivatives estimated for the symmetric configuration.
A_{sw} Swept area (m^2) of the oscillating system, in the cross-flow direction.
a Eccentricity of the mass centre (m), positive if downstream of the elastic centre.
B, b Reference dimensions of the cross section (m). Here $B = 2b$ is the section width (or chord).
C Theodorsen's circulatory function (–).
C'_L Slope of the lift aerodynamic coefficient (–).
C'_M Slope of the moment aerodynamic coefficient (–).
c_α, c_η Pitching (N m s rad^{-1}) and heaving (N s m^{-1}) damping coefficients.
D Depth (m) of the sectional model, facing the flow.
D_{sw} Swept distance (m) of the oscillating system, in the cross-flow direction.
e Eccentricity of the elastic centre (m), positive if downstream of the midchord of the cross section.
g_α, g_η Pitching and heaving rate-independent damping coefficients (–), in still air for the uncoupled mechanical system.
$g_{\eta e}$, $g_{\eta s}$ External additional 'e' and structural 's' rate-independent damping coefficients (–) in the heaving DoF.
H_i^* Dimensionless flutter derivatives for the heaving DoF (i=1, 2, 3, 4). The subscript '0' ($H_{i,0}^*$) is used to refer to the flutter derivatives estimated for the symmetric configuration.
I_α, I_η Pitching (kg m^2) and heaving (kg) inertias.
j Unit imaginary number.
K Reduced frequency of oscillation (–).
k_α, k_η Pitching (N m rad^{-1}) and heaving (N m^{-1}) stiffness coefficients.
L, $\overline{L}$ Lift load (N), the overline indicates the dimensionless form.
$\overline{L}_\alpha$, $\overline{L}_\eta$ Dimensionless lift load contributions due to the pitching and heaving motion components.
l Span of the sectional model (m).
M, $\overline{M}$ Moment load (N m), the overline indicates the dimensionless form.
$\overline{M}_\alpha$, $\overline{M}_\eta$ Dimensionless moment load contributions due to the pitching and heaving motion components.
$n_{\alpha 0}$, $n_{\eta 0}$ Pitching and heaving frequency (Hz) of oscillations of the uncoupled mechanical system, in still air.
n Frequency of oscillations during flutter motion (Hz). The symbol '^' ($\hat{n}$) is used to refer to the steady-state value of the equivalent harmonic motion.
P_D Dissipated power by the mechanical system (W m^{-1}). The subscript 'η' ($P_{D\eta}$) is used to refer to the heaving-damping counterparts.
P_{De}, P_{Ds} Dissipated power contribution due to the external 'e' and to the structural 's' damping (W m^{-1}). The subscript 'η' ($P_{D\eta e}$ and $P_{D\eta s}$) is used to refer to the heaving-damping counterparts.
P_E Power related to the electric current in the electric circuit linked to the transducer (W m^{-1}).
P_F Power of the flow-induced loads (W m^{-1}). The subscript 'η' ($P_{F\eta}$) is used to refer to the heaving-load counterparts.
P_Q Power related to the electric charge as converted by the transducer (W m^{-1}).
P_S Power associated with the mass unbalance (W m^{-1}).
P_W Power of the oncoming flow conventionally referred to the swept distance during the oscillations (W m^{-1}).
Re Reynolds number (–).
r_α Radius of polar inertia normalised with B (–).
S Mass unbalance (kg m).
T_n Period of oscillations during flutter motion (s). The symbol '^' ($\hat{T}_n$) is used to refer to the steady-state value of the equivalent harmonic motion.
t Time (s).
U Free-stream flow velocity (m s^{-1}).
U_R, $U_{R\alpha}$ Reduced flow velocities (–), with $U_R = U_{R\alpha}\sqrt{X}$. The apex '$c$' (*e.g.* $U_{R\alpha}^c$) is inserted to refer to the critical condition.
X Squared nondimensional frequency at the flutter instability threshold (-).
x_m Mass-centre eccentricity normalised with B (–), positive if downstream of the elastic centre.
x_e Elastic-centre eccentricity normalised with B (–), positive if downstream of the section midchord.
α Pitching displacement (rad). The symbol '^' ($\hat{\alpha}$) is used to refer to the steady-state value of the equivalent harmonic motion.
β Apparent damping due to the mass unbalance (–).
Γ Global performance factor (–). The subscript 'η' (Γ_η) is inserted to refer to the heaving counterpart.
Γ', Γ'', Γ''' Extraction, conversion, operation factors (–). The subscript 'η' (*e.g.* Γ'_η) is used to refer to the heaving counterparts.