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# Modeling of flutter stability margins in an aerofoil cantilever wing with multiple engines mounts under inherent structural nonlinearities

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ABSTRACT

This paper presents an aeroelastic analysis of aircraft wing having structural nonlinearities with two power plants subjected to time-dependent thrust loads in the event of failure of one of the engines. The equations of motion are derived based on continuous beam model of the wing system with two engines subjected to time dependent thrust by using Lagrange's formulation. The placement of engine at various positions along the span within variable distances between the engines enables us to locate the optimum configuration of engine placement. Firstly, the dynamic responses of the clean wing-with and without cubic nonlinearity- are studied, before illustrating the dynamic analysis of wing with engines subjected to thrust. The parametric analysis is carried out to find the most influencing parameter in the prediction flutter of the system. The multiple regression analysis as well as artificial neural network training is carried out to identify the flutter velocity for a given configuration of the system. Then, the system is subjected to various types of time-dependent engine thrusts, before studying its effects on dynamic responses in the event of a sudden failure of an engine. The flutter velocity boundaries are validated with the published data that generate some significant results.


## 1. Introduction

Due to stringent load requirements, modern aircraft wings have complex shapes with multiple engines and other systems located along the span. It is well known that the forward flight conditions are drastically influenced by flutter instability. Also, the time-dependent thrust loads of the engines mounted on the wings act as follower forces robustly affecting the dynamic behavior of the wing. The coupled unsteady aerodynamic loads and non-conservative engine thrust forces create unstable motions of the wing. Despite several works on the aeroelasticity of wings, only a few studies have so far focussed on the response of wings with thrust loads. Furthermore, most of the studies employ classical theories with linear aerodynamics and structural models [5]. However, in real practice, the nonlinearities always persist and usually lead to dynamic responses in case of limit cycle oscillations (LCO). Similarly, some earlier works have created various types of nonlinearities in aeroelastic equations. Woolston et al. [28] studied the freeplay, hysteresis, and cubic stiffness nonlinearities to measure the impact of initial conditions. Lee et al. [13] presented the effect of cubic nonlinearity in terms of soft or hard spring as added to either of the two degrees of freedom. The results demonstrated that instability was dependent upon the initial conditions in the soft spring case, while remaining independent in the hard spring case.

Theoretical models to predict the dynamic response, both in bending and torsional degree of freedoms for cantilever sweptback wings with high length-chord ratio were developed by Barmby et al. [2]. Later on, the aeroelastic response studies of cantilever wings were carried out in a full-fledged manner by considering various structural non-linearities. Ghadiri and Razi [7] studied the non-linear aeroelastic response by using the modified harmonic balance method to find the limit cycle oscillations. Then, the results were compared with the equation of motion by applying Lagrange's method.

The actual aircraft wing configuration consists of engines or power plants, having an impact on a dynamic response. The engine is considered as the external store and the thrust as the follower force while evaluating the system. The dynamic response in bending direction of a rectangular plate made up of functionally graded materials (FGM) with a concentrated load at the tip was studied earlier [25]. Likewise, the flutter onset of the cantilever wing with the concentrated mass at a point along the span was solved by applying differential equations through operational methods [26].

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**Nomenclature**

| | |
|---|---|
| $a_h$ | non-dimensional distance from wing section mid-chord to elastic axis |
| b | wing semi-chord |
| $b^*$ | non-dimensional semi-chord of the wing |
| $C_h$ | damping coefficient in plunge |
| $C_\alpha$ | damping coefficient in pitch |
| $dC_L$ | wing elemental aerodynamic lift coefficient |
| D | damping energy |
| $x_\alpha$ | non-dimensional distance between the wing centre of gravity and elastic axis |
| EI | bending rigidity |
| $F_h(\eta)$ | first plunge mode shape function |
| $F_\alpha(\eta)$ | first pitch mode shape function |
| GJ | torsional rigidity |
| h | plunging displacement |
| $h_1$ | time-dependent part of plunging displacement |
| H | Heaviside function |
| $I_{C.G}$ | mass moment of inertia about elastic axis |
| $I_{s1}$ | moment of inertia of first external store about elastic axis |
| $I^*_{s1}$ | dimensionless moment of inertia of first external store about an elastic axis |
| $I_{s2}$ | moment of inertia of second external store about elastic axis |
| $I^*_{s1}$ | dimensionless moment of inertia of second external store about an elastic axis |
| l | wing length |
| m | mass per unit length |
| $M_{s1}$ | first engine mass |
| $M^*_{s1}$ | dimensionless first engine mass |
| $M_{s2}$ | second engine mass |
| $M^*_{s2}$ | dimensionless second engine mass |
| $p_1$ | dimensionless first follower force |
| $P_1$ | first follower force |
| $p_2$ | dimensionless second follower force |
| $P_2$ | second follower force |
| $Q_h$ | generalized forces corresponding to plunge degree of freedom |
| $Q_\alpha$ | generalized forces corresponding to pitch degree of freedom |
| $T_e$ | kinetic energy of engine |
| $T_w$ | kinetic energy of wing |
| V | potential energy |
| U | free stream velocity |
| $U_\infty$ | non-dimensional flow velocity |
| u, v, w | displacements in x,y,z directions respectively |
| x, y, z | wing coordinate system |
| $x_{s1}$, $y_{s1}$, $z_{s1}$ | the first engine distance from wing root in x, y, and z directions respectively |
| $x^*_{s1}, y^*_{s1}, z^*_{s1}$ | dimensionless distance of the first engine from the wing root in x, y, and z directions respectively |
| $x_{s2}$, $y_{s2}$, $z_{s2}$ | the second engine distance from wing root in x, y, and z directions respectively |
| $x^*_{s2}, y^*_{s2}, z^*_{s2}$ | dimensionless distance of the second engine from the wing root in x, y, and z directions respectively |
| $\alpha$ | pitch angle of the wing section |
| $\alpha_1$ | time-dependent part of pitch motions |
| $\beta_1$,$\beta_2$ | constants in mode shape functions |
| $\delta_D$ | Dirac delta |
| $\varepsilon_1$,$\varepsilon_2$ | constants in Wagner's function |
| $\zeta_h$ | viscous damping ratios in plunge |
| $\zeta_\alpha$ | viscous damping ratio in pitch |
| $\eta$ | dimensionless coordinate along the wing span |
| $\mu$ | mass ratio |
| $\xi$ | dimensionless plunging displacement |
| $\xi_1$ | dimensionless time-dependent part of plunge motion |
| $\rho$ | air density |
| $\tau$ | dimensionless time |
| $\phi(\tau)$ | Wagner's function |
| $\psi_1$,$\psi_2$ | constants in Wagner's function |
| $\omega_h$ | plunge natural frequency |
| $\omega_\alpha$ | pitch natural frequency |
| $\bar{\omega}$ | frequency ratio |

The effect of stores on the instability of cantilever wing by sweeping the position of the store along the span of the wing was illustrated by Gern and Librescu [6]. The flutter onset velocity usually comes down as the store moves towards the half of the span, whereas it increases as the store moves towards tip from half of the span. The multi-store on sweptback cantilever wing delaying the flutter onset was reported by Mardanpour et al. [16].

Hodges [9] and Hodges et al. [10] studied the aeroelastic response of a cantilever wing subjected to lateral follower force at the tip without considering the mass of the store with the results showing the dependence of flutter onset only on the thrust magnitude. The non-linear dynamic response of a cantilever beam with the random follower force at the free end was studied by Young and Juan [29]. The dynamic effect of mass placed at the tip with the follower force on the dynamic responses of cantilever wing was studied by [4]. The instability of a deep cantilever beam subjected to lateral force with partial distribution was studied by Kazemi-Lari and Fazelzadeh [11]. The effect of the sweep angle of a cantilever wing was considered by Mazidi and Fazelzadeh [20] along with the modified Peter's unsteady aerodynamic modeling for identifying the flutter boundary. The study carried by Amoozgar et al. [1] reveals that parameters such as the thrust and mass of an engine make a significant impact on the dynamic stability of a cantilever wing. However, the above literature was limited to a time-independent follower force, but in an actual case, the thrust remains time-dependent. Mazidi et al. [21] investigated the aeroelastic responses of the cantilever wing subjected to time-dependent thrust. To precisely identify the optimum location of the engine, the chord-wise and span-wise position along with the time-dependent thrust was derived in the equation of motion by using Lagrange's method. The effect of time-dependent thrust on a high-aspect ratio wing was studied by using a high-end software viz. NATASHA by [17].

In usual practice, the design of a combat aircraft wing energizes a researcher to understand and concentrate on short period time-dependent external excitations such as blast and gust. The aeroelastic response of the airfoil with a two-degree of freedom under aerodynamic and external pulse load in terms of gust or blast was presented by Marzocca et al. [18] as well as Librescu et al. [14]. Marzocca et al. [19] introduced unique indicial functions which can be used to determine the aeroelastic response of an airfoil subjected to different flow regimes such as subsonic compressible, transonic and supersonic. Also, they studied the dynamic responses with the blast load. The dynamic response of the beam