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Flutter Margins for Multimode Unstable Couplings with Associated Flutter Confidence

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The Zimmerman–Weissenburger approach presents an innovative tool for the prediction of the onset of flutter during a flight test. This approach computes flutter margins as the distance from any test point to that onset point by noting that a flutter function, which relates the stability of the aeroelastic dynamics, has approximately a quadratic dependency on dynamic pressure. The approach has assisted envelope expansion for many flight tests; however, it is limited to the consideration of two-mode coupling for the flutter instability. This paper introduces an extension to the Zimmerman–Weissenburger approach that accounts for multimode coupling in the flutter instability. The resulting flutter margins are actually computed by analyzing a combinatorial set of modal pairings that may be related through a multiplicative or norm formulation. Also, a metric of flutter confidence is formulated that associates how well the data used to generate these flutter margins adhere to the theoretical assumptions used in the approach. Flutter margins are computed for a modified 747 aircraft with a four-mode instability to show that the multimode approach with associated confidence is able to accurately predict the onset of flutter.

Nomenclature

F_C = flutter confidence
F_f = approximate flutter function
F_M = flutter margin
$F_{\bar{q}}$ = flutter condition
F_π = flutter function
f_0, f_1, f_2 = coefficients of quadratic function
i, j = indices
$\bar{q}$ = dynamic pressure
S = set of modal pairings
$\mathcal{S}$ = set of sets of modal pairings
β = real part of eigenvalue
λ = pole of the characteristic polynomial
π = characteristic polynomial
ω = imaginary part of eigenvalue

I. Introduction

FLIGHT testing for envelope expansion remains dangerous and costly due to challenges in predicting the onset of flutter. Several methods have been formulated for such predictions, including extrapolating damping trends [1], an envelope function [2], the Zimmerman–Weissenburger flutter margin [3], the flutterometer [4], and a discrete-time autoregressive moving average model [5]. These methods have been demonstrated on simulated data [6] and flight tests [7] to observe the quality of the resulting predictions.

The Zimmerman–Weissenburger approach to computing flutter margins is of particular interest to the flight-test community [8–13]. This method uses the Routh criterion to derive a flutter function, which varies with dynamic pressure, that relates the stability of the aeroelastic dynamics. The onset of flutter is thus predicted as the roots of this flutter function. The traditional approach to extrapolate damping trends can also be used to predict the onset of flutter; however, the damping function can be highly nonlinear whereas the Zimmerman–Weissenburger method has been shown to be a quadratic for a classic type of flutter caused by the coupling of two modes.

The implementation of the Zimmerman–Weissenburger approach must recognize several limitations in the formulation. A critical issue is the theoretical foundation that builds upon the assumption of a two-mode coupling even though flutter for many aircraft involves higher-order coupling of many modes. The computation of roots that represent the flutter margins is also built upon an assumption of quadratic dependency even though the variation observed using flight data is rarely a pure quadratic. As such, these flutter margins are valuable but must be accepted with some level of caution.

This paper introduces an extension to the Zimmerman–Weissenburger approach that allows flutter margins to be computed for dynamics with higher-order coupling of more than a pair of modes. The extension notes that the characteristic polynomial for one system with n modes can be expressed as the product of the characteristic polynomials for $n/2$ systems with two modes. A flutter function is thus similarly formulated as the product of the Zimmerman–Weissenburger formulations for each of the $n/2$ systems with two modes. The resulting functional retains its quadratic dependency on dynamic pressure and so can compute the onset of flutter for multiple modes that couple in the instability.

Also, a metric associated with confidence is developed for the flutter margins. This metric relates the degree to which the flight data have properties that satisfy the theoretical assumptions behind the Zimmerman–Weissenburger approach. The quadratic nature of the flutter function and the closeness to the onset of flutter are all parameters included in the flutter confidence. The actual metric is normalized to easily analyze the associated flutter margin.

An envelope expansion is simulated for a modified version of a 747, noted as the SOFIA, that has a flutter instability induced by the coupling of four modes. A set of flutter margins are computed using the traditional two-mode assumptions for the Zimmerman–Weissenburger approach along with a four-mode formulation from the extended approach. The accuracy of the resulting margins are shown to correlate with the confidence metric. In this way, the concept of a flutter margin is shown for a vehicle that violates several assumptions of the initial Zimmerman–Weissenburger approach.

II. Two-Mode Flutter Margin

The flutter margin, as originally formulated by the Zimmerman–Weissenburger approach [3], is an indicator of distance to flutter in terms of dynamic pressure. The development of this method is based on the equations of motion for a classical aeroelastic system of

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