A CO-KRIGING-BASED FLUTTER BOUNDARY PREDICTION METHOD INTEGRATING AEROELASTIC MODELS WITH FLIGHT TEST DATA

Penghui Chao, Zhigang Wu*, Chao Yang

School of Aeronautic Science and Engineering, Beihang University,
No. 37, Xueyuan Road, Haidian District, Beijing
China

ABSTRACT

Flight flutter testing is a critical phase in the design and certification process of a new aircraft. During these tests, the structural dynamic responses are measured over a range of increasing airspeeds to identify the critical flutter speed. Conventionally, the most prevalent approach for flutter prediction is damping extrapolation, which involves estimating the modal damping from subcritical responses and tracking its trend against airspeed. However, due to the highly nonlinear relationship between modal damping and airspeed, subcritical damping data cannot always be safely extrapolated to obtain an accurate prediction for the critical flutter speed, particularly when only sparse flight test data are available.

To overcome the limitations inherent to conventional curve-fitting-based methods, including damping extrapolation, the flutter margin method and the autoregressive moving average (ARMA) method, the model-based flutter prediction methods have been proposed. These methods, exemplified by the Nissim-Gilyard method and the flutterometer, integrate aeroelastic models with experimental data to identify or update physical parameters. Theoretically, model-based methods can provide superior predictive accuracy with fewer test points at lower airspeeds. Nevertheless, their practical application remains limited, primarily due to the discrepancy between theoretical models and real flight conditions.

To address these challenges, a Co-Kriging-based flutter boundary prediction method is proposed to integrate sparse flight test data with extensive computations from analytical aeroelastic models. The highlight of the present approach lies in leveraging the synergistic advantages of two distinct information sources with different levels of fidelity: the global trend captured by expansive, low-fidelity analytical aeroelastic computations, and the local precision provided by sparse, high-fidelity flight test data. Unlike traditional flutter boundary prediction methods, the present framework does not merely update physical parameters but systematically captures the bias function between the analytical models and the experimental observations within a multi-fidelity surrogate model, thereby maintaining better physical consistency. The overall implementation of the proposed method is organized into the following four steps.

First, the aeroelastic equations of motion are formulated. The structural matrices (mass, damping, and stiffness) are initially derived and subsequently correlated with ground vibration test and structural modal coupling test. Rational function approximation (RFA) is then employed to transform these equations into state-space form, thereby reformulating the flutter boundary prediction as an eigenvalue analysis of the state matrix.

Second, a model updating procedure is executed to minimize the discrepancy between theoretical predictions and flight test observations. Recognizing flutter as a dynamic stability phenomenon, the objective function is defined based on the residuals of modal frequencies and damping ratios between experimental data and results of the aeroelastic model. A genetic algorithm (GA) is utilized to optimize the aerodynamic influence coefficient (AIC) matrices at specific Mach numbers, ensuring the model accurately reflects the observed flight physics.

Subsequently, a multi-fidelity surrogate model is constructed using the Co-Kriging method. The model takes Mach number and dynamic pressure as inputs to predict the system state matrices of aeroelastic models. Two distinct data sources are employed: a high-fidelity dataset with a limited number of samples incorporating corrections derived from flight test data, and a low-fidelity dataset consisting of a larger number of samples generated from the unmodified analytical aeroelastic model.

Finally, the flutter boundary is determined through the Co-Kriging surrogate model. Modal frequencies and damping ratios are extracted from the eigenvalues of the state matrices predicted by the model. Progressively increasing the dynamic pressure, the evolution of modal characteristics is tracked until instability is detected, thereby determining the critical flutter speed.

The proposed method is applied to the flutter boundary prediction of a conventionally configured aircraft. Preliminary results demonstrate that the Co-Kriging-based framework significantly enhances the accuracy of flutter boundary prediction compared to both purely analytical models and traditional damping extrapolation methods. These results demonstrate the potential of the proposed method for improving the reliability of flutter boundary prediction in flutter flight testing, particularly under conditions of limited flight test data.

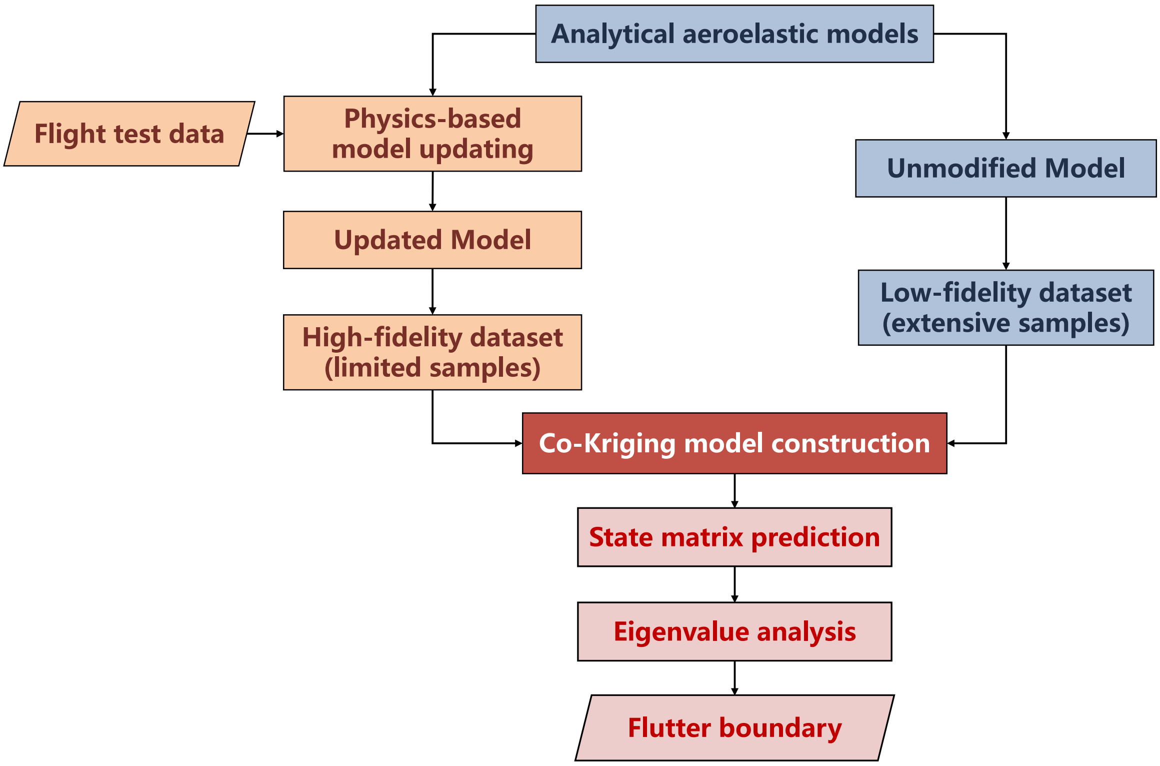

Fig. 1 Overview of the proposed Co-Kriging-based flutter boundary prediction method