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Modal Identification of Aircraft Wing Coupled Heave-Pitch Modes Using Wavelet Packet Decomposition and Logarithmic Decrement

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Abstract

Low frequency bending mode (heave) and high frequency twisting mode (pitch) are the two typical modes of motion that exist in an aircraft wing. Coupling of these modes produce flutter effect, which can severely distort the wing without warning. To avoid such distortions, flutter speed must be identified accurately by using modal parameters, so that necessary decision could be taken. This paper focuses on using an effective method for the modal testing of an aircraft wing to estimate the modal parameters of coupled heave-pitch modes. The method includes Wavelet Packet Decomposition (WPD) to uncouple a complex signal, followed by Logarithmic Decrement Method to estimate the modal parameters. Simulation is done to validate the effectiveness of the method. Finally the method is applied on the 2-DOF model (NACA 0012 aerofoil wing model) under free vibration test to estimate coupled heave-pitch modal parameters.

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Keywords: coupled heave-pitch; modal parameters; wavelet packet decomposition; logarithmic decrement; wing flutter

1. Introduction

Aeroelastic flutter is an unstable, self-excited structural oscillation at a definite frequency where energy is extracted from the airstream by the motion of the structure [1]. There occurs interaction of heave and pitch modes in such a way that energy absorbed from the airflow in heave mode gets transferred to the pitch mode. At a particular speed of airflow, the frequency of heave and pitch modes converge to the same value and only one combined mode

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of high amplitude is possible. The speed at which the convergence of modes occur is called as flutter speed. It is the lowest airspeed at which an aircraft wing will oscillate with sustained simple harmonic motion [2]. At speeds above the flutter speed represents condition of unstable (divergent) oscillation [2]. As the strength of wing becomes weaker in shear than in tension, it fails in shear catastrophically without warning.

To avoid such distortions, a flutter test is always required, so that necessary decision could be taken. Flutter test includes modal parameter identification, and prediction of the critical point of flutter through tracking damping ratio in the subcritical state, [3]. This paper focuses only on estimating accurate modal parameters of coupled heave-pitch modes using experimental modal analysis. There are various methods to estimate modal parameters in frequency domain, time domain, and time-frequency domain. Various system identification techniques related to flutter are presented in [4]. The conventional modal analysis technique in frequency domain (FFT based technique) shows physically little sense towards real signal (non-linear system and non-periodic or non-stationary signal), [5]. With the advancement of signal processing methods, it is now possible to characterize the real signal in time-frequency domain.

The problem associated with peak picking technique (basic frequency domain technique) includes: (i). there occurs deviation in the estimated modal parameters due to the presence of leakage, (ii). it has uncertainty in estimating damping (iii). it has limited frequency resolution, [6]. Shinde and Hou [7] incorporated Hilbert Transform with Wavelet Packet Decomposition that is effectively used for structural health monitoring. In [8], a wavelet-logarithmic decrement method to estimate damping has been introduced, in which the analytical and the numerical validation are investigated, followed by the application of the method to identify damping of in situ dynamic response of civil engineering building, [9]. The aim of this paper is to characterize the dynamic behavior of coupled heave-pitch modes of an aircraft wing, using the logarithmic decrement method applied to filtered (uncoupled) components of the original response (using Wavelet Packet Decomposition). Simulation is done to validate the effectiveness of the method. Finally the method is used for the modal identification of 2-DOF model (NACA 0012 aerofoil wing model) under free vibration test.

2. Wavelet Packet Decomposition

Wavelet analysis is a multi-resolution analysis (time-scale or time-frequency analysis), which is an alternative approach for Short Time Frequency Transform (STFT) to overcome the resolution problem. Like Fourier analysis (sine and cosine as basis), wavelet as a basis is used in wavelet packet analysis. It is a windowing technique (variable-sized window) that splits up the signal in to bunch of shifted and scaled versions of the mother wavelet. This is discussed in detail in [10]. Continuous Wavelet Transform (CWT) measures the similarity between the basis functions (wavelets) and the signal itself. Mathematically:

$$W_x(\tau, s) = \int x(t)\psi^*_{\tau,s}(t)dt \tag{1}$$

Here $W_x(\tau, s)$ is the wavelet coefficient, $x(t)$ is the input signal, $\psi^*_{\tau,s}(t)$ is the conjugate of window function (mother wavelet), τ and s are translation (position) factor and dilation (scaling) factor respectively.

There are infinite numbers of CWT coefficients in time-scale plane. Like FT and STFT, discrete wavelet transform (DWT) can be computed digitally by sampling the time-scale plane, in order to choose the finite numbers. In DWT, original signal is decomposed in to approximations (low frequency) and details (high frequency). The approximations can be further decomposed and can be iterated. The signal can be decomposed in to tree like structure "wavelet decomposition tree", as shown in Fig. 1(a). Mathematical representation of wavelet decomposition tree:

$$f(t) = \sum_{i=1}^{i=j} D_i(t) + A_j(t) \tag{2}$$

Here $D_i(t)$ denotes the wavelet details, and $A_i(t)$ denotes the wavelet approximation at the jth level.