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Identification of modal parameters for nonstationary mechanical systems

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Abstract This paper presents two different approaches to the identification of modal model parameters for nonstationary mechanical systems. The problem is related to model-based structural health monitoring. Damage in this approach is detected by tracking modal parameters of the structure during operation. The detected parameter changes can be indicators of structural damage. The recursive method based on the autoregressive moving-average model of signals and wavelet-transform-based algorithms are presented. The methods are tested using simulated data. Case studies of airplane flutter detection are shown using both methods.

1 Introduction

Many practical engineering systems change dynamic parameters during operation. Parameters may change as a result of damage. The problem of damage detection can be defined as the identification of parameter changes in a system model. In the literature [1] this approach is called model-based diagnostics. The classical approach to model-based damage detection is formulated [2] on the assumption that a system is stationary during the identification experiment. But nonstationary behavior due to system damage is expected for some experiments. In practical cases, however, the system model parameters can be changed during any given experiment, in which case the system should be treated as nonstationary. The identification and analysis of nonstationary systems is more difficult than of stationary systems. One of the most important cases of nonstationary behavior of aviation structures is flutter. Flutter is a complex phenomenon where, in the classical case, two or more structural modes are coupled and excited through aerodynamic loads [3,4]. The flutter phenomenon is related to a self-excited vibration phenomenon present at a certain forward flow speed. A self-excitation mechanism makes it possible to stimulate flutter even in cases where aerodynamic loading is time independent but is due to feedback between bending and torsion vibration modes. The feedback causes the damping force to decrease with constant excitation forces. For a given combination of flight parameters the vibration damping forces can be very low, even less than zero. In such a case, the amplitude will immediately increase and in certain cases the structure can lose integrity. The modal parameters, which are responsible for increases in the vibration amplitude at a given flight speed, are dampened [5–8]. The damping ratios of the critical modes are commonly used as the index of the flutter stability margin. Damping can change due to variations in air speed or air density during flight for a given aircraft design. If damping is less than zero, then in a system that has lost stability and vibration the amplitude can increase immediately to a very high value, which can be a reason for structural damage. Then vibration modes for which damping is very small should be carefully investigated according to flutter phenomena [9–11]. Modal parameters of the structure can be extracted using experimental modal-analysis techniques, but such techniques are formulated and valid for stationary mechanical systems (with constant
Methods for identifying modal parameters of the structure for the nonstationary case are presented in the following sections. An airplane case study is presented in [14].

Methods for in-flight modal parameter identification should be based on vibration measurements of air structure by ambient excitation (nonmeasured) because in-flight artificial excitation incurs extra costs and is not an easy task.

Currently several Operational Modal Analysis (OMA) methods are available in both the time as well as frequency domains [15–17]. The methods allow one to identify the modal parameters of a structure based solely on response measurements. Some of these methods can be used online to help detect early changes in damping for modes under investigation. The most commonly used method is one based on measurement data segmentation and independent identification of damping for each data segment. This method is formulated on the assumption that a signal is stationary within a defined signal segment. Different methods using an online approach of parameter updating for autoregressive (AR) or moving-average (ARMA) model parameters can be applied. The method of online identification applied in this study is based on a recursive least-squares (RLS) algorithm of regression model parameters and on the extraction of damping from characteristic polynomials of a discrete model. The main problem with an online realization of the identification procedure has to do with the online extraction of complex roots of characteristic polynomials. The test of quality of both presented algorithms for simulated and experimental data is presented in this paper.

The second approach, which is now available, is the application of a wavelet transform for signal processing [17, 18]. The wavelet transform is a technique that is dedicated to cases of nonstationary signals. There are a few possible techniques in the literature [19–22] for identifying modal parameters from nonstationary data. In this paper the method based on the Morlet wavelet transform is presented and tested on simulated and real flight data.

2 Applied identification procedures

The methods presented in this paper are based on a discrete representation of a linear dynamic model for an Multi Degrees of Freedom system. This model is commonly used for modeling time series and dynamic systems if only the output is measured. The most commonly used ARMA model has two parts; the AR part describes system properties, while the MA part describes disturbances of the measured signals.

Three algorithms are considered for application to flutter detection during airplane flight:

• Signal-segmentation method