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Identification of Volterra kernels for improved predictions of nonlinear aeroelastic vibration responses and flutter

R.M. Lin, T.-Y. Ng*

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Aeroelastic structural systems are intrinsically nonlinear and accurate predictions of dynamic responses of nonlinear aeroelastic systems have become of paramount importance since these directly affect the accuracy and reliability of subsequent stability analyses. Such nonlinear systems can be generally represented with Volterra series whose kernels have been found to be effective in their dynamic characterizations. This paper examines how first- and second-order Volterra kernels of nonlinear aeroelastic systems can be accurately identified and then incorporated into the theoretical models of aeroelastic analyses such as predictions of dynamic response and onset of aeroelastic flutter. A novel identification method based on correlation analysis to extract frequency components has been developed which can be applied to general nonlinear aeroelastic systems to obtain accurately the required Volterra transfer functions. The method is very accurate and extremely robust against measurement noise contaminations in both input and output signals, due to the correlation scheme which effectively filters uncorrelated signal components. Detailed aeroelastic behavior of a representative pitch-plunge airfoil dynamic model with nonlinear pitch stiffness has been examined. Its Volterra transfer functions are then identified which are found to be close to their exact analytical counterparts, though interaction between kernels becomes apparent as input level increases. Once inverse Fourier transformed, these identified Volterra kernels are then included in the modeling of the dynamics of aeroelastic systems for vibration response and flutter. Extensive numerical simulation results have demonstrated that the proposed method is very accurate and resilient to measurement errors when applied to the identification of second-order Volterra kernels, and the improvement in predictions of vibration response and flutter become significant when the contributions of these second-order Volterra kernels are included in the overall aeroelastic system dynamics. The identification and subsequent inclusion of second-order Volterra kernels into system dynamics model offer improved design capabilities of nonlinear aeroelastic structural systems.

1. Introduction

Aeroelastic structural systems are intrinsically nonlinear due to nonlinear aerodynamics effects such as shock wave motion and/or separated flow [1], geometrical structural nonlinearities due to large displacements [2] and free-play of control surfaces [3]. For linear aeroelastic structural systems, it is well known that they become unstable when certain critical flutter speeds are reached. For nonlinear aeroelastic structural systems however, such instability usually degenerates into limit cycle oscillations (LCOs) and different types of LCOs have been observed in practice [4]. This means nonlinearities in aeroelastic structural systems are somehow beneficial since they prevent catastrophic flutter failures to be built up. Nevertheless, nonlinearities have rarely been deliberately chosen and designed into aerospace vehicles and more often, aerospace structural designers are dealing with unanticipated and possibly unwanted nonlinearities as they manifest themselves throughout services [2]. As our analytical modeling and experimental characterization improve, there is an increasing awareness and growing demand nowadays that nonlinearities need to be accurately engineered and incorporated to form an improved mathematical model with better design prediction capabilities in order to achieve optimal and efficient structural designs. Such a shift in design paradigm becomes necessary since the operating envelopes of most modern structures have been constantly expanded to nonlinear regimes due to relentless drive for high performance and cost-efficient structures, especially those in aerospace engineering where structural safety margins are typically very small as compared with other industry standards such as those of civil engineering structures.

There have been enormous research interests and activities in the studies of nonlinear aeroelasticity over the last 3 decades and extensive

* Corresponding author.
E-mail addresses: mrmlin@ntu.edu.sg (R.M. Lin), mtyng@ntu.edu.sg (T.-Y. Ng).

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research publications have now been available. This paper focuses on identifications of nonlinear aeroelastic structural systems for improved predictions of vibration responses and flutter. System identification is a process of developing a mathematical representation of a physical system based on observed test data. It is a critical step in aircraft development, analysis, and validation for flight-worthiness. One such application in aerospace industry is the analysis of aeroelasticity. Aeroelasticity is concerned with the interactions of inertia with structural, and aerodynamic forces [5]. Previous approaches have modeled aeroelasticity with linear time-invariant models [6]. These linear models have been successful in providing approximate estimates of an aircraft's response to gust, turbulence, and external excitations [7]. However, as aircraft speed approaches supersonic or transonic regimes, linear models no longer provide accurate predictions of the aircraft's dynamic behavior. Some of the behavior that cannot be modeled linearly includes transonic dip, airflow separation, and shock oscillations, which can induce nonlinear phenomena such as LCOs [4,8,9]. The onset of LCOs has been observed on several aircraft such as the F-16 and F/A-18 [9]. This has led to the development of nonlinear identification techniques to accurately model LCO dynamics. To date, significant achievements have been made in several areas of non-parametric nonlinear system identification [10–12]. Leontaritis and Billings [13,14] have proposed the NARMAX structure as a general parametric form for modeling nonlinear systems. Ibrahim and Woodall [15] examined modal identification for nonlinear aeroelastic systems. Zeng et al. [16] employed Hammerstein model for the identification of nonlinear aeroelastic/aeroservoelastic system parameters. More recently, there have been rigorous attempts to address nonlinear aeroelastic phenomena using Volterra kernels [17]. Lin [18] and Lin and Ewins [19] developed an effective measurement and analysis technique to accurately measure and analyze first-order Volterra transfer functions for identification of structural nonlinearities. Morzocca et al. [20] investigated aeroelastic response and flutter prediction of a nonlinear airfoil via Volterra series. Balajewicz and Dowell [21] demonstrated that sparse Volterra reduced-order models are capable of efficiently modeling the aerodynamically induced limit-cycle oscillations. Wu et al. [22] conducted linear and nonlinear aeroelastic analysis of cable-supported bridges using an artificial neural network and Volterra series. Kurdila [23] identified the reduced-order Volterra models for aeroelastic systems with multiple inputs and multiple outputs by utilizing multiwavelet basis expansion method. Lind et al. [24] introduced parameter-varying Volterra series model from which the onset of flutter can be accurately predicted by analyzing test data at subcritical air speeds. Prazenica et al. [25] designed an extrapolation method to extend Volterra kernels beyond flight flutter test data.

However, for realistic nonlinear aeroelastic structural systems, it is perhaps justified to say that very little progress has been made in the accurate and reliable identification of higher-order Volterra kernels, not to mention their subsequent applications to improved aeroelastic vibration response and flutter predictions. Direct identifications of Volterra kernels of nonlinear aeroelastic systems in time domain have been reported in [24,25], the accuracy achieved to date has, nevertheless, not been quite satisfactory. Volterra kernels are not analytically explicitly defined in time domain given complete description of equations of motion of a nonlinear system and since the contribution of higher-order kernels to overall system response is usually relatively small as compared with that of the underlying linear system, direct measurement of these kernels becomes extremely prone to measurement noise. Nevertheless, it is worth mentioning that some attempts have been made to express Volterra kernels in terms of impulse responses of the nonlinear system with variable magnitudes of impulses applied at different times [26], the thus defined impulse responses are not strictly derivable in their explicit analytical forms. On the other hand, higher-order kernels do contribute to the overall dynamics of the system and will have to be identified and included. Fortunately, Volterra transfer functions in frequency domain, which are defined as the Fourier transforms of the corresponding kernels in time domain [27], are uniquely defined and by using the correlation analysis technique to be developed in this paper, they can be very accurately identified since the effect of random measurement noise can be effectively minimized through uncorrelated numerical integration scheme. Measurement noise has been a problem in both time and frequency domains, the proposed method works in frequency domain extremely well while there have yet to be similar method developed in time domain for Volterra kernel measurement. This paper examines how Volterra transfer functions of nonlinear aeroelastic systems can be accurately identified in frequency domain and effectively incorporated into the model for the accurate prediction of system dynamic responses and how these Volterra kernels can be utilized to predict more accurately the onset of aeroelastic flutter. Detailed aeroelastic behavior of a representative pitch-plunge airfoil dynamics model with nonlinear pitch stiffness has been examined. A novel identification method has been developed which can be used to measure the Volterra transfer functions, which are in turn transformed to Volterra kernels through inverse Fourier transform for vibration response and flutter prediction. The method is very accurate and robust in the presence of measurement noise. It has been shown that with the availability of thus identified Volterra kernels, nonlinear aeroelastic vibration responses can be predicted much more accurately. Further, such improved response prediction can be translated into improved flutter speed prediction when second-order Volterra kernels are employed.

2. Volterra series representation and higher-order FRFs

Volterra series have been described as "power series with memory" which express the output of a nonlinear system in "powers" of the input [28]. A wide class of nonlinear systems encountered in engineering can be represented as Volterra series. Given an input $f(t)$, the output $x(t)$ of a time invariant system can, in general, be expressed as

$$x(t) = \int_{-\infty}^{+\infty} h_1(\tau_1) f(t-\tau_1) d\tau_1 + \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} h_2(\tau_1,\tau_2) f(t-\tau_1) f(t-\tau_2) d\tau_1 d\tau_2 + \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} h_3(\tau_1,\tau_2,\tau_3) f(t-\tau_1) f(t-\tau_2) f(t-\tau_3) d\tau_1 d\tau_2 d\tau_3 + \cdots\cdots \tag{1}$$

where the kernels $h_n(\tau_1, \tau_2, \ldots, \tau_n)$ are the Volterra kernels which describe the system. It should be noted that the first-order kernel $h_1(\tau_1)$ is the impulse response due to the linear part of the nonlinear system and the higher-order kernels can thus be viewed as higher-order impulse responses which serve to characterize the various orders of nonlinearity. In the special case when the system is linear, all the higher-order kernels except $h_1(\tau_1)$ are zero.

The Volterra series representation of a general nonlinear system is theoretically infinite and, as will be discussed later, the effort of identifying the n^{th}-order kernel increases exponentially as n increases so that one has to be satisfied in practice with the first few kernels only. Fortunately, for the typical 2D nonlinear airfoil model to be studied in this paper, the contributions of n^{th}-order kernel ($n \geq 3$) to the overall vibration response become increasingly smaller as n increases, as will be shown in the component analysis of a typical vibration response later. This implies that good approximations can be still obtained for vibration analysis of the airfoil model even though only the first- and second-order kernels are available and included in the system dynamics model.

The n^{th}-order Volterra transfer function is simply defined as the n-dimensional Fourier transform of the n^{th}-order Volterra kernel,

$$H_n(\omega_1,\omega_2,\cdots,\omega_n) = \int_{-\infty}^{+\infty}\cdots\int_{-\infty}^{+\infty} h_n(\tau_1,\tau_2,\cdots,\tau_n) e^{-\mathbf{i}(\omega_1\tau_1+\omega_2\tau_2+\cdots+\omega_n\tau_n)} d\tau_1\cdots d\tau_n \tag{2}$$

If all the Volterra transfer functions $H_n(\omega_1, \omega_2, \ldots, \omega_n)$ $(n = 1, 2, \ldots)$ have been determined, system output $x(t)$ can be calculated for any form of inputs. Since $H_n(\omega_1, \omega_2, \ldots, \omega_n)$ are unique and independent of input and output of the system, the Volterra series representation is