# Chaotic Vibration-Based Damage Detection in Fluid-Structural Systems

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## Extended Abstract

Detecting parametric variations and damage detection are of great significance in various industries, and are a pervasive need in engineering applications. They are motivated by intellectual reasons and by industrial requirements. For example, advanced methodologies for monitoring structural integrity are needed by the manufacturing and aerospace industries. A highly publicized case, reiterating the importance of detecting parametric variations in fluid-structural systems, is the recent catastrophic accident of an airplane whose vertical stabilizer had been damaged by fatigue and led to a tragic crash. This paper discusses advanced vibration-based methods designed to predict such failures and assess structural integrity in fluid-structural systems.

Most of the vibration-based tools available for detecting damage in systems such as vertical stabilizers, panels and control surfaces of airplanes are based on linear modal analyses, and do not benefit from the features particular to chaos. Such analyses pertain to the field of linear mechanical vibrations, which is relatively mature, although there are several areas of this field where investigations are still necessary, such as mid-frequency analysis. In contrast, the field of nonlinear and chaotic vibrations presents many challenges and has re-captured recently the interest of researchers in academia and industry especially because many engineering systems, previously approximated as being linear, are in fact nonlinear. In structural dynamics for example, nonlinearity is often observed, and it is due to friction, the presence of rivets, bolts, free play, and other factors. Nonlinear phenomena are wide spread and very important because their dynamics can dramatically differ from predictions made by linear theories. The recent advances in the understanding of nonlinear and chaotic phenomena provide the means to tackle a new necessity, *i.e.* the development of reliable methodologies to mitigate and to benefit from the effects of chaos for damage detection. This paper proposes a novel approach to vibration-based damage detection which takes advantage of the features of chaos caused by complex fluid-structure interactions.

The area of damage detection and health monitoring has undergone a rapid development recently, and new methods and techniques continue to be proposed.[6] Health monitoring refers to the use of non-destructive sensing and analysis of system characteristics for the purpose of detecting structural changes which may indicate damage.[15] Health monitoring is often approached as a system identification problem[17] where changes in the parameters of an identified model are monitored.[4,5,7] A large portion of the work in this area has been focused on least-squares identification methods applied to linear models,[1,18,23,29] resonant frequencies,[31] mode shapes,[24] and subspace identification methods.[22,32] Most system identification procedures used for structural health monitoring are based on off-line approaches[27] although recently on-line damage detection methods have been proposed as well.[26,30] Also, the Yorke-Kaplan conjecture from the complex system theory has been used at NRL for the pioneering study of linear systems with chaotic excitation.[25] Both numerical[3] and experimental[33] investigations of linear structures have been performed. However, most of the current studies are based on linear theories and linear structures. In contrast, this paper is focused on chaotic dynamics and has the advantage of an increased accuracy in detecting damage.

In addition to these particularities of chaotic dynamics, the feature monitored to detect structural changes is the level of coherence in the dynamics of the system. The approach used for identifying these coherent structures is proper orthogonal decomposition (POD).[12–14] This approach requires

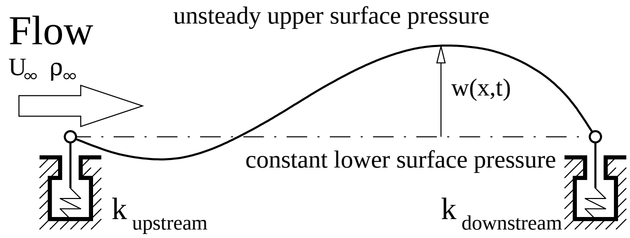


Figure 1: *Two-dimensional buffeting panel*

measurements of the dynamics of the system of interest over a time interval. A model for the spatial coherence of the dynamics is constructed based on these measurements. For linear systems, the models obtained using POD are similar to models obtained by modal analyses. However, distinct from linear modal analyses, POD may be used for *nonlinear* systems. Holmes, Lumley and Berkooz[19] and Sirovich[28] also used POD in the context of turbulent flows as a technique which allows for the identification of naturally forming coherent structures from numerical simulations or experiments. These coherent structures contain most of the energy and are the most important components of the dynamics.[16,20]

Exciting results have been obtained by investigating a panel forced by buffeting aerodynamic loads. This aeroelastic system includes structural nonlinearities due to the coupling between the bending and the elongation of the panel (Fig. 1). The aerodynamics is considered linear and piston theory[21] is used. The panel displacements are considered much smaller than its chord and comparable to the panel thickness. The panel is considered homogeneous, isotropic, and two-dimensional, and it is modeled using nonlinear von Karman plate theory. Such panels have been studied extensively by Dowell *et al.*[8–11] in the supersonic flow regime. They observed that the interaction of dynamic (flutter) and static (buckling) instabilities leads to very complex dynamics, which includes, static deformations, limit cycle oscillations, and chaos. Most of the previous studies of the dynamics of panels under buffeting aerodynamic loads are based on the Galerkin method for numerical simulations. Distinct from those methods, a finite-difference method is used herein, and POD[2,13,14,19] is used to detect parametric changes in the aeroelastic system. The sensitivity of the chaotic dynamics to parametric changes is shown to be an effective tool in detecting damage, such as loss of stiffness in the upstream and/or downstream mounting points of the panel.

Most of the current studies of such problems are based on linear theories and linear structures. In contrast, the results presented are obtained using chaotic dynamics. The sensitivity obtained by exploiting the features of chaotic dynamics is shown herein to be more than four orders of magnitude higher than the sensitivity of standard linear analyses where similar stiffness loss in the structure is monitored by detecting changes in the frequencies of vibration of the linearized system.

Finally, the inverse damage detection problem is investigated. The shape of the attractor of the chaotic dynamics in an embedded (state) space is shown to provide a wealth of information in regards to the type and magnitude of the parametric changes (damage). Separate and/or simultaneous changes in the stiffness of the upstream and downstream mounting points is detected and estimated based on an analysis of the geometric shape of the attractor of the chaotic dynamics.

The significant advantages of the proposed analysis are accompanied by a few limitations. The most important limitation is the requirement that a chaotic oscillation be present. However, this limitation may be overcome when a chaotic excitation may be provided to the system.

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