Flow-Oscillating Structure Interactions and the Applications to Propulsion and Energy Harvest

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Abstract

This manuscript reviews the advance in understanding of the mechanisms of the interactions between oscillating structures and fluid flows. Many analytical, numerical and experimental approaches to model and to identify the non-stationary, nonlinear interactions between fluid flows and oscillating structures are summarized. The applications of fluid flow-oscillating structure interaction to propulsion and energy harvest are discussed. The issue of the establishment of generalized, parametric, reduced-order models is discussed with an aim at illustrating the perspectives for improving the correlation between test data and physics-based modeling.

Keywords: fluid flows, oscillating structure, interactions, propulsion, energy harvest

1. Introduction

Fluid-structure interaction occurs when fluid flow causes deformation of the structure. This deformation of a solid structure, in turn, changes the boundary condition of the fluid flow. One example is the interaction between fluid flow and an oscillating structure. Functionally many natural and engineering systems require the operation of fluid flow-oscillating structure interaction. For example, many biological and engineering systems use flapping motion of their wings/fins for propulsion. In similar principle but in an inverse way, the similar systems are used to harvest kinetic energy from the fluid motion.

It has been widely recognized that fluid flows can exert many types of forces on a structure, such as viscous force, inertia force, added mass, diffraction force, Froude-Kryloff force, lift force, wave slamming force, etc, just to name a few. Many methods has been used to investigate interactions between oscillating structures and fluid flows to uncover the underlying mechanisms, to reconstruct the coupling forces, and to model critical parameters from coupled physics phenomena.

There has been ample research dedicated to modeling of fluid flow-oscillating structure interaction, with the fluid motion described by Navier-Stokes equations and the structure modeled by elastic continuum, idealized as a rigid body, or simplified by arbitrary Lagrangian-Eulerian formulation. In engineering applications, the majority of the methods use reduced-order models that only model specific cases empirically.

Because the standard assumptions of fluid dynamics associated with most models do not adequately represent the complexity of site boundary behavior in most application cases, it is difficult to accurately model the effects of fluid forces on the non-stationary, nonlinear responses of flexible structure. Moreover, from the perspective of structural dynamics, many empirically established fluid force models have their limitations from the decoupling assumption as the fluid forces are treated as external force to structure.

Therefore, while computational fluid dynamics techniques are increasing in power and sophistication, at thetime being they appear to still have a long way to go before they are capable of simulating with convincing accuracythe effect of intricate geometric details as well as structural motions and turbulence, so experimental tests are stilllikely to remain the most accurate tool.

This review summarizes the basic understanding on fluid flow-oscillator interaction and various modelsdeveloped in the literature. The review focuses on the models used for the structure analysis in fluid flow-oscillatorinteraction, and their limitations are discussed. The applications of fluid flow-oscillating structure interaction topropulsion and energy harvest are also discussed.

2. Flow-oscillator Interaction

The most widely known flow oscillator interaction is flow-induced vibration. Flow-induced vibration occurs whenstructures perform oscillatory motion under the effect of fluid-structure interaction. Varied kinds of flow-inducedvibrations such as vortex-induced vibration, flutter, galloping, and buffeting, have been widely studied and theunderlying mechanisms have been gradually understood. This review focuses on two widely studied phenomena.

2.1 Vortex-induced Vibration

When a fluid flow with an intermediate and high Reynolds number passes around a structure such as a cylinder, thefluid near the structure starts to oscillate due to vortex shedding. These shedding vortices exert an oscillatory forceon the structure in the direction perpendicular to both the flow and the structure. The frequency of oscillation f isrelated to the velocity of the incoming flow U, and the dimension of structure D by the non-dimensional Strouhalnumber $St = D f / U$. When the flow passes by a flexibly supported structure that is capable of performing oscillatorymotion, the shedding frequency is also controlled by the movement of the structure. When the shedding frequency is close to the first natural frequency of the structure system, the oscillator takes control of the vortex shedding. Thevortices will shed at the natural frequency instead of at the frequency determined by the Strouhal number. This is called lock-in or synchronization, which is a result of nonlinear interaction between the oscillation of the structurebody and the action of the fluid. Vortex-induced vibration is the subject of many conventional research and surveys (e.g., Ehsan & Scanlan, 1989; Larsen, 1995; Sarpkaya, 1995; Sarpkaya, 2004; Gabbaia & Benaroya, 2005; Williamson & Govardhan, 2004; El-Gammal, Hangan, & King, 2007; Williamson & Govardhan, 2008; Morse, Govardhanb, & Williamson, 2008).

Vortex formation is a key feature of fluid-structure interaction at intermediate and high Reynolds numbers. Agreat variety of wakes can be formed by oscillating the cylinder laterally in the free stream (Williamson & Roshko, 1988; Koochesfahani, 1989; Lai & Platzer, 1999). The wakes behind the oscillating cylinder include von Karmantypewakes in which two vortices of opposite sign are shed per oscillation period. In propulsion, usually the reversevon Karman vortex streets are generated in the fluid wakes in which vortices have opposite rotational directions.Whereas the von Karman street represents a drag wake, the reverse von Karman wake represents thrust production(von Karman & Burgers, 1963). As it is described (Schnipper, Andersen, & Bohr, 2009), the reverse von Karmanwakes are observed in the wakes of various flying and swimming animals and are believed to play an important rolein biological locomotion (Lighthill, 1969; Sfakiotakis, Lane, & Davies, 1999; Triantafyllou, Triantafyllou, & Yue, 2000). Some animals have more complex vortex structures in their wakes (Muller, Smit, Stamhuis, & Videler, 2001; Muller, van den Boogaart, & van Leeuwen, 2008). These vortex structures can also be observed in the wakes of aflapping foil. Visualization a variety of wakes, including von Karman vortex street, reverse von Karman vortexstreet, and other complex wake structures were studied by varying the frequency and amplitude of the oscillation ofa symmetric pitching foil (Ringuette, Milano, & Gharib, 2007). More complicated three-dimensional vortex wakestructures are observed behind an oscillating plate with low aspect ratio (Buchholz & Smits, 2008; Godoy-Diana, Aider, & Wesfreid, 2008).

Many efforts have been made to investigate the underlying mechanism of the vortex-induced vibration. Empirical, numerical and theoretical approaches have been used in these studies. Empirical modeling of vortex-inducedvibration has been widely reported in books and articles. For many engineering applications such as vortex-inducedvibration of cylinder oscillator, the empirical models can be classified into two groups: the forcedecomposition model and the wake oscillator model. In force decomposition model, fluid force is decomposed intotwo components, a fluid inertia force and a fluid damping force related to structure displacement and velocity, respectively. The fluid force has also been treated as an excitation part and a reaction part; the latter included allmotion-dependent force components. More generally, unsteady flow theory is used, and the fluid force is assumed tobe dependent on the displacement, velocity, and acceleration of the structure. In the modeling, data collected fromfree and forced vibration experiments was used to determine the fluid force components. In a wake-oscillatorapproach, a van der Pol-type equation has been developed as the governing equation of the lift force. This equationwas coupled to the structure dynamic equation through one or several terms related to the structure dynamics.

For flexible structures, hydrodynamic forces from the interactions might cause deformation of the structures, leading to more complex structure responses. The vortex-induced vibration of a flexible circular cylinder has beeninvestigated (Williamson, 1996; Khalak & Williamson, 1997a, b and 1999; Jauvtis, & Williamson, 2004; Xu, Wu, Zeng, Zhong, & Yu, 2010; Huera-Huarte & Bearman, 2011). The comprehensive flow-elastic continuum modelshave been simplified as reduced-order model with multiple degree-of-freedom. For example, Zhao & Chenginvestigated two-degree-of-freedom vortex-induced vibration model close to a plane boundary (Zhao & Cheng, 2011). The Reynolds-Averaged Navier-Stokes equations were solved using the Arbitrary Lagrangian Eulerianscheme with a turbulence model. Different vortex shedding modes were identified. Bearman presented a selectivereview of recent research on vortex-induced vibrations of isolated circular cylinders (Bearman, 2011). There havebeen debates about whether the flows generated by freely oscillating and forced oscillated cylinders can be the same.Controlled-vibration experiments demonstrated that under carefully controlled conditions there was a very closecorrespondence between these flows (Morse & Williamson, 2009). Li, Zhang, & Zhang presented a study to discussin detail the vortex-induced vibration of a cylinder oscillator (Li, Zhang, & Zhang, 2011). The 2D incompressibleNavier-Stokes equations were solved with the space-time finite element method. For the situation of low massdamping and low Reynolds, the locked in and beat phenomena with are captured. The nonlinear phenomena, such asthe limit cycle and bifurcation of lift coefficient and displacement, are analyzed. Another study showed the monofrequencyas well as multi-frequency vortex-induced vibration of a tensioned beam immersed in a linear shear flowand free to move in both the in-line and cross-flow directions, using direct numerical simulation (Bourguet, Lucor, & Triantafyllou, 2012). A reduced-order analytical model of nonlinear fluid-structure interactions was alsodeveloped by using the Hamilton's principle and Navier-Stokes equations (Benaroy & Gabbaia, 2008; Gabbaia & Benaroy, 2008). A similar study built a general low-order fluid-structure interaction model capable of evaluating themulti-mode interactions in vortex-induced vibration of flexible curved/straight structures (Srini, 2010). Aconservative fourth-order central finite differencing scheme for all the viscous terms of compressible Navier-Stokesequations to simulate the vortex-induced vibration was also developed (Shen, Zha, & Chen, 2009).

There are many models for studying the interactions between flexible plates and fluid flows. A nice summarycan be found in Shelley & Zhang (2010). A model was developed using a quasi-steady version ofBernoulli's equation on the flapping plate, and neglects the presence of a shed wake (Fitt & Pope, 2001). A furtherstudy (Argentina & Mahadevan, 2005) retained the effect of added mass, modeled the effect of vortex sheddingfrom the trailing end, and avoided calculation of a velocity potential by using an analytical approximation fromslender airfoil theory (Milne-Thompson, 1960). This model was adapted to study the effect of boundary conditionsand investigated sound production by a flapping plate (Manela & Howe, 2009). A linearized model was developedto encompass a finite-length flag coupled to a vortex sheet (Alben, 2008). The study showed that as the rigidity ofthe plate is reduced, an increasing number of high spatial-frequency modes become unstable, and there is acorrelation between the number of unstable linear modes and the complexity of nonlinear dynamics. A closelyrelated approach built a simpler, but fully nonlinear model wherein the continuous vortex sheet shed by the flexibleflag is replaced by the shedding of discrete point vortices with unsteady strengths (Michelin, Llewellyn-Smith, & Glover, 2008). There are other numerical models that include the viscosity of fluid. One of the most popularnumerical approaches to solve flow-induced vibration is the Immersed Boundary Method (Peskin, 2002). It is ahybrid method in which the fluid is represented in an Eulerian coordinates frame and the structures in a Lagrangiancoordinate frame. Forces acting on Lagrangian immersed boundary points are transformed to Eulerian fluid grids tosolve the Navier-Stokes equations. The coupling is also applied to the velocity of the immersed boundary points, which is determined by fluid velocity on neighboring grid points. The method has been applied to the problem offlapping plates (Zhu & Peskin, 2002; Kim & Peskin, 2008). Another widely used hybrid computational approachintegrates the Lattice Boltzmann Model (LBM) for the dynamics of incompressible viscous fluids and the LatticeSpring Model (LSM) for the mechanics of elastic solids (Masoud & Alexeev, 2010). In this approach, the twomodels are coupled through appropriate boundary conditions at the movable solid-fluid interface. Briefly, the LBMis a lattice method that is based on the time integration of a discretized Boltzmann equation for particle distribution functions. In three dimensions, LBM is characterized by a set of 19 distribution functions, describing the massdensity of fluid particles at a lattice node and time propagating in the direction with a constant velocity. Thehydrodynamic quantities are calculated as moments of the distribution functions (Succi, 2001).

2.2 Flow-induced Flutter

Another classic example of flow-induced vibrations is the flow-induced flutter (Chen, He, & Xiang, 2002; Li, Liao, & Qiang, 2003; Dowell, 2004; Paidoussis, 2004; Gu & Qin, 2004; Chen & Kareem, 2008). An everyday example ofthis phenomenon is the waving motion of flags in the wind. A cantilevered plate immersed in an otherwise uniformaxial flow may lose stability at high enough flow velocity by flutter. It is now generally understood that the flutter ofthe fluid-structure system is a self-excited phenomenon. Flutter occurs as a result of the fluid-structural interactionand is usually associated with complicated phenomena such as the boundary layer interaction, flow separation, nonlinearlimit cycle oscillations, etc. Flutter predictions using a 2D or 3D

Navier-Stokes model with fully coupllediteration are very challenging due to the perplexing physical phenomena and the large amount of computation work.

Plate flutter has been studied for a long time. When a cantilevered plate lies in an axial flow, it is known toexhibit self-sustained oscillations once a critical flow velocity is reached. This flutter instability has beeninvestigated theoretically, numerically and experimentally by different studies. An early monograph on this topicwas reported (Dowell, 1975). A comprehensive review is also available in the books (Dowell, 2004; Paidoussis, 2004). Flag flutter was investigated in a series of carefully conducted experiments (Taneda, 1968). Similarexperiments on strip flutter was conducted to give theoretical predictions of the critical flow velocity in terms ofstrip thickness and length, in which the strip was modeled as a cantilevered beam (Datta & Gottenberg, 1975). Theslender wing theory was used in the evaluation of the aerodynamic loads (Katz & Plotkin, 2001). Hanging stripswere recently studied (Yadykin, Tenetov, & Levin, 2001). A nonlinear beam model and slender wing theory was used for the aerodynamics (Semler, Li, & Paidoussis, 1992). The latest work on strip flutter focused on the possibleindependence of the critical flow velocity on strip length (Lemaitre, Hemon, & de Langre, 2005). After theconventional work (Shayo, 1980), cantilevered plates in axial flow were investigated (Huang, 1995; Balint & Lucey, 2005). An analytical model using Theodorsen's theory combined with a linear beam model was developed based onexperiments to predict the critical flow velocity and frequency. A linear beam model was coupled with a Navier-Stokes solver which examined the plates in axial flow with different upstream/downstream structural boundaryconditions (Guo & Paidoussis, 2000). It used a linear beam model and obtained the fluid loads through a directsolution of the potential flow surrounding the plate. Cantilevered plates in axial flow were also studied. Both sets ofresearchers separately conducted a large number of experiments to explore the relation between the critical flowvelocity and certain system parameters. In the theoretical work, they adopted a linear beam model for the structure.Studies (Yamaguchi, Yokota, & Tsujimoto, 2000; Yamaguchi, Sekiguchi, Yokota, & Tsujimoto, 2000) used alinearly varying vortex model together with a shedding wake to solve the lifting surface problem; whereas othersused Theodorsen's theory (Watanabe, Suzuki, Sugihara, & Sueoka, 2002; Watanabe, Isogai, Suzuki, & Sugihara, 2002). Moreover, a study (Watanabe, Isogai, Suzuki, & Sugihara, 2002) coupled their structural model with a two-dimensionalcompressible Navier-Stokes solver to obtain a few reference results for their analysis. A nonlinearstructural model with inextensibility condition was used to study cantilevered plates in axial flow (Tang, Yamamoto, & Dowell, 2003). They used a vortex lattice model to calculate the aerodynamic lift over the plate. This work wasextended theoretically to take into account nonlinearities in the vortex lattice model (Attar, Dowell, & Tang, 2003).Experiments were conducted in water flow and predicted the flutter boundary by means of a linear beam model andthe localized excitation theory (Shelley, Vandenberghe, & Zhang, 2005). Some studies dealt with the flutter of acantilevered plate subject to axial flow on both surfaces (Tang & Paidoussis, 2007; Doare, Sauzade, & Eloy, 2011).A nonlinear equation of motion of the plate is developed using the inextensibility condition and an unsteady lumpedvortex model was used to calculate the pressure difference across the plate. Both the instability and the post-criticalbehavior of the system were studied.

3. Applications

3.1 Propulsion

Knowledge of vortex formation and the interactions with structures is critical to understanding many natural andengineering systems ranging from how a swimming fish generates propulsive forces to how an energy harvestingdevice utilizes vortex formation. In the natural world, biological propulsion systems are found to have flexiblestructures, such as wings and fins. Both the driven and intrinsic flapping of these flexible structures are important tounderstanding flying and swimming (Lighthill, 1969; Childress, 1981; Vogel, 1994; Huber, 2000; Liao, Beal, Lauder, & Triantafyllou, 2003). Vortex shedding is widely present, as a means to deliver momentum into the fluid.The shedded vortices in turn cause deformation of flexible structures. The flapping motions used by flying andswimming animals are rather sophisticated and typically involve a combination of pitching and plunging motions.The effects of wing/fin flexibility on flapping fluid dynamics have been explored (e.g., Lighthill, 1960; Katz & Weihs, 1978; Long, Hale, Mchenry, & Westneat, 1996; Triantafyllou, Triantafyllou, & Yue, 2000; Yin & Luo, 2010). If the body is flexible, it is deformed by the fluid forces on it, and its motion is not prescribed but is insteaddetermined together with that of the ambient fluid as a coupled dynamical system. These deformations are importantin the locomotion of many swimming and flying organisms and are believed to improve propulsive performance.High-performance computations were used to simulate the performance of three-dimensional flexible flappingwings and found that passive flexibility can delay stall to a higher angles of attack (Lian, Shyy, Viieru, & Zhang, 2003). A three-dimensional vortex panel method was used to study the effect of span-wise flexibility on propulsion (Liu & Bose, 1997). It was found to increase propulsive efficiency only under a carefully controlled time-dependentmotion. Another used a dynamic conformal mesh to study a flexible airfoil in a heaving motion (Miao & Ho, 2006). It found that efficiency increased relative to a rigid foil for certain values of the flapping Strouhal number.

3.2 Energy Harvest

The applications of vortex-induced vibration for energy harvesting have been exploited (Meliga, Chomaz, & Gallaire, 2011; Raghavan & Bernitsas, 2011). These studies include using high-damping vortex-induced vibrationto convert hydrokinetic energy from ocean/river currents to electricity. For system design, the empirical model hasbeen used to quantify the harvested energy power and the vortex-induced vibration amplitude, lift coefficient flowvelocity. The flow induced flutter also has been exploited for energy harvester. Energy transfer and the concept offlutter-mill by using cantilevered flexible plates in axial flow were discussed (Tang, Paidoussis, & Jiang, 2009). Cantilevered flexible plates in axial flow lose stability and exhibit flutter at sufficiently high flow velocity. Theequations of motion of the plate are used by incorporating aero/hydrodynamic loads that are calculated using theunsteady lumped vortex model. The flow velocity is supposed to be low enough when flutter takes place for thefluid to be assumed to be incompressible. The flow can initially be considered to be inviscid; the effect of viscosityis incorporated in the drag empirically as a surface viscous force. A low-speed wind energy harvesting system wasstudied that transfers aerodynamically induced flutter energy into electrical energy using a flexible belt and theairflow (Fei, Mai, & Li, 2012). An electromagnetic resonator with copper coils and a permanent magnet is designedto efficiently harvest electrical energy from the induced mechanical vibrations. Different groups of springs are compared at various wind conditions to maximize the power output. The energy harvested from the flutter of a platein an axial flow by making use of piezoelectric materials was demonstrated (Doare & Michelin, 2012). Theequations for fully coupled linear dynamics of the fluid-solid and electrical systems are derived.

4. Previous Models and Their Limitations

How to efficiently predict flow-induced vibrations of structures with reliable accuracy remains largely a difficulttask. The oscillation of a structure interacting with fluid flow is an inherently nonlinear, self-regulated, continuumelasticity phenomenon. Vortex shedding gives rise to complex forces. This is only one of the factors that makevortex-induced vibration prediction in industrial applications far from a standard procedure.

Direct numerical simulations of flow-oscillator interaction solve the Navier-Stokes equations for the fluidaround the structure and compute the hydrodynamic loads on it. Empirical models, on the other hand, applyhydrodynamic coefficients or aero-elastic coefficients to represent the fluid forces on the structure. A popularempirical approach is to use phenomenological model or reduced-order model, which is combined with analyticalconsiderations and able to reveal the underlying physical nature. The reduced-order model possesses original kernelof van der Pol or Rayleigh equation. Because of its significant applications, the reduced-order models have beenextensively developed.

The reduced-order models of multiple-degree-of-freedom with van der Pol-type equations have been widelyused in engineering to investigate vortex-induced vibration (Marra, Mannini, & Bartoli, 2011). A typical case ofusing multiple-degree-of-freedom reduced-order model is given (Violette, de Langre, & Szydlowski, 2010), inwhich the motion induced by vortex shedding on slender flexible structures subjected to cross-flow was studied. Vortex-induced vibration was analyzed by considering the linear stability of a coupled system that includes thestructure dynamics and the wake dynamics. The latter was modeled by a continuum of wake oscillators, distributedalong the span of the structure under the assumption of uniform or non-uniform flows.

The description of vortex-induced vibration using reduced-order model requires that one weighs the relativemagnitudes of each of the model parameters and then tries to predict their contribution to the structural response.Part of the problem is that different models for vortex-induced vibration give different results. As an example, astudy once found large discrepancies in the predicted response of slender marine structures to vortex shedding whenseven different models were applied to the same structures under the same environmental conditions (Larse & Halse, 1997). Some of these discrepancies can be attributed to the fact that many of these models use experimentallyobtained values for the flow inputs. This approach remains hindered by the fact that Reynolds numbers of mostindustrial applications cannot be simulated. Moreover, the existing empirical models are limited in their applicationsbecause they are not able to predict the response oscillation amplitude for values of the mass and damping awayfrom those at which their aero-elastic parameters were estimated.

Three different types of coupling effects (displacement, velocity and acceleration) of the cylinder structuremovement on the lift fluctuation were investigated (Facchinettim, Delangre, & Biolley, 2004). It was found that bythe displacement and velocity couplings only, one fails to predict the lift phase observed in experiments of vortexshedding from cylinders that were forced to oscillate. By the displacement coupling alone, the lift magnification atlock-in and almost all important features of vortex-induced vibrations at low values of the Skop Griffin parameter cannot be predicted, while by the velocity coupling alone, the range of lock-in for low values of cannot bedetermined.

General reduced-order, analytical models of nonlinear flow-oscillator interactions were developed by usingHamilton's variational formulation coupling Navier-Stokes equations (Benaroy & Gabbaia, 2008; Gabbaia & Benaroy, 2008). Many wake-body models are shown to be recoverable from the more general model derived byexplicit assumptions. However, this general model still suffers from unifying failure to unify some cases, such asrelatively larger dissipations due to the inherent limit of Hamilton's principle, as tools for approximation analysis.

Despite the research dedicated to vortex-induced vibration, and the resulting development of qualitativeunderstanding, the realization of techniques for accurate prediction of structure response has been scarce. This is mainly because these models were based on limited empirical results with many assumptions. Most of the researchis confined to linear system parameter identification due to the complexity of the problems. In a study, the nonlinearmotion equilibrium between the flow-induced excitation forces and the structural dynamics was estimated andcharacterized by varying amplitude and phase along the structure, which were complex modes, mixtures of travelingand standing waves (Lucora, Mukundanb, & Triantafyll, 2006). This could provide some insight to characterizestructure motion pattern, but it cannot quantify system parameters. A linear instability theory and identificationapproach was developed (Violette, de Langrea, & Szydlowski, 2010), which could be used to efficiently estimate thethreshold of instability, but it cannot predict nonlinear response of system. The linear modal identification of steelriser under sheared current was investigated by employing a combination of signal filtering and least-squares fitting (Lie & Kaasen, 2006) and another study (Allan, 1995) used analysis-experiments response match approach toidentify the parameters in van der Pol oscillator of single-degree-of-freedom. The direct response match approach suffers from the shortcoming of unreliability. The direct response match approach is sensitive to certain parametersand it may lead to multiple solutions. Response match method is also used to identify system parameters (Wun & Chang, 2011).

There were numerous researches on the flow-induced flutter. Conventionally, most flutter models were linear, focusing on instability threshold determination. For example, the nonlinear higher order harmonics appeared in theexperiments of an aero-elastic energy harvester in aerodynamic flows (Dunnmon, Stanton, Mann, & Dowell, 2012), which are not represented in by linear models.

Determining flutter models for use in design simulators requires the model to be valid over a wide range oftesting data for design conditions. There are many research projects dedicated to the identification of flutterparameters, flutter derivatives or the linear aerodynamic stiffness and damping (e.g., Brownjohn & Bogunovic, 2001; Chen, He, & Xiang, 2002; Gu & Qin, 2004; Chen & Kareem, 2008; Perez & Fossen, 2009). Flutterderivatives and aerodynamic admittances provide a basis for predicting the critical flow speed in flutter analysis. Butalmost all of the research is confined to linear system parameter identification. For example, in a recent work (Chen, Han, Luo, & Hua, 2010), the equations are formulated about mass center of the system using the Lagrangianapproach. The subsection extended-order iterative least square algorithm was developed in the state space for directidentification of system matrices from free vibration data of a model obtained from wind tunnel experiments. Theflutter derivatives were extracted straightforwardly from the difference in the system matrices identified at zero windvelocity and at a specific wind velocity, respectively. By making use of complex modal decomposition technique, aprocedure was employed to correct the system matrix at zero wind velocity considering both eccentricities. Onlyrecent work used local model networks approach to identify flutter derivatives with nonlinearity (Seher-Weiss, 2011). The author built a global model through a weighted superposition of local simple models. The location of thelocal is determined automatically as part of the algorithm. This approach allows to identify influencing parametersfor locate nonlinearities. The shortcoming of this approach is that the globally valid model is needed.

The modeling of the nonlinear response of structures for given excitation forces is a matured mechanical engineering problem, which can be solved using finite element method or even semi-analytical solution. But theinverse problem, the force and boundary conditions identification through response, has been a challenging one.The advances of modern nonlinear dynamics identification techniques offer many opportunities to implementresponse-based system identification. The identification of nonlinear dynamics through the use of experimental datahas received considerable attention (e.g., Huang et al., 1998; Krauss & Nayfeh, 1999; Yasuda & Kamiya, 1999; Nelles, 2002). Many nonlinear identification methods have been proposed, which include: Volterra and Wienerseries, spectral analysis and the reverse-path formulation, nonlinear auto-regressive moving average models, therestoring force method, the describing function methods, direct parameter estimation, Hilbert transforms, wavelettransforms and neural networks, etc. A comprehensive review of nonlinear identification of structural dynamics canbe found (Worden & Tomlinson, 2001). The most commonly used nonparametric methods include the higher orderfrequency response function method, and the restoring force-surface or force-state mapping method. Most of theparametric identification methods are time-domain based, which have the advantages of requiring less time andeffort for data acquisition than some frequency-domain techniques and being suitable for the identification ofstrongly nonlinear systems. Frequency-domain techniques avoid the efforts of differentiation and observability ofsmall terms, but require more theoretical effort and are generally applicable to weak nonlinear systems.Conventionally, Fourier analysis based FFT, power spectrum density (PSD), time-frequency analysis (TFA), andwavelet transformation (WT) have been used to characterize vibration signal. Due to the fundamental assumption oflinearity in Fourier analysis, FFT, PSD and TFA are not suitable to deal with non-stationary and nonlinear signal inprinciple. The wavelet methods may also prove inadequate because its non-locally adaptive approach causesleakage. In the last decade, Hilbert-Huang transform (HHT) has been well developed for processing non-linear andnon-stationary signals, which could be used to effectively process non-stationary, nonlinear vibration signals andpinpoint dynamics features through its two elements, empirical mode decomposition (EMD) and Hilbert spectralanalysis (Huang et al., 1998; Huang & Attoh-Okine, 2005). In dealing with dynamics of fluid-structure interactionsystem, on one hand, all of the existing simulations have used nonlinear physics models with some assumed orempirical parameters. The existing modeling and simulation research had qualitatively characterized the nonstationary, nonlinear dynamics of the system, based conventional models and parameters that were established orextrapolated from experimentally observed fluid mechanics phenomena and structure phenomena under specifictested conditions with specific scale. However, there has been a lack of detailed and direct validation of the modelsand simulated results by using experimental results. In the conventional modeling, the integration of empiricalmodel and numerical simulation and testing have been used. But the contemporary nonlinear science identificationtechnology has not been applied. Moreover, all of the experimental investigations have used FFT (Bourguet, Lucor, & Triantafyllou, 2012), PSD, TFA (Hangana, Koppa, Vernetb, & Martinuzzi, 2001), or WT (Wanga, Soa, & Xie, 2007; Lewalle, 2010) to process flow/structure vibration signals from measured data. This is not proper as theresponses of flow-induced vibrations are usually non-stationary and strong nonlinear. Therefore, the further work onexperiment-based identification is highly needed to quantify real system and to identify or "calibrate" keyparameters in reduced-order model, so as to obtain validated, generalized reduced-order model for design simulator.

In addition to the above-mentioned problems, the conventional reduced-order models have many othershortcomings. For example, it was found that the traditional labels of ''high mass-damping'' and ''low mass-damping''are incomplete with regard to predicting a large or small-amplitude response profile in certain situations (Klamo, Leonard, & Roshko, 2006). Also, the damping due to fluid interaction has been found to be frequencydependent.But this has not been addressed by existing models (e.g. Zhang, Zhou, So, Mignolet, & Wang, 2003),though the accurate modeling of damping is of crucial importance for the prediction of response amplitude. It wasillustrated that flow-oscillator model must be improved properly by including the effect of frequency dependentcoupling; otherwise the model of wake oscillator with a van der Pol equation cannot accurately model the results ofvortex-induced vibration measurements (Ogink & Metrikine, 2010).

5. Further Study and Conclusive Remarks

New, transformative flow-oscillator models require that different types of oscillating structures can be efficientlyand effectively analyzed for their fluid-structure interactions without phenomenological assumptions. Studies should focus on understanding the underlying mechanism of fluid flow-oscillating structure interaction by exploring new methodology to model and identify system, aiming to better quantify the coupled nature of fluid-structure that may lead to instability of systems; to model the effect of nonlinear fluid damping and stiffness on the response and stability of oscillating structure.

A feasible methodology to improve the existing empirical models is to establish generalized reduced-ordermodels by directly using physics with the assistance of fluid-structure numerical analysis under standardassumptions. Further flow-oscillator models need to include the fundamental presence of non-stationary and strongnonlinear vibrations of structure with parameter/frequency-dependent stiffness and damping mechanism. To developnew models, one approach is to integrate theories in oscillatory structure and fluid dynamics to establish generalizedreduced-order models through parametric Hamilton's Law, so as to comprehensively unify existing models. Thegeneralized reduced-order models should be able to unify existing models and consist of undetermined parameterswhich could be calibrated for special applications. The test-based nonlinear system identification technique can beused to calibrate these parameters so as to attain validated generalized reduced-order models. After the models areestablished, it is necessary to use nonlinear system identification methodologies, based on experimental data, toidentify the undetermined parameters in the models to substantially improve the fidelity. This in-situ calibratingcould use criteria such as higher order frequency response functions, Hilbert transform, bifurcation diagrams, phaseportraits and Lyapunov exponents.

The following questions need to be answered to develop generalized reduced-order models:

•What is the most feasible and effective approach to establish generalized, parametric, reduced-order modelsto unify existing models? How can we substantially improve the fidelity of the models by parameteridentification through tested data or through comprehensive numerical analysis results?

•How can we effectively characterize the non-stationary and nonlinear dynamics of fluid-structureinteraction from recorded response signal and flow field data? What is the general spectral signaturebeyond Fourier transform format? How does the spectral signature vary with respect to interfaceparameters' changes?

•How can we extract coupling dynamics and interaction information and re-construct coupling forces withhigh time and frequency resolution from tested response signals? How can we effectively synthesize modelparameters based on identification? Does the vortex-induced vibration or flutter have one-on-onerelationship in terms of its output and input for all cases?

•How can we make use of the direct numerical simulation to identify the generalized reduced-order model, under the situation that experimental data is not available? If we have had validated, generalized reduced-order models from experiment-based identification, how can we make use of it to improve direct numericalsimulation by developing higher performance scheme or improving boundary assumptions?

•How can we make use of the identified models for prediction and optimal design? How can we make use ofthe identification technique to develop in-situ calibration technique for other empirical models or reduced-order models?

Obviously, the general approaches should be developed and unified to advance the analytical models for thecomplex fluid-structure interaction problems that are present in many engineering designs, providing also afundamental tool for a better understanding of the underlying physics. This would yield validated, generalized reduced-order models that can be used for optimization of oscillatory structure in fluid flows for locomotion propulsion orenergy-harvesting devices with exceptional efficiency.

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