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Revisiting the One-shot method for modeling limit cycle oscillations: Extension to two-degree-of-freedom systems

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ABSTRACT

In this paper, the harmonic-balance-based One-shot method is extended to model limit-cycle-oscillations (LCO) for pitch/plunge airfoils. The difference of this approach from more traditional partitioned aeroelastic analyses is presented. A careful investigation is carried out to determine the spurious energy generated by the coupling of segregated computational fluid dynamic and computational structural dynamic solvers. A remedy to eliminate this issue, which is inherent in time-accurate aeroelastic as well as aeroelastic harmonic balance (A-HB) techniques, is proposed for the One-shot method. It is shown that, unlike other approaches, the One-shot method eliminates the need to use dynamic meshing where the fluid mesh needs to be gradually deformed from one physical time to the next along with sub-iterations of the flow solver. In addition, methods for efficiently determining the LCO frequency are discussed. The One-shot method is applied to a two-degree-of-freedom Isogai aeroelastic model for the NACA 64A010 airfoil in the transonic flow regime. The results are compared to the so-called HB/LCO and A-HB methods as well as a classical time-accurate approach. Finally, the advantages of the One-shot method over these techniques is demonstrated.

1. Introduction

Limit cycle oscillation (LCO) prediction is of significant interest for the aeroelasticity community. Generally, LCO occurs following flutter onset when the amplitudes of the self-sustained oscillations reach a maximum value. This problem is a consequence of nonlinear phenomena which play an important role in aeroelasticity [1]. Traditionally, most aeroelastic problems are solved by coupling stand-alone computational fluid dynamics (CFD) and computational structural dynamics (CSD) solvers. In light of this approach, dynamic aeroelastic problems are solved through [2,3]:

1. Modeling of fluid dynamics from which the unsteady aerodynamic forces acting on a deforming structure are calculated.
2. Modeling of structural dynamics to determine structural deformation and velocity caused by external aerodynamic forces.
3. Modeling of moving fluid mesh that complies with the deforming structure.

For LCO problems, the response of the structure includes the amplitudes of vibration and the frequency of vibration if the LCO is self-excited. For a relatively simple aeroelastic problem in which the structural system has one or two degrees-of-freedom (DOF), the governing equation can easily be recast into the state-space form. Thus, the governing equations of both fluid and structure fields can be combined into one global governing equation and can be solved numerically in a monolithic way [4]. However, for a problem with a rather complex dynamic structural system, incorporation of structural and fluid dynamic governing equations in a monolithic way is usually difficult and the problem is generally solved using a partitioned method [2,3,5,6]. In this approach, each field (fluid and structure) is time integrated by respective solvers generally using different schemes that are optimized for each model. These two solvers are then coupled using the so-called staggered algorithm. Aerodynamic forces and structural amplitudes are exchanged through an interface between two solvers to ensure synchronization. However, a slight lag in the physical times for each solver may cause stability problems. In any case, the partitioned method has many advantages such as utilizing off-the-shelf solvers and ensuring modularity of the coupled solver.

Traditionally, a partitioned aeroelastic solver couples CFD and CSD solvers that are both time-accurate. However, for LCO problems in which the oscillation is periodic in time, time-accurate solvers usually suffer from high computational costs since long transients have to be resolved before the desired periodic state is reached. In addition, to ensure periodicity, the solver must be run

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Nomenclature

$\boldsymbol{A}_0, \boldsymbol{A}_n, \boldsymbol{B}_n$	Fourier coefficients of fluid variables
b, c	half-chord and chord length, respectively
C_l, C_m	lift and moment coefficients about elastic axis, respectively
$\boldsymbol{E}, \boldsymbol{E}^{-1}$	discrete Fourier and inverse Fourier transformation matrices, respectively
E_s	energy of structural system
$\boldsymbol{F}, \boldsymbol{G}$	flux vectors in x and y directions, respectively
I_α	second moment of inertia of airfoil about elastic axis
j	$\sqrt{-1}$
K_h	plunge stiffness of airfoil
K_α	torsional stiffness of airfoil about elastic axis
$\boldsymbol{K}, \boldsymbol{M}$	stiffness and mass matrices
N	number of harmonics
q_∞	free-stream dynamic pressure
$\boldsymbol{Q}$	fluid variable vector in conservation form
r_α	radius of gyration of airfoil about elastic axis, $r_\alpha^2 = I_\alpha/(mb^2)$
S_α	first moment of inertia of airfoil about elastic axis
t	physical time
u, v	Cartesian velocity components
U_∞	free-stream velocity
$\tilde{V}$	reduced velocity, $\tilde{V} = U_\infty/(\omega_\alpha c)$
x, y	Cartesian coordinates
x_α	airfoil static unbalance, $x_\alpha = S_\alpha/(mb)$
Z	figure of merit for frequency search
α, h	pitch and plunge displacements, respectively
μ	mass ratio, $\mu = m/(\pi\rho_\infty b^2)$
$\boldsymbol{\xi}, \boldsymbol{\Xi}$	steady mesh and set of unsteady meshes, respectively
ρ	density
τ	pseudo-time
ω	frequency
$\tilde{\omega}$	reduced frequency based on airfoil chord length, $\tilde{\omega} = \omega c/U_\infty$
ω_α, ω_h	uncoupled natural frequencies of pitching and plunging about the elastic axis

Superscripts and accents

n	aeroelastic iteration index
$*$	sub-time level variables
$\wedge$	Fourier coefficients
$\cdot$	time derivative
$'$	non-dimensional form of variable
$\sim$	variable in reduced form
$-$	amplitude of variable

for many cycles. This disadvantage makes time-accurate solvers less attractive compared to frequency-based (Fourier) approaches. One of these frequency domain methods that can model nonlinearities in time-periodic unsteady problems is the harmonic balance (HB) method [7,8]. This technique utilizes Fourier transformations to convert the unsteady problem into a mathematically steady one and deals directly with the periodic state by solving flow variables at equally-spaced sub-time levels over a single period.

In the literature to date, several partitioned methods based on the HB technique have been developed to solve dynamic aeroelastic problems. Thomas et al. [9,10] proposed the so-called HB/LCO method in which a solution vector consisting of structural amplitudes, the LCO frequency and reduced velocity is solved by Newton–Raphson iterations. The CFD solver is used to calculate the aerodynamic forces as well as all the Jacobian terms, which can be computationally costly when multiple DOFs exist in the structural system. Recently, a similar method was developed by Tardif and Nadarajah [11] that uses a CFD solver based on the non-linear frequency domain (NLFD) method of McMullen et al. [12]. In this approach, a Newton–Raphson technique is employed to determine the LCO frequency as well as the reduced velocity by defining a figure of merit based on the difference of lift coefficients between two successive aeroelastic iterations. This way, the size of Jacobian matrix becomes independent of the number of DOFs of the structural system resulting in an efficient method. Following the work of Thomas et al. [9,10], Blanc et al. [13] developed a partitioned solver that determined the LCO response, which was excited by another oscillating part of the structure. In their work, the oscillation frequency was known *a priori* and the HB form of the structural governing equations was solved using fixed-point iteration. Shortly after Blanc et al. [13], Ekici and Hall [14] proposed the One-shot method to predict self-excited LCO in turbomachinery, in which the problem was approximated by a single-degree-of-freedom aeroelastic model, and the unknown LCO frequency was determined by a separate procedure. In that work, the One-shot method was shown to be computationally more efficient than the HB/LCO method. Based on those previous efforts, Yao and Marques [15,16] developed the so-called aeroelastic harmonic balance (A-HB) method for solving LCO problems by coupling HB based CFD and CSD solvers where the CSD problem was modeled as mathematically steady. Although this method was shown to work, because of the exclusion of the pseudo-time term in the CSD solver, the structural variables and frequency update had to be highly under relaxed. In addition, a "dynamic mesh" approach had to be used where the CFD mesh had to be gradually deformed from one iteration to the next along with many sub-iterations of the CFD solver. Without these modifications, which significantly slow down the overall convergence rate of the aeroelastic problem, the solver may converge to a trivial solution or may even diverge.

In contrast, the One-shot method originally proposed by Ekici and Hall [14], can easily circumvent the issue of converging to the trivial solution (or diverging) by simply using a pseudo-time term in the CSD solver, which is time-integrated using an implicit technique that allows the use of much larger time steps compared to the explicit CFD solver. This approach is also superior in the sense that it minimizes the spurious energy generated in the system in a very robust way. In this paper, all these issues and the remedies to circumvent them are explained in detail. Insights into the mechanism of the One-shot method [14] are provided including frequency updating as well as optimum time step for the structural solver.

The following analyses constitute the novelty of the work presented herein. First, energy balance across the interface between the coupled CFD and CSD solvers is analyzed. The uniqueness of the One-shot method compared to more traditional partitioned methods is also highlighted. In addition, techniques for searching the LCO frequency are discussed in detail. After the theoretical developments, the method is applied to model LCO for a pitching-plunging NACA 64A010 airfoil in the transonic flow regime. To the best of our knowledge, this is the first time that the One-shot method is applied to 2 DOF system. Also a solver implementing the HB/LCO method of Thomas et al. [9,10] and another solver based on a classical time-accurate approach [6] are developed for verification purposes. Finally, the results of One-shot solver are compared to those obtained from the HB/LCO solver and the time-accurate solver as well as to those reported by Yao and

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