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ABSTRACT

A wide variety of pathologies such as store-induced flutter have been observed on high-performance aircraft and have been attributed to transient nonlinear aeroelastic effects. Ignoring the nonlinearity of the structure or the aerodynamics will lead to inaccurate prediction of these nonlinear aeroelastic phenomena. The current paper presents the development and representative results of a high fidelity multidisciplinary analysis tool that accurately predicts limit cycle oscillations (LCO) in an aeroelastic system with combined structural and aerodynamic nonlinearities. Wind-tunnel measurements have been carried out to validate the findings of the investigation. The current investigation will concentrate on the prediction of the critical physical terms that dominate the mechanism of LCO. The aeroelastic computations predict LCO amplitudes and frequencies in very close agreement with the experimental data. The results emphasize the importance of modeling the nonlinearities of both the fluid and structure for the accurate prediction of LCO for nonlinear aeroelastic systems. The current investigation is performed using the Multi-Disciplinary Computing Environment (MDICE).

INTRODUCTION

Aeroelastic problems represent a mutual interaction between the aerodynamics and structure of an aerospace vehicle. Several studies have established that aeroelastic systems are inherently nonlinear and that these nonlinearities lead to pathologies such as twin-tail buffet [1] and store induced flutter [2] of fighter aircraft. These nonlinear aeroelastic problems are not accurately simulated by linear models.

The design of a new generation of high-performance aircraft and improvement of the current generation of aircraft will depend primarily on the accurate prediction, understanding, and control of the critical physical terms that dominate the mechanism of nonlinear aeroelastic phenomena. Nonlinearity of the flow and structure is the reason why the behavior of the aircraft under the influence of these aeroelastic phenomena is not yet completely understood. The mechanism of the instability could be due to flow nonlinearities such as flow-separation and the presence of separation bubbles, the presence of an oscillating shock, the state of the boundary-layer, and shock/boundary-layer interaction. Other sources of the instability are structure nonlinearities which may be associated with kinematics, structural stiffness and damping properties, and pathologies such as internal resonances arising from design.

Limit cycle oscillations (LCOs), in particular, have been a persistent problem on several fighter aircraft designs and are generally encountered on external store configurations. Denegri and Cutchins [2], and Chen, et al. [3] observed evidence of a spring-hardening type nonlinearity in the F-16 wing torsional stiffness. LCO was also observed as low as M=0.6 at high angles of attack and it was found to be sensitive to the tip missile configuration.

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O'Neil and Srganac [4] compare analytical predictions to experimental measurements for continuous nonlinear stiffening behavior in the pitch mode. The existence of torsion stiffness nonlinearities are found to induce LCO which are dependent upon velocity and the nonlinear parameters. Woolston, et al. [5] investigated the effects of hysteresis and cubic stiffness nonlinearities on the flutter characteristics. The instabilities exhibited LCO due to cubic hardening only. Furthermore, Cole [6] observed an aerelastic behavior similar to that found in the LCO response of store configurations. The observed vibration characteristics suggested the presence of internal resonances. Internal resonance is not predictable with linear analysis (see Nayfeh and Mook [7]), and occurs as a result of nonlinearities that couple modes of motion and lead to an exchange of energy between the modes of the system as the natural frequencies become commensurable. An extensive review of the analysis of structural nonlinearities for a wing section such as discussed in this paper may be found in Lee, et al. [8]. Analytical studies of systems with continuous nonlinear structural stiffness such as those exhibited by the response of helicopter rotor systems have been addressed by several researchers (see Tang and Dowell [9], Woolston, et al. [5], Lee and LeBlanc [10], and Price, et al [11]). Tang and Dowell [9] have also reported experimental studies of systems with nonlinear stiffness behavior.

In this paper, experimental measurements of LCOs for the nonlinear aeroelastic system are conducted, and a high fidelity Multi-Disciplinary Computational Environment (MDICE) is used to predict transient LCO behavior of the nonlinear aeroelastic system. MDICE has been developed by CFD Research Corporation in collaboration with APRL. MDICE provides an environment in which several engineering analysis programs run concurrently and cooperatively to perform a multi-disciplinary design, analysis, or optimization problem. Using MDICE, engineers are able to couple inherently dissimilar disciplines and programs from a variety of sources, performing distinct tasks such as geometry modeling, grid generation, CFD-structural analysis, controls, and post processing into a single software system. The computational results will be compared with experimental data. The investigation will cover a wide range of flight conditions to give more insight on the parameters that dominate LCO of nonlinear aeroelastic systems.

**MDICE ARCHITECTURE**

MDICE is a distributed object oriented environment which is made up of several major components. The first component in MDICE is a central controlling process that provides network and application control, serves as an object repository, carries out remote procedure calls, and coordinates the execution of several application programs via MDICE specific script language. The second component is a collection of libraries, each containing a set of functions callable by the application programs. These libraries provide low level communication and control functions that are hidden from the application programs, as well as more visible functionality such as object creation and manipulation, interpolation of flow data along interfaces, and safe dynamic memory allocation services. Finally, the environment also encompasses a comprehensive set of MDICE compliant application programs. MDICE provides capabilities for parallel execution of participating application programs and has a full Fortran interface for those codes written in Fortran 77 or 90, C, in addition to C++.

In the application control panel of MDICE, the application modules are selected. For each module, the computer on which the program is to be run is chosen. Other information is provided, such as specifying a directory to run each module and any command line arguments the module might require. Once the simulation has been set up, it is run and controlled by MDICE using a short script in the graphical user interface which explicitly specifies the synchronization between the modules. The MDICE script contains all the conveniences found in most common script languages. In addition, MDICE script supports remote procedure calls and parallel execution of the application modules. These remote procedure calls are the mechanism by which MDICE controls the execution and synchronization of the participating applications. Each application posts a set of available functions and subroutines. These functions are invoked from MDICE script, but are executed by the application program which posted the function.

There are many advantages to the MDICE approach. Using this environment one can avoid giant monolithic codes that attempt to provide all needed services in a single large computer program. Such large programs are difficult to develop and maintain, and by their nature cannot contain up-to-date technology. The MDICE allows the reuse of existing, state-of-the-art codes that have been validated. The flexibility of exchanging one application program for another enables each engineer to select and apply the technology best suited to the task at hand. Efficiency is achieved by utilizing a parallel distributed network of computers. Extensibility is provided by allowing additional engineering programs and disciplines to be added without modifying or breaking the modules or
disciplines already in the environment. For more details of MDICE architecture, see Kingsley, et al. [12].

LIMIT CYCLE OSCILLATION OF NONLINEAR AEROELASTIC SYSTEM

In this section, the experimental apparatus of this study is discussed and the particular set of analysis modules used in MDICE for the prediction of LCO of the nonlinear aeroelastic system is presented.

Nonlinear Aeroelastic Test Apparatus (NATA)

The experimental system that serves as the testbed for experimental investigations and validation of the numerical predictions of the nonlinear LCO is shown in Figure 1. A model support system has been developed to provide direct measurements of nonlinear aeroelastic responses (O'Neil and Srganac [4]). The support system permits prescribed pitch and plunge motion for a mounted wing section. The plunge degree-of-freedom is provided by a carriage that translates freely. Pitch motion is provided by a rotational cam mounted on this carriage. Large angles of attack are permitted, but protective constraints limit the amplitude of motion to prevent model/tunnel damage from large amplitude LCOs or flutter.

Figure 1. Schematic view of the Nonlinear Aeroelastic Test Apparatus (NATA).

The model support system provides freedom in test conditions and parameters. The structural stiffness response of the apparatus is governed by a pair ofcams that are designed to provide tailored linear or nonlinear stiffness response. The shape of each cam, stiffness of the springs, and pretension in the springs dictate the nature of the nonlinearity. With this approach, these cams provide a large family of prescribed responses. Other physical properties, such as the eccentricity, the moment of inertia of the wing, the stiffness characteristics, and the wing shape, are easily modified for parametric investigations. System response is measured with accelerometers and optical encoders mounted to track motion in each degree-of-freedom.

Nonlinear Aeroelastic Model

The nonlinear aeroelastic system shown in Figure 1 is modeled using the two-degree-of-freedom model shown in Figure 2.

Figure 2. The Aeroelastic structure model with pitch and plunge degrees of freedom.

The nonlinear equations of motion that prescribe the aeroelastic response of the described aeroelastic system are given by

$$m \ddot{h} + [m_w x_c \dot{\alpha} \cos(\alpha) - m_c r c \dot{\beta} \sin(\alpha)] \ddot{\alpha} + c_h h = -L(t) - \mu_h m_e \frac{\dot{h}}{h}$$

$$+ k_h (h) h = -L(t) - \mu_h m_e \frac{\dot{h}}{h}$$  \hspace{1cm} (1)

$$I_{EA} \ddot{\alpha} + [m_w x_c \dot{\alpha} \cos(\alpha) - m_c r c \dot{\beta} \sin(\alpha)] \ddot{\alpha} + c_\alpha \dot{\alpha}$$

$$+ k_\alpha (\alpha) \dot{\alpha} = M(t) - \mu_\alpha M \frac{\dot{\alpha}}{\dot{\alpha}}$$ \hspace{1cm} (2)

where $m_i$ is the total mass of the wing and its support structure, $m_w$ is the mass of the wing only. The elastic axis location "h" is nondimensionalized with respect to
the half chord length $b$ and is positive for the elastic axis located aft of the midchord. In these equations, $r_e$ represents the nondimensional distance between the elastic axis and the center of rotation of the cam; and $c_{sa}$ and $c_{se}$ are plunge and pitch viscous damping coefficients, respectively. The mass moment of inertia about the elastic axis, $I_{EA}$, is the contribution of the wing, cam, and the offset masses and is given by

$$I_{EA} = I_{Wcg} + I_{Ccg} + m_c (r_e b)^2 + m_w (x_{cb} b)^2$$ (3)

Structural stiffnesses are represented by $k_h$ and $k_a$ for plunge and pitch motions, respectively. The nonlinear aerodynamic normal force, $L$, and nonlinear pitching moment, $M$, are referenced to the elastic axis, and they are dependent upon the motion of the wing. The nonlinear aerodynamic loads are computed by solving the full Navier-Stokes equations. The last terms in the RHS of the equations represent the Coulomb structural damping, where $M_f$ is the frictional moment and $\mu_a$ and $\mu_h$ are the structural damping coefficients in pitch and plunge motions, respectively.

The developed aeroelastic module incorporates various nonlinear features. These features include aerodynamic nonlinear loads (from the Navier-Stokes Equations), Coulomb structural damping, nonlinear stiffness, and higher-order kinematics. For example, the nonlinear torsional stiffness is given in the equations of motion in a polynomial form as

$$k_a(\alpha) = k_\alpha + k_{\alpha_1} \alpha + k_{\alpha_2} \alpha^2 + k_{\alpha_3} \alpha^3 + \cdots$$

In the experiments, the nonlinear torsional stiffness is realized by nonlinear camus, and the actual coefficients in the above polynomial representation are obtained from measured displacements and loads. The aeroelastic equations are integrated using a time marching finite-difference routine based on the model introduced by Lee & LeBlanc [10].

**Fluid-Dynamics Module**

The fluid-dynamics analysis module used for the current study is CFD-FASTRAN [13]. CFD-FASTRAN is a state-of-the-art full Navier-Stokes flow solver for modeling compressible, turbulent flow problems using structured and/or unstructured grids. CFD-FASTRAN employs an upwind scheme with Roe's flux-difference splitting or Van Leer's flux-vector splitting for spatial differencing. Temporal differencing is done using a Runge-Kutta scheme, point-implicit scheme or a fully-implicit scheme. Turbulent models in CFD-FASTRAN include Baldwin-Lomax, k-\varepsilon, and k-\omega models. CFD-FASTRAN also provides the state-of-the-art for modeling flow problems with multiple moving bodies using Chimaera overset gridding methodology coupled with a 6 DOF model. The current simulation uses a fully-implicit scheme with Roe's flux-difference splitting.

**Grid Motion Technique**

In order to carry out the computations, a C-type grid is generated around NACA 0015 airfoil (the airfoil section of the wing tested in the wind tunnel). The size of the computational grid is 300x40 grid cells with 200 grid cells on the airfoil surface. The farfield boundary extends to 10 chord lengths in all directions. A close-up view of the grid is shown in Figure 3. At every time step, the grid is deformed due to the motion of the airfoil. The grid is deformed using Transfinite Interpolation Functions (TFI). The advantages of using TFI are that TFI is an interpolation procedure that conforms to specified boundaries and TFI is very computationally efficient [14]. The TFI routine is invoked automatically when the aerodynamic and aeroelastic data are exchanged between application modules.

![Figure 3. C-type grid for the NACA-0015 airfoil.](image)

**RESULTS AND DISCUSSION**

The nonlinear pitch spring stiffness of the presented aeroelastic system is measured, and 5th-order polynomial approximation of the stiffness is modeled and given in Table 1 along with the other physical parameters and characteristics of the aeroelastic system. The measured restoring moment vs. pitch angle is compared to the computed moment, using the approximated polynomial stiffness, in Figure 4.
A more detailed study for the case of the freestream velocity of 18 m/sec is given in the next few figures. Figure 8 shows the phase diagram (velocity vs. displacement) of the pitch and plunge LCO responses for both the measured and predicted results. The LCO in both pitch and plunge is obvious and they compare well with the measured data. The pitch oscillation exhibits LCO in the range of ±0.2 rad/sec (predicted and measured) and the plunge oscillation exhibits LCO in the range of ±0.3 m/sec for the measured results, and ±0.4 m/sec for the predicted results.

Figures 9 and 10 show the power spectral density (PSD) of the pitch and plunge LCO amplitudes and accelerations, respectively. The first peak shows that the predominant frequency of the nonlinear system is 2.78 Hz and it is the same for both the plunge and pitch. The computational model has predicted very accurately the predominant frequency and the PSD peak of the pitch and plunge amplitudes and accelerations. The figure shows that the nonlinear system exhibits another peak in the higher-order harmonics and it is more significant in the pitch degree of freedom. The higher-order harmonics are indicative of the nonlinearity of the structural model. The computational model also predicted accurately this higher harmonic frequency and peak. In a separate study by Tang and Dowell [9], they showed a comparison of experimental and analytical FFT with higher-order harmonics caused by the structural nonlinearity of the system. Their primary frequency was over estimated by about 1 Hz. In their model, they used linear unsteady aerodynamic model without stall. This is an indication of the importance of including the nonlinearity of the fluid flow instead of an analytical formulation of the unsteady aerodynamic forces. Thus, as indicated from the previous figure, including the nonlinearity of the fluid as well as of the structure will result in capturing the frequency and peaks of the response including the higher harmonics.

Hence, to give more insight about the effect of the whole system nonlinearity and different physical parameters on the nonlinear system response, the pitch and plunge responses are computed using different methodologies at a freestream velocity of 18 m/sec and plunge initial condition of \( h_m = -0.02 \). The results have been summarized in Figures 11-16. The measured data corresponding to this case are shown in Figures 5 and 6. In Figure 11, the responses are computed using a high-fidelity model utilizing Navier-Stokes flow solver and a nonlinear structural model with viscous damping to model the effect of flow viscosity on the structure. The results are in very close agreement with the measured data. The frequency of oscillations is predicted within 1% of the measured value. This model also captured the
PSD peaks and frequencies efficiently as shown in Figures 9 and 10.

In Figure 12, the responses are computed using the nonlinear structural model and a quasi-steady aerodynamic model based on Theodorsen's functions [15]. This model is often effective to model aerodynamic forces for similar aeroelastic systems [4,10,16]. Although the nonlinear system exhibits LCO in both the pitch and plunge degrees of freedom, the amplitude of the plunge LCO is almost 2.6 times that of the measured amplitude. This is another indication that the LCO pathology is a phenomenon that is affected by both the fluid and structure nonlinearities. In Figure 13, the responses are computed using a high-fidelity Navier-Stokes flow solver and assuming linear structural model. As expected, due to the extensive structural nonlinearity of this system, the predicted responses are much smaller than the measured data and they even show a slight increasing response. The frequency of oscillations is 1.82 Hz, which is 35% less than the measured value. Recall that the nonlinear structural model predicted the frequency within 1% of the measured value. In Figures 14 and 15, the responses are computed using a nonlinear structural model and a Navier-Stokes flow solver. The responses shown in Figure 14 are with structural damping only, while the responses shown in Figure 15 are with no viscous or structural damping. In both cases, the results are much better than the low fidelity models presented in Figures 12 and 13. The pitch LCO is accurately predicted. However, the case of structural damping only produces a plunge LCO that is 2.25 times the measured value. The case of no damping is worse; the plunge LCO amplitude is 5.36 times the measured value. This is an indication about the importance of modeling the effect of viscous damping on the structural response even if the viscosity is modeled in the fluid-flow model. In Figure 16, the responses are computed using the nonlinear structural model and Euler (inviscid) flow solver. The results show good agreement with the measured data. However, the plunge LCO amplitude is higher than both the measured value and the value computed using the Navier-Stokes flow model of Figure 11. This shows the importance of modeling the effect of flow viscosity on the unsteady aerodynamic forces which directly affect the response of the structure. From Figures 14-16, we can conclude that the fluid-flow viscosity in the fluid-flow model and the damping effect of this viscosity on the structure should be modeled which is a feature the analytical aerodynamic formulation cannot model.

In summary, the results of this paper clearly indicate the importance of modeling all nonlinearities of the aeroelastic system. In addition, the physical characteristics of the aeroelastic system, such as damping and viscous effects, should also be modeled. Even though the cases considered in this paper are for low reduced frequency and in the low subsonic regime, the importance of high-fidelity flow model is apparent. In cases of high reduced frequency, transonic flow, oscillating shocks, or shock/boundary-layer interaction, the importance of modeling the nonlinearity of the fluid will be further emphasized.

CONCLUSION

Computational and experimental investigations are conducted to measure and accurately predict LCOs of nonlinear aeroelastic systems. Linear analysis of structure-dynamics response and/or low-fidelity flow models fail to predict the LCO behavior of the nonlinear aeroelastic system. A high fidelity analysis tool that models the nonlinearity of both the fluid and structure is developed and integrated into the Multi-Disciplinary Computing Environment (MDICE). The computational results of this analysis tool predict LCO amplitudes and frequencies in very close agreement with the experimental data. The results indicated the importance of modeling the nonlinearities of both the fluid and structure for the accurate prediction of LCO of nonlinear aeroelastic systems. Nonlinearities of the fluid and structure may significantly affect the performance and stability of high-performance aircraft. For example, stiffness tests of certain wings show evidence of a spring hardening type of nonlinearity in the wing torsional mode. This type of nonlinearity will lead to LCO behavior and it may lead to store-induced LCO as found in several fighter aircraft configurations. Future work will address the prediction and control of this problem.

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| $m_c$ | 12.0 kg |
| $m_w$ | 1.662 kg |
| $m_e$ | 0.718 kg |
| $b$ | 0.1064 m |
| $\text{span}$ | 0.6 m |
| $a$ | -0.4 |
| $r_{cg}$ | $(0.82 * b - a * b)$ m |
| $I_{EA}$ | $0.04325 \text{ kg.m}^2 + m_w \cdot r_{cg}^2$ |

| $r_c$ | 0.127 m |
| $k_s$ | 2844.4 N/m |
| $k_a$ | 6.861422 (1+1.1437925 $\alpha + 96.669627 \alpha^2 + 9.513399 \alpha^3 - 72.664120 \alpha^4)$ N.m.rad. |
| $c_s$ | 27.43 kg/sec |
| $c_a$ | 0.036 kg.m$^2$/sec |
| $\mu_a$ | 0.0113 |
| $\mu_s$ | 0.0221 |

Table 1. Physical parameters of the nonlinear aeroelastic system.
Figure 5. Measured and predicted responses of pitch oscillations of the nonlinear aeroelastic system at different freestream velocities, and initial condition of $h_w = -0.02$. 
Figure 6. Measured and predicted responses of plunge oscillations of the nonlinear aeroelastic system at different freestream velocities, and initial condition of $h_0 = -0.02$. 

(a) Measured

(b) Predicted
Figure 7. Comparison of pitch and plunge LCO amplitude and LCO frequency between measured and predicted responses.

Figure 8. Phase diagram of pitch and plunge LCO responses compared with the measured responses at freestream velocity of $u = 18$ m/sec, and initial condition of $h_{ic} = -0.02$. 
Figure 9. Power Spectral Density (PSD) of pitch and plunge LCO amplitudes compared with the measured data.

Figure 10. Power Spectral Density (PSD) of pitch and plunge LCO accelerations compared with the measured data.

Figure 11. The computed pitch and plunge responses of the nonlinear structural model utilizing the Navier-Stokes flow solver with viscous structural damping.
Figure 12. The computed responses of the nonlinear structural model using Quasi-Steady Theoderson's functions.

Figure 13. The computed responses using linear structural model and Navier-Stokes flow solver.

Figure 14. The computed responses using nonlinear structural model with structural damping and Navier-Stokes flow solver.

Figure 15. The computed responses using nonlinear structural model with no viscous or structural damping and Navier-Stokes flow solver.

Figure 16. The computed responses using nonlinear structural model and Euler flow solver.