Development of Unsteady Aerodynamic State-Space Models from CFD-Based Pulse Responses

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A method for computing discrete-time state-space models of linearized unsteady aerodynamic behavior directly from aeroelastic CFD codes is presented. The method involves the treatment of CFD-based pulse responses as Markov parameters for use in a system identification/realization algorithm. Results are presented for the AGARD 445.6 Aeroelastic Wing with four aeroelastic modes at a Mach number of 0.96 using the EZNSS Euler/Navier-Stokes flow solver with aeroelastic capability. The System/Observer/Controller Identification Toolbox (SOCIT) algorithm, based on the Ho-Kalman realization algorithm, is used to generate 15th- and 32nd-order discrete-time state-space models of the unsteady aerodynamic response of the wing over the entire frequency range of interest.

Introduction

THE inclusion of CFD-based analyses into disciplines such as aeroelasticity, aeroservoelasticity, and optimization is currently not performed on a routine basis due to the high computational costs of the CFD portion of the analyses. One solution to this problem is the development of CFD-based reduced-order models (ROMs). These ROMs capture the essence of the dynamical system under investigation while reducing the complexity of the computational model.

At present, the development of CFD-based ROMs is an area of active research at several industry, government, and academic institutions.[1] Development of ROMs based on the Volterra theory is one of several ROM methods currently under development.[2–5] Reduced-order models based on the Volterra theory have been applied successfully to Euler and Navier-Stokes models of nonlinear unsteady aerodynamic and aeroelastic systems. Volterra-based ROMs are based on the creation of unsteady aerodynamic impulse or step responses that are then used in a convolution scheme to provide the linearized and nonlinear responses of the system to arbitrary inputs. In this setting, the impulse or step responses are the functional ROMs.

A traditional approach for obtaining linearized generalized aerodynamic forces (GAFs) from an aeroelastic CFD model is to perform a time-domain perturbation of all the modes (one mode at a time) resulting in a GAF influence coefficient matrix. This time-domain influence coefficient matrix is then transformed into the frequency domain[6] using standard Fourier transform techniques. The resultant frequency-domain GAFs can then be used in standard frequency-domain aeroelastic analyses. In addition, if time-domain aeroservoelastic (ASE) analyses are desired, the frequency-domain GAFs are transformed back into the time domain using rational function approximation (RFA) techniques. These techniques include, for example, the well-known Rogers approximation[7] and the Minimum State technique.[8] The RFA techniques transform frequency-domain GAFs into state-space (time domain) models amenable for use with modern control theory and optimization. This overall process transforms time-domain information (CFD results) into the frequency-domain only to have the frequency-domain information transformed back into the time domain. Gupta et al[9] and Cowan et al[10,11] applied a set of inputs to an unsteady CFD code and used the information to create an ARMA (autoregressive moving average) model that was transformed into state-space form. Although this technique is applied

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entirely within the time domain, the shape of the inputs applied to the CFD code requires tailoring in order to excite a specific frequency range, resulting in an iterative process. A more direct method is desired for this type of analysis.

In structural dynamics, the realization of discrete-time state-space systems that describe the modal dynamics of a structure has been enabled by the development of algorithms such as the Eigensystem Realization Algorithm (ERA)[12] and the Observer Kalman Identification (OKID)[13] Algorithm. These algorithms perform state-space realizations by using the Markov parameters (discrete-time pulse responses) of the systems of interest. These algorithms have been combined into one package known as the System/Observer/Controller Identification Toolbox (SOCIT)[14] developed at NASA Langley Research Center. The present research is the first application of these techniques to the development of state-space models of linearized unsteady aerodynamic systems based on the modal pulse responses of a nonlinear (CFD) aeroelastic system.

The method presented in this paper provides a new approach that bypasses the need for generating CFD-based, frequency-domain GAFs by directly transforming the CFD-based, time-domain modal pulse responses into discrete-time unsteady aerodynamic state-space models. These state-space models can then be used for computing the aeroelastic/aerodynamic response of the vehicle due to arbitrary motions for ASE analyses, including time-domain flutter analyses, simulations, and control-law design. The goal of this paper is to demonstrate the applicability of the SOCIT algorithm to the development of state-space models of unsteady aerodynamic systems using CFD-based pulse responses.

This paper begins with a brief outline of the overall process, followed by a description of the ERA algorithm (contained within the SOCIT) and a description of the CFD-based pulse response technique. Details regarding the computational model of the AGARD 445.6 Aeroelastic Wing are presented including some results from previous research to provide the reader with an adequate background for the present study. Results are presented for state-space models generated directly from CFD-based pulse responses, including an assessment of the accuracy of the technique.

Description of Methods

Process Outline

An outline of the process that tranforms CFD-based pulse responses into state-space models is as follows:

1. Implementation of pulse (or step) response technique into aeroelastic CFD code;

2. Computation of pulse (or step) responses for each mode of an aeroelastic system using the aeroelastic CFD code;

3. Pulse (or step) responses generated in Step 2 are the Markov parameters used by the SOCIT algorithm; if step responses are used, then the derivative of the step responses (which are pulse responses) need to be computed prior to implementation in the SOCIT algorithm;

4. Evaluation/validation of the state-space models generated using SOCIT; this involves a comparison of the frequency content of the original CFD-based pulse responses (Step 2) with the frequency content of the state-space models;

Steps 1 and 2 are described in greater detail in the references that address Volterra-based Reduced-Order Models (ROMs) such as Refs. 1-5. The basic premise of Volterra-based ROMs is the extraction of linear and nonlinear kernel functions that capture the input-output functional relationship between, for example, unsteady motion of a wing (input) and the resultant loads created by that motion (output). For Volterra-based ROMs, these kernel functions are linearized and nonlinear impulse response functions. When applied to a discrete-time system such as a CFD code, these impulse response functions are referred to as pulse response functions or, simply, pulse responses. Additional details can be found in the stated references. For completeness, however, the relevant aspects of Step 2 are discussed in the following section.

CFD-Based Discrete Unit Pulse Response Technique

Considering an aeroelastic system as the coupling of an unsteady aerodynamic system (CFD code, in this case) and a structural system (Figure 1), the present study focuses strictly on the unsteady aerodynamic model. A standard technique for computing linearized generalized aerodynamic forces (GAFs) for an aeroelastic system with n modes using a CFD code is the application of a Greens function (influence function) approach. Using the CFD code, each mode is individually excited to obtain the response of all the modes to this excitation. This process is applied to all n modes, resulting in an n by n "matrix" of responses. The term "matrix" is in quotes to indicate that the responses obtained using this method are usually time-domain functions rather than the constants that usually populate a standard matrix.

This technique is a linearization by virtue of the fact that, in a computational aeroelastic analysis, the input to the nonlinear flow solver is the total physical deformation of the wing consisting of the summed total of all the modes of interest. By applying a separate excitation to each mode through the nonlinear flow solver, the total nonlinear aeroelastic response is being approximated by a linear superposition of its individual responses. For a linear flow solver, this approach would be exact. In this case, because the flow solver is nonlinear, this approach is a linearized approximation.

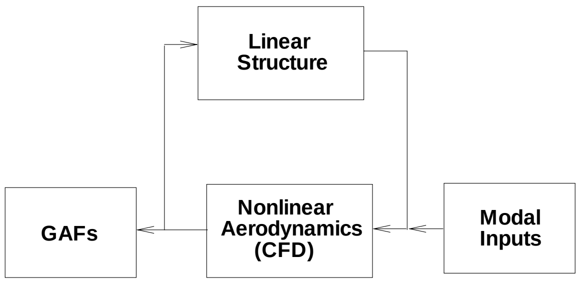

Fig. 1 Schematic of identification of generalized aerodynamic forces (GAFs).

Consistent with this assumption, this approximation is valid only for small input amplitudes. This is not necessarily a drawback as, quite often, the linearized dynamic aeroelastic response about a nonlinear steady (or static aeroelastic) condition is a reasonable representation of the system under investigation.

There are three types of modal excitation inputs that are typically used when implementing this technique. The first is a brute-force approach based on the input of sine waves of individual frequencies. The individual modal responses to these inputs for n modes and r frequencies requires n times r separate code evaluations. In addition, the time length required for each one of these evaluations can be quite large (i.e., computationally expensive) in order to get an adequate number of cycles for accurate post-processing, especially for the lower frequencies. This approach is clearly the least efficient.

A second, more elegant approach, involves the use of an exponential (Gaussian-shaped) pulse.[6] The exponential pulse can be shaped to excite a particular range of frequencies with a broad exponential pulse exciting primarily low frequency modes and a sharper exponential pulse exciting primarily higher frequency modes. Because an exponential pulse excites a preselected frequency range, only one code evaluation is required per mode. This is a significant computational savings compared to the brute force approach, but shape optimization of the exponential pulse is required when targeting a particular frequency range. In addition, for low frequencies, the exponential pulse needs to be wide, resulting in long computational times.

A third, recently-developed, approach consists of replacing the exponential pulse input with a unit pulse (discrete-time equivalent of unit impulse) or step input consistent with the Volterra-based ROM method.[2–5] Since the unit pulse/step input excites the entire frequency range of a system, no shape optimization is needed. In addition, due to the short time length of these responses, each code evaluation is significantly shorter in computational length (and cost) than the code evaluations for the exponential pulse input. Raveh et al[5] applied this technique successfully to the AGARD 445.6 Aeroelastic Wing using an aeroelastic CFD code. The shapes of the first four structural modes for this wing are presented in Figure 2.

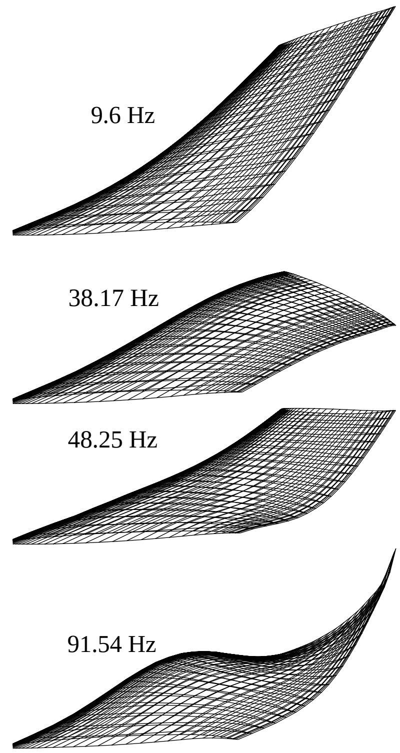

Fig. 2 AGARD 445.6 wing first four elastic mode shapes mapped into the CFD surface grids

Consistent with the linearization process described above and in order to reduce the possibility of numerical problems with aeroelastically-deforming grids, small amplitudes are used with this technique.

For the CFD computations, the flow field around the wing was evaluated on a C-H type grid, with 193 points in the chordwise direction along the wing and its wake, 65 grid points in the spanwise direction, and 41 grid points along the normal direction. The flow was analyzed using the EZNSS (Elastic Zonal Navier-Stokes Solver) Euler/Navier-Stokes code.[18] This code provides a choice between two implicit algorithms, the Beam and Warming algorithm[15] or the partially flux-vector splitting algorithm of Steger et al.[16] Grid generation and inter-grid connectivity are handled using the Chimera approach.[17] The code was enhanced with an elastic capability to compute trimmed maneuvers of elastic aircraft.[18]

The process of mode-by-mode excitation using various types of inputs, discussed previously, was performed for this wing using four elastic modes at several Mach numbers. The mode-by-mode excitation technique provides the unsteady aerodynamic response in all four modes due to an excitation of one of the modes. In this fashion, the matrix of four-by-four response functions is developed, resulting in a total of sixteen response functions.

Two sets of excitation inputs were used by Raveh et al:[5] the discrete-time unit pulse input and the discrete-time unit step input. Only one of these inputs is needed for computing the necessary responses, but Raveh et al[5] applied both a pulse and a step input for comparisons regarding numerical sensitivity of each input. The rapid convergence of the responses (to either a pulse or a step) resulted in computationally-efficient code evaluations. In addition, the mode-by-mode excitation process required a total of only four code evaluations (one per mode for pulse, one per mode for step). These sixteen pulse (or step) responses define the linearized Volterra-based ROMs for this configuration at this Mach number.

Several CFD solutions due to various sinusoidal excitations of a given mode were generated, as in the brute force approach described above, for the purpose of comparison with the Volterra-based ROM approach. Figure 3 presents the GAFs for all four modes due to a 5 Hz frequency excitation of the first mode, comparing the direct CFD solutions with the results obtained via convolution of the modal step responses with a 5 Hz sinusoid. As can be seen, the comparison is excellent for most of the responses with a slight discrepancy for the responses of the fourth mode. The full CFD solution, consisting of 8000 iterations required approximately 24 hours on an SGI Origin 2000 computer with 4 CPUs. By comparison, the Volterra-based ROM response required about a minute of computing time using digital convolution. Even including the cost of computing the modal step (or pulse) responses, the computational cost savings are significant. More importantly, the same step (or pulse) functions can now be used to predict the response of the unsteady aerodynamic system to any arbitrary input of arbitrary length. As additional examples, Figure 4 presents the resultant GAFs due to 40 and 80 Hz sinusoidal excitations of the first mode, comparing the direct CFD solutions with the results obtained via convolution of the modal step responses with the corresponding 40 and 80 Hz sinusoids. Comparisons are excellent, verifying the capability of the step responses to predict the response to arbitrary inputs. Similar results were obtained using the pulse responses as well.

In order to compare with published frequency-domain GAFs for this configuration, Raveh et al[5] generated the frequency-domain GAFs for the AGARD 445.6 wing by performing convolutions of the corresponding modal pulse/step responses with various frequencies of interest. Another approach, as discussed in Ref. 3, is to perform a Fourier transform of the pulse responses directly, resulting in the desired full frequency spectrum without the need for multiple convolutions. In the interest of brevity, those results will not be repeated here as they are discussed in detail in Ref. 5. However, the pulse responses computed for that study will be reviewed and discussed since these are the principal components used by the System/Observer/Controller Identification Toolbox (SOCIT) algorithms.

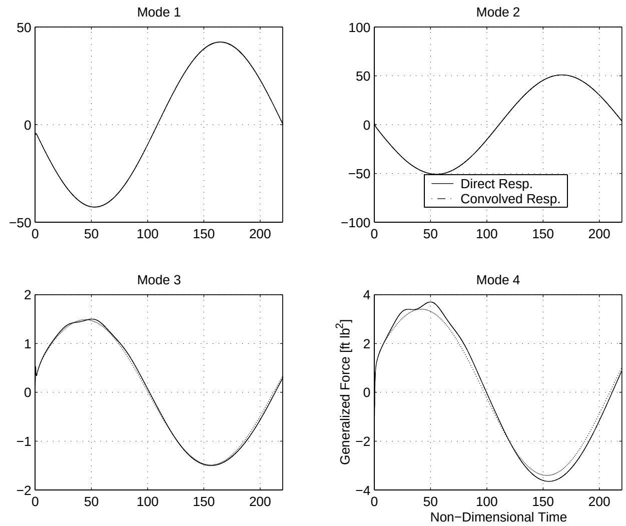

Fig. 3 Comparison of modal responses to a 5 Hz sinusoidal input for direct (CFD) and convolved (Volterra-based ROM) methods.

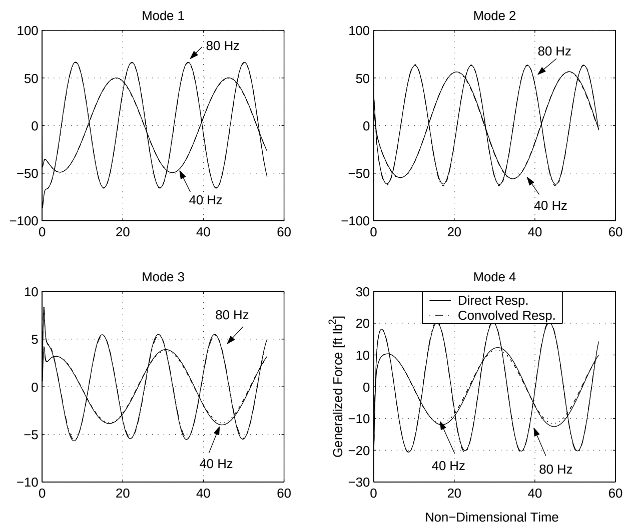

Fig. 4 Comparison of modal responses to a 40 Hz and an 80 Hz sinusoidal input for direct (CFD) and convolved (Volterra-based ROM) methods.

System/Observer/Controller Identification Toolbox (SOCIT)

The primary algorithm within the SOCIT group of algorithms used for the present system realization is known as the Eigensystem Realization Algorithm (ERA). A brief summary of the basis of this algorithm follows.

A finite dimensional, discrete-time, linear, time-invariant dynamical system has the state-variable equations

$$x(k+1) = Ax(k) + Bu(k) \tag{1}$$

$$y(k) = Cx(k) + Du(k) \tag{2}$$

where x is an n-dimensional state vector, u an m-dimensional control input, and y a p-dimensional output or measurement vector with k being the discrete time index. The transition matrix, A, characterizes the dynamics of the system. The goal of system realization is to generate constant matrices (A, B, C) such that the output responses of a given system due to a particular set of inputs is reproduced by the discrete-time state-space system described above.

For the system of Eqs. (1) and (2), the time-domain values of the systems pulse response (discrete-time equivalent of impulse response) are also known as the Markov parameters and are defined as

$$Y(k) = CA^{k-1}B \tag{3}$$

with B an n by m matrix and C a p by n matrix. System realization techniques provide the constant matrices A, B, and C using Y(k). The ERA algorithm,[12–14] similar to the Ho-Kalman procedure, begins by defining the generalized Hankel matrix consisting of the pulse responses (Markov parameters) for all input/output combinations. The algorithm then uses the singular value decomposition (SVD) to compute the A, B, and C matrices. Although Eq. (2) does not contain it, often, the direct feedthrough matrix, D, is required whenever the initial values of the Markov parameters are nonzero.

The ERA algorithm has been used successfully for the identification of several experimental structural dynamic systems. Although the algorithm also has been used to extract damping and frequency information from CFD-generated aeroelastic transients (no published references), this research represents the first time that the ERA algorithm is applied to the development of unsteady aerodynamic state-space models using aerodynamic pulse responses (Markov parameters). The ability to generate state-space models of systems using pulse responses was a primary motivation for the development of aerodynamic pulse response functions.[3] Additional details regarding the ERA algorithm and its numerous applications are discussed in the references provided.

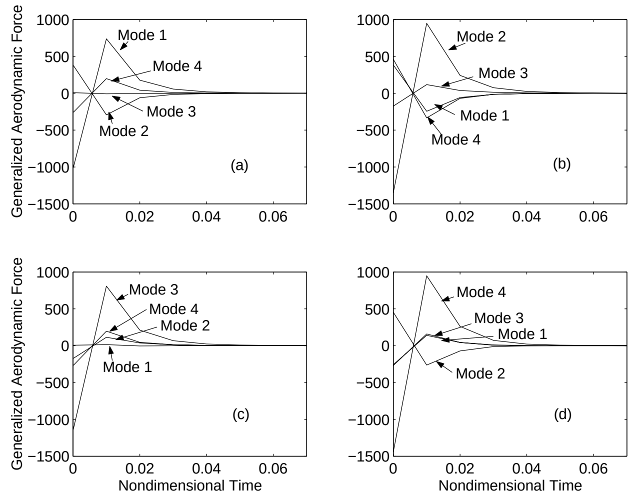

Fig. 5 Pulse responses due to inputs in a) Mode 1, b) Mode2 c) Mode 3, d) Mode 4.

Results

CFD-Based Pulse Responses

The results presented in this study are for a Mach number of 0.96. The GAF pulse responses due to pulse inputs in modes 1, 2, 3, and 4, respectively, are presented in Figure 5. As can be seen, the responses are well-behaved and exhibit a rapid converge to zero. It is precisely this rapid convergence to zero that results in an efficient computation of these functions. The "discrete" (non-smooth) nature of the responses is consistent with results obtained by Silva.[3]

Inspection of Figure 5 indicates that each one of the modes has the strongest response to its own excitation, a physically consistent result. In addition, those modes that are minimally correlated (i.e., the small response of mode 3 to mode 1 and the small response of mode 1 to mode 3) can be readily identified as well. Although not applied in the present study, this feature of time-domain modal responses may prove useful in modal truncation and/or modal residualization studies. The metric used, in the present study, to determine the quality of an identified state-space system is the accuracy to which the state-space system reproduces the CFD-based pulse responses presented in Figure 5.

32nd-Order State-Space System

The SOCIT algorithms are used to generate discrete-time unsteady aerodynamic state-space matrices (A, B, C, and D) using the set of modal pulse responses presented in Figure 5. The first system to be realized using this data is a 32nd order model. A discrete-time (z-transform) pole-zero plot of the eigenvalues of this system is presented in Figure 6. For a discrete-time system, if all the poles of the system are contained within the complex unit circle, then the system is stable. This is analogous to a continuous-time system being stable if all of its poles are on the left-hand side (roots with negative real parts) of the

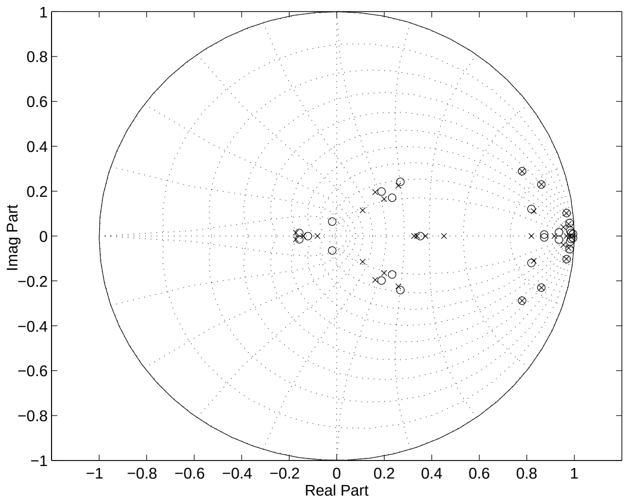

Fig. 6 Pole-zero map for 32nd order aerodynamic state-space system.

complex plane. As can be seen in Figure 6, the unsteady aerodynamic system realized is stable, as it should be, with a dominant cluster of low-frequency, low-damped roots.

Pulse responses for the 32nd-order state-space model were generated and compared with those of Figure 5. The comparison of these responses is presented as Figure 7, where it can be seen that the approximations of the sixteen GAFs are identical (to within plotting accuracy) to the GAFs in Figure 5. However, in order to thoroughly quantify the growth of error as the order of the model is reduced, comparisons of the percent error for corresponding responses is presented for a subset of the results. Figure 8 presents the percent error for the CFD and state-space modal pulses for the first four modes due to an input in the first mode. The percent error is quite small, as can be seen. But for the third mode (due to an input in the first mode), the percent error is noticeably larger. Although these are very acceptable values of percent error, the increased error for the third mode indicates an increased difficulty of the SOCIT algorithm to accurately capture responses that are small compared with the rest of the responses. This is related to the level of correlation between modes and can be interpreted as a measure of observability/controllability from one mode to another. This concept needs to be considered in the future development of these state-space models.

Figure 9 is the magnitude and phase of the frequency response for the CFD and state-space pulses for the four modes due to an input in the first mode. As expected, the comparisons for the magnitude are very good for the first, second, and fourth modes with a slight discrepancy for the second and fourth mode results at very low frequencies. The error in the third mode manifests itself as an error within the 1 to 4 Hz frequency range. The phase results show good comparison for the first, second, and fourth modes with

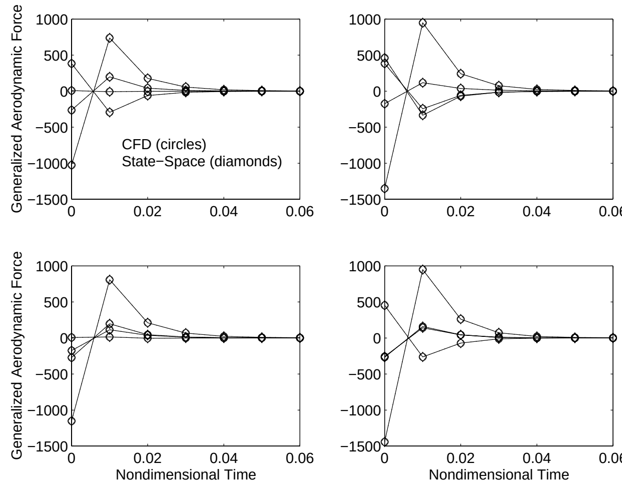

Fig. 7 Comparison of pulse responses due to input in a) Mode 1, b) Mode 2, c) Mode 3, d) Mode 4 for CFD and state-space model (32nd order).

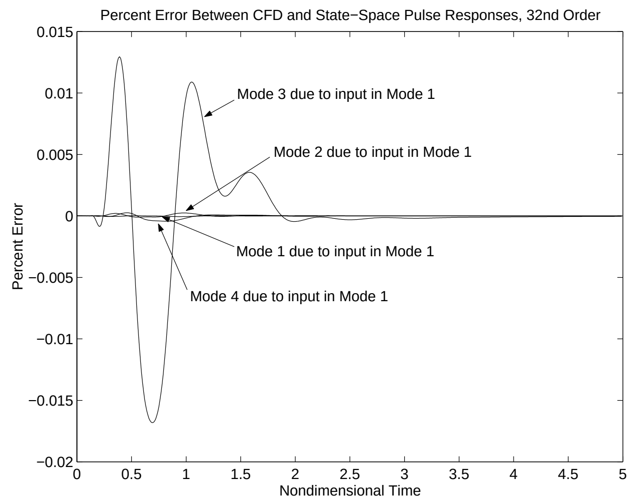

Fig. 8 Percent error between CFD and state-space pulse responses, 32nd order.

noticeable error for the third mode.

Although a 32nd-order state-space model of the unsteady aerodynamic system is somewhat larger than might typically be desired, it is nonetheless a significant reduction of order when considering the alternative: the full, three-dimensional Euler CFD computational model and solution process. In addition, there is no need to perform any shape optimization of the pulses as these are computed only once per mode. The SOCIT algorithm computes state-space models very quickly (within seconds) on a workstation with no iterative process involved unless the user is interested in evaluating various model orders.

15th-Order State-Space System

Using the SOCIT algorithm and selecting the more dominant components of the 32nd-order state-space system, a 15th-order state-space system was generated. The z-plane pole-zero map for this system is

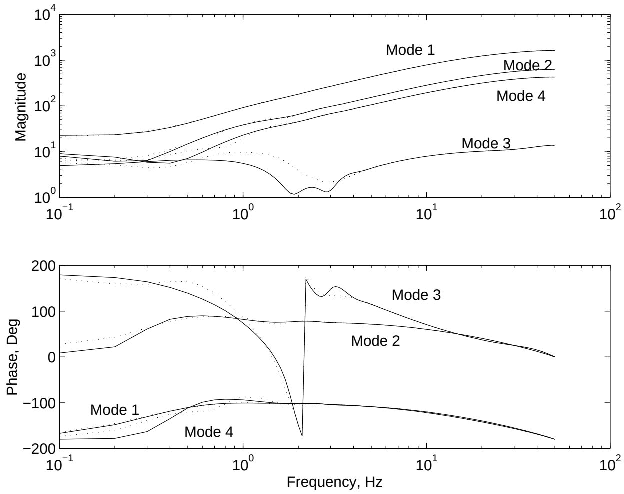

Fig. 9 Comparison of modal frequency responses due to input in mode 1, 32nd order.

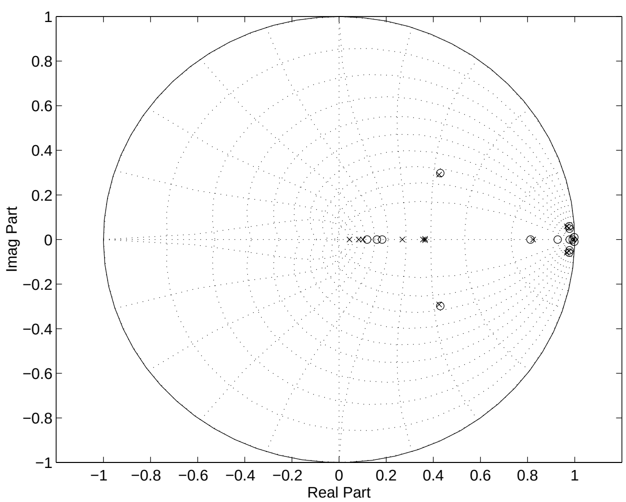

Fig. 10 Pole-zero map for the 15th order state-space model.

presented in Figure 10 with stability of the approximated unsteady aerodynamic system preserved, as expected. More importantly, inspection of z-plane pole-zero maps are helpful in identifying the dominant roots of a system as the order of an approximate system is varied. Figure 11 presents comparisons for the CFD and state-space pulse responses for the 15th-order model.

The comparisons are very good but error analysis for the first four modes due to an input in the first mode indicates an increase in the error, in particular for the third modal response as shown in Figure 12. It is interesting to note that if the correlation between two modes is low, then the response of one of the modes with respect to the other has a relatively smaller amplitude in comparison with the other modal responses. This smaller amplitude response, in turn, results in an increase in the error between the CFD pulse response and the state-space model.

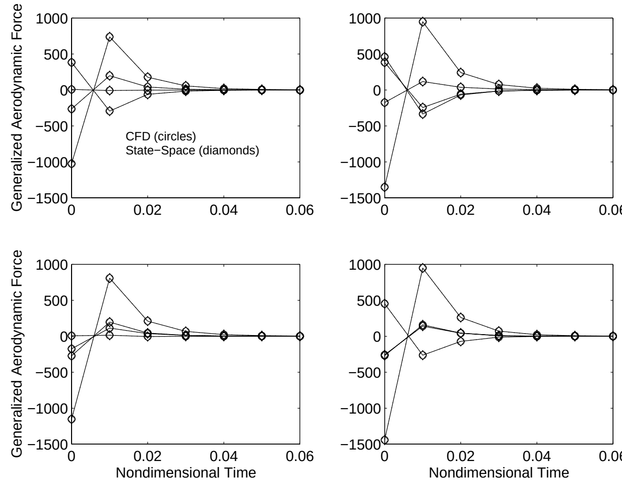

Fig. 11 Comparison of pulse responses due to input in a) Mode 1, b) Mode 2, c) Mode 3, d) Mode 4 for CFD and state-space model (15th order).

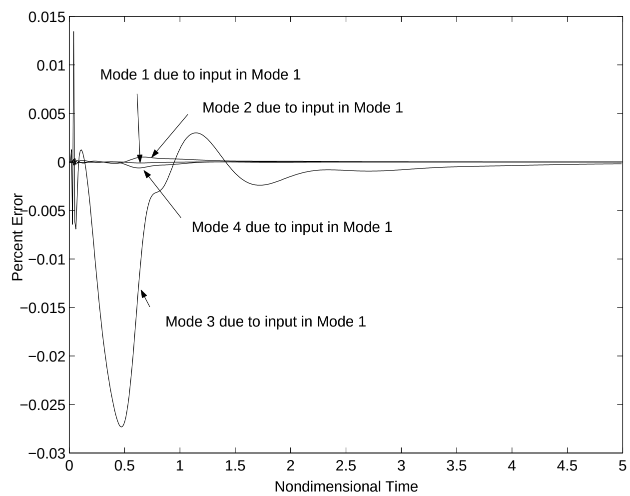

Fig. 12 Percent error between CFD and state-space pulse responses 15th order.

Finally, Figure 13 presents the comparison of magnitude and phase for the frequency responses for the CFD pulse responses and the 15th-order state-space model. Compared with the 32nd-order model, an increase in the error for both magnitude and phase, in particular for the third mode, in the low frequency range is evident with good comparison for the remainder of the frequency range. However, there does appear to be an improvement in the approximation of the magnitude for the third mode over a range of low frequencies. However, the phase approximation for the third mode has a noticeable increase in the error. Additional research, currently underway, is needed to fully understand the impact of these modeling errors on aeroelastic and aeroservoelastic analyses.

Concluding Remarks

This study presented the direct, time-domain realization of linearized, unsteady aerodynamic state-

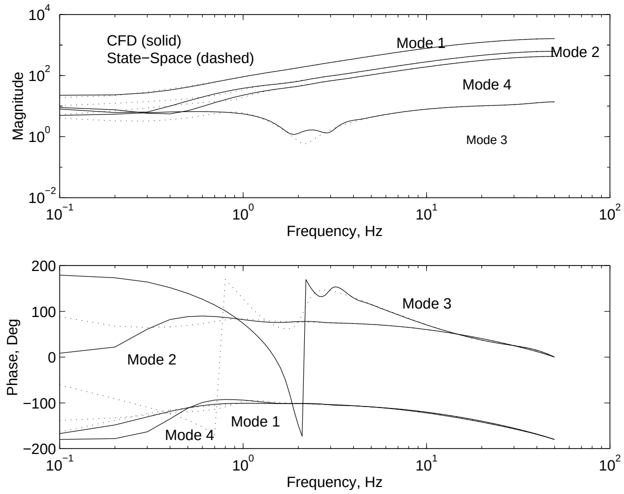

Fig. 13 Comparison of modal frequency responses due to input in mode 1, 15th order state-space model.

space models using CFD-generated pulse responses. By performing this realization entirely in the time domain, the traditional and inefficient approach of transforming time-domain GAFs into the frequency domain only to convert these back into the time domain via rational function approximations was avoided.

The results presented were for the AGARD 445.6 Aeroelastic Wing using pulse responses that were computed for this wing using the EZNSS Euler/Navier-Stokes flow solver with aeroelastic capability. The pulses were computed for a transonic Mach number of 0.96 and a mode-by-mode excitation process resulted in a linearized set of GAF influence functions. The System/Observer/Controller Identification Toolbox (SOCIT) was then used to generate four-input, four-output discrete-time state-space models of various orders that accurately capture the dynamics of the CFD-generated unsteady aerodynamic responses. A 32nd-order state-space model was shown to capture the frequency content of the pulse responses with negligible errors. Further model-order reduction resulted in a 15th-order state-space model with slight increases in the error for low frequencies but with excellent correlation for the higher frequency range.

The results provided some insights into the applicability and efficiency of the technique. It was noticed that if a given mode does not strongly excite another mode, then that portion of the identification process results in larger errors. This appears to be related to an observable/controllable aspect of the modal system but additional research is needed to fully understand this effect. Future research will address the inclusion of these state-space models into an aeroelastic/aeroservoelastic analysis to better understand the impact of these mathematical approximations. Comparisons of these systems with the more traditional rational function approximations will be performed as well. Finally, the results presented provide a first step towards the development of bilinear state-space matrices that will incorporate the effects of the nonlinear (higher-order) kernels.

Acknowledgements

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