JOURNAL OF PROPULSION AND POWER
Vol. 15, No. 3, May–June 1999

Comparative Study of Coupled-Mode Flutter-Analysis Methods for Fan Configurations

R. Srivastava* and T. S. R. Reddy*
University of Toledo, Toledo, Ohio 43606

A comparative computational study of current flutter-analysis methods, for fan geometry in subsonic flow, is carried out to evaluate the relative advantage of the methods. The flutter characteristics are computed using the following three methods: time domain, work per cycle, and the eigenvalue analysis. The eigenvalue analysis is based on a pulse method in combination with the influence coefficient method. The aeroelastic analyses are performed using a time-accurate solver based on Euler equations. The aeroelastic characteristics of the fan are obtained by coupling the unsteady Euler equation solution with a normal-mode analysis of elastic blades. For the coupled-mode flutter analyzed, the time-domain method indicated stability or instability faster than the eigenvalue method, whereas the work-per-cycle method failed to predict the flutter. The eigenvalue method provided the results in the form of aerodynamic damping and flutter frequency for each interblade phase angle analyzed. However, it was more expensive than the time-domain method, and it was better suited for analysis with a fewer number of modes.

Introduction

LARGER fan diameters with swept and wider chord blades are being used to improve the performance and efficiency of the new generation of aircraft engines. However, large-diameter, sweep, twist, and wide chord blades make the fans susceptible to aeroelastic problems. Several methods for analyzing the unsteady aerodynamic characteristics of the flowfield around vibrating blades have been reported in Refs. 1–5. Reference 2 provides a review of analytical methods developed for the unsteady aerodynamic analysis of turbomachinery configurations. Numerical analysis of aeroelastic characteristics for fan configurations is computationally expensive, and a full three-dimensional analysis has not been practical until recently. Over the years, several methods, with varying degrees of simplifying assumptions, have been developed to calculate the aeroelastic flutter stability characteristics of a fan. The most commonly used method, the work-per-cycle calculation method, calculates the aeroelastic characteristics based on energy exchange between the vibrating blades and the surrounding flowfield. This method, also referred to as the energy method by Bendiksen,[6] calculates flutter for isolated natural modes. It ignores the coupling of the modes. This assumption provides fast calculation of the aeroelastic characteristics, and is reasonably adequate for straight-blade designs. Several methods based on the energy method, using linearized[6–8] as well as nonlinear aerodynamic analyses,[9–11] have been reported. In the modern designs of turbomachinery with large swept blades, the energy method for single-mode flutter may not be sufficient. Also, to compute the flutter boundary with the energy method will require a significantly large number of calculations, as the calculation must be repeated for all frequencies, normal modes, and interblade phase angles (IBPAs) of interest.

Three-dimensional aeroelastic methods for ducted fan configurations have been reported in literature in the last few years. Williams et al.[12] reported a method for ducted-fan flutter analysis, based on an eigenvalue method using linear potential flow analysis. The eigenvalue analysis was based on a pulse-response method in conjunction with an influence-coefficient method. Ku and Williams[13] used the full potential equations to solve for flutter stability using the eigenvalue approach. Bakhle et al.[14] reported a method based on pulse response and influence coefficient using the full-potential aerodynamic analysis. Recently, Srivastava and Reddy[15] reported an analysis based on Euler equations to calculate flutter characteristics of ducted rotors using a time-domain analysis method. Based on the eigenvalue-analysis method of Ref. 14, Srivastava et al.[16] developed an analysis method based on Euler equations. Both the time-domain analysis[15] and the frequency-domain analysis[16] can calculate the flutter characteristics for all possible IBPAs, and can couple any arbitrary number of natural modes in the analysis.

Each of these methods for calculating the aeroelastic characteristics has certain benefits and advantages. Depending on the objective of the analysis, one method may be more suited than another. The objective of this paper is to investigate and report the relative advantages of each of the three methods, namely, the time-domain method, the work-per-cycle method, and the eigenvalue-analysis method for a fan configuration. Accuracy, advantages, disadvantages, CPU requirements, output parameters, and limitations of the methods are discussed.

There are limited experimental data available in the open literature for flutter of fans. There are, however, significant data available for unducted rotors (propfans). In the present work, a propfan geometry that showed flutter[17] is chosen for the analysis. The propfan is modified to represent a fan configuration by enclosing it within a rigid cylindrical duct. Depending on the tip gap, enclosing the propfan within a duct makes the flow nearly two dimensional. Similar geometry has been used by Williams et al.[12] for aeroelastic studies, and by Hall and Delaney[18] for unsteady aerodynamic study. It was shown in Ref. 12 that enclosing the propfan within a duct decreases the aeroelastic stability of the fan.

An aeroelastic solver, DuctE3D,[19] based on the Euler equations, has been developed for calculating the flutter of ducted rotor configurations. The solver can calculate flutter characteristics using any of the three flutter computation methods: time-domain flutter-analysis method, work-per-cycle method based on simple harmonic oscillation, or the eigenvalue-analysis method based on pulse and influence coefficient. The DuctE3D solver is used in the present study. The results are obtained for an inflow condition and geometry close to the flutter boundary of the unducted configuration.

Formulation

Aerodynamic Analysis

The unsteady aerodynamic forces are obtained by solving the three-dimensional unsteady Euler equations using a time-marching technique. The analysis uses a hybrid solution algorithm by treating two flux directions implicitly. The third flux direction is treated in a semi-implicit manner to reduce CPU time and memory requirements, which is critical for computationally expensive aeroelastic

Received April 9, 1998; revision received Sept. 21, 1998; accepted for publication Sept. 22, 1998.

*Senior Research Associate; currently Resident Research Associate, John H. Glenn Research Center at Lewis Field, Cleveland, OH 44135. Member AIAA.

calculations. A detailed description of the numerical analysis is given in Ref. 20.

Aeroelastic Analysis

The aeroelastic analysis is described in detail in Ref. 15 for the time-domain method, and in Ref. 16 for the eigenvalue-analysis method. Only a brief description is provided here for the sake of completeness. For the aeroelastic analyses, the hub and the duct are assumed to be rigid. This assumption simplifies the problem by structurally decoupling the blades from one another as well as from the hub and the duct. Consequently, each blade can be structurally modeled separately. Ignoring the structural coupling could, however, impact the calculations adversely for low-order, low-nodal-diameter blade–disk vibration modes.

The governing aeroelastic equation in normal modes can be written as follows:

$$[M_g]\{\ddot{q}\} + [C_g]\{\dot{q}\} + [K_g]\{q\} = \{F\} \tag{1}$$

where M_g, C_g, and K_g are the modal mass, damping, and stiffness matrices, respectively. These matrices are obtained using a finite element analysis; $\boldsymbol{q}$ is the normal-mode perturbation from a steady state, and $\boldsymbol{F}$, a function of $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$, is the modal unsteady aerodynamic force vector.

Time-Domain Analysis

In the time-domain method, one of the blades of the fan is perturbed from the steady state by providing it a velocity impulse in all of the normal modes included in the analysis. The response of the system is then calculated for this initial disturbance from the steady state by integrating the governing equation [Eq. (1)], in time using the method of constant acceleration (trapezoidal rule). The normal-mode perturbations obtained by solving Eq. (1) provide a new deflected blade shape. The new blade shape is then used to obtain the new aerodynamic loads. This iteration process is repeated and the subsequent variation of the normal-mode vector is analyzed to obtain the stability characteristics. The flutter frequency and IBPA can be inferred by a Fourier analysis of the rotor blade responses, if required. The intermodal coupling is included only by aerodynamic coupling in the current model.

Work-per-Cycle Analysis

In this analysis, the blades are harmonically oscillated at a prescribed mode shape, frequency, and IBPA. The work done on the blade by the surrounding fluid is calculated. If the net work being done on the blade by the fluid is positive, the blade is considered aeroelastically unstable for the given condition. This process needs to be repeated for all of the mode shapes, frequencies, and IBPAs of interest.

Eigenvalue-Analysis Method

In this analysis, one of the blades is forced to undergo a small deflection from a steady state. The unsteady aerodynamic forces, caused by deflection, are obtained for all of the blades, and the unsteady aerodynamic coefficients are calculated using Fourier analysis. These coefficients are used in the Laplace transform of the governing aeroelastic equation [Eq. (1)] to form an eigenvalue problem:

$$\det\left[M_g s^2 + C_g s + K_g - Q(\sigma, s)\right] = 0 \tag{2}$$

where σ is the IBPA and $Q(\sigma, s)$ is obtained by taking the Laplace transform of $\boldsymbol{F}$ for each blade and combining them using linear superposition based on the influence coefficient method[14] for the IBPAs of interest. The stability of the blades is determined by finding the roots of Eq. (2). The roots of the eigenvalues indicate the aerodynamic damping at the coupled-mode frequency for a given IBPA to provide the aeroelastic characteristics. If the real part of any of the roots of Eq. (2) is greater than zero (negative aerodynamic damping), the fan is unstable for that IBPA. For a given fan, the number of possible IBPAs for flutter are same as the number of blades in the fan.[21] Therefore, Eq. (2) is solved for only these possible phase angles.

The aerodynamic coefficients can be obtained either by a harmonic analysis or by a pulse-response method. The pulse-response method significantly reduces the computational time required, compared with the harmonic-analysis method, by utilizing the principles of superposition. In a single run, the unsteady aerodynamic coefficients can be obtained for a range of frequencies contained within the pulse. The harmonic-analysis method will require separate runs for each frequency of interest. If the flutter frequency is not known a priori, the harmonic analysis must be carried out over a range of frequencies, resulting in much higher computational cost. The unsteady aerodynamic coefficients are obtained for the normal modes of interest, using separate runs for each mode.

Results and Discussion

The DuctE3D code has been validated for steady performance in Ref. 22 and for flutter of unducted fans in Ref. 23. The unsteady flowfield analysis for a fan configuration is validated here by first applying it to a flat-plate helical fan for subsonic flow conditions. The unsteady pressures obtained are compared with results for a linear theory[24] and a three-dimensional linearized Euler analysis.[8] The code is then applied for flutter analysis of a fan configuration using the three flutter-analysis methods. All of these analyses have been carried out on a Cray C-90.

Flat-Plate Helical Fan

The flat-plate helical fan has a tip diameter of 8.488, a hub diameter of 6.790, a constant blade chord of 1, a stagger angle at midspan of 45 deg, 24 blades, and no gap at the tip. All of the lengths are scaled with the blade chord. The inflow conditions are such that the inflow relative Mach number at the midspan is 0.7 with an axial Mach number of 0.495. These conditions result in a flat-plate at zero incidence under steady flow conditions. The flat-plate helical fan is harmonically oscillated about the steady-state position, with a reduced frequency based on a chord of 1. This example has been presented by Montgomery and Verdon[8] and is a good subsonic test case. Because the Mach number is in the subsonic range, the results are expected to be linear and should compare well with linear analytical methods[24] for unsteady pressures.

The results are presented for two different cases: pitching about midchord with 0-deg IBPA and plunging with 180-deg IBPA. The pitching amplitude is 0.2 deg and the plunging amplitude is 1% of chord at the midspan. The results obtained are compared with results presented in Ref. 8 for linearized three-dimensional Euler analysis (3D LINFLUX) and for two-dimensional Smith theory.[24] The comparisons are shown in Fig. 1 for pitching, and in Fig. 2 for plunging. The variation of unsteady pressure difference at the midspan, normalized with oscillation amplitude, is plotted against the distance along the blade chord. Good correlation is obtained for both cases presented, indicating the unsteady aerodynamic analysis

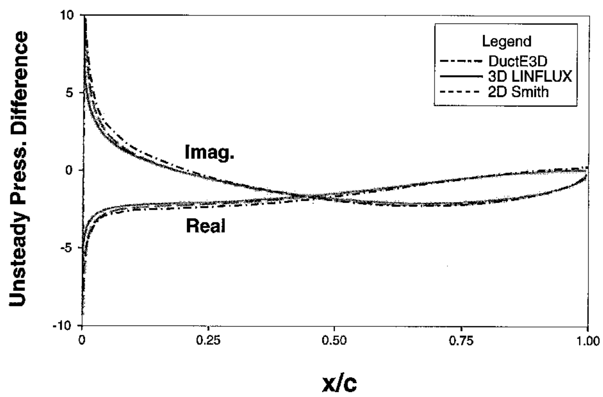

Fig. 1 Comparison of unsteady pressure difference normalized with oscillation amplitude for the flat-plate helical fan undergoing in-phase pitching motion.

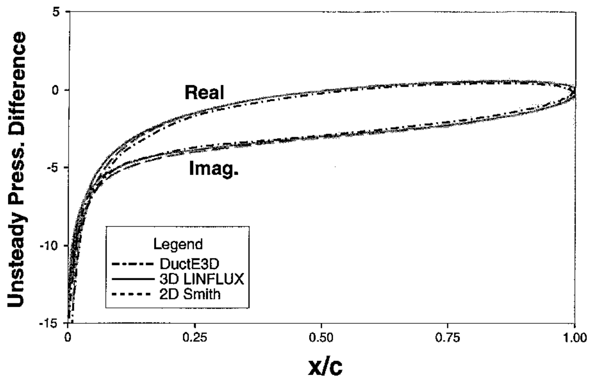

Fig. 2 Comparison of unsteady pressure difference normalized with oscillation amplitude for the flat-plate helical fan undergoing out-of-phase plunging motion.

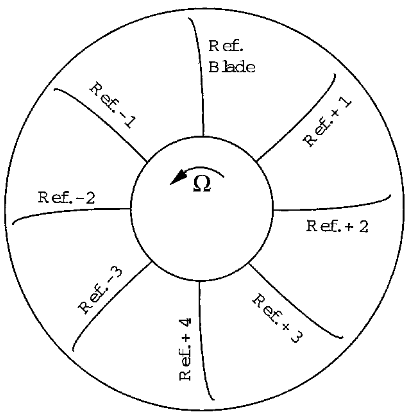

Fig. 3 Schematic of the eight-blade-passage computational domain.

of DuctE3D to be accurate for vibrating fan blades. The analysis was carried out using a $140 \times 13 \times 21$ grid with 70 points on the blade surface. The code required 8 MWord of memory and slightly less than 5 min per oscillation cycle. A total of five cycles with 352 steps per cycle were required for convergence.

SR3C-X2 Ducted Fan

The aeroelastic analysis was then applied to a fan configuration obtained by enclosing the eight-bladed SR3C-X2 propfan within a rigid cylindrical duct with a tip gap of 1.0% of the blade tip radius. It should be noted here that the flowfield within the gap is not being resolved. The gap, however, does provide a pressure relief at the tip. The propfan is highly swept with the first natural mode being primarily flexural with significant torsional component. The second mode is primarily first torsion, and the third mode is primarily second flex. The natural frequencies of the first three modes for nonrotating blade are 221, 431, and 695 Hz, respectively.

The propfan, in the unducted configuration, fluttered for several test configurations.[17] One of the measured flutter conditions for the eight-bladed configuration was at advance ratio $J = 3.55$, blade setting angle $\beta = 61.2$ deg, and a freestream Mach number $M_\infty = 0.60$ (Ref. 17). The flutter was reported to be a coupled-mode flutter and was measured at a frequency of 264 Hz and at an IBPA of 225 deg (Ref. 17), implying a coupling between the first and second modes. In the present paper, the aeroelastic stability is calculated for $M_\infty = 0.5$, $J = 3.55$, and $\beta = 61.2$ deg. The experiments[17] and calculations[23] showed the unducted propfan to be stable at a 0.5 Mach condition; however, the fan configuration was found to be unstable in the numerical analysis.[15] A coupled-mode instability was found for the unducted propfan at a Mach number greater than 0.62 (Ref. 23).

A schematic of the fan layout and blade-numbering scheme is shown in Fig. 3. Several different phase angles are analyzed. The nonzero IBPAs are analyzed by stacking the number of blade passages required. The flutter was observed between the first and the second normal mode; hence, the analysis is carried out using up to three normal modes.

Time-Domain Results

The time-domain analysis is carried out using the first three normal modes. The fan is analyzed using one, two, and all eight-blade passages. The single-blade-passage analysis can resolve only the 0-deg IBPA characteristics, and the two-blade passages can resolve the 0- and the 180-deg characteristics. The eight-blade-passage analysis will resolve the flutter characteristics of all possible IBPAs for the eight-bladed fan, namely, 0-, 45-, 90-, 135-, 180-, 225-, 270-, and 315-deg IBPAs. For these cases, the initial perturbation is provided to the reference blade (Ref. Blade, Fig. 3) in all of its normal modes, with no perturbations to any of the other blades. The subsequent responses of all the blades are observed. The time-domain responses of blade oscillations would be such that the steady IBPA contributions having a positive aerodynamic damping would diminish, whereas the IBPA with negative aerodynamic damping will have increasing amplitudes, and the net response will be a combination of the responses of all unstable IBPAs. These responses can be Fourier analyzed to provide the frequency and the IBPA for flutter.

The response of the blade for the single-passage analysis is shown in Fig. 4. As can be seen, the initial perturbation provided to the blade rapidly dies out. However, for the two-blade-passage analysis (Figs. 5 and 6), the response amplitude for the blade increases with time. Further, from Fig. 5, it can be seen that the response frequency of all the modes have coalesced, indicating a flutter instability. Only the reference blade response is shown in this figure. Similar response was obtained for the other blade as well. Not only does the reference blade, the blade that was perturbed, show diverging response, but the other blade also shows a diverging response. An examination of the first mode response (Fig. 6) shows the two blades moving about

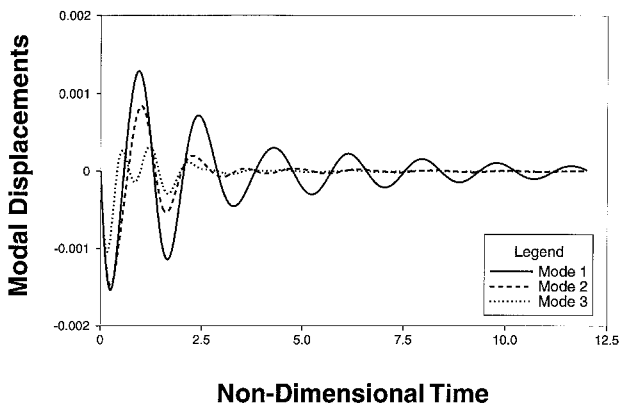

Fig. 4 Time history of the modal displacements for single-blade-passage analysis of the eight-bladed SR3C-X2 fan.

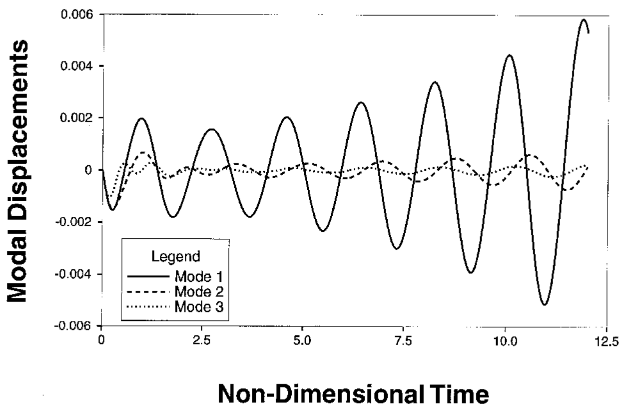

Fig. 5 Time history of the modal displacements of reference blade for two-blade-passage analysis of the eight-bladed SR3C-X2 fan.

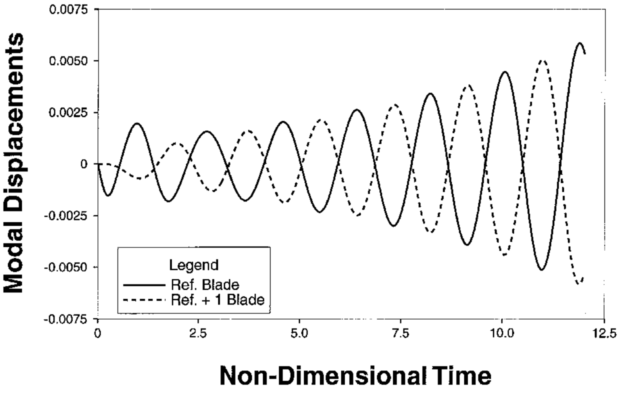

Fig. 6 Time history of first mode displacements for two-blade-passage analysis of the eight-bladed SR3C-X2 fan.

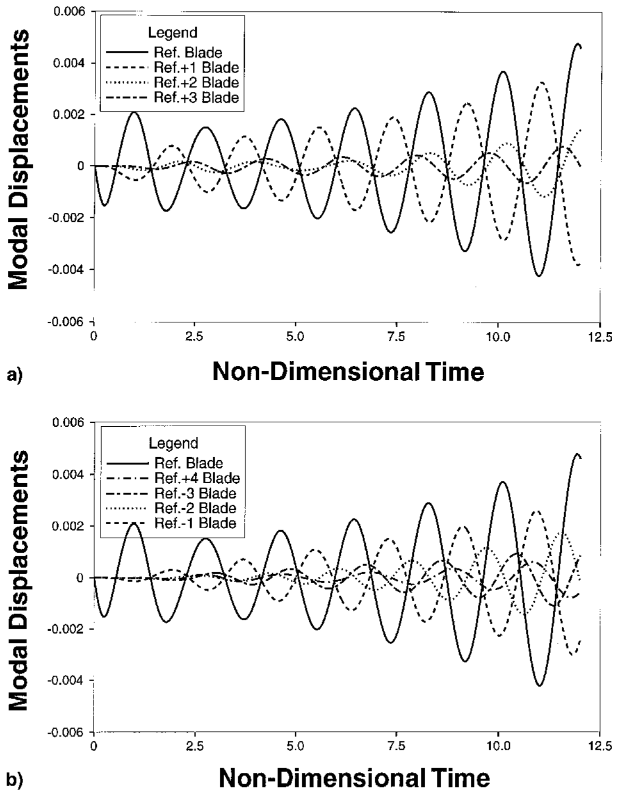

Fig. 7 Time history of first mode displacements for eight-blade-passage analysis of the eight-bladed SR3C-X2 fan. a) Blades: Ref., Ref.+1, Ref.+2, Ref.+3. b) Blades: Ref., Ref.+4, Ref.− 3, Ref.− 2, Ref.− 1.

180-deg out-of-phase, indicating the flutter IBPA to be 180 deg. A Fourier analysis of the responses indicated the flutter frequency to be ~290 Hz, indicating a coupled-mode instability with coupling between the first and the second normal modes. This was further verified by analyzing the fan with only one of the normal modes at a time. No instability was found for the single-mode analysis.

The response for the eight-blade-passage analysis (all possible IBPAs) is shown in Fig. 7. Again, not only does the perturbation to the reference blade start growing, the responses for the other blades also show an increasing amplitude oscillation. For this case also, the oscillation frequency of all three modes analyzed is observed to coalesce, indicating a flutter instability. However, no clear pattern of IBPA is obvious from these responses.

The analysis assumes all of the blades to be structurally identical; however, perturbing only one blade introduces aerodynamic mistuning into the system. Because of the spatial periodicity, the general motion of blades in the mistuned system can be represented in a traveling wave form of the corresponding tuned system.[25] The real and

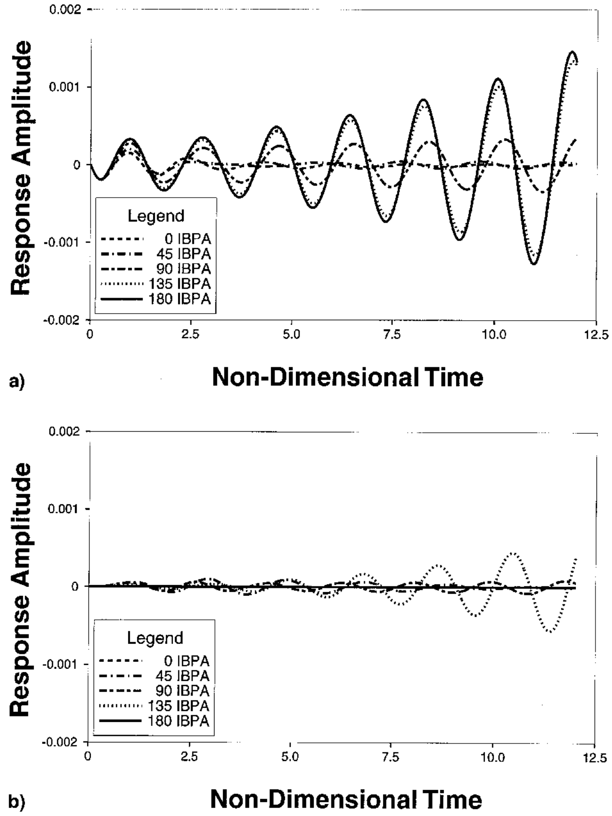

Fig. 8 Time history of amplitudes for various IBPAs for eight-blade-passage analysis of the eight-bladed SR3C-X2 fan: a) real and b) imaginary amplitudes.

imaginary components of the traveling-mode response amplitudes are plotted with respect to time in Fig. 8. Because the traveling mode assumes a harmonic variation, 0- and 180-deg IBPA responses do not have an imaginary component. Further, the responses for 225-, 270-, and 315-deg IBPAs are complex conjugates of the responses for 135-, 90-, and 45-deg IBPAs, respectively, and are not shown. From these figures, it can be seen that 0- and 45-deg IBPAs are stable, and 135 and 180 deg are unstable. An IBPA of 90 deg appears to be mildly unstable. It is also evident from these figures that perturbing only one blade in the rotor provides perturbation to all of the IBPAs, so that the stability of all IBPAs can be determined from a single calculation.

These responses indicate that the eight-bladed fan for the given conditions is unstable, in the 180-deg IBPA, whereas the 0-deg IBPA is indicated to be stable. The stability or instability is indicated fairly quickly, within five or six cycles of oscillation. A Fourier analysis of the responses can provide the frequency and aerodynamic damping associated with each IBPA. For the length of time of the calculated time history, the frequency and phase, particularly for the eight-blade-passages case, were not uniform and were still changing. A more accurate determination of these quantities will require a much longer time history. For the time history shown, the analysis required approximately 45 min of CPU time per blade passage analyzed, and scaled linearly with blade passages. On the other hand, it was found that including more normal modes in the analysis does not significantly increase CPU time. Each additional mode increased the CPU requirement by approximately 3%.

Work-per-Cycle Results

The results from the work-per-cycle analysis are presented next. For this method, all of the blades are forced to undergo a harmonic oscillation at a prescribed mode shape, frequency, and IBPA. Depending on the IBPA being analyzed, the analysis uses the required number of blade passages. The results have been obtained for one blade passage, undergoing 0-deg IBPA motion, and two blade passages, undergoing 180-deg IBPA motion. Variation of the

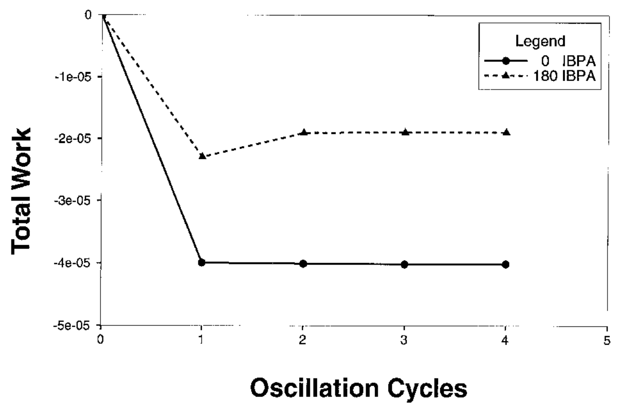

Fig. 9 Variation of nondimensional work per cycle with oscillation cycle for first mode for the eight-bladed SR3C-X2 fan.

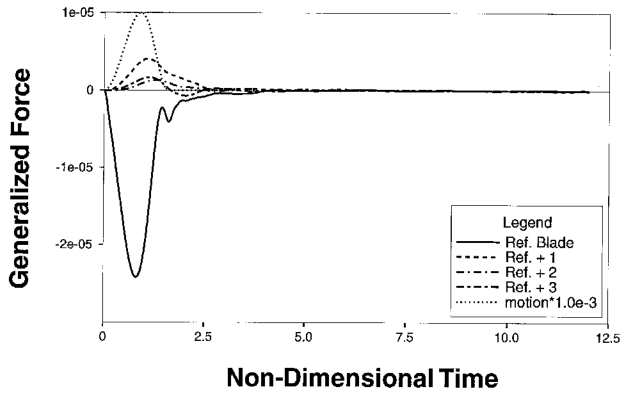

Fig. 10 Time history of the generalized force caused by pulse motion for four-blade-passage analysis of the eight-bladed SR3C-X2 fan.

nondimensional work per cycle with an oscillation cycle, for the first mode, is shown in Fig. 9. The net work for a cycle of oscillation is shown by solid circles for the 0-deg IBPA, and by solid triangles for the 180-deg IBPA. As can be seen, a negative work is obtained, implying a stable fan. Several modes and frequencies, including the one indicated by other methods for instability, were analyzed. In all of the cases, a negative work was calculated, implying the blade was doing work on the surrounding fluid, indicating a stable fan. This was not unexpected as flutter occurs in a coupled mode, whereas, in the analysis, only one of the normal modes of the blade was included at a time. This method required approximately 28 min of CPU time per blade passage and scaled linearly with blade passages. Further, because only one mode is analyzed at a time, the CPU time scales linearly with the number of modes of interest. The CPU time was also dependent on the frequency of oscillation. The time step required for the analyses was determined by stability considerations of the flow solver, and was independent of the frequency of oscillation. This resulted in lower frequencies, requiring more time steps per oscillation cycle; hence, higher CPU time than higher frequencies.

Eigenvalue Results

The eigenvalue analysis was carried out using one-, two-, or four-blade passages, and only the first two normal modes to save computational time. In this case, again, the pulse motion was provided only to the reference blade with no motion to the other blades. The resulting unsteady aerodynamic responses were recorded for all of the blades. The Fourier transforms of the unsteady aerodynamic responses were used to solve Eq. (2) to obtain the stability characteristics for all of the possible phase angles. For a two-passage analysis, 0- and 180-deg IBPAs can be resolved, whereas, for a four-passage analysis, 0-, 90-, 180-, and 270-deg IBPAs can be analyzed.

A typical pulse (dotted line), along with a time variation of the generalized force amplitude, is shown in Fig. 10. The pulse motion,

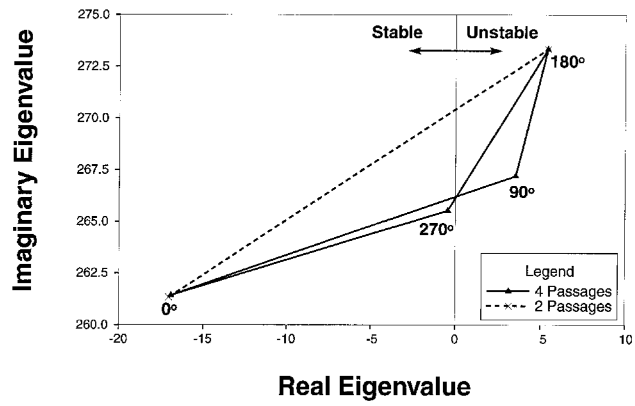

Fig. 11 Eigenvalue plot for two- and four-blade-passage analysis of the eight-bladed SR3C-X2 fan.

provided only to the reference blade, smoothly ramps up from zero to a prescribed peak value, and then smoothly ramps down to zero, remaining there for all subsequent time. The analysis is carried out until all of the disturbances resulting from pulse motion die out. It can be seen that it requires approximately four to five pulse durations, after the pulse motion has subsided, for the transients to diminish to a prescribed tolerance, even though it becomes fairly small after about one pulse duration.

The eigenvalues obtained are plotted in Fig. 11. The variation of the imaginary part of the eigenvalue, a representative of the characteristic frequency, is plotted vs the real part of the eigenvalue, representative of the aerodynamic damping. Both of these calculations show that the 0-deg IBPA has a negative real part, indicating it to be stable, whereas the 180-deg IBPA has a positive real part, indicating instability. The other two IBPAs, for the four-blade-passages analysis, are very close to the stability boundary with 90-deg IBPA being unstable and 270-deg IBPA being stable. The frequency for the 180-deg IBPA was calculated to be 274 Hz. The eigenvalue analysis carried out with only one normal mode did not indicate instability. This implies that the instability is a coupled-mode instability and requires coupling between the first and the second mode. Also, the results obtained from the two- and four-blade-passage analyses correlate very well with each other.

The eigenvalue analysis required ~45 min of CPU time per blade passage per normal mode analyzed. The CPU time, as expected, scales linearly with blade passages. However, unlike the time-domain analysis, the CPU time for the eigenvalue analysis scales linearly with the number of normal modes. For the coupled-mode flutter calculation, eigenvalue analysis requires that the generalized forces be calculated for motion in each mode of interest. This requires separate runs for each mode included in the analysis, resulting in a linear scaling of CPU time with the number of normal modes.

Discussion of Results

The results obtained from time domain and eigenvalue analysis correlate well with each other. Both of these methods indicated that the 0-deg IBPA is stable and that the 180-deg IBPA and a few other IBPAs are unstable. The flutter was indicated by both methods to be a coupled-mode flutter with coupling between the first two modes. The flutter frequency was calculated to be 274 Hz by the eigenvalue analysis, whereas it was calculated as ~290 Hz by the time-domain method. This difference in frequency could be attributed to the inability to accurately calculate the frequency from the available time histories. A longer time history will provide better correlation for frequency, albeit at a higher computational cost. On the other hand, the work-per-cycle analysis failed to indicate flutter altogether.

The time-domain method provided the stability behavior much faster than the eigenvalue-analysis method. It required only a few oscillation cycles to indicate the stability or instability of the fan. Any number of normal modes, with little additional computational cost, can be easily included in the analysis. There are, however, a few areas of concern that are foreseen for the time-domain analysis. A marginally stable or unstable fan, or a limit-cycle behavior, may require a much larger run time to establish the stability characteristics of the fan. Also, to obtain a more accurate estimate of the flutter frequency and the IBPA of flutter, much larger time histories will be required. A larger time history will not only be computationally expensive, but also may not be always feasible, as large oscillation amplitudes could lead to numerical problems for the computational fluid dynamics analysis.

The eigenvalue-analysis method provides all of the characteristics needed to clearly understand the behavior of the fan. However, there were several problem areas encountered by the pulse-response method. First of all, it requires a, very steady, steady-state aerodynamic condition to start the analysis. If the aerodynamics is not very steady, the variation in the generalized forces because of changes in the steady state would mask the variations caused by unsteady pulse motion, thus leading to erroneous results. To obtain this steady state, a much longer aerodynamic steady run was required, leading to increased CPU requirements. This may also pose a problem for the viscous calculations because there are inherent unsteadiness in the flowfield caused by vortex shedding and turbulence. For these disturbances to be at the noise level, a much larger pulse amplitude may be required for viscous analysis. However, a larger pulse may lead to questions of linearity, invalidating the method. Another problem foreseen for the eigenvalue analysis is that the calculations must be carried out until the unsteadiness of the flowfield, after the blade has returned to its steady-state position, diminishes. For certain configurations and inflow conditions, this may take significantly longer. It may also not work for a viscous analysis where unsteadiness resulting from wake vortices may not allow the unsteadiness in the calculated aerodynamic responses to die out. Because of these limitations, the eigenvalue method may not be suitable at off-design conditions, as viscous effects must be included for the analysis. Further, each additional mode included in the analysis increased the CPU cost significantly. For example, the time-domain analysis required ~6 h of CPU time to analyze eight-blade passages (eight IBPAs) with three normal modes, whereas for the eigenvalue method only four IBPAs with two normal modes could be analyzed in 6 h. Using three normal modes and eight-blade passages, as in the time domain, would have required a total of 18 h of CPU time. This implies that an analysis with a large number of modes could be prohibitively expensive with this method.

Based on these results, it appears that the work-per-cycle method is best suited for a single-mode flutter, such as stall flutter. The method reported by Gerolymos[9] may be able to predict a coupled-mode instability using the work-per-cycle method, and needs to be applied to this configuration to evaluate its effectiveness. If stability indication is the primary interest, the time-domain method provides the fastest solution. For flutter details, such as flutter frequency, IBPA, and aerodynamic damping at all of the IBPAs of interest, one may have to use the eigenvalue-analysis method. It should also be noted, however, that a Fourier analysis of time histories from time-domain analysis will provide reasonably accurate flutter details. Further, for viscous aeroelastic analysis, where the pulse method may not be applicable, a harmonic oscillation method may have to be used to provide the aerodynamic coefficients for all of the frequencies of interest. This could increase the computational cost significantly.

Concluding Remarks

Three different analysis methods were applied to a fan configuration to understand the relative merits of the methods in predicting flutter behavior. For the example case of a coupled-mode flutter, it was found that all of the analysis methods failed to indicate instability for a single-mode analysis. The coupled-mode analyses using the time-domain and eigenvalue-analysis methods indicated a coupled-mode instability and correlated well with each other. Both indicated the 0-deg IBPA to be stable and the 180-deg IBPA, along with a few other IBPAs, to be unstable. The time-domain method for the eight-blade-passage analysis, even though it indicated instability, did not converge to a state where the values of flutter frequency, aerodynamic damping, and the IBPA could be accurately obtained. It, however, required less than half the CPU time of the eigenvalue analysis for the same problem size. Also, the pulse method may be fairly expensive when more normal modes are included in the analysis. Further, including the structural coupling would increase the CPU cost for the time-domain analysis.

From this study it is felt that for an indication of stability the time-domain analysis is the best choice, whereas the pulse method is best suited if one is interested in all of the details of the flutter characteristics. The pulse method may fail for flows with inherent unsteadiness; the harmonic oscillation method may then be used to obtain the unsteady aerodynamic coefficients for the eigenvalue method. This will lead to requiring even larger CPU time for the eigenvalue method. The work-per-cycle method may be best suited for blade geometries, where the flutter occurs in a single normal-mode and there is negligible modal coupling.

Acknowledgments

This work has been carried out under NASA Grant NAG 3-1230 from the Machine Dynamics Branch of the John H. Glenn Research Center at Lewis Field. The numerical results were obtained on the Cray C-90 of the Numerical Aerospace Simulation facility at NASA Ames Research Center.

References

[1]Namba, M., "Three-Dimensional Flows," *AGARD Manual on Aeroelasticity in Axial-Flow Turbomachines*, Vol. 1, edited by M. F. Platzer and F. O. Carta, AGARD, AG-298, Sec. 4, 1987, pp. 1–29.

[2]Chi, R. M., "An Unsteady Lifting Surface Theory for Ducted Fan Blades," *Journal of Turbomachinery*, Vol. 115, No. 1, 1993, pp. 175–188.

[3]Hall, K. C., and Lorence, C. B., "Calculation of Three-Dimensional Unsteady Flows in Turbomachinery Using the Linearized Harmonic Euler Equations," *Journal of Turbomachinery*, Vol. 115, Oct. 1993, pp. 800–809.

[4]Peitsch, D., Gallus, H. E., and Weber, S., "Computation of Unsteady Transonic 3D-Flow in Turbomachine Bladings," *Proceedings of 7th International Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines*, edited by Y. Tanida and M. Namba, Elsevier, Amsterdam, 1995, pp. 161–176.

[5]Gerolymos, G. A., and Vallet, I., "Validation of Three-Dimensional Euler Methods for Vibrating Cascade Aerodynamics," *Journal of Turbomachinery*, Vol. 118, Oct. 1996, pp. 771–782.

[6]Bendiksen, O. O., "Aeroelastic Problems in Turbomachinery," AIAA Paper 90-1157, April 1990.

[7]Carta, F. O., "Coupled Blade-Disk-Shroud Flutter Instabilities in Turbojet Engine Rotors," *Journal of Engineering for Power*, Vol. 89, July 1967, pp. 419–426.

[8]Montgomery, M. D., and Verdon, J. M., "A Three-Dimensional Linearized Unsteady Euler Analysis for Turbomachinery Blade Rows," NASA CR-4770, March 1997.

[9]Gerolymos, G. A., "Coupled 3-D Aeroelastic Stability Analysis of Bladed Disks," American Society of Mechanical Engineers, Paper 92-GT-171, June 1992.

[10]He, L., and Denton, J. D., "Three Dimensional Time Marching Inviscid and Viscous Solutions for Unsteady Flows Around Vibrating Blades," *Journal of Turbomachinery*, Vol. 116, July 1994, pp. 469–476.

[11]Bakhle, M. A., Srivastava, R., Stefko, G. L., and Janus, J. M., "Development of an Aeroelastic Code Based on an Euler/Navier-Stokes Aerodynamic Solver," American Society of Mechanical Engineers, Paper 96-GT-311, June 1996.

[12]Williams, M. H., Cho, J., and Dalton, W. N., "Unsteady Aerodynamic Analysis of Ducted Fans," *Journal of Propulsion and Power*, Vol. 7, No. 5, 1991, pp. 800–804.

[13]Ku, C. C., and Williams, M. H., "Three-Dimensional Full Potential Method for the Aeroelastic Modeling of Propfans," AIAA Paper 90-1120, April 1990.

[14]Bakhle, M. A., Keith, T. G., Jr., and Williams, M. H., "Unsteady Aerodynamics and Flutter Based on the Potential Equation," AIAA Paper 93-2086, June 1993.

[15]Srivastava, R., and Reddy, T. S. R., "Aeroelastic Analysis of Ducted Rotors," *Proceedings of International Symposium on Computational Fluid Dynamics in Aeropropulsion*, AD-Vol. 49, American Society of Mechanical Engineers, New York, 1995, pp. 1–9.

[16]Srivastava, R., Reddy, T. S. R., and Stefko, G. L., "A Numerical Aeroelastic Stability Analysis of a Ducted-Fan Configuration," AIAA Paper 96-2671, July 1996.

[17]Mehmed, O., and Kaza, K. R. V., "Experimental Classical Flutter Results of a Composite Advanced Turboprop Model," NASA TM-88792, July 1986.

[18]Hall, E. J., and Delaney, R. A., "Investigation of Advanced Counterrotation Blade Configuration Concepts for High Speed Turboprop Systems," Task-1 Final Rept., NASA CR-185217, April 1990.

[19]Srivastava, R., and Reddy, T. S. R., "User's Manual for DuctE3D: A Program for 3D Euler Unsteady Aerodynamic and Aeroelastic Analysis of Ducted Fans," NASA CR-202335, April 1997.

[20]Srivastava, R., Sankar, L. N., Reddy, T. S. R., and Huff, D. L., "Application of an Efficient Hybrid Scheme for Aeroelastic Analysis of Advanced Propellers," *Journal of Propulsion and Power*, Vol. 7, No. 5, 1991, pp. 767–775.

[21]Lane, F., "System Mode Shapes in the Flutter of Compressor Blade Rows," *Journal of the Aeronautical Sciences*, Vol. 23, Jan. 1956, pp. 54–66.

[22]Srivastava, R., "Time-Marching Euler Analysis of Ducted-Propellers," *Journal of Propulsion and Power*, Vol. 12, No. 1, 1996, pp. 134–138.

[23]Srivastava, R., Reddy, T. S. R., and Mehmed, O., "Flutter Analysis of Propfans Using a Three-Dimensional Euler Solver," *Journal of Propulsion and Power*, Vol. 12, No. 2, 1996, pp. 267–273.

[24]Smith, S. N. , "Discrete Frequency Sound Generation in Axial Flow Turbomachines," British Aeronautical Research Council, R&M 3709, London, England, UK, 1972.

[25]Kaza, K. R. V., and Kielb, R. E., "Flutter and Response of a Mistuned Cascade in Incompressible Flow," *AIAA Journal*, Vol. 20, No. 8, 1982, pp. 1120–1127.