Unsteady Aerodynamic Analysis of Ducted Fans

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A steady and unsteady aerodynamic analysis of ducted fans has been developed using a frequency domain panel method based on three-dimensional linear compressible lifting surface theory. The duct is assumed to be a finite-length right-circular cylinder concentric with the rotor. Both the duct and rotor blades are modeled by simple harmonic rotating doublet sheets. The model spans a single reference passage with the influence of the rest of the configuration included by symmetry. Results for the steady state performance characteristics of a ducted rotor are compared with an Euler calculation. The effect of the duct on the unsteady aerodynamic forces induced by blade vibration is examined, and comparisons are made with two-dimensional unsteady cascade theory. Finally, it is shown that the duct has an adverse effect on the aeroelastic stability of the rotor.

Introduction

DUCTED rotors are a standard component of existing turbofan engines and some VSTOL vehicles and are a proposed variant of the advanced turboprop technology, which allows for conventional underwing installation because of the reduced diameter. The present work is focused on a computational method for both steady and unsteady aerodynamic analyses of ducted fans, based on a direct application of a three-dimensional frequency domain panel method originally developed for unducted propfans. The method has applications to performance prediction, forced vibration, flutter, and aeroacoustic analysis of ducted fans.

Early work on ducted propellers was done by Wright,[1] who gave a method for selecting design parameters for heavily loaded fans using vortex sheet models. In 1987, Weir[2] applied blade element theory to ducted propeller design. Recently, Hall and Delaney[3] presented a three-dimensional Euler method for steady aerodynamic analysis, based on the work by Celestina et al.[4]

For aeroelastic and aeroacoustic purposes, unsteady flows are often modeled using two-dimensional theory, as exemplified by Smith's[5] two-dimensional linear unsteady subsonic cascade theory. This approximation is believed to be good for straight, ducted blades at low incidence, outside the transonic regime. Current trends in high performance turbine engine axial compressors stress high pressure rise per stage, which leads to a general increase in blade tip speeds. In order to reduce the shock-induced total pressure loss associated with high rotational speeds, compressor designers are utilizing ever increasing amounts of blade sweep. As the levels of sweep approach those associated with unducted propfans, concern has arisen over the accuracy of aeroelastic predictions based on two-dimensional unsteady aerodynamic theory. Therefore, three-dimensional methods are needed. Namba[6] has developed an unsteady lifting surface theory for three-dimensional ducted rotors in which the duct is infinitely long and the duct wall boundary condition is embedded in the Green's function.

The present work is based on a lifting surface panel method developed by Williams[7-9] for the unsteady aerodynamic and aeroelastic analysis of single rotation propfans, for which the blade loading can be represented by a single frequency. The panel method is based on linearized compressible aerodynamics and does not account for embedded shocks that may occur in the transonic speed regime or leading edge vortices that may be present for highly swept, loaded blades. The flowfield is constructed by superposition of simple harmonic doublets moving along the helical paths swept out by the rotor. The doublet axes are normal to the blade. This method has been successfully extended to the unsteady aerodynamic analysis of wing-propeller[10] and counter-rotation[11] configurations.

The extension of this isolated rotor lifting surface method to ducted single rotation rotors will be described here. The method differs from Namba's in two primary respects: our ducts are finite, and the free space Green's function is used. This implies that the duct as well as the blades must be paneled, but greatly simplifies the calculation of the Green's function and, consequently, the evaluation of the influence coefficient matrix.

Ducted-Fan Model

We assume that the rotor consists of N identical, equally spaced blades and that the duct is a concentric right circular cylinder of length L and radius R_H (which is greater or equal to the blade radius). The blades and duct are rigid or undergo simple harmonic vibration with fixed frequency ω and interblade phase angle $2\pi m/N$, where m is any integer between 0 and $N-1$.

An inviscid fluid is insensitive to rotation of a body of revolution about its axis. Therefore, a circular cylinder duct may be treated either as a rotor or as a stator (although real ducts do not rotate). In this work we have treated the duct as corotating with the blades.

The advantage of treating the duct as a rotor (instead of as a stationary lifting surface) is that, if a simple harmonic load exists on the blades, the loads on the duct will be simple harmonic in the rotating frame, but multiple harmonic in the stationary frame. If the duct were treated as a stator, a large number of harmonics would be required to resolve its loading,

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as done in Refs. 10 and 11 (although the solution effort per harmonic is small because of the circular symmetry). In fact, our initial attempt to solve this problem did treat the duct as a stator. Although this scheme worked, the current method was found to be far superior both in terms of computational time and accuracy. The system is azimuthally periodic at the blade to blade angle. Consequently, it is sufficient to model one reference blade and one blade passage segment of the duct, which we take to be centered circumferentially at the blade tip, as shown in Fig. 1. Note that the duct segment edges are helical lines at the rotor advance ratio. The influence of the rest of the configuration is included in the aerodynamic influence coefficient matrix.

Since our emphasis is on analyzing the influence of a duct on the unsteady forces acting on the fan blades, the thickness of both blades and duct is ignored. The hub is also ignored, since it would primarily effect the loads near the hub, which are aeroelastically inactive. (However, the code can model hubs in the same way as the duct.)

With the neglect of thickness and the assumption of simple harmonic motion, the problem can be reduced to an integral equation relating the complex amplitude of the load, $\Delta\bar{p}$, to the complex amplitude of the normal velocity, $\bar{w}$, on the surfaces,

$$\iint \Delta\bar{p}(P_0)K(P, P_0)\,\mathrm{d}A(P_0) = \bar{w}(P)$$

where P and P_0 denote points on the surface, and the integral is over the surface area of the reference blade and duct segment. The kernel function K contains the influence of the remaining blades and duct segments, and so represents the normal velocity at point P induced by N point harmonic loads at point P_0 and its images. The form of the kernel is the same whether the points are on the duct or the blade. An explicit formulation of the kernel is given in Ref. 7.

The blade and duct surfaces are divided up into panels, as indicated in Fig. 1. The blade paneling consists of quadrilaterals bounded by radial and constant partial chord lines. The duct paneling consists of quadrilaterals bounded by constant partial chord lines and helices at the rotor advance ratio. Care is taken to match the panel edges and to make the panel widths on the blade and duct the same at the junction. One control point is placed on each panel at its midspan, 85% of the way from the panel leading edge. This placement minimizes sensitivity to panel density (in effect it accounts for the square root load singularity at the leading edge of a lifting surface in subsonic flow). The integral equation is discretized by what amounts to a point doublet approximation in the far field and a constant load approximation in the near field, where near field means that the control point lies in the wake of the panel. This scheme is essentially the same as that used in Ref. 7.

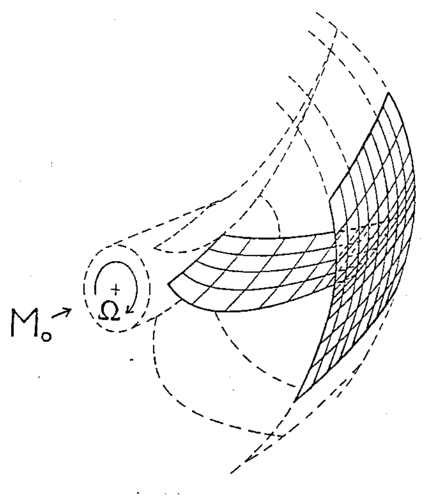

Fig. 1 Ducted-fan paneling.

Results

Three sets of results will be presented: 1) steady loading with comparisons to an Euler calculation; 2) unsteady vibration response with comparisons to two-dimensional strip theory and a convergence study; and 3) the effect of a duct on rotor stability.

Steady Operation

The following conventional performance parameters are used (with R the propeller tip radius, Ω the rotational speed, and U the freestream velocity): advance ratio, $J = \pi U/\Omega R$; power coefficient, $C_P = \pi^3/4\rho\Omega^3 R^5$(power); and thrust coefficient, $C_T = \pi^2/4\rho\Omega^2 R^4$(thrust).

The first example is the steady state loading on a highly swept advanced turboprop with eight SR7 blades, at axial Mach number 0.7, advance ratio 3.1, and blade setting angle at 3/4 tip radius of 60.2 deg. The blade shape is uncorrected for centrifugal deformation. The duct length is one blade tip radius and the blade root section is centered at the duct midchord. For zero gap between the blade tip and duct, the reference blade is discretized with 9 radial and 7 chordwise panels and the reference duct segment with 10 circumferential and 11 chordwise panels. Thus the total number of panels is 173 for one passage and 1384 for the entire configuration. For moderately small gaps, the panel density near the tip must be increased to resolve the tip losses.

Figure 2 compares the sectional thrust distribution when the gap between blade tip and duct is increased from 0 to ∞. It is apparent that the effect of the duct on the blades dies out quickly as the duct is moved outward. Even for small gaps, the duct has little influence inboard from 0.75 tip radius. The primary effect of the duct is to eliminate the tip losses on the blade. It might be noted that real ducted fans have extremely small gaps (on the order of 0.003 tip radius). In such cases the gap flow could not be reasonably modeled with the present method and therefore should be treated as effectively zero clearance.

Also shown in Fig. 2 is the result for a truncated duct, or tip device, with zero gap. This model is identical to the full duct model, but with only the two nearest panels on either side of the blade tip retained, so that the total number of duct panels is reduced to 44. This produces a relatively small change from

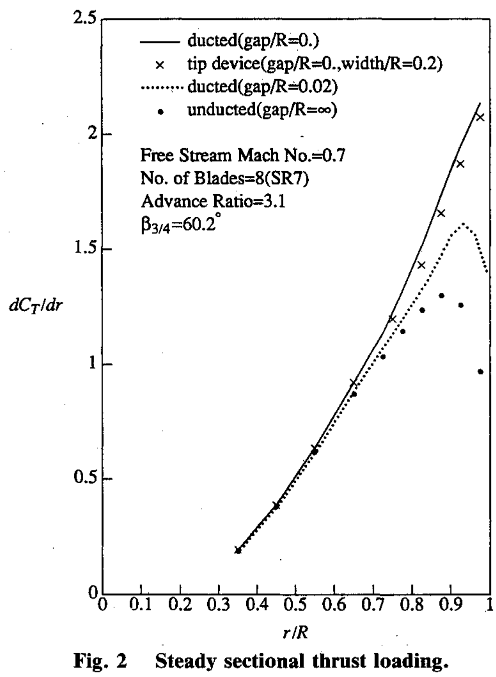

Fig. 2 Steady sectional thrust loading.

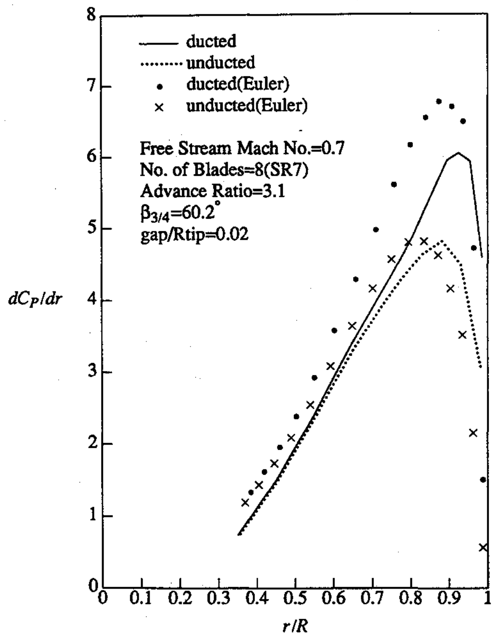

Fig. 3 Steady sectional power loading.

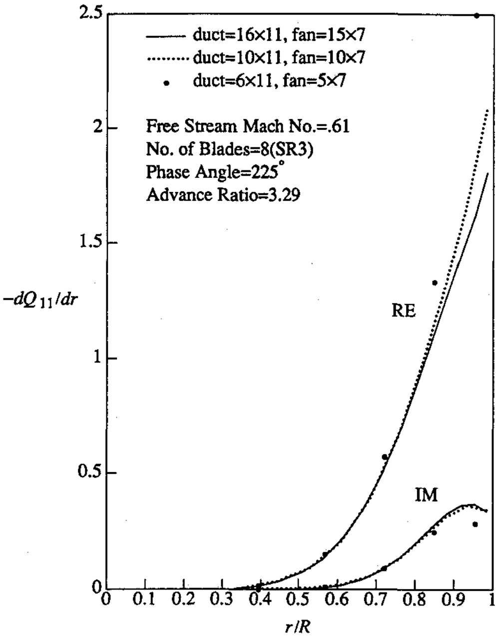

Fig. 4 First mode vibration at 220.4 Hz, effect of number of radial panels.

the full duct model solution, which indicates that the blade loading is effectively influenced only by a small portion of the duct.

Since no test data are available for this ducted-fan configuration, sectional power loadings are compared with three-dimensional Euler calculations by Hall and Delaney[3] in Fig. 3, both for the ducted and unducted cases. Although not shown, both methods show good agreement with measured data in Ref. 12 for the unducted configuration. The present method predicts slightly lower power than the Euler scheme in both cases with a somewhat larger difference in the ducted case. Overall the agreement is fairly good. The differences between the two results may arise in part from the absence of a hub model in the panel calculation, nonlinear compressibility effects, and discretization errors in both methods. The relative importance of these three items is not clear, and it cannot be said which of the two numerical results might be closer to experiment. Discounting discretization errors, the best that any panel method could hope to be is a reasonable approximation to the Euler solution.

It is important to note that the present calculation uses a small fraction of computing time of the Euler method. For the zero gap case shown in Fig. 2, the present calculation takes roughly 60 s on a Gould NP1 machine. The truncated duct calculation takes only 27 s and the unducted case 12 s because of the smaller number of panels. We estimate that, depending on the number of panels, the cost of the present method will be less than 2% of the cost of the Euler calculation (though the two have not been run on the same machine). The cost ratio would, of course, be greater for unsteady flows because of the higher cost of doing time-accurate Euler calculations.

Unsteady Loads

In this section we will consider unsteady blade loading caused by blade vibration. The duct is assumed to be rigid (though this is not an essential part of the model, and aeroelastic deformations of the duct are an important problem because of the small gaps).

The first question to be addressed is the convergence of the results with increasing panel density. For this purpose, a ducted eight-bladed SR3CX2 configuration with zero gap was examined. The blades vibrate in their first in-vacuum mode (220.4 Hz) with a 225-deg interblade phase angle. (This corresponds to a measured flutter condition for the unducted 2-ft diam rotor at 6100 rpm.)

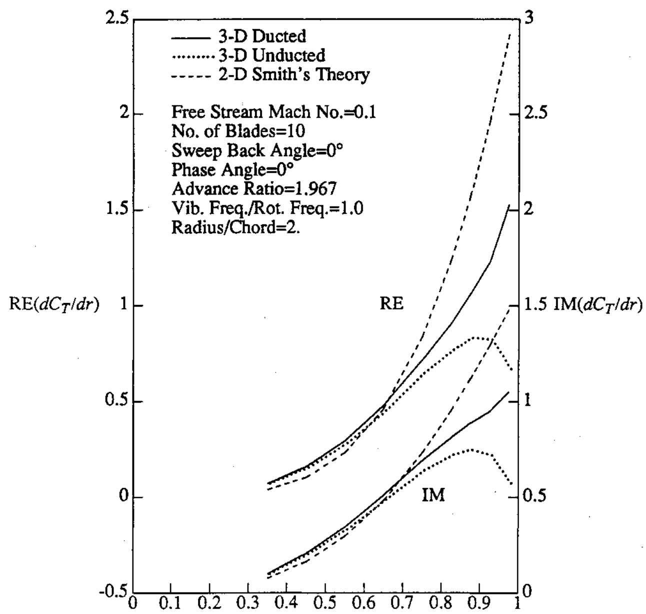

Fig. 5 Unsteady sectional thrust loadings when vibration frequency = rotational frequency.

Results will be presented in terms of the generalized force, defined as

$$Q_{nm} = \iint \Delta \bar{p}_m \delta_n \, dA$$

where δ_n is the normal displacement in mode n and Δp_m is the load resulting from mode m vibration.

Figure 4 shows the radial variation of the generalized force associated with the first mode (normalized with freestream density, tip radius, and revolutions per minute.) The blade radial and duct circumferential paneling was varied. The chordwise panel density was held fixed, since this integrated load was found to be insensitive to chordwise paneling. Note that, in the three calculations shown, the number of blade and duct panels are in fixed ratio. Increasing panel density has little effect inboard of 0.75 radius and little effect on the out-of-phase generalized force even near the tip. Inadequate panel density does, however, cause a significant overprediction of the in-phase loading near the tip. We are investigating means of overcoming this sensitivity.

In the absence of a better alternative, we have compared the present three-dimensional calculations to Smith's[5] two-dimensional unsteady cascade theory. For simplicity, straight constant chord blades were examined with two different aspect ratios and no gap. The blades have pure helical twist distributions and oscillate in torsion about their leading edges. The local gap/chord ratio and reduced frequency used in the two-dimensional strip calculation are easily deduced from the three-dimensional model. The results are shown in Fig. 5 for the lower aspect ratio and Fig. 6 for the larger, in terms of the radial distribution of sectional thrust amplitude. (Unducted three-dimensional results are also shown for reference.) The strip and three-dimensional results show qualitative agreement at both aspect ratios, but considerably better quantitative agreement at the higher aspect ratio, as expected. The two-dimensional tip loads are generally higher than indicated by the three-dimensional calculation. The phase of the response agrees better than the amplitude. It is clear that, even for these straight blades with a duct, there are significant three-dimensional relief effects arising from the radial variation of relative speed.

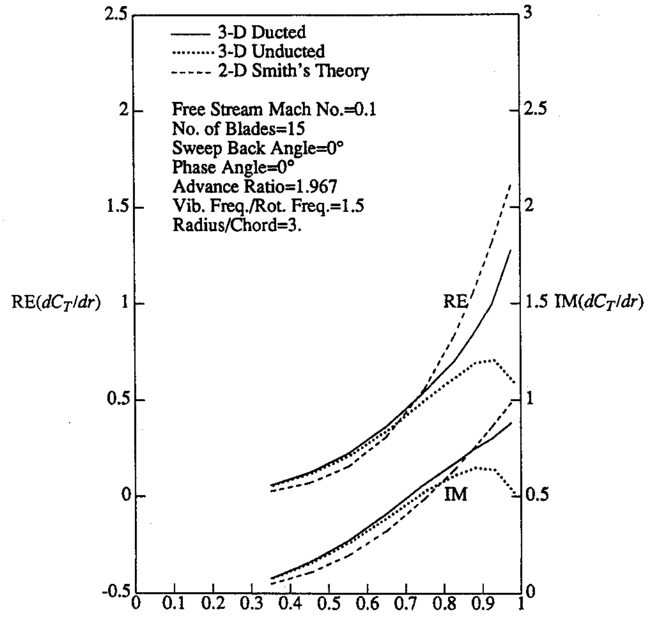

Fig. 6 Unsteady sectional thrust loadings when vibration frequency = rotational frequency.

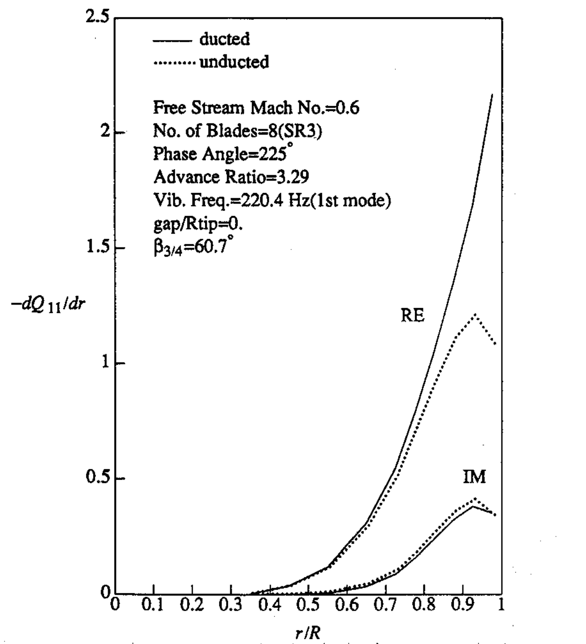

Fig. 7 Generalized forces on reference blade for first mode vibration at 220.4 Hz.

Aeroelastic Results

The SR3CX2 is a composite advanced propfan blade designed for flutter testing (in an unducted configuration) at NASA Lewis Research Center.[13] The aeroelastic stability of the blade has been analyzed with the present three-dimensional panel method (unducted), first by Williams and Hwang[9] and then more extensively by Kaza et al.[14] We have examined the effect of a duct (with no gap) on the stability of an eight-bladed SR3CX2.

As observed already, the duct increases the tip loading. This is illustrated for the present case by the radial distribution of generalized force Q_{11} on the reference blade shown in Fig. 7. In comparison to the unducted result, we see that the real part of dQ_{11}/dr increases towards the blade tip, whereas the imaginary part is relatively unaffected. This change can be expected to have a destabilizing effect on the rotor.

A flutter analysis was performed (following the method of Ref. 9) using the first two in-vacuum vibration modes for the 6100-rpm, 60.9-deg blade setting angle condition. The in-vacuum modal data were generated at NASA Lewis Research Center using COSMIC NASTRAN. The flutter analysis provides the frequency and damping for all the rotor degrees of freedom. The lowest frequency roots for all possible interblade phase angles for both ducted and unducted configurations are shown in Fig. 8. (The labels are the multiples of blade to blade passage angle of 45 deg; e.g., label 5 means 225 deg. The higher frequency roots are not presented here since they are more stable.) The duct slightly increases the frequency, because of the increase in aerodynamic stiffness. In addition the duct decreases the damping, as expected, so that this case, which is marginally stable unducted, is marginally unstable ducted. Detailed calculations show that the flutter point at 0.605 axial Mach number, 225 deg interblade phase angle, and frequency of 298 Hz for the unducted configuration,[9] shifts for the ducted configuration to 0.59 axial Mach number the same 225 deg phase and a frequency of 303 Hz. The critical modes (225 deg with 180 deg just behind)

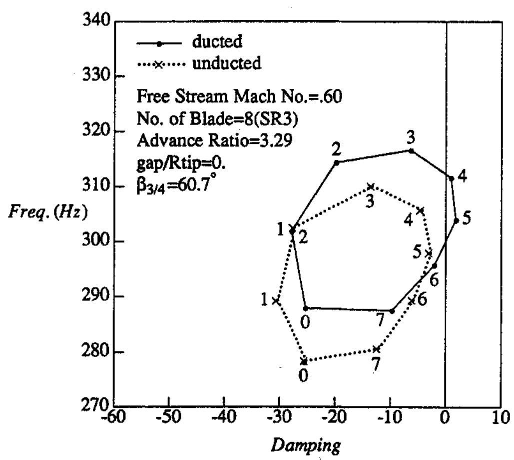

Fig. 8 Effect of rigid duct on blade stability.

are the same ducted and unducted, and the critical Mach number drops slightly because of the duct.

Conclusions

The results presented here indicate that the three-dimensional lifting surface method originally developed for isolated rotors applies as well to ducted configurations and should be a useful tool for the aerodynamic and aeroelastic analysis of ducted fans. Steady performance predictions compared well with a three-dimensional Euler method. The low cost of the present panel method (compared to the Euler code) shows that it is well suited for parametric studies and the preliminary design of ducted fans.

The principal application of the scheme, though, is to the prediction of unsteady loads due to blade and duct vibration and forced response. Only a limited number of vibratory response results have been shown here, including some comparisons to two-dimensional strip theory and an assessment of the duct's effect on rotor stability. Important problems that need to be addressed are the effect of flow incidence and the coupled aeroelastic behavior of the fan with a flexible duct (which introduces the possibility of rubbing nonlinearities in the structural dynamics). Also, the fact that the model employs a finite-length duct makes it suitable for extracting the radiated sound field from the rotor, which can be done with little additional effort once the loads have been determined and should show large changes in directivity from the unducted configuration.

A clear extension of the present single rotation analysis is to ducted counter-rotation systems. This can be done using the harmonic balance methodology developed in Ref. 11. Since that method couples the isolated unducted rotor analysis to itself, the extension should require only small modifications of the existing counter-rotation code.

Finally, it should be noted that all of the comparisons in this paper have been to alternative calculations. In order to validate the method, it is imperative that both steady and unsteady experimental data be obtained for ducted configurations.

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