Calculation of Unsteady Fan Rotor Response Caused by Downstream Flow Distortions

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A method for the calculation of the circumferentially-varying flowfield in an axial-flow fan with downstream stator guide vanes and casing support struts is described. A time-marching solution for the rotor is coupled to a potential flow solution for downstream flow in the vane and strut regions. The influence of strut design parameters is studied employing the method. It is found that strut thickness, circumferential spacing, and sepation distance from the rotor are primary variables determining unsteady rotor response. The stator row is shown to reduce the effective rotor-strut spacing, contributing to increased rotor-strut flow interaction. Good agreement is obtained between predicted and measured on-rotor pressure fluctuations from a test rig.

Nomenclature

A	= area vector
B	= strut thickness
$C_p(X)$	= pressure disturbance at the rotor trailing edge due to the upstream potential field of the strut, $=P-P_{ref}/\frac{1}{2}\rho U^2$
H	= enthalpy
P	= static pressure
P_T	= stagnation pressure
P_{ref}	= reference static pressure
R	= gas constant
SP	= strut spacing
T	= static temperature
U	= blade tip speed
V	= local velocity
V	= velocity vector
X	= proportional to the rotor-strut spacing
Δt	= time step
ΔV	= element volume
ρ	= density

Introduction

FLUCTUATING lift caused by flow unsteadiness over fan airfoils is a mechanism for noise generation and aeromechanical excitation in turbofan engines. One source of flow unsteadiness is the interaction between the moving fan rotor and the upstream flow disturbances from downstream bodies. Fan casing struts, which are required in turbofan engines to support the engine core and to provide access for auxiliary services, create strong local flow disturbances due both to their large size and large circumferential spacing. Recent measurements of noise from operating engines[1] have disclosed noise frequencies and directionality associated with disturbances originating from fan flow interaction with downstream struts in a JT15D engine. At typical aircraft approach and takeoff powers this is a major fan noise generating mechanism. Subsequent experimental investigations[2,3] have shown that pressure fluctuations on the rotor blades of a fan test rig can be measured when a downstream strut is present, and can be correlated with rotor blade-strut passage. These experiments showed that the magnitude of the on-rotor pressure fluctuations increased with decreased rotor-strut spacing. The fluctuations decreased in a manner described approximately by the simple potential flow result for a source in uniform flow,[3]

$$C_p(X)=\frac{1}{\pi}\left(\frac{B}{X}\right)-\frac{1}{4\pi^2}\left(\frac{B}{X}\right)^2 \tag{1}$$

The present paper describes a mathematical model developed to predict the magnitude of rotor blade pressure fluctuations due to interaction with downstream struts. The upstream potential disturbance of the struts, including the effect of a stator vane row, is calculated for inviscid, incompressible flow employing the Douglas-Neumann singularity superposition program.[4,5] The resulting pressure perturbation at the trailing edge of the rotor blade row is used as a boundary condition for a time-marching solution of the two-dimensional flow equations for the cascade of fan blades. The calculation predicts the local velocity and pressure fluctuations on the rotor blades as a response to the downstream static pressure disturbance obtained from the Douglas-Neumann potential flow program.

Stator-Strut Flowfield Solution Method

The general arrangement of the fan rotor-stator-strut flowfield interaction problem is shown in Fig. 1. From the results of Eq. (1), the effect of the strut on the rotor flowfield may be expected to approximately correlate with (B/X). However, in the case of an actual fan flowfield there is both a stator row, where the vanes are small and closely spaced, and a strut row of large, nearly isolated bodies. As will be shown subsequently, these two rows may not be treated separately because the interaction between them projects the strut distortion forward.

The solution method presented for the stator-strut flow is the classical Douglas-Neumann singularity superposition program as developed by Giesing[4] to model infinite, two-dimensional linear cascades. As used, this program has been modified by Yocum[6] to include a matrix solution algorithm that speeds computation time and reduces storage require-

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ments. Derivation of the equations used in the Douglas-Neumann potential flow solution can be found in Ref. 4.

In general, the program forms specified bodies in a uniform potential flowfield by superposing a series of point sources along the boundary of each body. The magnitude of each source and individual cascade circulations are then calculated to satisfy the zero through-flow condition along the vane surfaces and the Kutta condition,, respectively. There is wide latitude in input parameters so that any arbitrary cascade blade shape may be modeled in virtually any flowfield configuration. In addition, results for both on- and off-body points may be obtained. The comparison of program results with previous analytical and experimental solutions is excellent and well documented.[4,5,6]

Rotor Flowfield Calculation Method

The rotor calculation employs the upstream perturbation caused by the potential field of the strut, projected onto the flow at the trailing edge of the rotor as the downstream static pressure boundary condition. The rotor flow is solved in the relative reference frame with a stationary downstream strut-induced pressure perturbation to yield the quasisteady rotor response. A schematic of the procedure is presented in Fig. 2. A time-marching technique was selected because of the simplicity of the basic scheme, and because it would be readily modified for either steady or unsteady flow analyses. The program is used here to solve for a quasisteady response; therefore, a steady-state solution is required.

The Time-Marching Method

The time-marching algorithm used in the analysis is based on the method presented by Denton[7] for the solution of the time-dependent Euler equations. These equations are solved in the finite volume form for either steady or unsteady compressible flow. In the present solution, a program has been written to solve the steady equations by repeated iteration of the time-dependent Euler equations until sufficient convergence to a steady-state solution is obtained.

The program calculates the flow through a two-dimensional blade-to-blade grid using elements formed by the intersection of quasistreamlines and pitchwise lines. The changes in density and x and y momentum are calculated for each element and these changes are distributed to nodes at the element corners. The values for the pressure and temperature are then calculated using perfect gas relationships. The grid used in the calculation of the rotor flowfield incorporates five rotor blade passages as shown in Fig. 3. Five blade passages were used because of the length of the modeled strut distortion. For other strut spacings, a different number of blade passages would be required. An advantage of this periodic grid design is that, by combining results from all blades, the response of the rotor throughout the entire distortion may be obtained after only one full grid calculation.

Basic Equations and Differencing Scheme

The approach used in the time-marching method is to solve the two-dimensional Euler equations over a grid of finite volume elements formed by the intersection of quasi-streamlines and pitchwise lines, as shown in Fig. 3. In the present code, both streamlines and pitchwise lines may be unequally spaced. The Euler equations written in conservation form for a control volume ΔV over a time step Δt are:

Continuity:

$$\Delta\rho = \Sigma_n (\rho V \cdot dA) \Delta t / \Delta V \tag{2}$$

x momentum:

$$\Delta(\rho V_x) = \Sigma_n (P dA_y + \rho V_x V \cdot dA) \Delta t / \Delta V \tag{3}$$

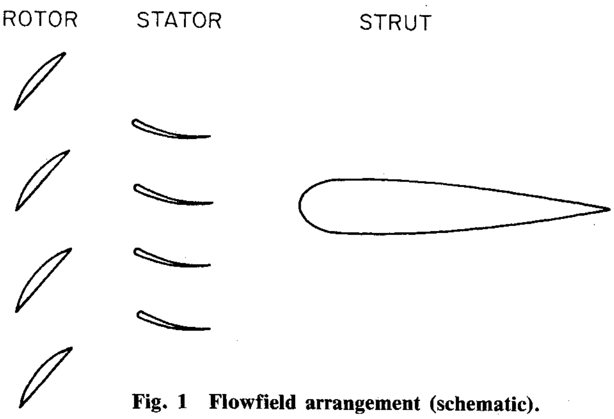

Fig. 1 Flowfield arrangement (schematic).

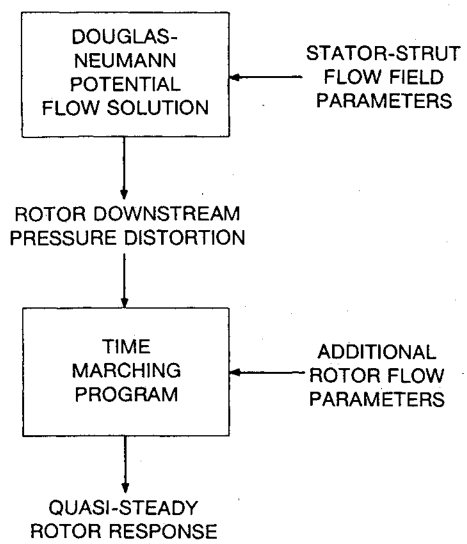

Fig. 2 Procedure for calculating rotor flow response.

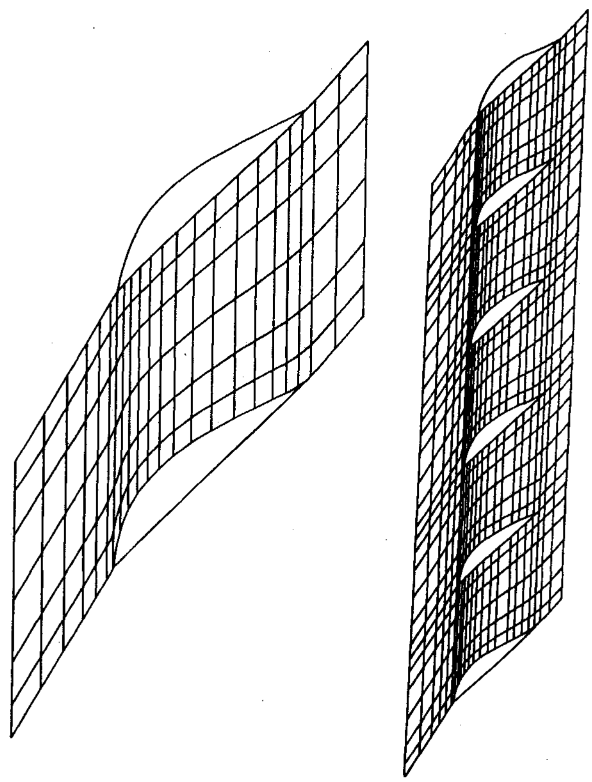

Fig. 3 Grid system in two dimensions (grid used is finer than the one shown).

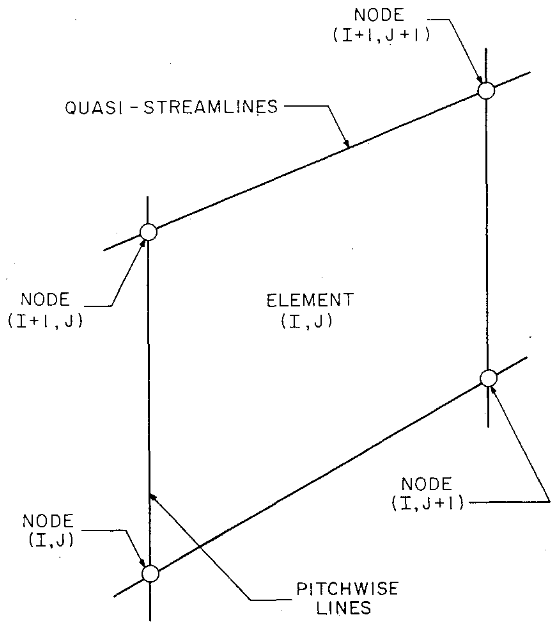

Fig. 4 Basic finite volume grid used in the time-marching program.

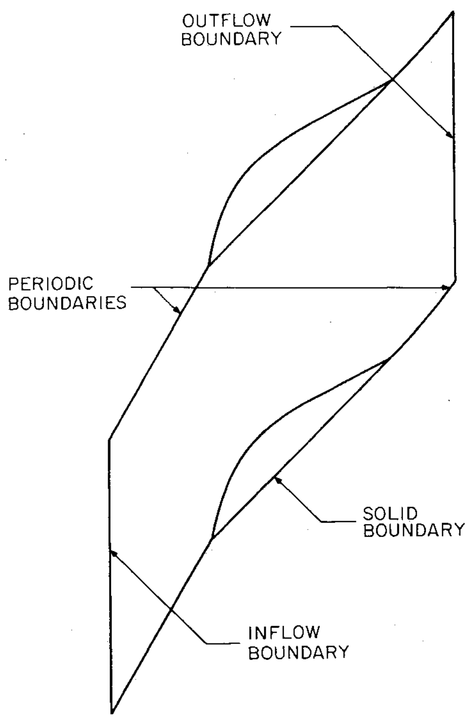

Fig. 5 Boundary condition definition in the time-marching program.

y momentum:

$$\Delta(\rho V_y) = \Sigma_n (P\mathrm{d}A_x + \rho V_y V \cdot \mathrm{d}A)\Delta t / \Delta V \tag{4}$$

where dA is the area vector of the face of the element in the direction of the inward normal and the summations are over n-element faces. To obtain the flow pressure and temperature, these equations must be solved with the ideal gas relationships

$$H = C_p T + \tfrac{1}{2} V^2 \tag{5}$$

$$P = \rho R T \tag{6}$$

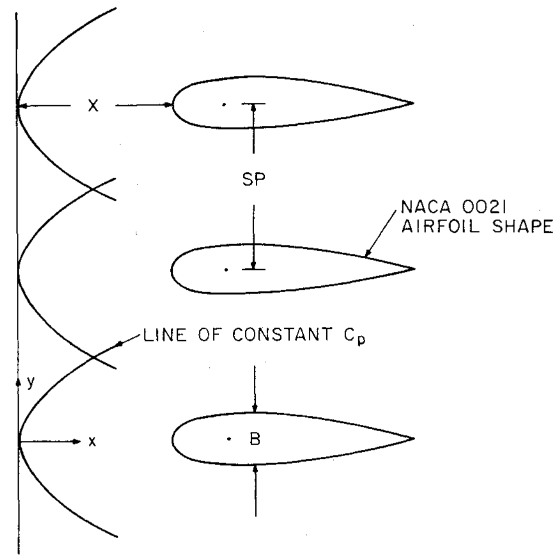

Fig. 6 Definition of strut and spacing variables.

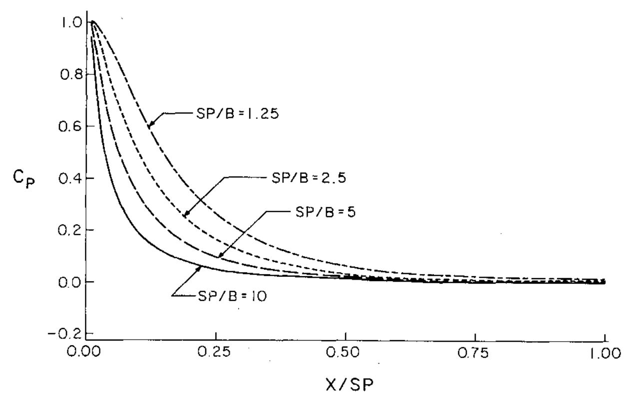

Fig. 7 Perturbation magnitude in front of the strut from the Douglas-Neumann potential flow program.

For the quasisteady rotor solution, the Euler equations are solved to a steady-state value. Because steady flow is assumed, the energy equation is replaced by the assumption that the enthalpy H is constant at the stagnation value. This condition causes the true time dependence (i.e., the transients in convergence to the steady-state solution) to be lost.

The finite volume grid used in the solution algorithm is shown in Fig. 4. The element nodes are located at the four corners of the element with fluxes of mass and momentum through each face calculated from the average of flow properties stored at these nodes. These fluxes are used in the right-hand side of Eqs. (1-3) to calculate the changes in ρ, ρV_x, and ρV_y for the time step Δt. Once these changes are determined, they are distributed to the element nodes.

Because the program converges to a steady-state solution, the differencing scheme used to distribute the changes in properties in the element volumes to the corner nodes only influences the stability and rate of convergence of the solution and not the final answer. (In the steady-state limit, the property changes in the element volumes are zero.) The method used here sends density changes upstream and momentum changes downstream. The method is stable for cases where the axial-flow Mach number is subsonic,[7] and remains stable for negative values of the streamwise velocity, thus allowing the calculation of a stagnation point on the pressure side of the blade and reverse flow about the leading edge.

The Inflow and Outflow Boundaries

Conditions at the inlet and outlet flow boundaries are applied in the usual way, as in other time-marching methods.[7] Referring to Fig. 5, the relative stagnation pressure and temperature are specified and held constant along with the inlet flow angle at the inflow boundary. At the outflow boundary the static pressure distribution is specified (from the Douglas-Neumann potential flow program). It is important to note that, while the inlet flow angle to the calculation domain is held constant, the angle of attack at the rotor leading edge is not constrained. The specification of a nonuniform downstream pressure requires a nonuniform inlet flow to the rotor to allow for variations in vorticity that will yield differences in lift between the airfoils. Although specification of the inlet flow direction does not specify the rotor angle of attack at the blade leading edge directly, the location of the inflow boundary must be chosen to reduce its influence as much as possible. In the present case, this was done by increasing the spacing between the blade leading edge and the inflow boundary in the computational grid until an essentially uniform inlet flow was obtained. Because the flow is subsonic, the distortion in downstream pressure is an elliptic effect and will propagate infinitely far upstream in the flow. Therefore, a cutoff in angle variation must be selected in determining flow uniformity. The value chosen in the present case was a variation of 1.5 deg in the flow direction at the first pitchwise grid line downstream of the inflow boundary. This produced a spacing between the inflow boundary and the blade leading edge of one axial rotor chord for a downstream pressure perturbation amplitude of 0.075% of the mean pressure. As the downstream distortion level is increased, this spacing must also increase if the same level of upstream flow uniformity is to be maintained.

Solid Boundaries

The boundary conditions applied to the blade surfaces were found to have the greatest effect on stability and the accuracy of the final solution. Grid density at the leading edge was increased to resolve the locally large flow changes. The quasistreamline grid spacing was also reduced near both blade surfaces for the same reason. The method selected for the solid boundaries was to resolve the velocities along the blade surface into normal and tangential components and to discard the normal component. The continuity calculations at the blade surfaces were changed so that any mass flux through these solid boundaries was neglected.

The condition employed at the leading edge was to use a "hard" cusp with a "split characteristic" in the flow variables at the coincident leading-edge points. This "split-characteristic" condition allows different values to be calculated at the leading-edge point such that no specification of the flow direction is required. At the trailing edge all flow property values at the coincident points are averaged to produce a single flow direction which, therefore, satisfies the Kutta condition. This trailing-edge condition may be used because the rotor flow is being solved as quasisteady and, therefore, the amount of vorticity shed at the trailing edge is small. In a fully unsteady flow, a different Kutta condition must be used to allow for vorticity shedding.

Periodicity

The final condition on the flowfield is the specification of periodicity upstream of the blade leading edge and downstream of the trailing edge. The periodicity condition is used to create an infinitely repeating cascade by equating all flow properties along the same pitchwise grid line at the upper and lower quasistreamline boundaries. This has the effect of allowing any flow that leaves the computational domain at one boundary to enter the grid at the opposite boundary. Because of the range of effect of the downstream distortion, the calculation grid used in this analysis was extended to five rotor blade passages. Thus, periodicity is satisfied only at the top- and bottom-most quasistreamlines with values along the blade streamlines for the interior blades found by averaging the two calculated values. (There are actually two coincident quasistreamlines up- and downstream of the blades with separate values calculated along each.)

Initial Checks of the Time-Marching Method

To ensure that the computer code developed for the time-marching method was working properly, several checks were conducted. For test cases with uniform flow, the code satisfied continuity and preserved uniform pressure across the calculation boundaries. For the case of uniform upstream and downstream pressures, the Douglas-Neumann potential flow solution could be used for comparison, and gave the same results as the time-marching code. Finally, surface pressures predicted by the code for a compressor airfoil cascade were compared with experiments with good results.

Results

Initial studies were conducted employing the Douglas-Neumann potential flow program for the stator-strut flow region. Strut separation, distance from the rotor, and strut size parameters were varied to determine the effect on the predicted flow disturbance at the rotor trailing edge. Disturbances are expressed as a pressure coefficient

$$C_p = (P - P_{\text{ref}})/\tfrac{1}{2}\rho U^2 \tag{7}$$

where P is the local static pressure at the point under consideration.

For the limiting case of no stator row in front of the struts, the flow perturbation was investigated for the parameters shown in Fig. 6. An NACA-0021 airfoil profile was chosen as a reference strut airfoil shape.

For a given distance-spacing ratio (X/SP), the magnitude of the pressure coefficient increases for smaller SP/B ratios as shown in Fig. 7. This indicates that, for a given circumferential spacing, thicker struts produce larger upstream disturbances. Larger spacings increase the upstream distance at which a given value of C_p exists, since X/SP is the primary independent variable; that is, for a constant X/SP, increasing the magnitude of SP will increase the magnitude of X proportionally. It can be concluded that the magnitude of the upstream flow disturbance at a fixed distance X is reduced by 1) decreasing strut spacing, and 2) reducing strut thickness.

A point on a rotor moves in the y direction as shown in Fig. 6, traversing the pressure disturbances produced by the struts. Since the strut pressure fields intersect as shown, the *amplitude* of the perturbation as seen by a rotor will be the difference in the maximum and minimum C_p values in the flowfield at distance X. The behavior of the perturbation amplitude is shown in Fig. 8 for the same variables as in Fig. 7. Similar comments apply, but the effect of strut thickness is exaggerated; that is, a smaller strut thickness B strongly reduces the perturbation amplitude through the variable X/SP. Conversely, the penalty for a thick strut is increased with respect to the amplitude. The results of Fig. 8 are the most significant for design guidance, since the usual goal is to reduce the strut perturbation as seen by the rotor.

The effect of a stator row between the strut row and an upstream location corresponding to the plane of the rotor is of interest, since this is the usual design arrangement. A study of this effect was conducted using the geometry shown in Fig. 9. A stator row was simulated as a row of flat plates located at a fixed distance upstream of the strut. The solidity of the stator row was varied by increasing the chord of the

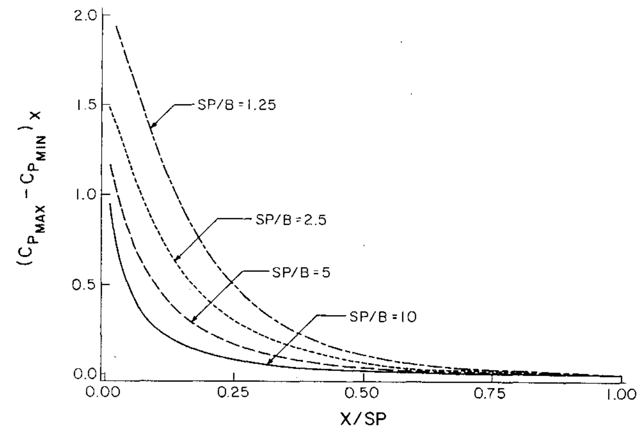

Fig. 8 Perturbation amplitude in front of the strut from the Douglas-Neumann potential flow program.

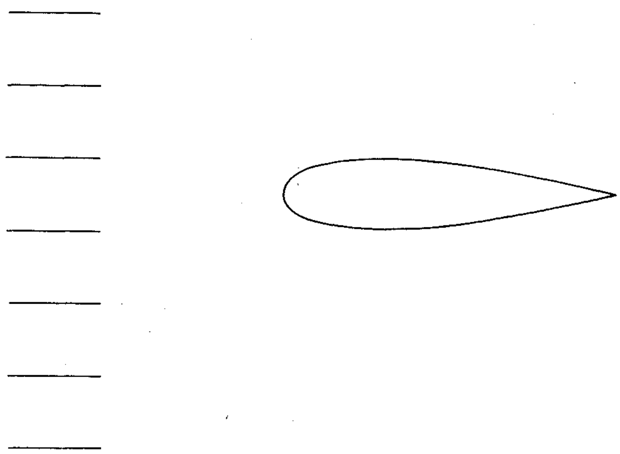

Fig. 9 Simplified stator-strut flowfield to illustrate the stator broadcast effect.

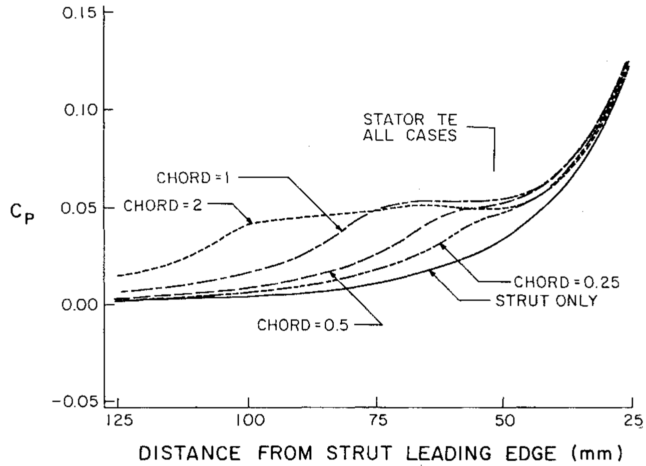

Fig. 10 Decay of pressure coefficient perturbation—with and without stator.

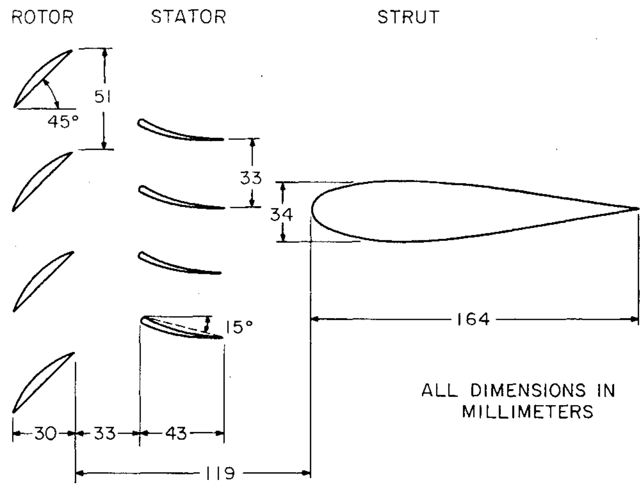

Fig. 11 Principal dimensions of modeled flow path.

flat plates. Results are shown in Fig. 10 for distances corresponding to actual values in an experimental rig. It is seen that the stator row interrupts the decay of the strut perturbation magnitude for a distance essentially equal to the stator chord. In the effect, the stator row "broadcasts" the strut disturbances upstream, and the effect is to increase the perturbation seen at the rotor plane. This most interesting effect may be understood by considerations of continuity. For the constant-area channel formed between the two stators, the average inlet and outlet velocities must be equal. Therefore, the decrease in C_p with upstream distance will cease across the stator row. The effective distance between the strut and an upstream location is reduced by the chord of the stator row. While a flat-plate stator row was used for these studies, the Douglas-Neumann potential flow program is capable of modeling actual stator rows with turning, and could be used to assess the effect of design changes with actual stator geometries.

Additional studies of the effect of selected variables on upstream perturbation magnitude were conducted. Strut chord was found to have little effect on predicted C_p values, as was the angle of attack (swirl) of the flow approaching the struts. It must be recalled that these results are the predictions of an inviscid flow model, and that viscous effects would operate to increase the effects of strut chord and angle of attack.

The time-marching program was configured to accept as a downstream boundary condition the predicted perturbation of the strut and stator rows of an experimental machine. In previous work,[3] the unsteady pressure response of the rotor blades of this machine had been measured through the use of on-rotor transducers. Figure 11 shows the principal dimensions of the modeled flow path. The time-marching program predicts the unsteady pressure at any location within the rotor. Experimental measurements on the suction and pressure sides of the rotor blade at the 85% chord position were utilized for comparison with predictions of the theory. The agreement shown in Fig. 12 is very good for the fundamental frequency of disturbance of the struts. The higher frequency pressure fluctuations measured experimentally are due to the stator row, and occur at a rate that cannot be calculated by the present quasisteady model. It was appropriate to model the unsteady effects of the strut perturbation on the rotor flow as a quasisteady effect, since the reduced frequency of the strut disturbance for the case modeled is within a range justifying quasisteady assumptions. Disturbances produced by stators are at higher reduced frequency, requiring an unsteady model for accurate representation.

The degree of agreement observed is encouraging evidence that the model is suitable for representing the principal effects involved in low-speed fan rotor-strut interactions. Since the Douglas-Neumann potential flow program models incompressible, inviscid, and irrotational flow, none of these latter effects are included.

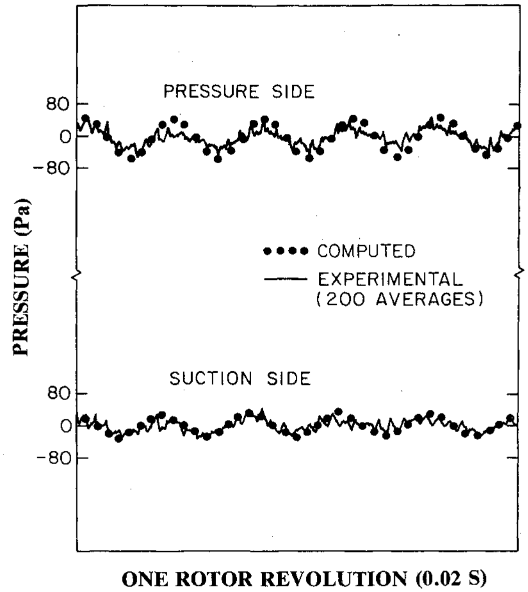

Fig. 12 Comparison of predicted and measured rotor pressure fluctuation at 85% rotor chord.

Summary and Conclusions

A model for fan rotor-strut interaction has been developed employing a time-marching code for the rotor flow, coupled with a potential flow model for the stator-strut region. Study of the effect of strut design variables showed that rotor flow disturbance is increased by the primary variables of larger strut thickness and circumferential spacing, and decreases exponentially with increased rotor-strut separation. The presence of a stator row between the rotor and strut rows interrupts the decrease of the strut flow perturbation with separation distance, in effect decreasing the rotor-strut separation distance. Other variables such as strut chord and strut flow angle of attack were found to have a relatively small effect on rotor-strut interaction.

The time-marching code predicts local rotor pressure and flow perturbations in response to an unsteady downstream boundary condition. Agreement was considered good between experimental measurements at one rotor chord position and predictions of the theory. The method is limited to the prediction of varying flow effects that may be considered quasisteady, and is intended for the small-perturbation effects of interest in acoustics. In addition to the results shown, the calculation method is suitable for the prediction of varying force and moment on the rotor blades.

The method described here is a useful design tool for minimizing unsteadiness at a fan rotor caused by downstream flow distortions. By splitting the flowfield into two computation domains, considerable savings in computer time is possible. The current time-marching code takes 10 min of CPU time on an IBM 3081 machine. Solution for the Douglas-Neumann potential flow program can be obtained within a few minutes of CPU time. Thus it is relatively inexpensive to run the programs for parametric study. If the entire flowfield (rotor, stator, and strut) was to be modeled by the time-marching method, the cost to run the program would limit the usefulness of the method.

Acknowledgments

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