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A Review of Turbomachinery Blade-Row Interaction Research

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A REVIEW OF TURBOMACHINERY BLADE-ROW INTERACTION RESEARCH

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SUMMARY

Analytical and experimental research within the area of unsteady aerodynamics of turbomachinery has conventionally been applied to blading which oscillates when placed in a uniformly flowing fluid. Comparatively less effort has been offered for the study of blading which is subjected to nonuniformities within the flow field. The fluid dynamic environment of a blade-row embedded within multi-stage turbomachines is dominated by such highly unsteady fluid flow conditions. The production of wakes and circumferential pressure variations from adjacent blade-rows causes large unsteady energy transfers between the fluid and the blades. Determination of the forced response of a blade requires the ability to predict the unsteady loads which are induced by these aerodynamic sources.

A review of the research publications was performed to determine the recent efforts to investigate the response of turbomachinery blading subjected to aerodynamic excitations. Such excitations are a direct result of the blade-row aerodynamic interaction which occurs between adjacent cascades of blades. The reports and papers reviewed within this report have been organized into areas which emphasized experimental or analytical efforts.

INTRODUCTION

This document describes the findings of a literature review which was conducted within the area of blade-row aerodynamic interaction. The motivation for such a review was to determine the current state of the technology for measuring and predicting aerodynamic interaction within turbomachinery blade rows. The review was specifically focused on those research papers and reports which were related to turbomachinery components such as fans, compressors, and turbines.

The current state-of-the-art design techniques for estimating the forced response of turbomachinery blading is deficient in terms of quantitatively predicting blade response levels. The Campbell diagram method of estimating the occurrence of forced response problems can only indicate the likelihood of encountering a significant resonant condition. Unfortunately, no method is currently available which can predict the actual level of vibratory stress caused by aerodynamic excitations.

The apparent confusion regarding which type of aerodynamically induced forcing function causes the greatest forced response problems has necessitated the drive to perform a literature review. Recent forced response problems which have occurred within the Space Shuttle Main Engine (SSME) turbopump turbines underscores the need for an advanced analytical tool which can account for the many unsteady aerodynamic loads and predict the blade response to such loads.

The construction of an accurate forced response analytical capability requires that an embedded blade-row can be suitably isolated from the other components of the machine and analyzed separately. This isolation necessitates replacing the physically adjacent rotating blade rows with the proper aerodynamic forcing functions which they induce. Figure 1 shows how the presence of adjacent blade-rows and upstream stages complicates the process of isolating a specific blade-row for detailed dynamic analysis. Specification of the replacement forcing functions requires that the level of aerodynamic interaction between blade-rows can be determined. Proper definition of the relevant aerodynamic forcing functions is the key to solving the forced response problem for such multi-blade-row machines.

An aeroelastic forced response system, the Forced Response Prediction System (FREPS), is being assembled to address the specific problem of quantifying the aerodynamic forcing functions. This computer program is intended to give the turbomachinery designer a tool for prediction of actual blade vibratory response levels resulting from aerodynamic disturbances. FREPS will provide dynamic response information which can be used to estimate the vibrational stresses and blade life.

Proper development of aerodynamic forcing function models dictates a need to fully understand the energy transport processes which exist between adjacent blade-rows. This energy transfer is commonly referred to in the open literature as "blade-row aerodynamic interaction." Aerodynamic interaction between blade-rows (i.e., stator/rotor) occurs in the form of periodic disturbances in the velocity and potential fields within the machine. These disturbances result because of the unsteadiness due to adjacent blade-rows undergoing relative motion. Such disturbances propagate into the cascade from both upstream and downstream to excite the isolated blade (fig. 2). Generalization of these aerodynamic forcing functions can often be reduced to a definition of those disturbances due to (1) viscous wake passing and (2) potential-field disturbances (pressure waves).

The level of unsteadiness of these fluctuations is typically very high (reduced frequency based on semichord $k = 2 - 20$) because they are generated at blade number multiples of the engine speed. The magnitude of the induced unsteady loads which these disturbances cause are fairly low, typically 5 percent of steady blade loads. But the lack of sufficient damping, both aerodynamic and structural, can drive the blades to large deflections, especially when approaching a resonant condition. The cumulative effect of these unsteady deformations is to reduce the effective design life of the component.

A search of the publications from NASA, AIAA, ASME, STAR, and DOD was conducted to determine the reports and papers which have been recently published within the area of blade-row aerodynamic interaction. A computer-based literature search system was used to automate the selection of suitable reports and articles. Many papers were discovered which were chiefly concerned with aerodynamic performance or off-design flows. This review was limited to those contributions devoted to studies of airfoil response and aeroelastic applications.

EXPERIMENTAL STUDIES

Experimental methods to measure the unsteady aerodynamic response of turbomachines has traditionally emphasized study of the flow field within oscillating airfoil cascades (refs. 1 to 7). Such investigations are concerned with measuring the blade motion-dependent unsteady aerodynamic response of blades. Only recently has the investigation of the response of airfoils to nonuniform flow fields, termed motion-independent aerodynamics, been studied. The growth in experimental study of such flows is primarily due to the advances which have been made in the area of computer-based data acquisition and high-response measurement systems.

Investigation of aerodynamic interaction within full-scale components requires instrumentation which can perform at extremely high frequencies. The majority of the experimental work in this area has been conducted on low-speed, large-scale models of components to allow for better data resolution at reasonable frequencies. Most of the experiments employ high-response semiconductor pressure transducers embedded within the surfaces of the blades to measure the instantaneous pressures. Several of the experiments also use pneumatic or hot-wire probe traverses to measure the pressure and velocity fields entering and leaving the blade rows.

A detailed comparison of each of the experimental papers and the specific problem which was studied is included as table I. This table organizes the publications into more specific areas of aerodynamic interaction. Most of the recent experimental research related to aerodynamic interaction can be generalized into two categories: (I) blade-row interaction, and (II) blade viscous wake characteristics. A detailed description of each of the research papers related to these categories follows.

Category I. Blade-row Interaction

The published research related to blade-row aerodynamic interaction studies the level of interaction which occurs between upstream and downstream blade rows. These effects are typically described as viscous wake passing from the upstream blade row (stator) to the downstream row (rotor) and downstream blade row pressure disturbances which propagate to the upstream blades. The measurement of the effects of these phenomena is obtained by determining the instantaneous pressure distributions on the surfaces of the airfoils. These instantaneous pressures can then be integrated over the blade surface to estimate the unsteady blade loads and phase.

Adachi and Murakami (ref. 8) describe an experiment where rotating rods were used to generate wakes which were passed over stationary compressor blades (fig. 3). The data from this experiment includes the variation in unsteady blade lift coefficient and drag coefficient as a function of time for one wake passing period (fig. 4). This experiment indicated that the lift forces resulting from wake passing over the blades can vary by as much as 5 percent. Measurements of the three-dimensional unsteady velocity vectors within the compressor passages were also provided for several time increments which show the passing of the wake and the distortion of the wake as it passes through the passage.

Insight into the effect of wake passing on the unsteady pressure field within practical compressor blading has been reported by Fleeter et al. (ref. 9). A high speed, full scale compressor stage was tested which could accommodate differences in the axial spacing between stator and rotor rows to measure the effect of spacing on interaction. The effect of wake passing had a strong influence on the pressure distribution and total unsteady loads on the downstream stator blades. This particular machine had realistically high reduced frequencies (based on semichord, $k = 8$ to 20). One full stator blade passage was instrumented (fig. 5) and a cross-wire probe was used to traverse upstream of the stator row to measure the incoming wake. Figure 6 shows a typical unsteady pressure distribution for the stator blade. The emphasis of this experiment was to determine the effect of axial spacing on the wake-induced unsteady loads. The data from this study found that the axial spacing effect was minor.

An investigation of the effect of loading and incidence on forcing functions within a multi-stage machine was reported by Capece and Fleeter (ref. 10). Their study was chiefly concerned with measuring the forcing functions caused by wakes shed from upstream blading. The actual forcing function was assumed to be due to the perturbation velocity which results when the rotor wake is transformed to a stationary stator reference frame (fig. 7). The dependence of the wake velocity defect upon the level of blade loading and the indexing of the stator vanes was measured along with the unsteady pressures (fig. 8) resulting from the wake forcing function (fig. 9). Blade response was found to be strongly coupled to the level of machine loading and the resulting perturbation velocity forcing function. An indirect observation of the potential interaction of the downstream blades was reported but there was little elaboration.

Binder et al. (ref. 11) presented a qualitative study of the distortion and trajectory of stator wake segments as they pass through a turbine rotor. This research utilized a laser-2-focus velocimeter to measure the flow field and turbulence intensity within the rotor passage. The instantaneous measurements of the velocity vectors show how the stator wakes are chopped by the rotor blades and how the wake segment distorts and forms in-passage vortices which pass through the rotor passage. These counter-rotating in-passage vortices have been postulated by other researchers and they are a result of the fluid migration in the relative frame towards the rotor blade suction surface. The significant effects of high turbulence and unsteady behavior upon the complex flow phenomena within the rotor passage are well demonstrated.

An experiment to measure the rotor wake which was generated within a single-stage transonic fan stage has been reported by Hathaway et al. (ref. 12). This experiment utilized a Laser Anemometry method to measure the velocity field aft of a rotor blade. The results from this experiment indicate that this rotor wake shed Karman vortices aft of the rotor blades and the results correlated well with a classical vortex model. These results indicate that the nature of the fluid flow within the wake must by carefully modeled to determine if the source of the velocity field variation is due to the viscous effects from the upstream blade or due to the shed vortices from the blade.

Gallus et al. (ref. 13) reports how the aerodynamic interaction within a single-stage subsonic compressor was measured. Stationary and rotating probes were used to measure the wake profiles while surface pressure transducers sensed the surface pressure response of the airfoils. Figure 10 shows an illustration adapted from this report which describes the cascade configuration and the transducer measurement locations (denoted as MDn and RSn). The experiment covered several flow Mach numbers and reduced frequencies. Results from this experiment indicated that the stator steady lift force varied by as much as 6 percent due to the passing of the wakes from the upstream rotor. The time-varying lift force for the stator blade is plotted on figure 11 for configurations which had both inlet guide vanes (IGV) in place and removed. The presence of the IGV's had a clear influence upon the unsteady stator loads and this demonstrates the multi-stage nature of the unsteady flows in these machines.

An investigation of the effect of rotor-stator interaction and the influence of the secondary flows between these blades was reported in Sharma, et al. (ref. 14). The experiment on the UTRC Large-Scale Rotating Rig (LSRR) measured the flow effects which occurred between the blade-rows of a 1-1/2 stage turbine rig. The emphasis of this test was to determine the influence of the blade-row flow distortions caused by the tip and endwall vortices and the boundary layer growth within the machine. This particular report was also concerned with regard to how these blade-row secondary flows affected the heat transfer performance and the fluid losses in the machine. They found that the tip and hub vortices from the upstream stator have a fairly high strength and that they retain much of their form even after passing through the downstream rotor passage.

Dring et al. (ref. 15) describe an experiment which measured the interaction within a large-scale subsonic turbine stage. Their experiment provides a large amount of detailed data regarding the unsteady flow resulting from stator/rotor interaction. A scaled stator/rotor pair of blades were instrumented (fig. 12) with surface pressure transducers over the blade stator trailing edge and rotor leading edge regions. The measured steady and unsteady pressure distributions for both the stator and the rotor cascades are presented on figure 13. The unsteady pressure envelope over the surface of the blades indicates that the effect of the stator wake passing over the rotor blades results in a highly unsteady region over the suction surface, particularly at the rotor leading edge. The effect of the potential disturbance from the rotor blade upon the stator blade results in a high unsteadiness at the stator trailing edge pressure surface. Unfortunately, the results are presented in a manner which distorts the unsteady character of the flow. Specifically, the unsteady pressure coefficient is nondimensionalized with respect to inlet dynamic pressure for the rotor, and exit dynamic pressure for the stator. Although the essential unsteady character of the flow is still obvious.

Category II. Blade Viscous Wake Characteristics

A significant level of experimental research has been conducted over recent years in order to determine proper empirical models which may be used to predict the velocity wakes which emanate from compressor, fan, and turbine airfoils. This experimental data proves that under many circumstances, a fairly simple model can be used to adequately describe the wake structure. It should be noted that much of this work is limited to development of wake models for isolated cascades and blade-rows. Direct extension to a multi-stage configuration should be taken cautiously because of the inherently complex nature of wake generation, transport, and diffusion in such machines.

The following papers all describe the experimental techniques used to measure the velocity field immediately aft of isolated and cascaded airfoils and include references to the similarity laws which govern the flow field. All of these experimental studies utilize hot-wire and pneumatic probes to traverse the wake region and measure the steady velocity vectors and pressure magnitudes.

Study of the near-wake (<30 percent chord) and far wake velocity profiles was reported by Hobbs et al. (ref. 16). Measurement of the wake structure and the dissipation within a large-scale linear compressor cascade for 13 downstream axial locations (fig. 14) was reported. The far wake velocity profile was found to obey a Gaussian similarity correlation very well. Attempts to model the near-wake profiles met little success because of the complexity of this flow region. Figure 15 contains a plot showing the velocity wake profile for several downstream traverses compared to a simple gaussian distribution. The nature of the near-wake velocity profiles is dominated by strong turbulent mixing and is not as easy to correlate as the far-wake region. It is noteworthy that most practical turbomachinery are designed such that the blade-row spacing causes the blades to operate under these near-wake conditions.

An experimental study of the three-dimensional structure of the viscous wakes behind a compressor rotor was reported by Dring et al. (ref. 17). This experiment measured the wakes, boundary layers, and turbulence intensity behind a large-scale compressor rotor. The wake character was studied at four downstream axial locations for several different machine flow coefficients. Measurement of the fluid velocity vectors (magnitude and direction) within the wake region were provided (fig. 16). A conclusion from this experiment was that the radial flow effects for such a machine are very strong and that such nonideal flow properties question the validity of using the conventional "strip theories" for streamline calculations. The wake structure was found to be dependent strongly upon the rotor loading conditions. The wake defect and semi-width increase with rotor loading (lower flow coefficient).

The structure of the viscous wakes within a turbine stage was investigated by Joslyn et al. (ref. 18). This experiment studied a 1-1/2 stage (vane-rotor-vane) turbine configuration (fig. 17) in which traverses were performed aft of each blade row. The generated wake from the first vane was found to still have a sustained influence on the flow exiting the second vane row. This data confirms the observations that the wake passing influence is not a localized phenomena but that it may effect the flow character downstream from the source. Plots of the velocity profiles aft of the first vane and the last vane details the influence of the first vane wake on the second vane exit flow (fig. 18).

A large amount of experimental research related to measuring the development of viscous wakes behind airfoils and cascades has been performed at Pennsylvania State University (refs. 19 to 22). Raj and Lakshminarayana (ref. 19) focused on determining the applicability of empirical similarity laws for estimating viscous wake shape. Their experiments measured the wake profiles and turbulence intensity at nine axial distances aft of a cascade of cambered airfoils (fig. 19). The effect of incidence showed that variation in the airfoil angle of attack leads to a strong asymmetry of the wake shape (fig. 20). The gaussian similarity law was found to describe the far wake structure very accurately. An algebraic Reynolds stress model was introduced in an attempt to model the turbulent near-wake flow properties.

GENERAL COMMENTS

Many experimental investigations of blade-row interaction and the related transports mechanisms have been reported on in the technical literature over the past decade. Some experiments have been performed with the sole purpose of measuring the actual stator/rotor interaction (refs. 13 and 14). Others intended to study the separate processes which are involved in blade-row interaction, such as wake passing (ref. 8), or secondary flow effects (ref. 15).

The range of experiments reported on in this paper was intentionally limited to test configurations on machinery which represent modern turbomachinery designs. Cascades were typically cambered and in the case of turbines there was sufficient thickness and loading to consider these cascades as practical for turbomachinery. Most of the tests were performed on large-scale, low-speed machines which were intended to represent configurations of compressors and turbines. Because of the large dimensional scale and the low speeds, some of these rigs exhibited poor aerodynamic performance which may not have demonstrated the intended flow phenomena as closely as expected.

The experimental evidence suggesting that similarity exists for the far-wake region behind airfoils is well demonstrated. The Gaussian similarity correlation proposed by Lakshminarayana (refs. 19, 20, and 22) has a strong supporting experimental basis. The dependence of the wake profile on airfoil loading has also been modeled accurately. Further development of accurate descriptions of the turbulent behavior of the fluid, especially within the dissipative near-wake region, is required.

The following observations regarding the areas which require further experimental investigation and characterization are based on the results of this survey.

(1) Experiments which measure the surface response of blade-rows within full-scale multi-stage machinery for both high-speed compressors and turbines is needed.

(2) Measurement of the level of distortion of wakes passing through multiple blade-rows would be useful for development of analytical and CFD models of wake distortion within turbomachines.

(3) Advancements in flow measurement (i.e., laser velocimetry, tracer gas injection) would prove helpful for the unobtrusive measurement of wake profile development and passing.

(4) An experiment which measures the overall aerodynamic environment (passage velocity field, blade surface pressures, wake traverses, etc.) could provide a valuable benchmark for further research into the blade-row interaction problem.

ANALYTICAL STUDIES

Analytical and computational methods for prediction of unsteady aerodynamic response of airfoils to flow disturbances are traditionally based on applications of aerodynamic small-disturbance theory. Recently, computational fluid dynamic (CFD) methods which solve the unsteady Euler and Navier-Stokes equations for interacting blade rows have grown in popularity. In both of these approaches the aerodynamic forcing function is due to either upstream wakes passing down through the cascade or potential-field disturbances which pass from downstream into the cascade. The description of the analytical studies of these phenomena will be classified as either (I) blade-row interaction and (II) CFD simulations. A quick reference table is provided (table II) which compares many of the analytical models reviewed within this survey.

Category I. Blade-Row Interaction

Classical unsteady aerodynamics methods form the foundation of analytical models of aerodynamic interaction. These conventional methods are often of limited practical use for turbomachinery due to the assumptions of small-disturbance theory; flat airfoils, zero incidence, and low camber. Such methods can prove applicable for subsonic fan stages which typically meet such limitations, but general application to loaded compressors and turbines should be considered carefully.

Theoretical models of blade-row interaction assume that the disturbances resulting from adjacent blade-row motion can be modeled as a small perturbation within the velocity or pressure fields impinging upon the airfoil. Such disturbances are referred to as vortical gusts (velocity field disturbances) or acoustic gusts (pressure or potential-field disturbances).

The vortical gust is a mathematical model of the effect of a wake upstream of the airfoil or the cascade passing into and over the airfoils. Vortical gusts may only travel from upstream to downstream and they are convected with the mean fluid flow. The potential-field excitation is modeled as an acoustic gust which may impinge upon the blading from either upstream or downstream. Most of the theoretical models discussed within this category can account for either vortical or acoustic gusts.

The original theoretical formulation for the vortical gust problem was introduced by Kemp and Sears (ref. 23). In their analysis of an isolated airfoil they utilized incompressible small-disturbance assumptions to simplify the problem of an airfoil passing through a transverse sinusoidal gust. This work found that the pressure response of the airfoil varied drastically with the speed with which the gust passes over the airfoil.

Several researchers followed this original application of small-disturbance aerodynamics to account for cascade effects (refs. 24 and 25). Meyer (ref. 26) extended the simple gust model to a more general nonlinear model of stator wakes impinging upon a downstream rotor blade. Fleeter (ref. 27) accounted for the effects of fluid compressibility on the response of cascades to flow disturbances.

Further extension to the general problem of inflow velocity distortions was presented by Horlock (ref. 28). His model utilized simple momentum conservation principles to demonstrate the analysis of the airfoil lift response to the passing of both a transverse and a chordwise gust. The incoming flow disturbance was modeled as a variation in velocity normal and tangent to the blade chord (fig. 21). The combination of these two-dimensional flow distortions introduced a new concept for the generalized wake passing problem. A more rigorous approach to model wake effects in turbomachinery cascades was developed by Naumann and Yeh (ref. 29) and similarly by Henderson and Horlock (ref. 30) who accounted for cambered airfoils at incidence.

One major shortcoming of these aerodynamic models is that the wake disturbance (vortical gust) is assumed to convect through the cascade undisturbed by the surrounding flow (referred to as a "frozen gust"). Goldstein (ref. 31) has advanced a theoretical development to prove that the passing of a wake distorts significantly over airfoils of nontrivial shape. This analysis considers the effect of the mean potential flow on the passing gust and how the gust interacts with the mean steady flow. Goldstein and Atassi (ref. 32) have applied this analysis to the general problem of a two-dimensional gust (fig. 22) passing over an airfoil which has thickness and camber distributions. Atassi (ref. 33) then limited this theory to the case of an isolated airfoil at low incidence to indicate that the interacting gust problem could by modeled by using linear superposition of the separate mean flow effects due to camber, thickness, and incidence.

Namba (ref. 34) has developed a three-dimensional lifting surface theory to estimate the acoustic response of subsonic rotating blade-rows to incident inlet flow gusts. This formulation is concerned primarily with the acoustic problem and transmission of sound waves resulting from vortical gusts. Significant variation in blade unsteady loads along the blade span were reported. This three-dimensional effect diminished as the reduced frequency was increased. The resulting unsteady blade loads were found to be strongly dependent upon the nature of the underlying acoustic modes for the given aerodynamic conditions.

An analytical model of blade-row interaction and the potential-field interaction was first investigated by Kemp and Sears (ref. 35). They applied classical incompressible unsteady aerodynamic models to predict the unsteady effects induced due to adjacent blade rows undergoing relative motion. Their analysis suggested that the effect of the potential-field fluctuations of the downstream blade passing was stronger than the effect of the upstream blade wake passing over the downstream blades. This mathematical formulation found that the unsteady loads due to potential-field interactions decay exponentially with increasing cascade spacing. The variation in rotor and stator harmonic lift components versus axial spacing is shown on figure 23. Osborne (ref. 36) has extended their original work to account for the effects of compressibility up to $M = 0.9$.

A parallel effort to predict the unsteadiness due to potential-field interaction has been studied by Parker (refs. 37 and 38) with specific emphasis on the acoustical problem and noise reduction. This model was based on solving the two-dimensional wave equation for variations in blade-row separation. The studies which Parker presented were primarily intended for use as a design tool to minimize noise generation.

A more complete study of the combined vortical and acoustic gust problem was reported by Kaji and Okazaki (ref. 39). This method used an acceleration potential theory in conjunction with small-disturbance assumptions to predict the compressible unsteady aerodynamics due to both wake and pressure disturbances entering a cascade. The emphasis of this approach was for the determination of the reflection and transmission of acoustic waves which would generate unacceptable noise. This method allows for the acoustic gust to travel into the cascade from either upstream or downstream.

Smith (ref. 25) has presented a compressible unsteady aerodynamic model which accounts for the incident gust problem and prescribed blade motion. This model included both the vortical and acoustic gust problem for a cascade but emphasized the resulting unsteady blade loads as opposed to the acoustical transmission through the cascade. This approach has been utilized by many recent aeroelastic analyses because of the ease of use of the model. The model is based on the small-disturbance approximation which limits the overall applicability to turbomachinery which have thin, uncambered airfoils.

Category II. CFD Simulations

The CFD approach to aerodynamic interaction attempts to simulate the interaction problem by solving the conservation laws (continuity, momentum, energy) for a stator and rotor blade simultaneously. These solutions model the relative motion between a moving disturbance or rotating blade rows by incrementally solving the governing equations in a time-accurate fashion. This type of solution typically solves the Euler or Navier-Stokes equations by using fundamental time integration schemes. The majority of the results are represented in the time domain.

A simplified approach to investigate the transport of a wake segment as it passed through a turbine stage was described by Joslyn, et al. (ref. 40). Their method used an inviscid streamline procedure to trace how an infinitely thin wake centerline distorts as it passes through the potential field of a blade row. An example of such a wake line distortion is shown on figure 24 for a turbine rotor. The contour lines on this figure indicate different time levels. A conceptual description of the application of a drift function to describe the distortion and transport of wake segments within the inviscid flow is included in this paper. This relatively simple procedure illustrates the complex trajectory and kinematics of upstream flow disturbances as they pass through a cascade.

The computational simulation of wake passing through a cascade has been demonstrated by Giles (ref. 41). This approach modeled the wake velocity defect using the gaussian similarity form of the profile at the upstream boundary of a turbine cascade. The solution then proceeded with time to simulate how the wake disturbance distorts and travels through the turbine passage. This method simulates the full passage of an upstream flow disturbance as it reacts to the blading and convects through the blade passage. A contour plot showing the entropy contours at several time levels is included on figure 25. The computed flow behavior of the wake within the turbine cascade was compared qualitatively with experimentally observed wake distortion data and found to emulate the essential flow properties. Of particular interest for this approach was the time transformation technique which was used to allow for the analysis of cascades with unequal pitch ratios.

Korakianitis (refs. 42 and 43) has used the above computer program to investigate the effect of cascade solidity on the wake induced and potential-field induced unsteadiness of several parametric cascade configurations. He has found that the effects of these two aerodynamic forcing functions on the resulting unsteady blade loads are strongly dependent upon the cascade loading, geometry, and flow conditions. This report in particular was concerned with the level of unsteady blade loads compared to the steady loading level of the blade.

Joslyn et al. (ref. 18) have modified a fairly simple cascade potential analysis program to allow for pressure-field disturbances which pass into the cascade through the downstream boundary. Results from this program indicate that the effect of such potential-field unsteadiness can be modeled relatively accurately by properly modifying relatively simple full-potential codes.

Warfield and Lakshminarayana (ref. 21) have used a Navier-Stokes program with a modified turbulence model to numerically predict the boundary layer and wake formation behind a three-dimensional airfoil cascade. The emphasis of their work was to develop an appropriate closure model to capture the turbulent flow regimes which occur in the viscous sublayer and near-wake regions. Their turbulence model is based on an algebraic Reynolds stress formulation. The predicted circumferential and radial near-wakes are predicted fairly well when compared to other Navier-Stokes solvers and to some measured wake profiles.

The simulation of an inviscid stator/rotor blade interaction was reported by Lewis et al. (ref. 44). Their two-dimensional numerical simulation of a turbine vane upstream of a rotor blade performed a coupled solution of the Euler equations for the full stage. This approach utilizes an iterative scheme which solves the conservation laws in the upstream cascade separately from the solution for the downstream cascade. The flowfield information from the two cascades is shared through patched solution meshes (fig. 26) which translate relative to one another to simulate blade motion. This solution scheme demonstrates the strong unsteady effects of potential-field interaction between the two blade rows. Unsteady surface pressure envelopes are provided for the stator and rotor blades of a turbine stage showing the regions of high unsteadiness (fig. 27).

Investigation of the effect of stator/rotor interaction and shock wave passage within a highly loaded turbine is reported by Giles (ref. 45). The author uses the same technique to transform the time-dependent terms of the unsteady Euler equations as was presented in his prior work (ref. 39). This approach uses two solution grids for the stator and rotor which are coupled by using a "shearing" interface between the grids to permit relative motion. An application of this program for a transonic turbine stage details the strong influence that the stator trailing-edge shock wave has upon the rotor flow. Figure 28 contains surface pressure distributions for the stator and the rotor blades at several time increments which show the highly nonsteady character of the interaction. Giles reports that the rotor blade lift coefficient varies by up to 40 percent due to the interaction with the stator's convected vorticity and shock waves. The oblique shock waves which reflect from the trailing edge of the stator blade case a highly discontinuous pressure field within the downstream rotor blade passage.

Further work on the coupled analysis of stator/rotor interaction for both inviscid and viscous two-dimensional flow was presented by Jorgenson and Chima (ref. 46). This approach uses patched, overlaid solution meshes for each blade cascade (fig. 29) which are translated in time to simulate blade motion. The passing of the rotor mesh past the stator mesh from startup is computed several times to allow for the start-up oscillations to die out and for the solution to become periodic. The simulation of the flow within the SSME turbine stage is included which indicated that the effect of the viscous wake passing induced much higher unsteady blade loads than the potential-field interaction effect. Plots showing the variation in lift force for the stator and the rotor blade of the SSME stage is shown on figure 30. Isomach contours for a time instant of this simulation is included as figure 31. There is currently no experimental data to correlate these computational results with.

A full simulation of the three-dimensional unsteady viscous flow within a turbine stage was developed by Rai (ref. 47). This investigation presents a thin-layer three-dimensional Navier-Stokes simulation of the interaction between a turbine vane and rotor blade. The formulation accounts for the span-wise transport of the fluid over the blades and to a lesser extent, the effects of the hub and endwall boundary layer regions. The turbine stage modeled is the same as that reported experimentally by Dring et al. (ref. 11). The author states that the method used is limited to stages which have equal pitch ratios for the rotor and stator. Direct comparison with the experimental data mentioned previously is impossible because the tested machine has unequal cascade pitches for the rotor and stator rows.

An important area of current research is focused on developing unsteady analyses by using linearized aerodynamic models. Such linearized models are appealing because of the rapid computational time when compared to full time-accurate solutions. This feature combined with the good correlation with unsteady measurements presents the linearized approach as an attractive method for design-oriented applications. Verdon and Caspar (ref. 48) and Verdon (ref. 49) describe the development of a linearized unsteady potential theory. Likewise, Hall and Crawley (ref. 50) have advanced a linearized unsteady Euler method for turbomachinery.

GENERAL COMMENTS

Many of the analytical models of blade-row interaction outlined above have been compared with some form of experiment. In most instances, the specific formulation presented by the authors proves very limited especially when searching for a universal model applicable to practical turbomachinery. The CFD approaches provide a thorough simulation of the fluid mechanical processes which occur for such machines, although their application is now largely prohibited by the excessive computational requirements.

Theoretical solutions have been developed (refs. 23, 25, and 27) which can be used to study the complexity of the effect of wake passing over thin-airfoils. A primary shortcoming of these methods is that the blading is assumed to be unloaded (i.e., flat plat, zero incidence) and that the wake remains undistorted as it passes over the airfoil. A more general theoretical model for distorting wake passage was advanced by Goldstein (ref. 31) who assumed that the unsteadiness could be modeled as a small perturbation from the mean potential flow field.

Developments in the CFD techniques to solve the governing equations for internal flows lends hope to enhancing the capability for simulating blade-row interaction. Several investigators (refs. 41, 44, and 45) have proven that the simulation of stator/rotor blade-row interaction can be performed using an incremental solution of the unsteady Euler equations. Research has also been reported (refs. 46 and 47) concerning solution of the stator/rotor interaction problem by applying coupled solution of the thin-layer Navier-Stokes equations in a time-accurate fashion.

A major drawback of using the many computational methods to quantify the aerodynamic forcing functions is the prohibitive computer time and memory requirements needed for these solutions. CFD simulation will prove to be an important vehicle to study the specific flow phenomena associated with aerodynamic blade-row interaction and may fill the vacancy in experimental data which is required to generate suitable semi-empirical models for these aerodynamic forcing functions. But the excessive computational requirements of these techniques will prohibit their application to specific problems concerned with aeroelasticity.

The linearized methods fulfill an important role in providing a cost-effective alternative for predicting unsteady aerodynamic response to aerodynamic excitations. The chief difficulty in applying such models is that a fully coupled solution for adjacent blade-rows is not currently available. Such methods can be used successfully if the effects of blade-row interaction can be modeled as the basic aerodynamic excitations of (1) wake passing and (2) incident potential-field disturbances. Recently, the aeroelasticity research community has embraced linearized methods for such stability and forced response analysis problems because of the aforementioned advantages.

The following general conclusions regarding the current state of analytical modeling of blade-row interaction are provided as results from this survey.

(1) The traditional small-disturbance models for wake passing over cascades (vortical gusts) are severely limited due to the inherent assumptions of zero loading and a simple "frozen" gust formulation.

(2) Analytical models of potential-field interactions between blade-rows (acoustic gusts) have been advanced but they are primarily intended for acoustic performance and noise generation.

(3) Analytical models of a distorting wake-blade interaction (e.g. Goldstein) could be compared with a CFD simulation to determine the range of applicability of the theoretical model.

(4) A full comparison of an unsteady flow problem using a linearized method (e.g. Verdon, Hall) and a time-accurate CFD simulation is necessary to define the appropriate aerodynamic conditions where each method is more generally applicable.

(5) Unsteady Euler simulation of wake passing and stator/rotor interaction has shown that the convected vorticity from the upstream blade wake can capture the viscous wake effect reliably using an inviscid formulation.

(6) CFD simulation of stator/rotor interaction using unsteady Euler and Navier-Stokes solutions have been proposed but with little direct comparison to experimental results.

(7) Further developments in algorithms and computer architectures for CFD methods are necessary to allow for the CFD techniques to be used as a replacement for some of the expensive experimental studies.

SUMMARY OF RESULTS

The research activity within the field of turbomachinery blade-row interaction provides some detailed experimental observations of the unsteady phenomena. Analytical modeling of these same phenomena now relies on CFD methods to simulate the "real-world" problems of aerodynamic interaction in turbomachinery.

An attempt to formulate analytical or empirical models to describe the influences of blade-row aerodynamic forcing functions will require significant experimentation, both physical and numerical. The predictions from some of the stator/rotor interaction CFD codes described in this report suggest that the technology for numerically simulating the interaction problem is maturing. The current technology for CFD time-accurate solutions requires excessively long computer times and large memory limits. Advancements in CFD algorithms and computer technology are reducing these requirements.

Application of the original theoretical models of wake passing and potential-field interaction should generally be avoided. Many of the early models, especially of potential interaction, have severely limiting assumptions which may limit their general application to turbomachinery. These models may be used to investigate the essential physics of the unsteady disturbance, but use as a defining tool for forcing functions should be done carefully.

Linearized aerodynamic models can be applied to turbomachinery for specific flow regimes and are cost-effective in terms of computational requirements. A linearized method is most amenable for coupling within a structural dynamic response system as required for aeroelasticity work. A disadvantage of such linearized methods may be because of the limited applicability to problems free of strong shock motion and flows which occur at very large reduced frequencies.

Definition of specific forcing function levels due to (1) viscous wake passing and (2) potential-field disturbances could be correlated based on the information obtained from this survey.

Wake Passing Forcing Functions

The shape and dissipation of velocity wakes is well-defined and the response of both trivial and complex airfoils to such a passing disturbance can be studied using time-accurate CFD. Such CFD simulations can be used to create simple semi-empirical models which describe blade unsteady loads from wakes and their dependence on cascade geometry and flow conditions.

Potential-Field Disturbance Forcing Functions

The contribution of potential-field disturbances to unsteady blade loads in an embedded blade-row is not well understood. Traditional analytical models applying small-disturbance assumptions are not technically strong enough to capture the phenomena. Computational methods based on utilizing rapid full potential codes to simulate potential interaction have been shown to be accurate. Full simulation of the time-accurate Navier-Stokes techniques may be used, but the computational effort is very prohibitive.

ACKNOWLEDGEMENT

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REFERENCES

1. Hoyniak, D.; and Fleeter, S.: The Coupled Response of Turbomachinery Blading to Aerodynamic Excitations. J. Aircraft, vol. 21, no. 4, Apr. 1984, pp. 278-286.

2. Tadros, R.N.; and Botman, M.: Dynamic Response of Blades and Vanes to Wakes in Axial Turbomachinery. ASME Paper 81-DET-33, Sept. 1981.

3. Fleeter, S., et al.: An Experimental Determination of the Unsteady Aerodynamics in a Controlled Oscillating Cascade. J. Eng. Power, vol. 99, no. 1, Jan. 1977, pp. 88-96.

4. Carta, F.O.: Unsteady Aerodynamics and Gapwise Periodicity of Oscillating Cascaded Airfoils. J. Eng. Power, vol. 105, no. 3, July 1983, pp. 565-574.

5. Fujita, H.; and Kovasznay, L.S.G.: Unsteady Lift and Radiated Sound From a Wake Cutting Airfoil. AIAA J., vol. 12, no. 9, Sept. 1974, pp. 1216-1221.

6 Satyanarayana, B.: Unsteady Wake Measurements of Airfoils and Cascades. AIAA J., vol. 15, no. 5, May 1977, pp. 613-618.

7. Patel, B.R.; and Desai, K.J.: Direct Blade Force Measurements in Transonic Cascade Flows. ASME Paper 78-GT-45, Apr. 1978.

8. Adachi, T.; and Murakami, Y.: Three-Dimensional Velocity Distribution Between Stator Blades and Unsteady Force on a Blade Due to Passing Wakes. Bull. JSME, vol. 22, no. 170, Aug. 1979, pp. 1074-1082.

9. Fleeter, S.; Jay, R.L.; and Bennett, W.A.: Wake Induced Time-Variant Aerodynamics Including Rotor-Stator Axial Spacing Effects. Nonsteady Fluid Dynamics, D.E. Crow and J.A. Miller, eds., ASME, 1978, pp. 147-163.

10. Capece, V.R.; and Fleeter, S.: Unsteady Aerodynamic Interactions in a Multistage Compressor. J. Turbomachinery, vol. 109, no. 3, July 1987, pp. 420-428.

11. Binder, A., et al.: An Experimental Investigation Into the Effect of Wakes on the Unsteady Turbine Rotor Flow. J. Eng. Gas Turbines Power, vol. 107, no. 2, Apr. 1985, pp. 458-466.

12. Hathaway, M.D., et al.: Rotor Wake Characteristics of a Transonic Axial-Flow Fan. AIAA J., vol. 24, no. 11, Nov. 1986, pp. 1802-1810.

13. Gallus, H.E.; Lambertz, J.; and Wallman, T.: Blade-Row Interaction in an Axial Flow Subsonic Compressor Stage. ASME Paper 79-GT-92, Mar. 1979.

14. Sharma, O.P., et al.: Rotor-Stator Interaction in Multi-Stage Axial-Flow Turbines. AIAA Paper 88-3013, July 1988.

15. Dring, R.P., et al.: Turbine Rotor-Stator Interaction. J. Eng. Power, vol. 104, no. 4, Oct. 1982, pp. 729-742.

16. Hobbs D.E., et al.: Experimental Investigation of Compressor Cascade Wakes. ASME Paper 82-GT-299, Apr. 1982.

17. Dring, R.P.; Joslyn, H.D.; and Hardin, L.W.: Experimental Investigation of Compressor Rotor Wakes. AFAPL-TR-79-2107, Jan. 1980. (Avail. NTIS, AD-A081911.)

18. Joslyn, H.D.; Dring, R.P.; and Sharma O.P.: Unsteady Three-Dimensional Turbine Aerodynamics. J. Eng. Power, vol. 105, no. 2, Apr. 1983, pp. 322-331.

19. Raj, R.; and Lakshminarayana, B.: Characteristics of the Wake Behind a Cascade of Airfoils. J. Fluid Mech., vol. 61, pt. 4, Dec. 18, 1973, pp. 707-730.

20. Hah, C.; and Lakshminarayana, B.: Measurement and Prediction of Mean Velocity and Turbulence Structure in the Near Wake of an Airfoil. J. Fluid Mech., vol. 115, Dec. 1982, pp. 251-282.

21. Warfield, M.J., and Lakshminarayana, B.: Calculation of a Three-Dimensional Turbomachinery Rotor Flow With a Navier-Stokes Code. ASME Paper 87-GT-232, May 1987.

22. Lakshminarayana, B.; and Zhang, J.: Analysis of Three-Dimensional Turbulent Wakes by Momentum Integral Technique. AIAA Paper 87-1437, June 1987.

23. Kemp, N.H.; and Sears, W.R.: The Unsteady Forces Due to Viscous Wakes in Turbomachines. J. Aeronaut. Sci., vol. 22, no. 7, Jul. 1955, pp. 478-483.

24. Whitehead, D.S.: Force and Moment Coefficients for Vibrating Aerofoils in Cascade. ARC-R&M-3254, Feb. 1960.

25. Smith, S.N.: Discrete Frequency Sound Generation in Axial Flow Turbomachines. ARC-R&M-3709, Mar. 1972.

26. Meyer, R.N.: The Effect of Wakes on the Transient Pressure and Velocity Distributions in Turbomachines. Trans. ASME, vol. 80, no. 7, Oct. 1958, pp. 1544-1552.

27. Fleeter, S.: Fluctuating Lift and Moment Coefficients for Cascaded Airfoils in a Nonuniform Compressible Flow. J. Aircraft, vol. 10, no. 2, Feb. 1973, pp. 93-98.

28. Horlock, J.H.: Fluctuating Lift Forces on Aerofoils Moving Through Transverse and Chordwise Gusts. J. Basic Eng. vol. 90, no. 4, Dec. 1968, pp. 494-500.

29. Naumann, H.; and Yeh, H.: Lift and Pressure Fluctuations of a Cambered Airfoil Under Periodic Gusts and Applications in Turbomachinery. J. Eng. Power, vol. 95, no. 1, Jan. 1973, pp. 1-10.

30. Henderson, R.E.; and Horlock, J.H.: An Approximate Analysis of the Unsteady Lift on Airfoils in Cascade. J. Eng. Power, vol. 94, no. 4, Oct. 1972, pp. 233-240.

31. Goldstein, M.E.: Unsteady Vortical and Entropic Distortions of Potential Flows Round Arbitrary Obstacles. J. Fluid Mech., vol. 89, pt. 3, Dec. 13, 1978, pp. 433-468.

32. Goldstein, M.E.; and Atassi, H.: A Complete Second-Order Theory for the Unsteady Flow About an Airfoil Due to a Periodic Gust. J. Fluid Mech. vol. 74, pt. 4, Apr. 22, 1976, pp. 741-765.

33. Atassi, H.M.: The Sears Problem for a Lifting Airfoil Revisited - New Results. J. Fluid Mech. vol. 141, Apr. 1984, pp. 109-122.

34. Namba, M.M.: Three-Dimensional Analaysis of Blade Force and Sound Generation for an Annular Cascade in Distorted Flows. J. Sound Vibration, vol. 50, no. 4, Feb. 22, 1977 pp. 479-508.

35. Kemp, N.H.; and Sears, W.R.: Aerodynamic Interference Between Moving Blade Rows. J. Aeronaut. Sci., vol. 20, no. 9, Sept. 1953, pp. 585-597.

36. Osborne, C.: Compressible Unsteady Interactions Between Blade Rows. AIAA J., vol. 11, no. 3, Mar. 1973, pp. 340-346.

37. Parker, R.; and Watson, J.F.: Interaction Effects Between Blade Rows in Turbomachinery. Proc. Inst. Mech. Eng., vol. 186, no. 21, 1972, pp. 331-340.

38. Parker, R.: Relation Between Blade Row Spacing and Potential Flow Interaction Effects in Turbomachines. Thermodynamics and Fluid Mechanics Convention 1970, Proc. Inst. Mech. Eng., vol. 184, pt. 3G, 1969-1970, p. 1.

39. Kaji, S.; and Okazaki, T.: Propagation of Sound Waves Through a Blade Row. II. Analysis Based on the Acceleration Potential Method. J. Sound Vibration, vol. 11, no. 3, Mar. 1970, pp. 355-375.

40. Joslyn, H.D.; and Caspar, J.R.; and Dring, R.P.: Inviscid Modeling of Turbomachinery Wake Transport. J. Propulsion Power, vol. 2, no. 2, Mar.-Apr. 1986, pp. 175-180.

41. Giles, M.B.; Calculation of Unsteady Wake/Rotor Interaction. AIAA Paper 87-0006, Jan., 1987.

42. Korakianitis, T.P.: On the Prediction of Unsteady Forces on Gas-Turbine Blades. Part 1: Typical Results and Potential-Flow Interaction Effects. ASME Paper 88-GT-89, June, 1988.

43. Korakianitis, T.P.: On the Prediction of Unsteady Forces on Gas-Turbine Blades. Part 2: Viscous-Wake-Interaction and Axial-Gap Effects. ASME Paper 88-GT-90, June 1988.

44. Lewis, J.P.; Delaney; R.A.; and Hall, E.J.: Numerical Prediction of Turbine Vane-Blade Aerodynamic Interaction. AIAA Paper 87-2149, June 1987.

45. Giles, M.: Stator/Rotor Interaction in a Transonic Turbine. AIAA Paper 88-3093, July 1988.

46. Jorgenson, P.C.E.; and Chima, R.V.: An Explicit Runge-Kutta Method for Unsteady Rotor/Stator Interaction. AIAA Paper 88-0049, Jan. 1988. (NASA TM-100787.)

47. Rai, M.M.: Unsteady Three-Dimensional Navier-Stokes Simulations of Turbine Rotor-Stator Interaction. AIAA Paper 87-2058, 1987.

48. Verdon, J.M.; and Caspar, J.R.: A Linearized Unsteady Aerodynamic Analysis for Transonic Cascades. J. Fluid Mech., vol. 149, Dec. 1984, pp. 403-429.

49. Verdon, J.: The Unsteady Aerodynamic Response to Arbitrary Modes of Blade Motion. Proceedings of the 4th Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellors, Aachen, West Germany, 1987.

50. Hall, K.; and Crawley, E.: Calculation of Unsteady Flows in Turbomachinery Using the Linearized Euler Equations. Proceedings of the 4th Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellors, Aachen, West Germany, 1987.

TABLE I. - COMPARISON OF AERODYNAMIC INTERACTION RESEARCH EXPERIMENTAL STUDIES

Referenced authors	Experiment classification	Test configuration	Experimental apparatus (a,b)	Data presentation (c)	Unsteady results (c)
Adachi and Murakami (ref. 8)	Wake passing	Compressor stator	Surface P sensors Hot-wire probes	Cp,Cl versus time V vectors versus time	Clmx = 5%, k = 4.6 Cdmx = 2.2%, k = 4.6
Fleeter et al. (ref. 9)	Wake passing	Compressor 1-stage rotor-stator	Surface sensors Hot-wire probes	V profiles Cp,Cp distributions	Stator dynamic Cp k = 8 to 20
Capece and Fleeter (ref. 10)	Wake passing	Compressor 3-stage IGV-rotor-stator	Surface P sensors Hot-wire probes	V profiles Cp,Cp distributions	Stator dynamic Cp k = 5.0
Binder et al. (ref. 11)	Wake distortion	Turbine 1-stage stator-rotor	Laser 2-focus velocimetry	V profiles V,Tu contours	None
Hathaway et al. (ref. 12)	Wake distortion	Fan 1-stage stator-rotor	Laser anemometry	V profiles V vectors	None
Gallus et al. (ref. 13)	Blade-row interaction	Compressor 1-stage IGV-rotor-stator	Pneumatic probes Surface P sensors	P,V profiles P,Cp versus time	Stator Clmx = 6%, k = 3.0
Sharma et al. (ref. 14)	Blade-row interaction	Turbine 1-1/2-stage IGV-rotor stator	Surface P sensor Pneumatic & hot-wire	Stanton number Pressure contours	None
Dring et al. (ref. 15)	Blade-row interaction	Turbine 1-stage stator-rotor	Surface P sensors	Cp,Cp distributions	Stator Cpmx = 15%, k = 2.5 Rotor Cpmx = 80%, k = 1.6
Hobbs et al. (ref. 16)	Wake traverse	Linear cascade	Pneumatic & hot-wire Surface P sensors	BL,Cp distributions V,Tu profiles	None
Dring et al. (ref. 17)	Wake traverse three-dimensional	Compressor rotor	Pneumatic probes	BL,Tu distributions V,P profiles	None
Joslyn et al. (ref. 18)	Wake traverse	Turbine 1-1/2-stage Stator-rotor-stator	Pneumatic & hot-wire Probes	V,V profiles Cp,Cp distributions	None
Raj and Lakshminarayana (ref. 19)	Wake traverse	Linear cascade	Pneumatic & hot-wire Probes	V,Tu profiles	None
Raj and Lakshminarayana (ref. 20)	Wake traverse	Isolated airfoil	Hot-wire probes	V,Tu profiles	None

(a) Surface pressure sensors are typically high-response "Kulite" semiconductor transducers.

(b) Hot-wire and pneumatic probes typically used for wake traverse aft of airfoils.

(c) Nomenclature notes: P - instantaneous pressure; V - relative or absolute velocity; BL - boundary layer thickness; Cp - static pressure coefficient; Tu - turbulence intensity; k - reduced frequency (semichord).

TABLE II. - COMPARISON OF AERODYNAMIC INTERACTION RESEARCH ANALYTICAL STUDIES

Referenced authors	Analytical classification	Theoretical formulation	Configuration
Kemp and Sears (ref. 23)	Wake passing (trans. gust)	Small-disturbance incompressible	Isolated, unloaded thin-airfoil
Smith (ref. 25)	Wake passing & potential distributions (trans. gust)	Small-disturbance incompressible	Cascade, unloaded thin-airfoils
Fleeter (ref. 27)	Wake passing (trans. gust)	Small-disturbance compressible	Cascade, unloaded thin-airfoils
Naumann and Yeh (ref. 29)	Wake passing (trans. long. gust)	Small-disturbance incompressible	Isolated, loaded cambered thin-airfoil
Goldstein and Atassi (ref. 32)	Wake passing & distortion	Small-disturbance incompressible	Isolated, loaded cambered thin-airfoil
Kemp and Sears (ref. 35)	Potential interaction	Small-disturbance incompressible	Cascades, stator/ rotor thin airfoils
Osborne (ref. 36)	Potential interaction	Small-disturbance compressible	Cascades, stator/ rotor thin airfoils
Giles (ref. 41)	Wake passing & distortion	Two-dimensional unsteady Euler	Turbine cascade
Warfield and Lakshminarayana (ref. 21)	Wake character and distortion	Three-dimensional Navier-Stokes	Compressor cascade
Lewis et al. (ref. 44)	Aerodynamic interaction	Two-dimensional unsteady Euler	Turbine stator/ rotor overlaid grids
Giles (ref. 45)	Aerodynamic interaction	Two-dimensional unsteady Euler	Turbine stator/ rotor shearing grids
Jorgenson and Chima (ref. 46)	Aerodynamic intersection	Two-dimensional thin-layer Navier-Stokes	Turbine stator/ rotor overlaid grids
Rai (ref. 47)	Aerodynamic intersection	Three-dimensional thin-layer Navier-Stokes	Turbine stator/ rotor overlaid grids

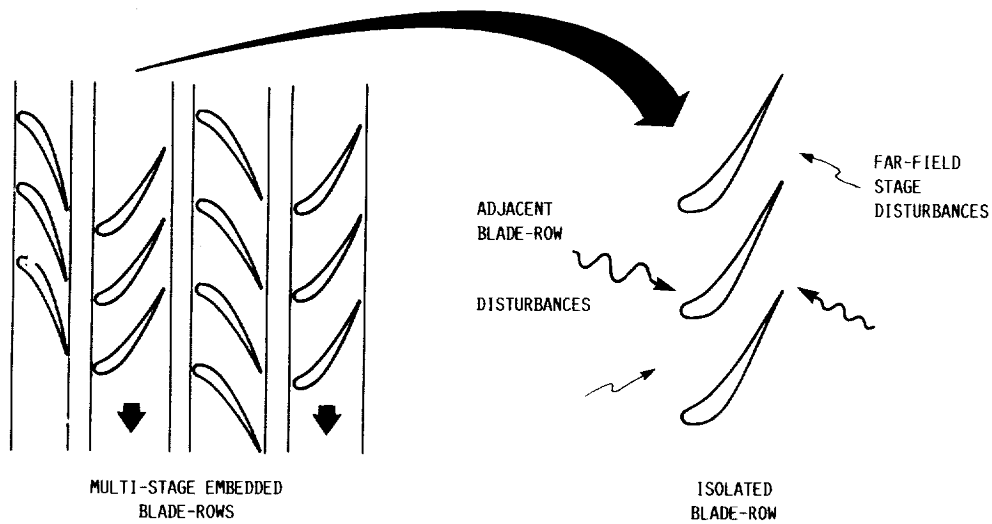


FIGURE 1. - MULTI-STAGE BLADE CASCADES AND ISOLATION TO SINGLE BLADE-ROW.

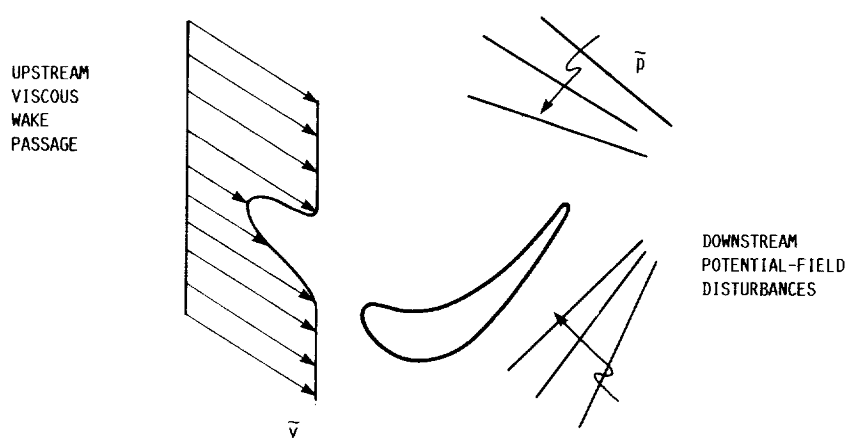


FIGURE 2. - AERODYNAMIC SOURCES OF UNSTEADY EXCITATIONS.

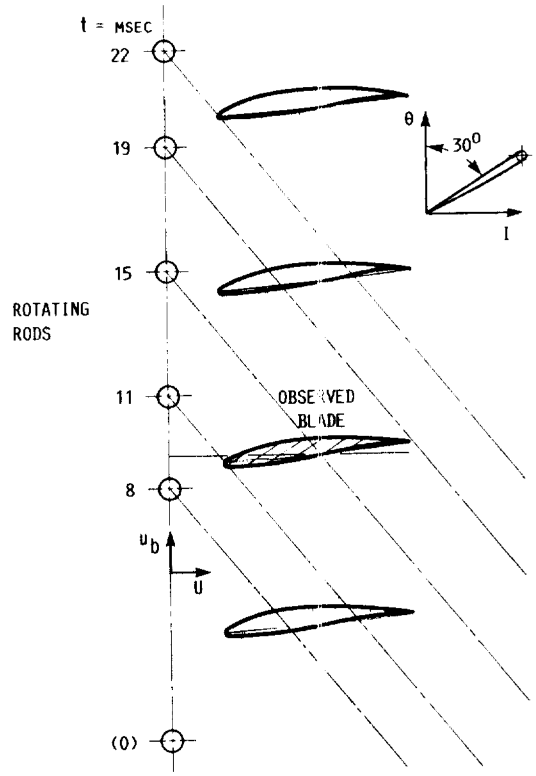


FIGURE 3. - CONFIGURATION SHOWING ROTATING RODS POSITIONED UPSTREAM OF STATOR BLADES (FROM [8]).

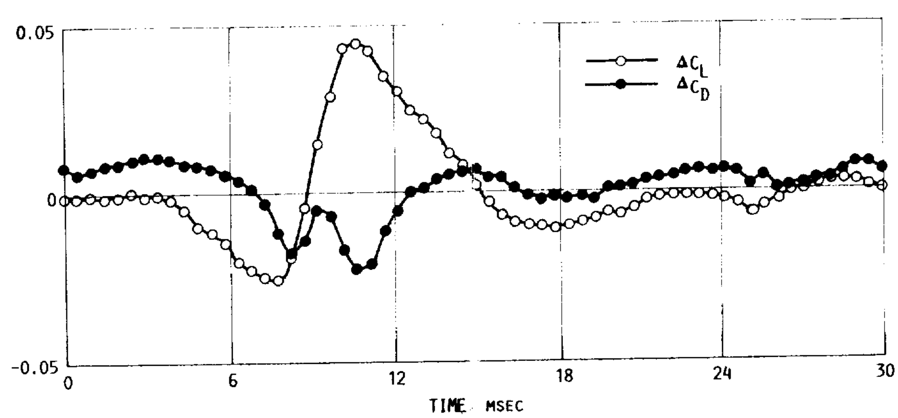


FIGURE 4. - TIME VARIATION IN STATOR BLADE LIFT AND DRAG COEFFICIENTS FOR ONE BLADE PASSING PERIOD (FROM [8]).

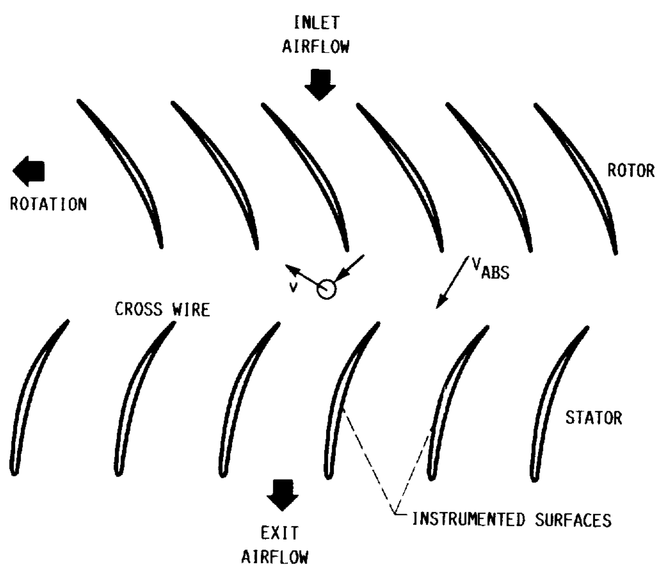


FIGURE 5. - EXPERIMENTAL CONFIGURATION FOR COMPRESSOR STAGE SHOWING TRAVERSE LOCATION AND MEASURED PASSAGE (FROM [9]).

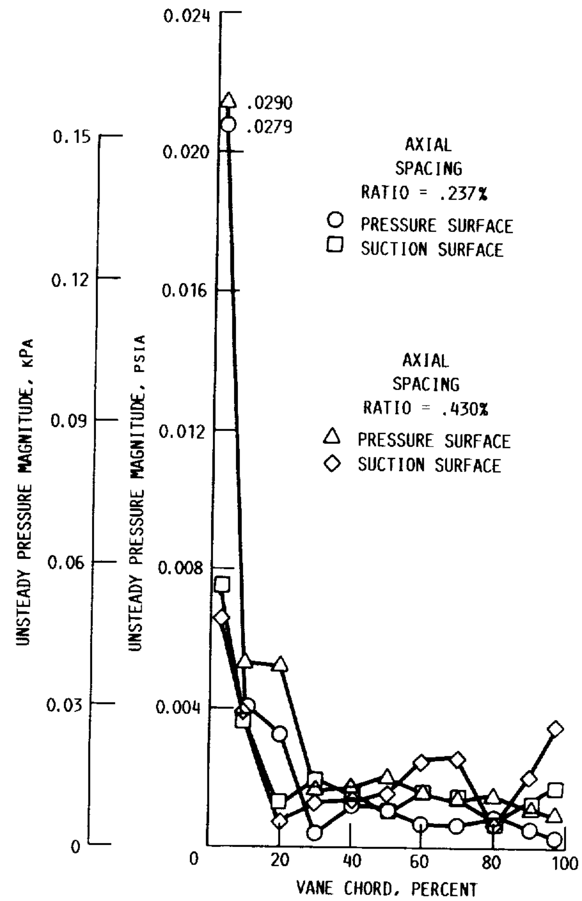


FIGURE 6. - STATOR VANE UNSTEADY PRESSURE DISTRIBUTION DUE TO WAKE PASSING - 2 AXIAL SPACINGS (FROM [9]).

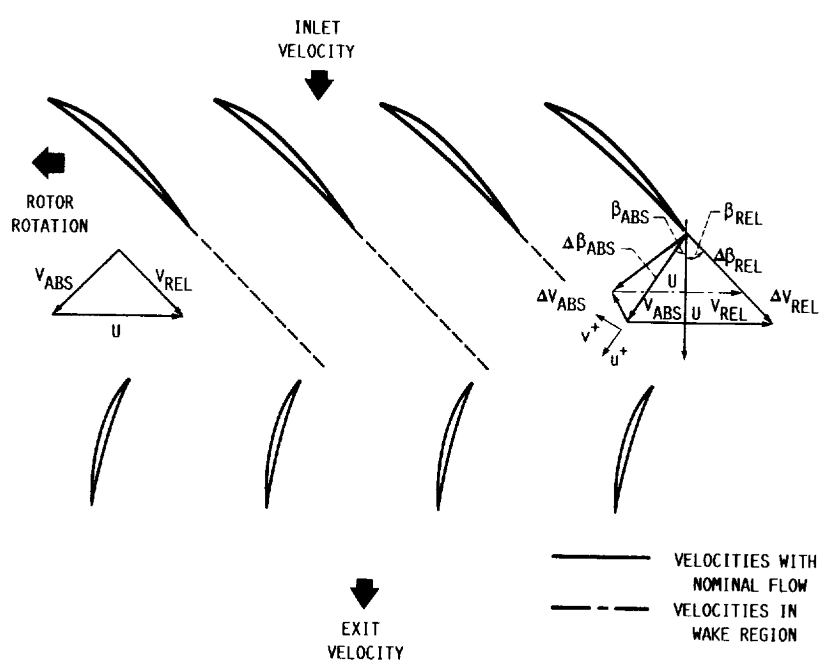


FIGURE 7. - CASCADE VELOCITY TRIANGLE INDENTIFYING PERTURBATION VELOCITY AND FORCING FUNCTION INDUCED BY WAKES (FROM [10]).

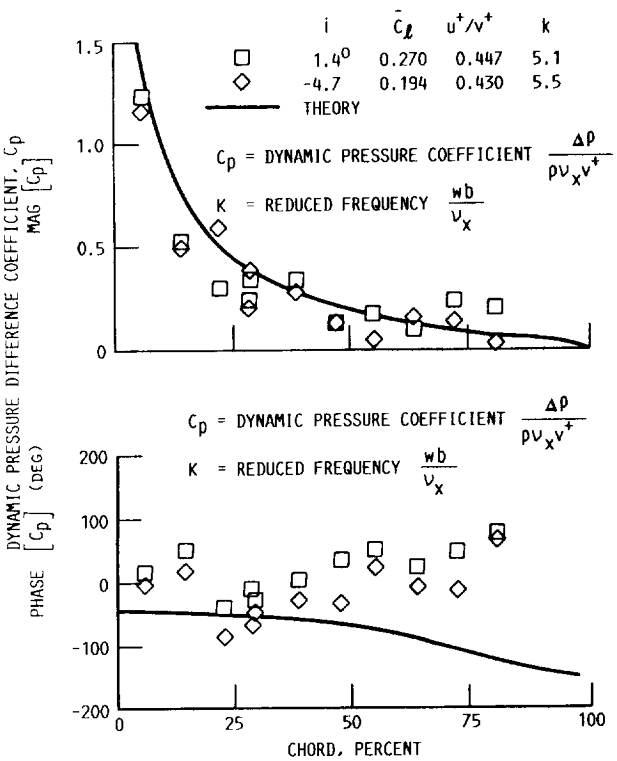


FIGURE 8. - DYNAMIC UNSTEADY PRESSURE AND PHASE OVER STATOR CHORD CAUSED BY WAKE FORCING FUNCTION (FROM [10]).

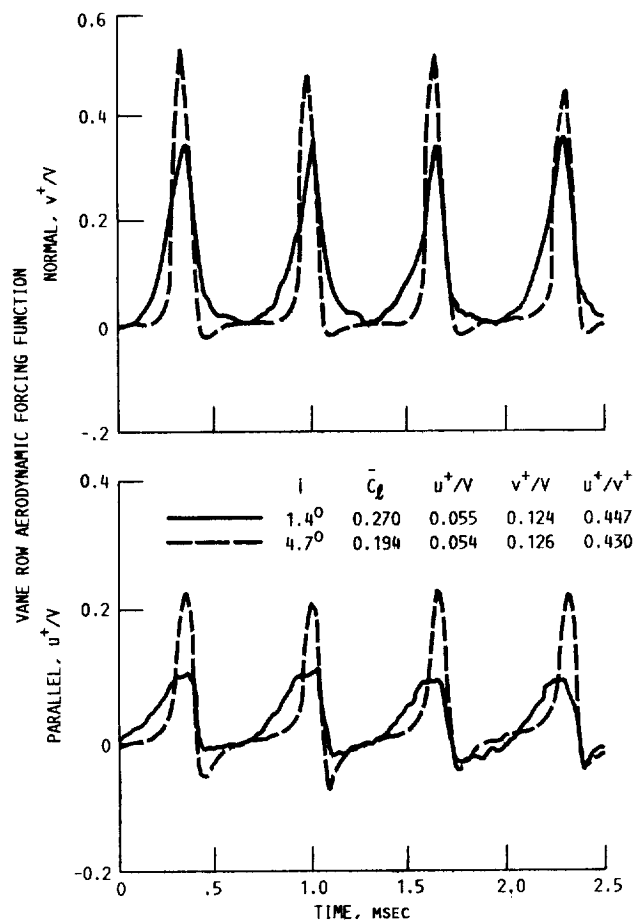


FIGURE 9. - VELOCITY PERTURBATION CAUSED BY WAKE FORCING FUNCTION (FROM [10]).

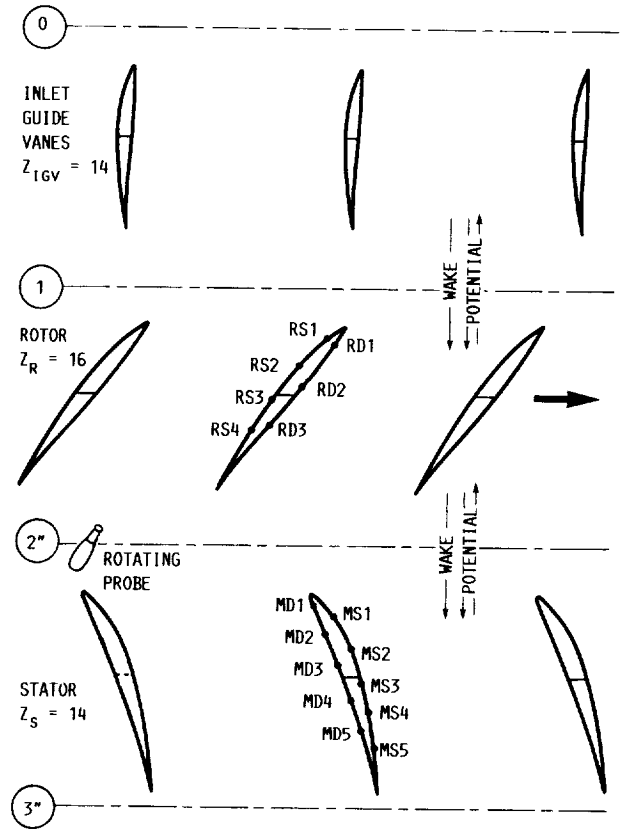
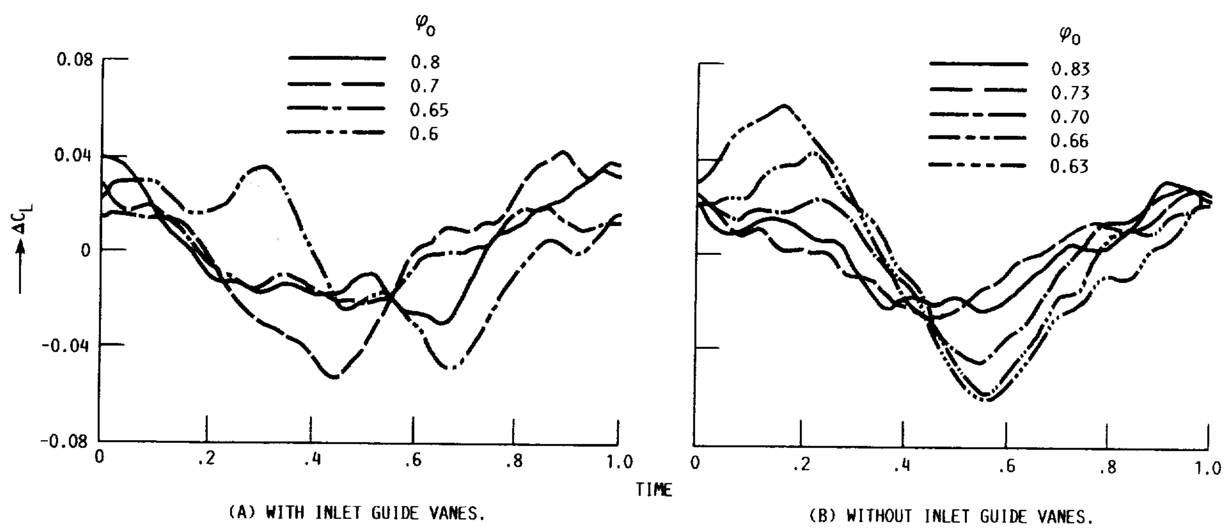


FIGURE 10. - COMPRESSOR STAGE MEASUREMENT STATIONS AND TRANSDUCER LOCATIONS (FROM [13]).



(A) WITH INLET GUIDE VANES.

(B) WITHOUT INLET GUIDE VANES.

FIGURE 11. - TRANSIENT VARIATION IN UNSTEADY STATOR LIFT FORCE FOR SEVERAL FLOW COEFFICIENTS (FROM [13]). (Φ_0 = FLOW COEFFICIENT = $\frac{V_x}{u}$).

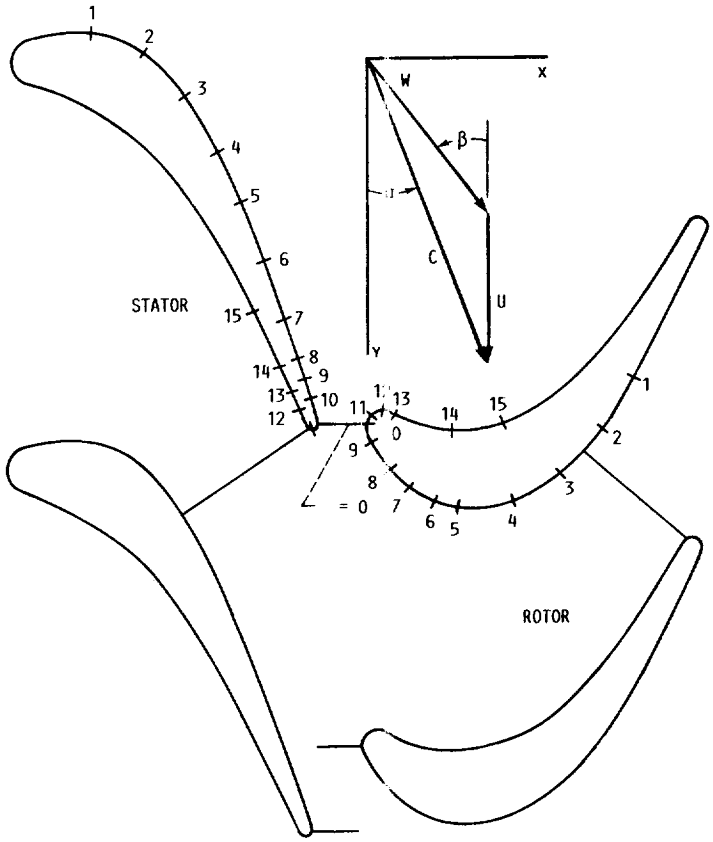


FIGURE 12. - LOCATION OF SURFACE PRESSURE TRANSDUCERS FOR STATOR AND ROTOR BLADES (FROM [14]).

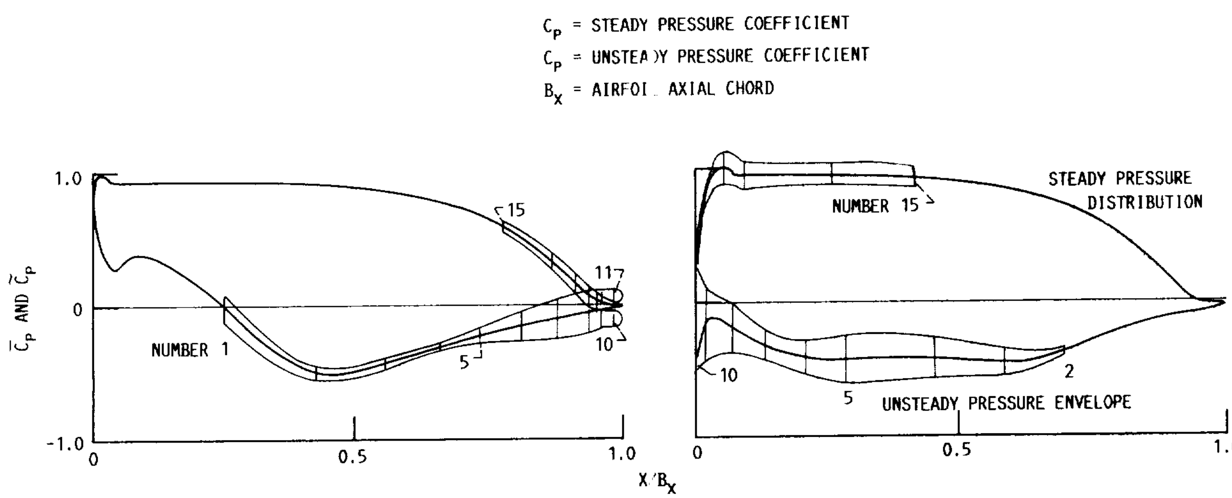


FIGURE 13. - STEADY AND UNSTEADY PRESSURE DISTRIBUTIONS OVER SURFACE OF STATOR AND ROTOR BLADES (FROM [14]).

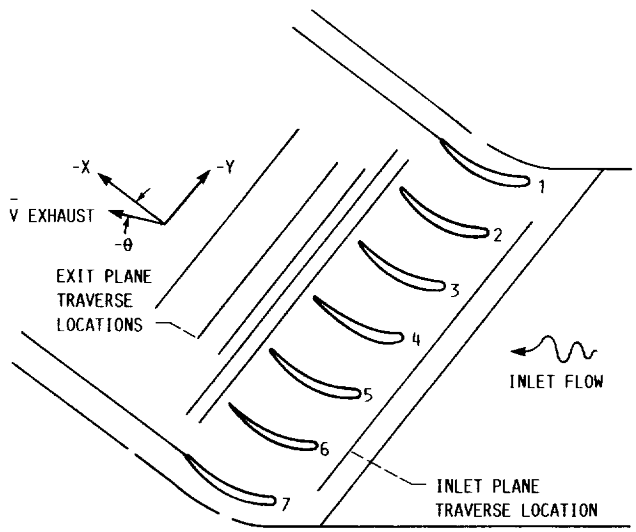


FIGURE 14. - TEST CONFIGURATION FOR LINEAR COMPRESSOR CASCADE SHOWING WAKE TRAVERSE STATIONS (FROM [16]).

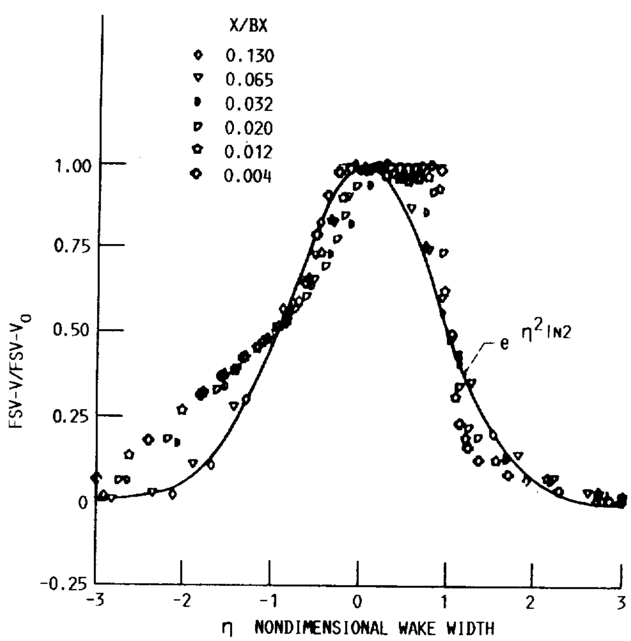


FIGURE 15. - WAKE PROFILE CORRELATION COMPARING SEVERAL TRAVERSE STATIONS WITH SIMILARITY LAW (FROM [16]). FSV = FREE STREAM VELOCITY; V = WAKE VELOCITY; V_0 = WAKE CENTERLINE VELOCITY.

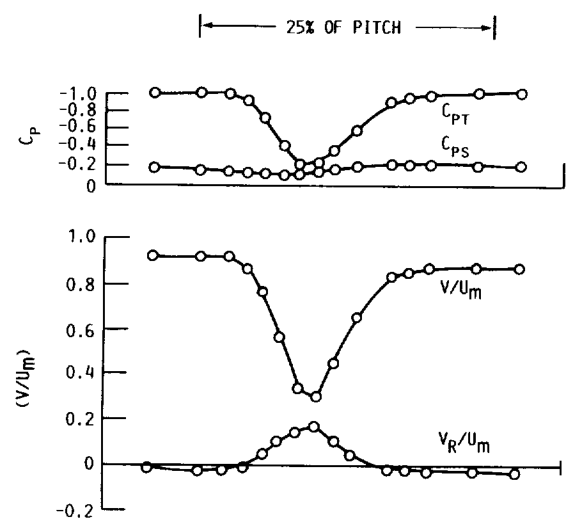


FIGURE 16. - COMPRESSOR ROTOR WAKE CHARACTERISTICS AT MIDSPAN - 10 PERCENT AFT OF BLADE, HIGH LOADING (C_x/U_m = 0.65), (FROM [17]). V = RELATIVE VELOCITY; U_m = WHEEL SPEED (MIDSPAN); C_p = PRESSURE COEFFICIENT.

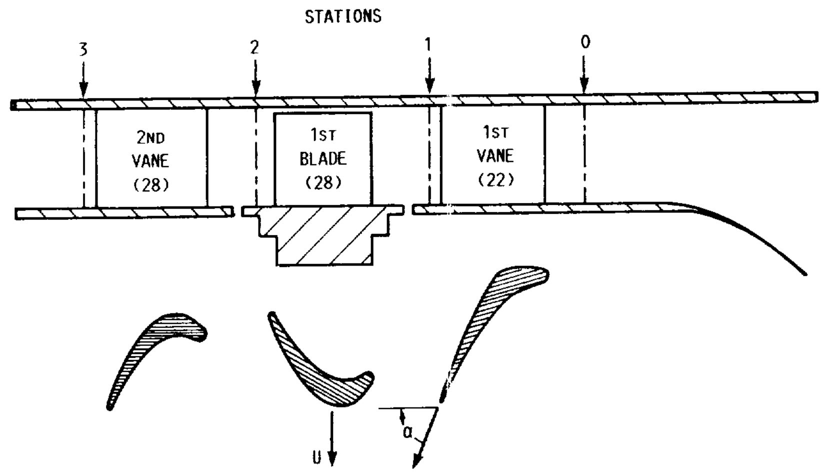
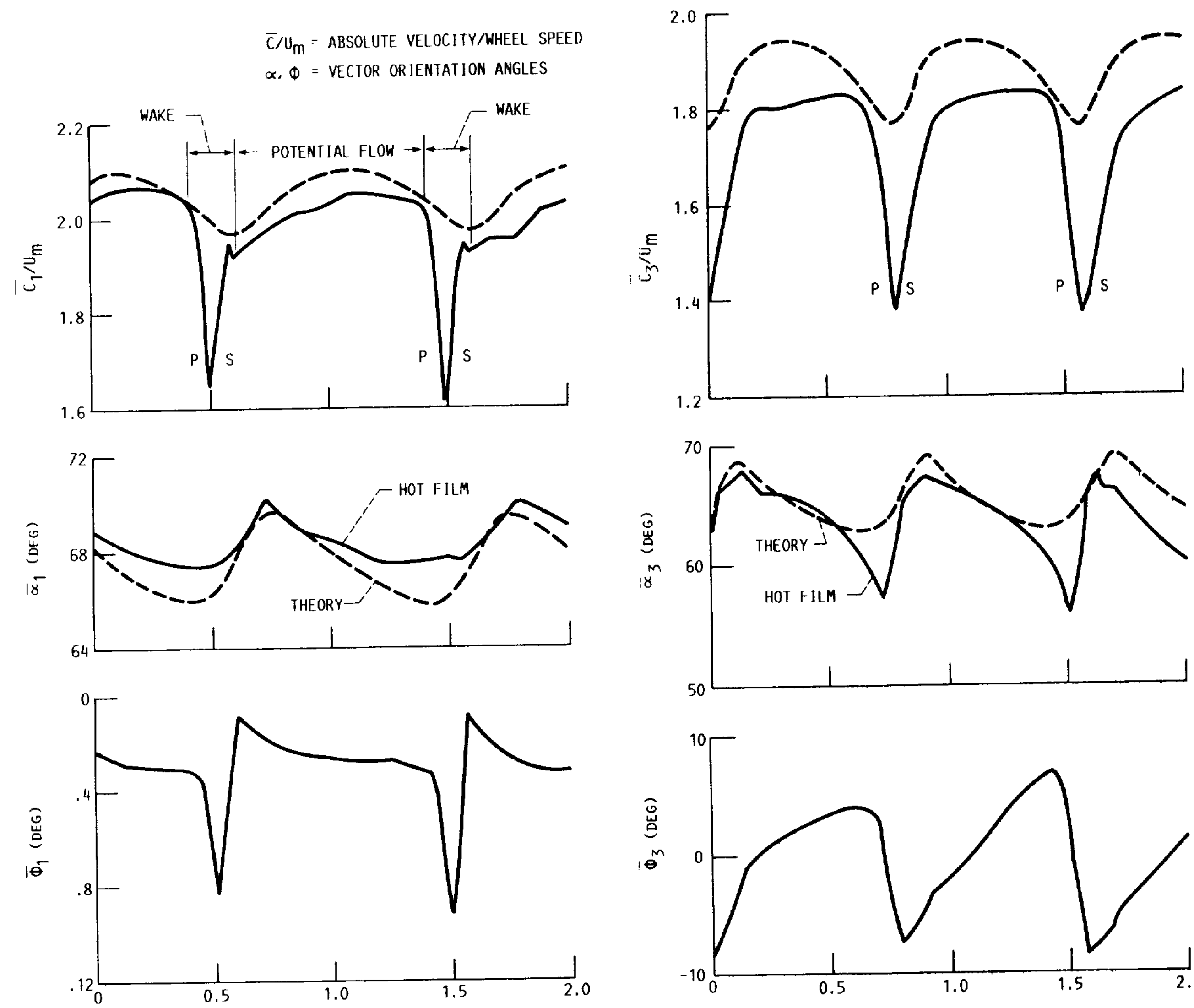


FIGURE 17. - 1.5 STAGE TURBINE TEST CONFIGURATION SHOWING 3-D WAKE TRASVERSE STATIONS (FROM [18]).



(A) VANE 1 EXIT PLANE.

(B) VANE 2 EXIT PLANE.

FIGURE 18. - ABSOLUTE VELOCITY PROFILE VARIATION AT STATOR VANE EXITS (FROM [18]).

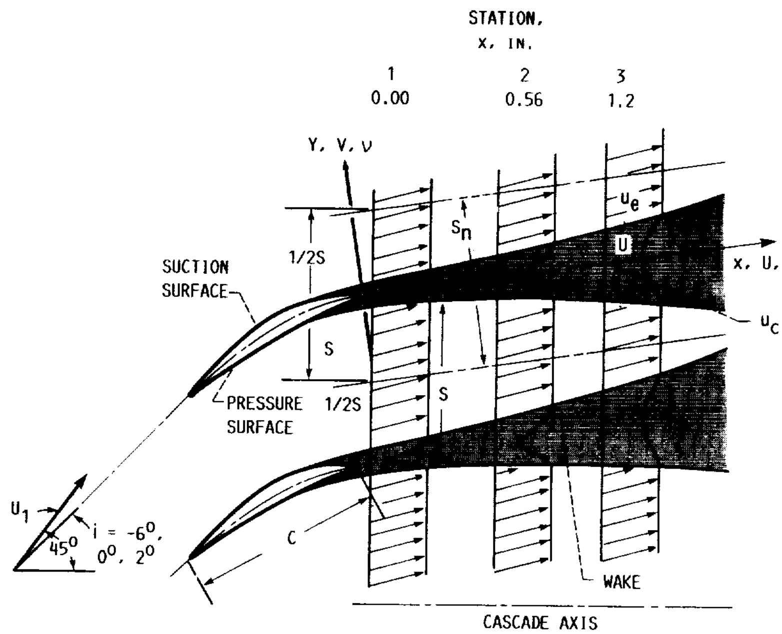


FIGURE 19. - LINEAR COMPRESSOR CASCADE TEST CONFIGURATION SHOWING DOWNSTREAM WAKE TRAVERSE STATIONS (FROM [19]).

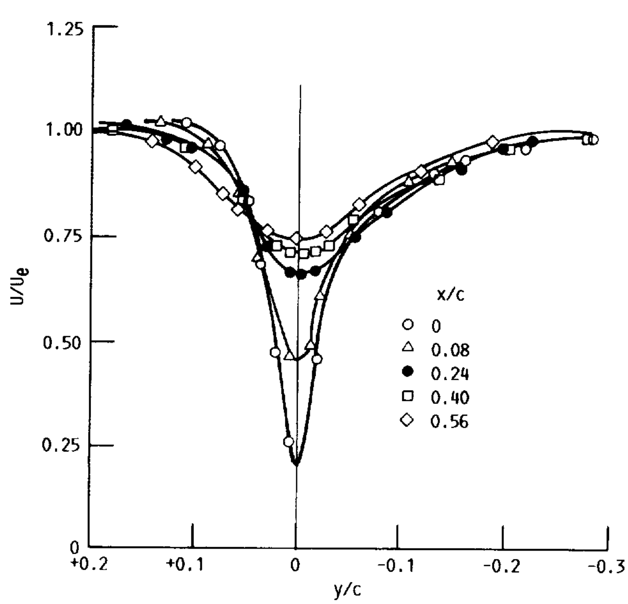


FIGURE 20. - MEAN VELOCITY PROFILE.

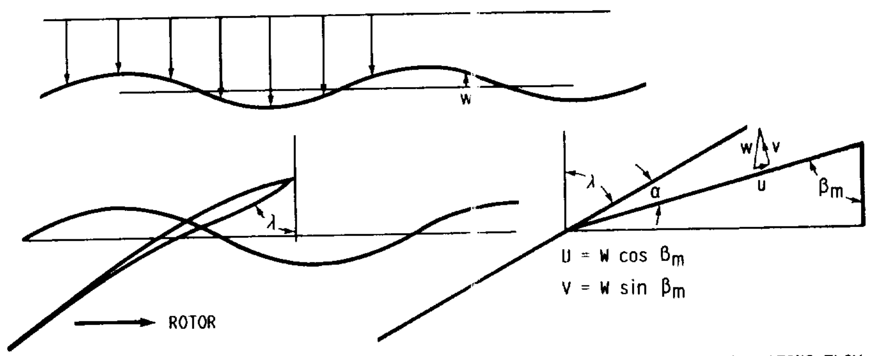


FIGURE 21. - IDEALIZED MODEL REPRESENTING ROTOR BLADE PASSING THROUGH AN OSCILLATING FLOW DISTURBANCE (FROM [28]).

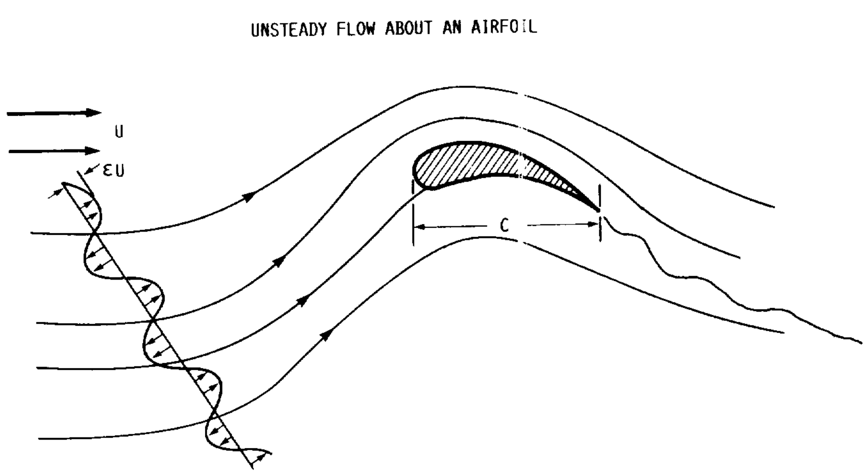


FIGURE 22. - ARBITRARY GUST PASSING OVER CAMBERED ISOLATED BLADE AND POTENTIAL FIELD (FROM [32]).

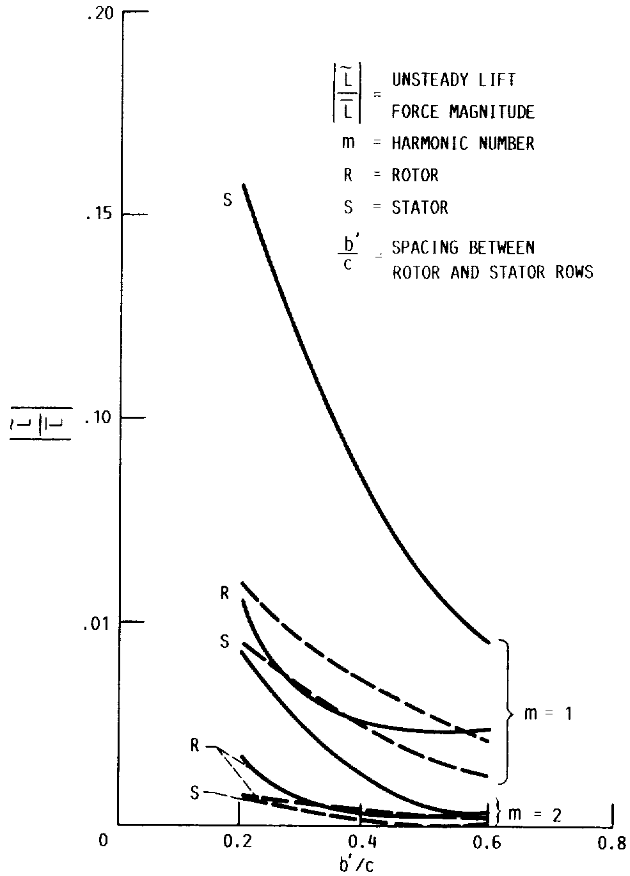


FIGURE 23. - STATOR AND ROTOR UNSTEADY LIFT HARMONIC COMPONENTS AS FUNCTIONS OF AXIAL SPACING, PITCH RATIO = 1.- (FROM [35]).

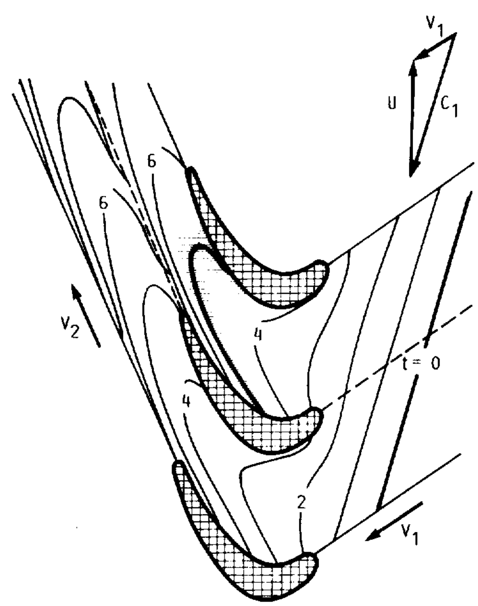


FIGURE 24. - CALCULATED WAKE DISTORTION AND POSITION FOR SEVERAL TIME STEPS, TURBINE ROTOR (FROM [40]).

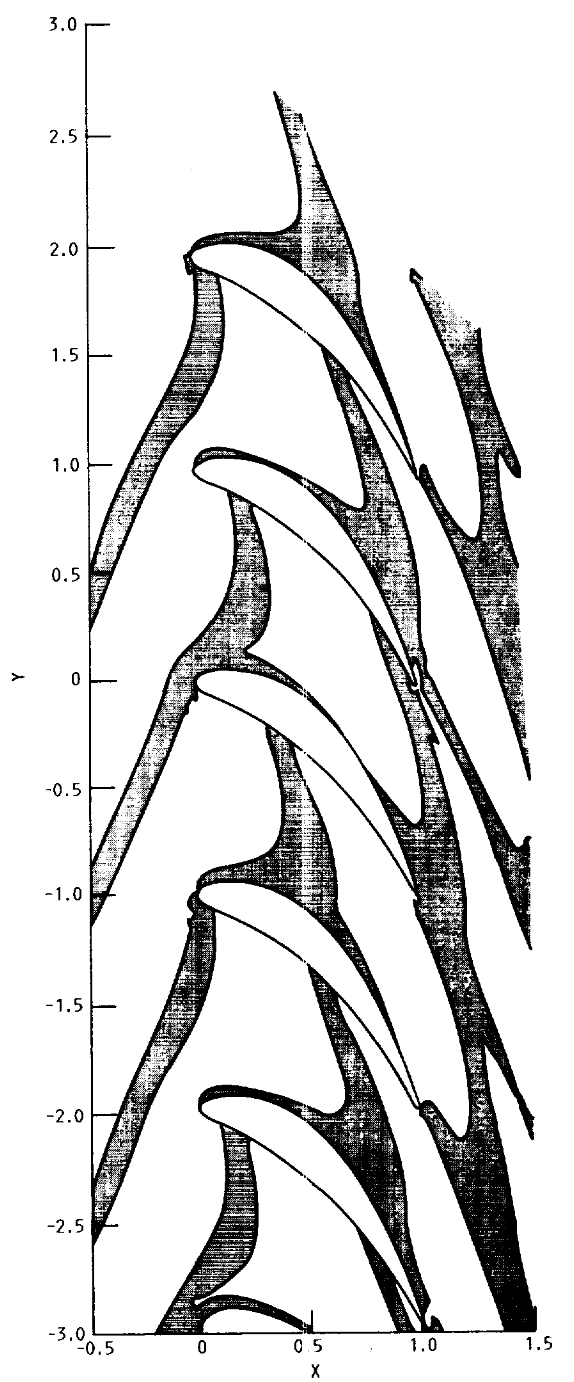


FIGURE 25. - ENTROPY CONTOURS COMPUTED USING UNSTEADY EULER 2-D CODE WITH WAKE PASSING, HODSON'S TURBINE (ADAPTED FROM [41]).

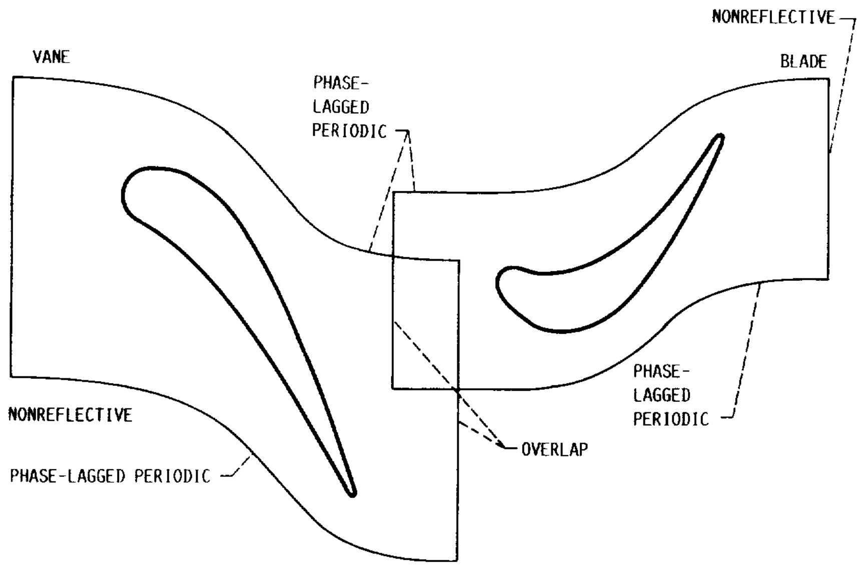


FIGURE 26. - TURBINE VANE-ROTOR OVERLAID MESHES AND BOUNDARY CONDITIONS FOR 2-D STATOR/ROTOR EULER COMPUTATION (FROM [44]).

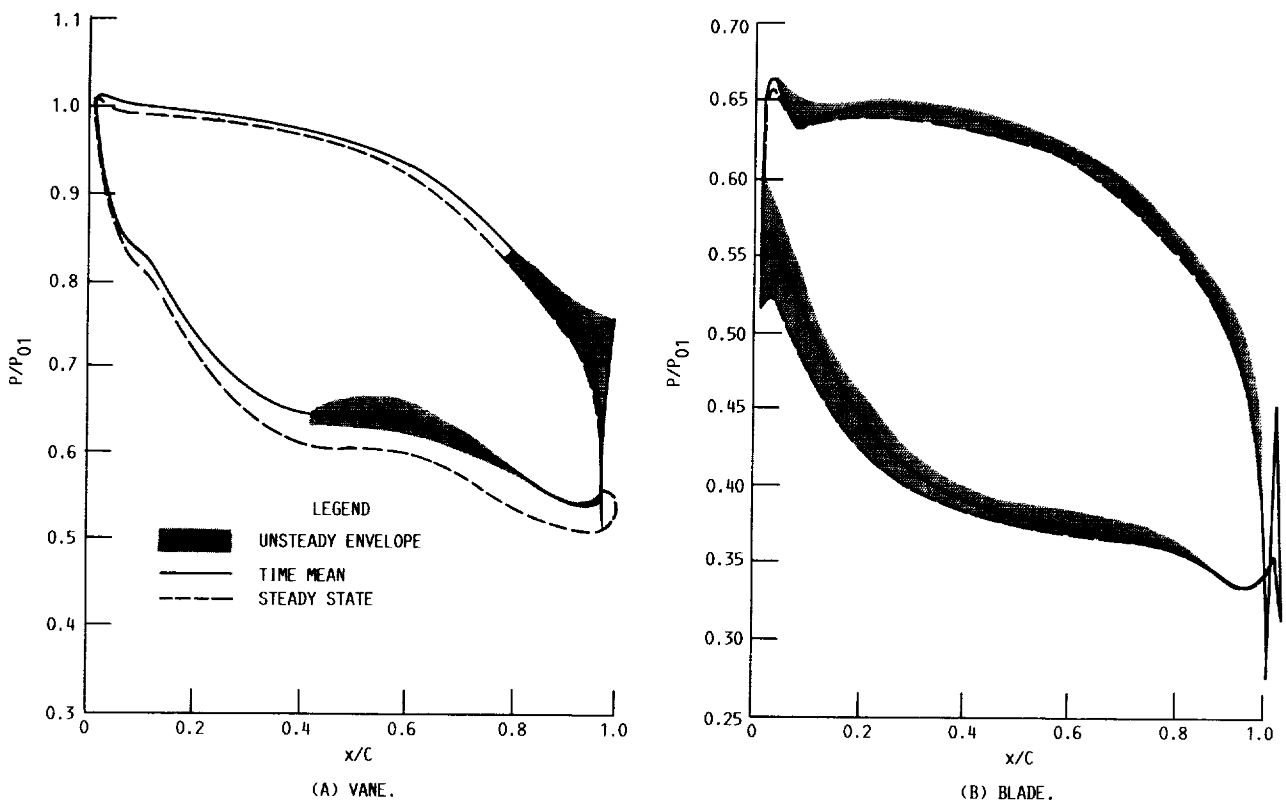
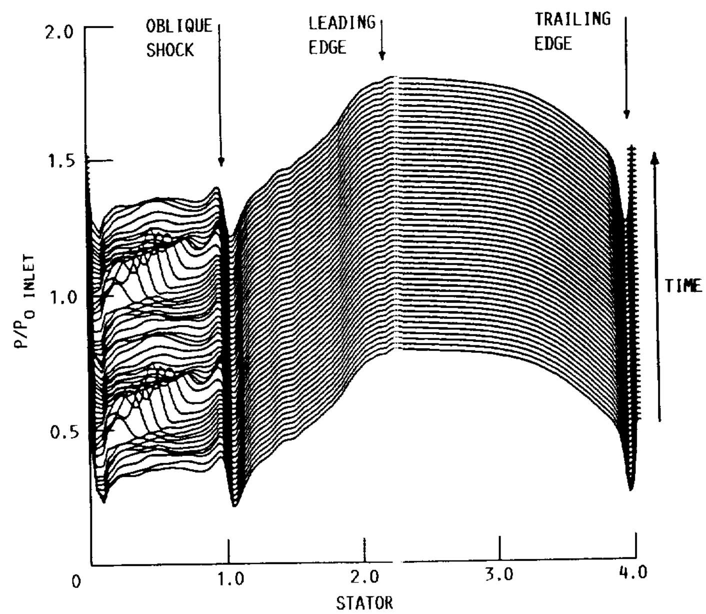


FIGURE 27. - VANE AND ROTOR BLADE STEADY AND UNSTEADY PRESSURE ENVELOPES RESULTING FROM COMPUTED INTERACTION (FROM [44]).



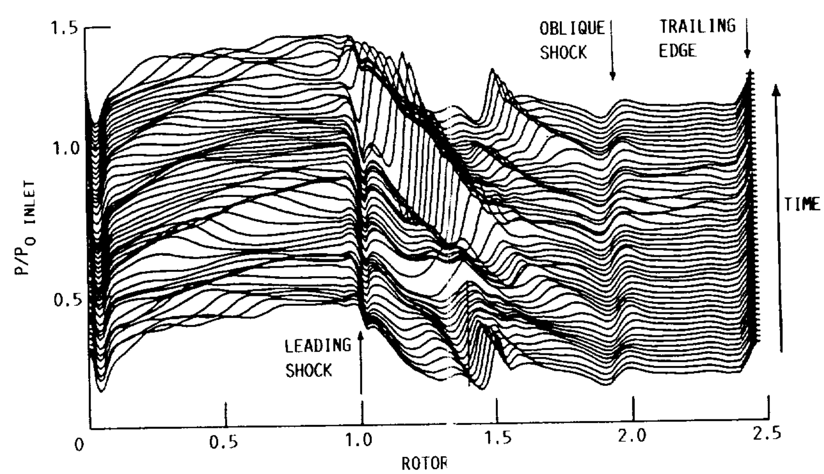


FIGURE 28. - ROTOR AND STATOR INSTANTANEOUS SURFACE PRESSURE DISTRIBUTIONS FOR SEVERAL TIME INCREMENTS (FROM [45]).

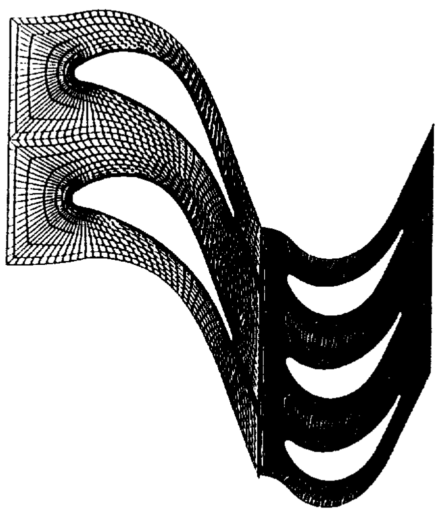


FIGURE 29. - OVERLAID, TRANSLATING SOLUTION MESHES FOR COMPUTATIONAL SOLUTION OF ROTOR/STATOR NAVIER-STOKES SIMULATION (FROM [46]).

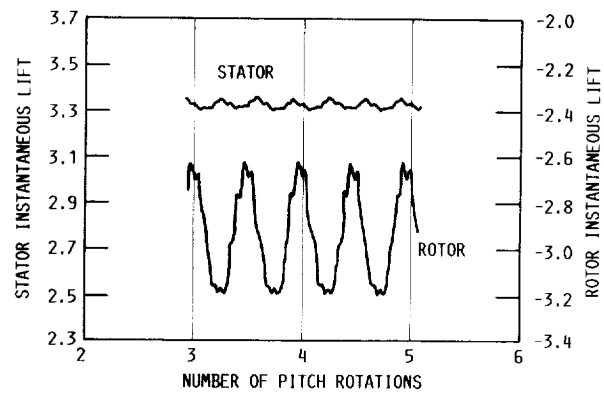


FIGURE 30. - SSME TURBINE STATOR AND ROTOR TIME VARYING LIFT RESULTING FROM ROTOR/STATOR AERODYNAMIC INTERACTION (FROM [46]).

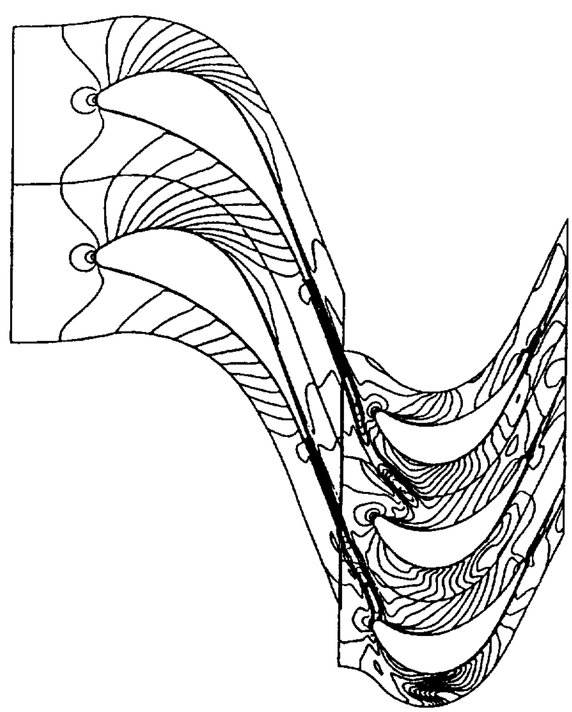


FIGURE 31. - SSME TURBINE MACH NUMBER CONTOURS SHOWING COMPLEX INTERACTION EFFECTS (FROM [46]).

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15. Supplementary Notes

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16. Abstract

Analytical and experimental research within the area of unsteady aerodynamics of turbomachinery has conventionally been applied to blading which oscillates when placed in a uniformly flowing fluid. Comparatively less effort has been offered for the study of blading which is subjected to nonuniformities within the flow field. The fluid dynamic environment of a blade-row embedded within multi-stage turbomachines is dominated by such highly unsteady fluid flow conditions. The production of wakes and circumferential pressure variations from adjacent blade-rows causes large unsteady energy transfers between the fluid and the blades. Determination of the forced response of a blade requires the ability to predict the unsteady loads which are induced by these aerodynamic sources. A review of the research publications was performed to determine the recent efforts to investigate the response of turbomachinery blading subjected to aerodynamic excitations. Such excitations are a direct result of the blade-row aerodynamic interaction which occurs between adjacent cascades of blades. The reports and papers reviewed have been organized into areas which emphasized experimental or analytical efforts.

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