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# Rotor Wake/Stator Interaction Noise Prediction Code

Technical Documentation and User's Manual

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Pratt & Whitney, East Hartford, Connecticut*

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## SUMMARY

This report documents the improvements and enhancements made by Pratt & Whitney to two NASA programs which together will calculate noise from a rotor wake/stator interaction. The code is a combination of subroutines from two NASA programs with many new features added by Pratt & Whitney. To do a calculation V072 first uses a semi-empirical wake prediction to calculate the rotor wake characteristics at the stator leading edge. Results from the wake model are then automatically input into a rotor wake/stator interaction analytical noise prediction routine which calculates inlet and aft sound power levels for the blade-passage-frequency tones and their harmonics, along with the complex radial mode amplitudes. The code allows for a noise calculation to be performed for a compressor rotor wake/stator interaction, a fan wake/FEGV interaction, or a fan wake/core stator interaction.

This report is split into two parts, the first part discusses the technical documentation of the program as improved by Pratt & Whitney (P&W). The second part is a user's manual which describes how input files are created and how the code is run.

## **PART 1: TECHNICAL DOCUMENTATION**

### **1. INTRODUCTION**

In 1982 and 1984, two codes were developed: the GE/NASA semi-empirical rotor wake/vortex model (Ref. 1.) and the BBN/NASA analytical rotor wake/stator interaction noise prediction computer program (Ref. 2.). These codes together calculate noise in the duct from a rotor wake/stator interaction. Pratt & Whitney under independent research and development funding has combined and improved these codes. Additional improvements to the code's wake model were made under Task 10 of contract NAS3-25952 along with the ability to run the code on a Silicon Graphics Workstation. This section of the report documents the technical improvements to this new computer code (from here on called V072 or the BBN/PW code). Documentation of the wake model improvements are not discussed here but are instead discussed in the documentation of the above referenced contract.

The remainder of this part of the report is organized as follows. First there will be a brief discussion of P&W program enhancements. From there, a physical discussion of how the new code works will be introduced. The program assumptions will be introduced next including the rotor/core stator interaction and duct assumptions. The program's P&W developed automatic radial and chordwise integration station criteria used in calculations will then be presented. Lastly, calculation inaccuracies due to program "computational noise" will be introduced so the user will be aware of where it is important.

## 2. P&W ENHANCEMENTS TO V072

A number of additions and improvements were made to the two NASA programs which now form V072 since their receipt from NASA. The resulting code has the following capabilities:

- The program will now run:
  - The wake model by itself at any radii.
  - A compressor rotor wake/stator interaction or fan wake/FEGV interaction.
  - A fan wake/core stator interaction
  - Both a fan wake/FEGV interaction and fan wake/core stator interaction.
- Additional wake model capabilities:
  - Preliminary hub vortex model.
  - A tip vortex model.
  - A choice of three wake profiles: Gaussian or Hyperbolic Secant or Loaded Rotor
  - A choice of two wake width and velocity deficit correlations: Original GE/NASA correlation or the P&W high tip speed rotor correlation
- Multiple run capability (program input can be stacked).
- Input is based on output from a 2D or axisymmetric streamline-type, steady aerodynamic prediction code.
- Program criteria setting the number of spanwise and chordwise integration points. This option may be replaced with user input integration station values.

These capabilities were achieved by initially combining the two NASA decks. In addition the program was modified so that:

- The code is no longer dependent on any external subroutines such as the matrix inversion routine (except to obtain today's date).
- User is notified of any program errors.
- Program is now in double precision (necessary when working with small numbers like acoustic pressures).
- Bessel function subroutines were changed or replaced. The J-Bessel function subroutine was replaced with one that is more reliable and calculates the J-Bessel function and its derivative simultaneously. The Y-Bessel function subroutine was changed so that it will calculate the Y-Bessel function and its derivative simultaneously. These changes were intended to increase program speed and accuracy.

- The matrix inversion routine was changed from an IMSL routine to a routine created by SIAM called LINPACK (Ref. 3.). This makes the code independent of specific packages which may not be available on other computer systems.
- The code will run on both Sun and Silicon Graphics Workstation platforms and should be portable enough to run on other platforms.

The Loaded Rotor wake profile and the P&W high tip speed rotor correlation were created using Rotor 67 data under Task 10 of contract NAS3-25952. The details of how these items were created is documented in a separate document.

### 3. PHYSICAL DISCUSSION OF PROGRAM CALCULATIONS

The V072 program as originally received from NASA in the mid 1980's was designed by Bolt, Beranek and Newman (Ref. 2.) to handle standard rotor wake/stator interactions in an infinitely long constant area annular duct (Figure 1). Later, the wake model of Ref. 1. was added to the code to form the present code. Discussions in this section will concentrate on how the program as updated by P&W calculates noise from a rotor wake/stator interaction noise source. In Section 4. the method utilized to set up the constant area duct will be covered. In addition, the extension of this procedure to include rotor wake/core stator interactions will be discussed.

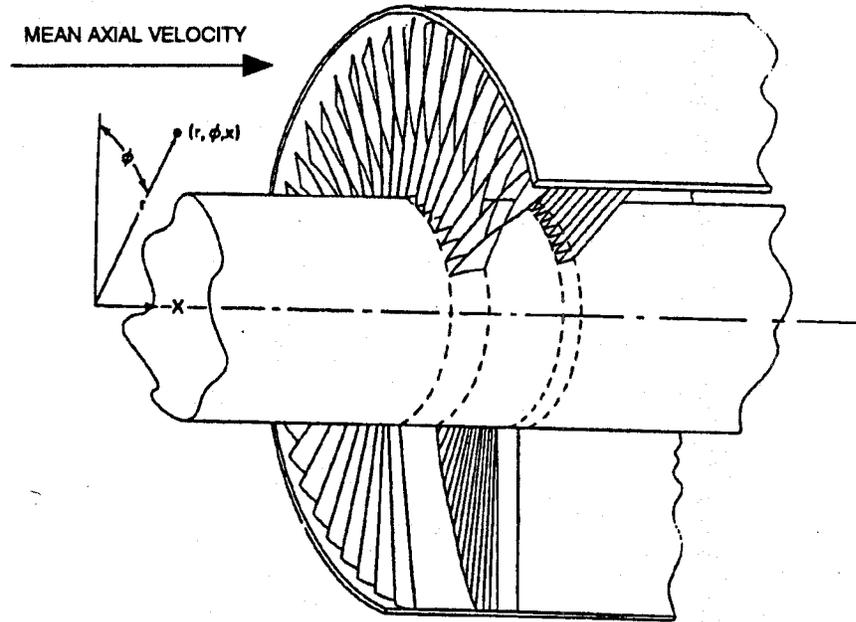


Figure 1 Sketch of V072 Rotor/Stator Geometry

The rotor wake/stator calculation is divided into two parts: the rotor wake calculation and the stator noise response calculation. The performance input to this program will need to come from a two dimensional or axisymmetric streamline-type, steady aerodynamic prediction code. To expedite the noise calculations the new program non-dimensionalizes all input geometry and performance. Then before any calculations are done the program linearly interpolates the streamline (radially-distributed) non-dimensional parameters to a "program-determined" number of spanwise locations or "radial integration stations" (for the P&W developed criteria see section 1.2). From there the program proceeds to the wake model calculation.

To calculate the rotor wake, a program originally developed by General Electric under contract to NASA was utilized (Ref. 1.). Essentially this program divides the annulus into streamlines (or strips). It then unwraps each strip to form a two dimensional flow in the circumferential and axial directions (see Figure 2). No radial flow is permitted. A two-dimensional mean flow is calculated analytically along each streamline with the assumption of incompressible flow across the rotor. This incompressible flow assumption allows for the application of an analytical expression for the drag coefficient which was utilized in creating the rotor wake empirical relationships used in the program. A series of rotor wakes (combined with hub and tip vortices if desired) are then superimposed on the mean flow to describe the flow field (see Figure 3). The streamwise wake widths and velocity deficits are calculated empirically at the stator leading edge. The resulting wakes are then combined with hub

and tip vortices which are also calculated semi-empirically at the stator leading edge. Details of these calculations may be found in Reference 1.. Thus a combined wake/vortex profile is developed in rotor fixed coordinates at the stator leading edge. A coordinate transformation to stator fixed coordinates is then performed to calculate the flow upwash perpendicular to the mean flow direction in stator fixed coordinates. From these upwash velocity profiles, wake harmonic magnitudes and phases are calculated at the stator leading edge for each harmonic at each radial strip location.

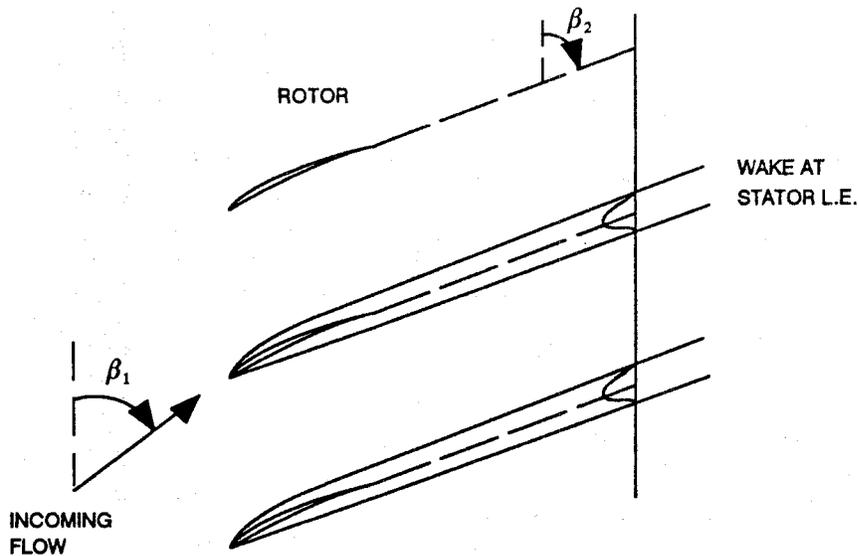


Figure 2 Wake Model

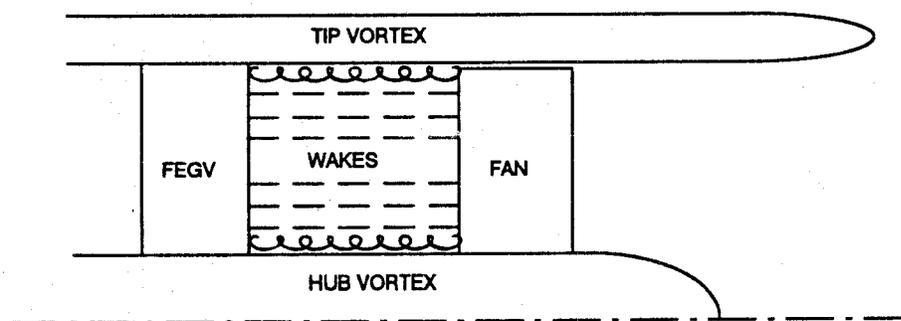


Figure 3 Wake/Vortex Flowfield

At this point we arrive at the second part of the calculation: the calculation of noise due to the unsteady flow upwash on the stators. For this calculation a program developed by Bolt, Beranek, and Newman (BBN) under contract to NASA (Ref. 2.) was used. Essentially this program calculates the total harmonic power levels travelling forward and aft in the duct. To do this the program individually calculates the circumferential/radial mode power levels for every propagating mode resulting from this interaction. It then sums up all of the circumferential/radial mode power levels to obtain inlet and aft total power levels for each harmonic. Two different sets of radial mode amplitudes and phases are also calculated and output by the program. In the main output file the dimensional amplitude and phase of the complex radial mode amplitudes normalized using the method outlined in Ref. 2. are output. In a separate file, the real and imaginary parts of the dimensional complex radial mode amplitude normalized as required by the Eversman Radiation Code (Ref. 4.) are output.

Originally the BBN/PW code had its own partial wake model which P&W replaced with the more complete GE/NASA model. However, the wake “phase lag” (or wake skew) calculation in the original code was retained to account for the greater distance that a wake at one radius must travel relative to the distance that another wake must travel at another radius. This feature allows for the real effects of wake/vane “slicing” to occur, rather than the simultaneous wake “slapping” limitation that was imposed by earlier theories. In addition to the wake width and velocity deficit developed by General Electric in Ref. 1, P&W has developed high tip speed wake width and velocity deficit correlations under NASA Lewis funding. Also a skewed loaded wake profile based on Rotor 67 high tip speed wake data (Ref. 5.) was developed. These additions to the wake model are included in the present code. The development of these correlations are discussed in a separate document.

Given this unsteady wake/vortex flow we must now calculate the unsteady chordwise pressure distributions on the vanes along the stator span. This type of calculation has been developed by a number of authors including Verdon (Ref. 6.), Whitehead (Ref. 7.) and Smith (Ref. 8.). Verdon’s case is the most recent in which he developed a two dimensional cascade calculation which includes real cascade geometries and steady as well as unsteady lift. Whitehead and Smith are older but are more like what the program utilizes. In both of these cases the authors assume two dimensional compressible flow over a cascade of unloaded flat plates at zero incidence to the incoming flow (see Figure 4). In each case the annulus of vanes was unwrapped to form an infinite cascade along each streamline (or strip). For this rotor wake/stator interaction program a procedure outlined by Goldstein (Ref. 9.) utilizing the same assumptions as Smith and Whitehead was employed so that according to Ventres (Ref. 2) all three formulations give the same results.

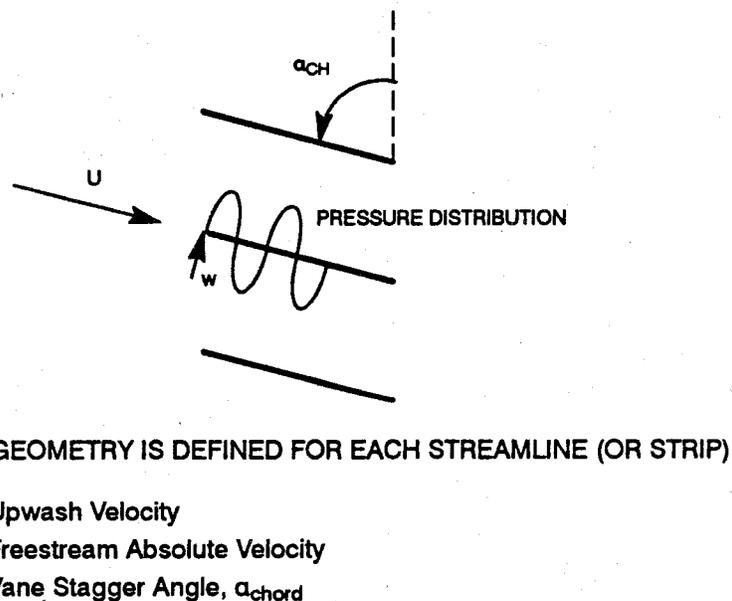


Figure 4 Cascade Unsteady Aerodynamics Geometry

The program extends the strips formed during the wake calculation along the stator cascade and proceeds to calculate unsteady pressure distributions on a reference vane of the cascade at a program-specified number of chordwise stations (for the P&W developed criteria see section 1.1). The program assumes that all the vanes in the cascade are of the same geometry and are equally spaced in the circumferential direction.

At this point the program rewraps the strips to re-form an annular duct. We now have chordwise pressure distributions along the span of a reference vane in an annular duct. Pressure distributions on the other vanes may be calculated knowing the phase relationships that are a function of the blade and vane number. Physically we can say that we now have an annular duct which contains chordwise pressure distributions along every stator in the cascade and across the vane span (see Figure 5).

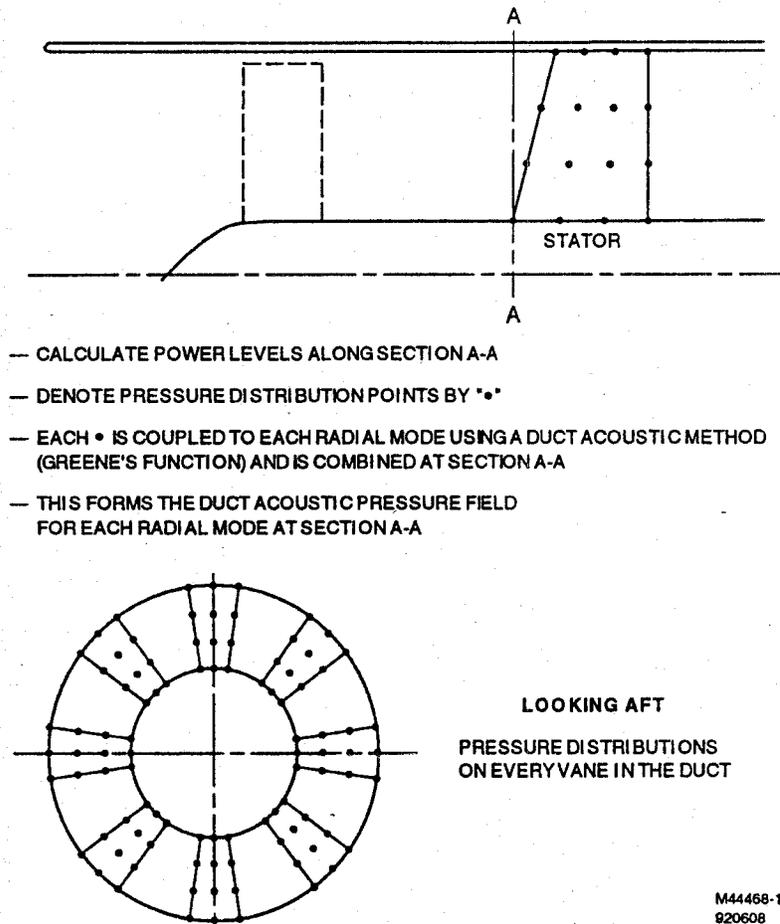


Figure 5 Coupling the Unsteady Aerodynamics to the Noise

Assuming a mean axial flow in a constant area annular duct we can now calculate the radial mode amplitudes for each propagating circumferential/radial mode. To understand this calculation we can look at an axial location, A-A, in Figure 5. At this location we can evaluate the effect of the unsteady pressures propagating from the cascade and then sum up these effects to calculate the amplitude of each propagating mode in the duct (termed the Greene's function approach outlined in Ref. 2. or Ref. 9.). The calculation is done preserving all magnitudes and phases of every pressure in the pressure distributions including how those pressures couple to each circumferential and radial mode. These pressures are then integrated for each mode thus giving us an inlet and aft power level and complex radial mode amplitude for each propagating mode. This process is repeated for every propagating mode and the power levels are then summed up to give the circumferential mode power levels and total power levels for each harmonic.

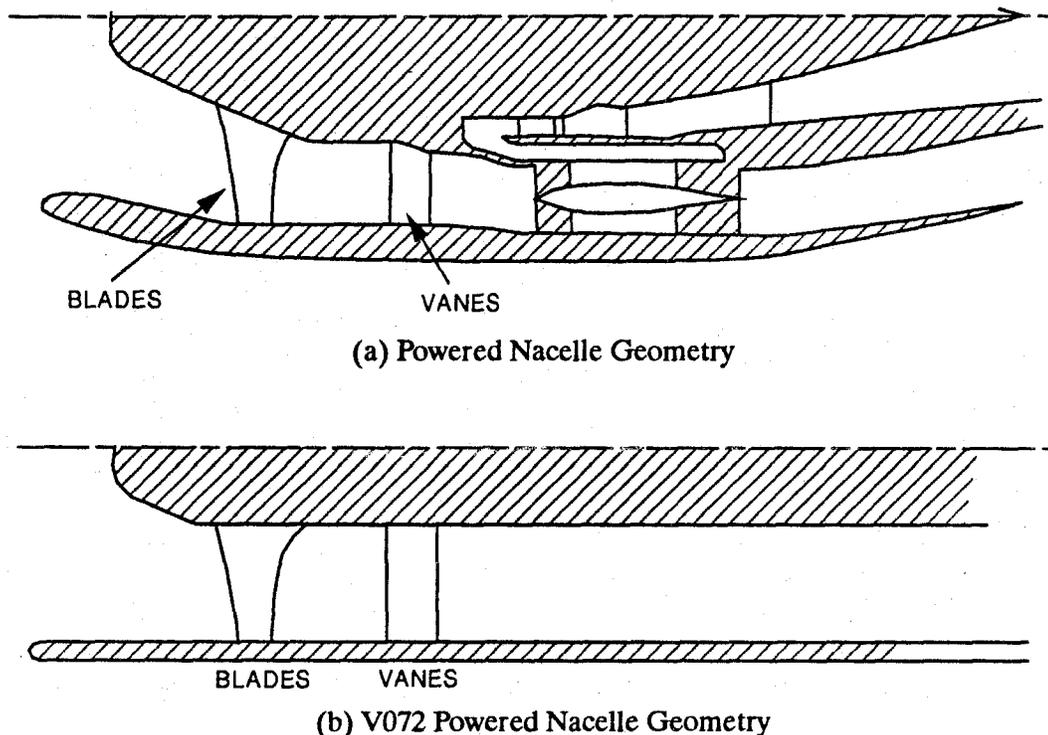
It should be noted that these noise calculations give inlet and aft mode amplitudes, phases and power levels which are at an axial location associated with the stator hub leading edge (section A–A in Figure 5). Thus this axial location should be used as a starting point for propagating the modes upstream and downstream in the duct. Further details of this method may be found in Reference 2..

#### 4. PROGRAM ASSUMPTIONS

The previous section physically discussed the program assumptions and calculation procedures for a rotor wake/stator interaction occurring in a constant area duct (Figure 1). Real life configurations of concern are, however, somewhat more complicated than this geometry. The real duct configurations of interest include the following applications:

1. Compressor rotor wake/stator interactions,
2. Fan wake/FEGV interactions,
3. Fan wake/core stator interactions.

To calculate noise using V072 it is necessary to simplify the real duct geometry by making some reasonable assumptions. To best visualize the problem let us look at the rotor wake/stator interaction configuration of Figure 6. Figure 6a shows the Pratt & Whitney Powered Nacelle (APN) fan rig geometry while Figure 6b illustrates how the APN geometry is represented in V072 using a constant area duct.



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Figure 6 Powered Nacelle Geometry Vs. V072 Representation

To choose a constant area duct we must consider its effect on the modal content of the noise, and its influence on the rotor wake and stator pressure distribution calculations. The effect of the choice of duct radii on the wake calculation occurs in the computation of the drag coefficient (to obtain wake width and velocity deficit) and in the computation of the tip vortex. In the pressure distribution the choice of duct radii effects the calculation of vane solidities and certain streamline performance such as wheel speeds. The noise propagation calculation is influenced by radius in the calculation of the cutoff ratio which sets the number of propagating modes and calculates mode dipole alignment.

Therefore, the chosen location for the constant area annular duct should occur near the stator where the noise is generated but not far from the rotor where the wake is generated and where the wheel speed is set. As a result the rotor leading edge is recommended for most configurations unless the change in radii from the rotor to the stator is very large. It should be noted, however, that all geometry and performance at the rotor leading edge and downstream should be selected along the streamlines starting at the rotor leading edge. The method for creating the input to the code using this method may be found in Part 2 of this document, the program user's manual.

What do these assumptions mean? Effectively what we have done is to choose streamlines at radii at the rotor leading edge. We have then followed those streamlines to the stator using the geometry and performance along each streamline with the exception of the effects of changing radii. We then effectively treat the streamline like a string which goes from the rotor leading edge to the stator trailing edge with geometry and performance (except the radii) which vary according to the real streamline geometry. We can think of this string as being pulled taught to form streamlines in our constant area duct in Figure 6b.

Now consider the more complicated case of a real fan stage like that shown in Figure 7a. The simplification of this configuration is shown in Figure 7b. To obtain to Figure 7b from Figure 7a we made a number of reasonable assumptions. First, as we concluded in the rotor wake/stator interaction case discussed above the rotor leading edge radii could be used. In the case of the fan wake/FEGV interaction, FEGV's are usually far enough back from the splitter so that the propagation or decay of modes from this noise source will occur in the fan bypass duct. Therefore the rotor leading edge radii are chosen for this interaction from the splitter streamline to the tip streamline with all modes propagating in the fan bypass duct.

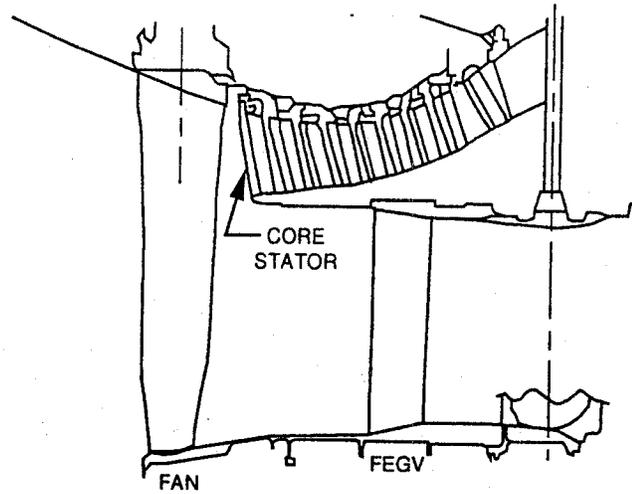
For the rotor wake/core stator interaction many more assumptions are needed. If the core stator leading edge is less than a wavelength (at 3BPF) from the splitter leading edge, then we can reasonably assume that decay will not be significant in the inner duct forward of the core stator and that all noise propagation and decay will occur in the fan inlet duct. Thus the fan inlet duct is the core stator's "constant area duct." However, no noise may propagate radially through the splitter until the stator leading edge. Consequently, while only noise will be generated on the core stator itself we must effectively extend the core stator across the entire inlet duct (see Figure 7b). An effect of these assumptions is that any wave reflections off the splitter leading edge at the entrance to the primary duct are neglected. In addition, these assumptions have effectively removed the splitter from the problem.

The application of these assumptions to the computer program input can now be explained. For the fan wake/core stator interaction there is no wake impinging on the core stator extension shown in Figure 7. Thus in applying the above assumptions the program need only integrate across the real core stator. As will be found in Part 2 of this document, only streamlines for flow through the core stator need to be specified in the program. Then to create the fan inlet duct the program will ask for the fan outer diameter. Therefore the core stator duct has been created.

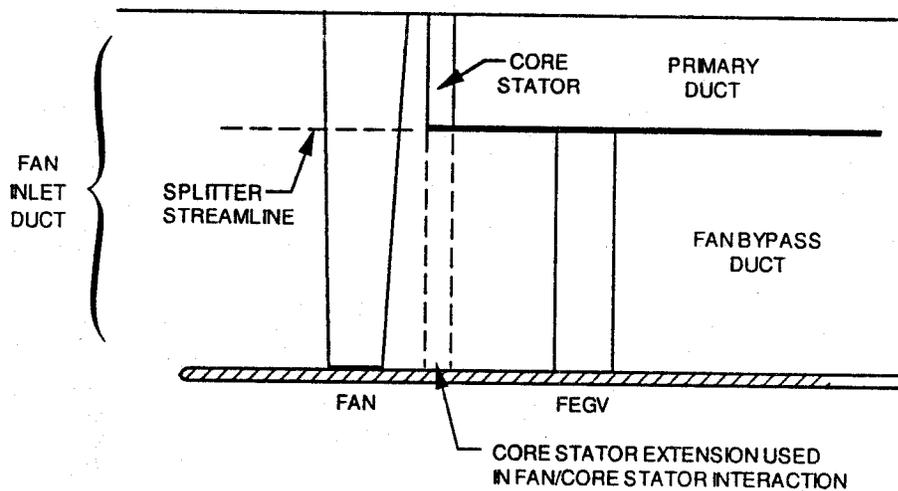
In applying these assumptions to the fan wake/FEGV interaction, only streamlines associated with the fan bypass duct need be specified. This, plus the fan outer diameter (which will be the same as the radius of the most outer streamline) will form the constant diameter duct.

When doing both predictions simultaneously the splitter diameter is simply input twice at the point where the fan/core stator interaction input ends and the fan/FEGV interaction input begins. Then both ducts will be automatically specified. See Part 2 of this document for more information on the mechanics of the input.

As a result we have defined our constant area ducts for all three configurations of interest.



(a) Full Scale Engine Geometry



(b) V072 Full Scale Engine Geometry

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Figure 7 Full Scale Engine Geometry Vs. V072 Representation

## 5. PROGRAM INTEGRATION STATION CRITERIA

As was discussed earlier the program chooses how many points it needs along the stator span and stator chord to effectively calculate the total power levels. The program as received from NASA lacked this capability. Consequently, it was necessary to create these criteria. In each case we need to ask how rapidly in space the important parameters relating to the noise will change in the spanwise and chordwise direction. These criteria were developed based on a total power level accuracy of plus or minus 1dB.

### 5.1 CHORDWISE DIRECTION

Let us first look in the chordwise direction. As the rotor wakes reach the stator they cause an upwash to convect along the stator (Figure 8). This upwash varies along the chord causing an unsteady pressure distribution to form along the chord (Figure 8a). As the wake continues travelling down the stator chord another wake reaches the stator at a later time (Figure 8b). This wake will cause an upwash velocity at an upstream location on the chord while the earlier wake is disturbing a downstream section. In our case we are looking at a specific harmonic of the wake so that the wake disturbance on the chord will be a sinusoidal shape. For BPF this sine wave will have as many cycles on the vane as there are wakes on the vane; for 2BPF there will be twice as many, for 3BPF three times as many, etc. In other words, the more variations we have on the chord at once, the more points we will need to accurately calculate the chordwise pressure distribution on the vanes, and to later integrate these chordwise pressures during the duct noise calculation.

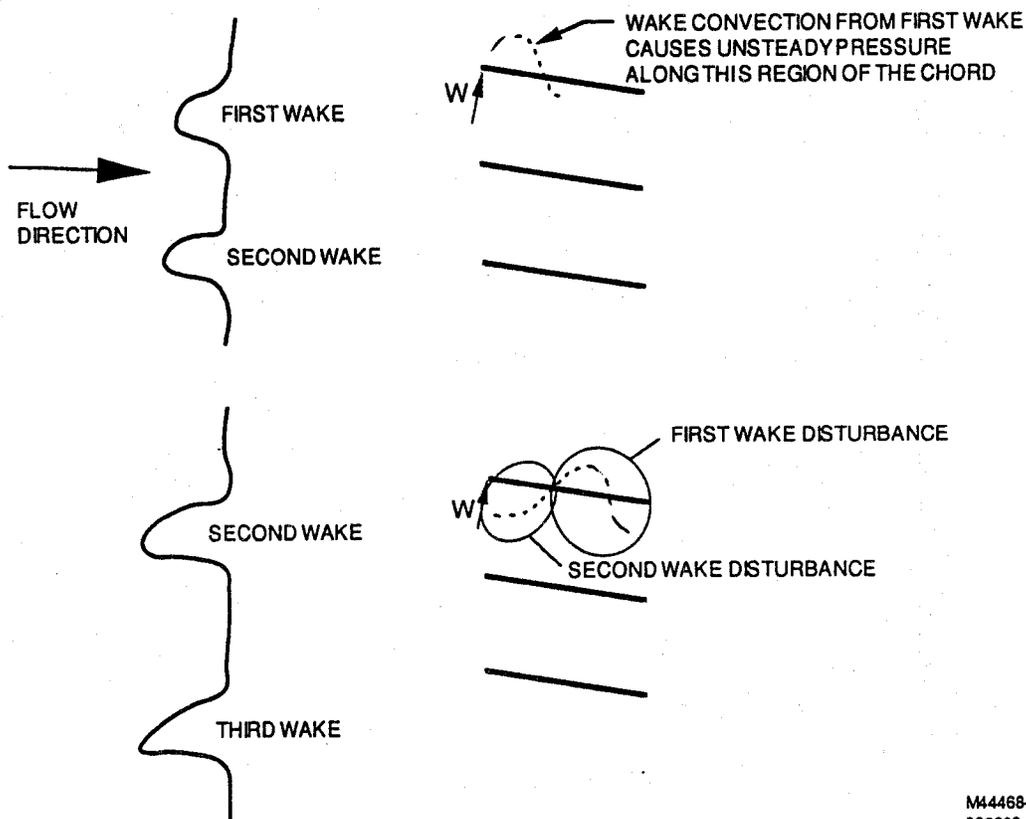


Figure 8 Wake Convection Along the Cascade

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The criteria which was formed to represent this variation is:

$$\text{NCHORD} = 2 \times \text{PI} \times (\text{Number of convected disturbances on the vane})$$

where NCHORD = number of points on the chord at which unsteady pressures are calculated.

This criteria is found to be equivalent to setting NCHORD equal to two times the reduced frequency of the convected wakes in the chordwise direction.

$$\text{e.g. NCHORD} = 2 \times (\text{Reduced Frequency}) = 2 \times \left( \frac{2\pi n B N_1 b}{60U} \right)$$

where: n = BPF harmonic,  
 B = Number of Rotor Blades,  
 N<sub>1</sub> = Fan rotational speed (revolutions/sec),  
 U = flow velocity in stator fixed coordinates (ft/sec),  
 b = 1/2 stator aerodynamic chord (ft).

Because the program Simpson's rule integration requires an even number of data points this criteria is then raised to the nearest even number. To insure reasonable accuracy at low reduced frequencies a minimum value of 8 is used. To increase program running efficiency a different NCHORD value is utilized for each wake BPF harmonic. In addition, the maximum NCHORD value is set to 60.

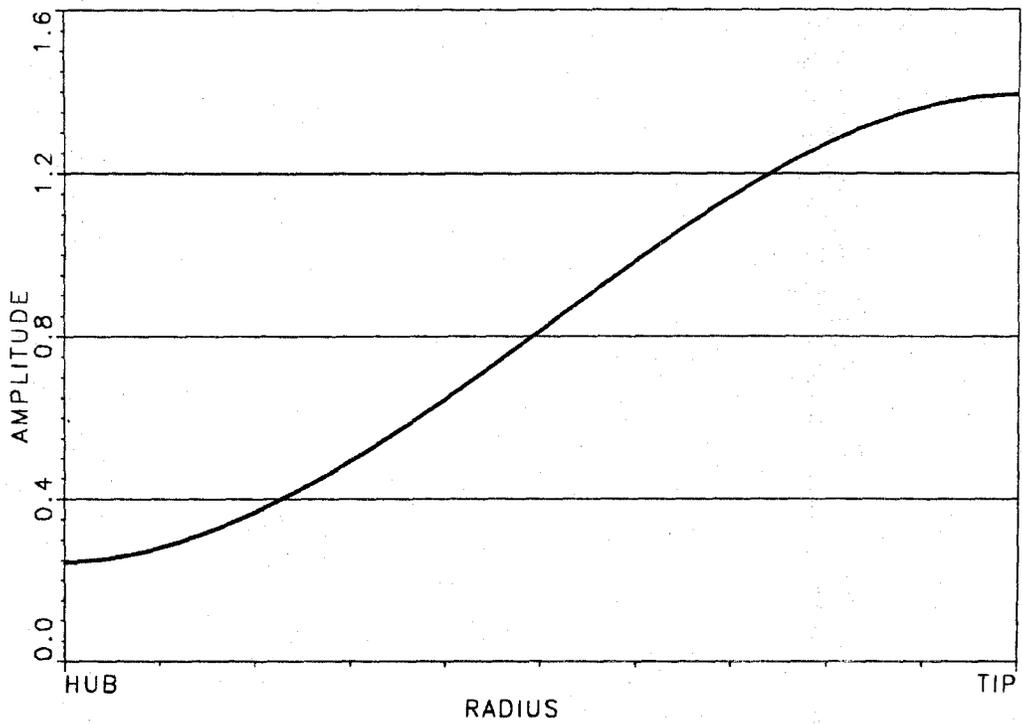
## 5.2 RADIAL DIRECTION

Obtaining a radial integration station criteria was found to be significantly more involved than the chordwise case. Two parameters are important in this case. The first one relates to the number of zero crossings a radial mode shape makes across the span. An example of this is shown in Figure 9 for the (4,0) and the (4,21) modes. We know that the radial mode shape of the (4,0) mode has no zero crossings while the radial mode shape of the (4,21) mode has 21 sign changes along the span. As can be seen the number of radial stations needed to effectively represent the (4,21) mode shape is going to be many more than are needed to represent the (4,0) mode shape. The problem then becomes one in which we cannot efficiently calculate which modes will be cuton and cutoff before we enter the program for every circumferential and radial mode and effectively use this information. However we can do this calculation for one mode per harmonic: i.e. the m = 0 mode, which if generated would have the highest number of propagating radial modes. Since we can calculate how many radial modes will propagate from this circumferential mode for each harmonic then we can efficiently utilize this information to choose a conservative estimate for the number of radial integration stations we need.

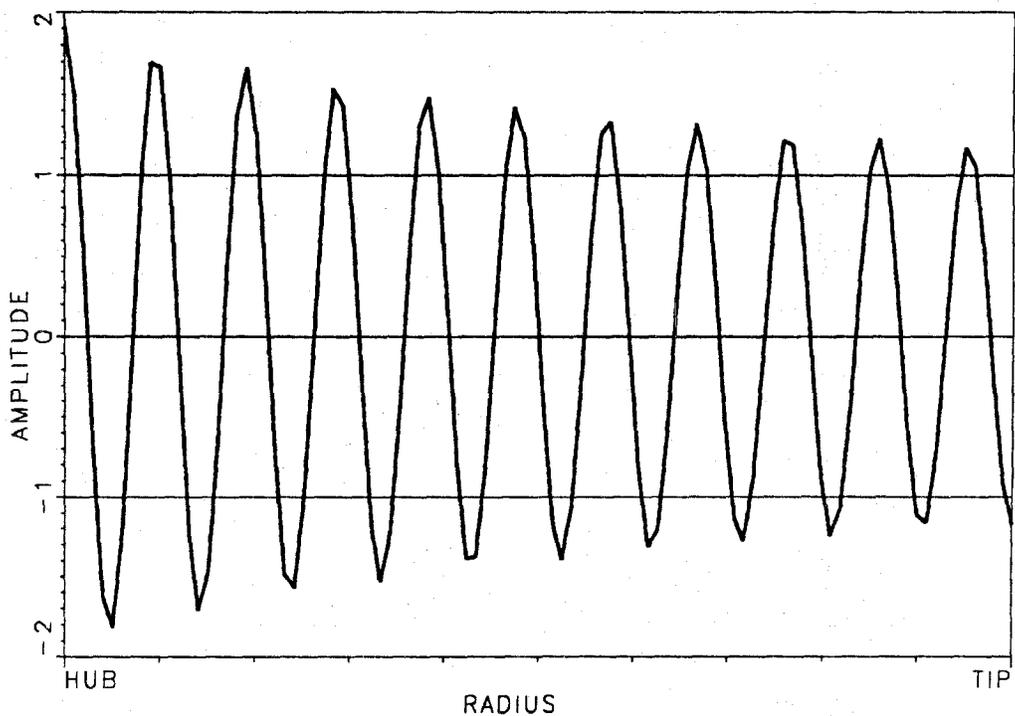
Consequently, it was determined that we need at least two points along the span (i.e. the hub and the tip points) plus two more points for every time the radial mode shape crosses zero. In addition, the specialized integration procedure in the program requires an odd number of radial integration points. As a result the criteria becomes:

$$\begin{aligned} \text{NRAD}_1 &= 2 ( \text{MU} + 1 ) + 1 \\ &= 2 \times (\text{No. of radial mode zero crossings}) + 2 + 1 \\ &= 2 \times \text{MU} + 3 \end{aligned}$$

where: NRAD<sub>1</sub> = Number of Radial strips required based on acoustic radial mode shape.  
 MU = Highest order radial mode which propagates at a given BPF harmonic for an m = 0 circumferential mode (Also equal to the number of radial mode zero crossings).



(a) (4,0) Mode



(b) (4,21) Mode

Figure 9 Radial Mode Shapes

The second parameter we need to consider relates to the number of wakes “slicing” along the stator span at any one time. To best explain this aspect we consider Figure 10 which illustrates the rotor/stator geometry relative to the wake flow geometry. To obtain maximum aerodynamic efficiency, standard high bypass ratio fans are highly twisted along the span. This twist from hub to tip causes the wakes at the tip to travel further than the wakes at the hub (Figure 10a). The result is that the circumferential locations of the wakes from hub to tip create a line which is highly canted where the cant angle increases as the wakes travel downstream. Consequently, at any one time the stator may experience more than one rotor wake on its span at once (Figure 10b) resulting in pressure variations along the span. At any one time on a high bypass ratio engine there may be up to four spanwise wake variations along the span. These variations are handled in terms of harmonics in much the same fashion as the chordwise variations where the number of pressure variations increases with each higher harmonic (i.e. if there are four actual wakes in contact with a given vane, then at 3BPF there will be 12 spanwise phase variations in upwash velocity).

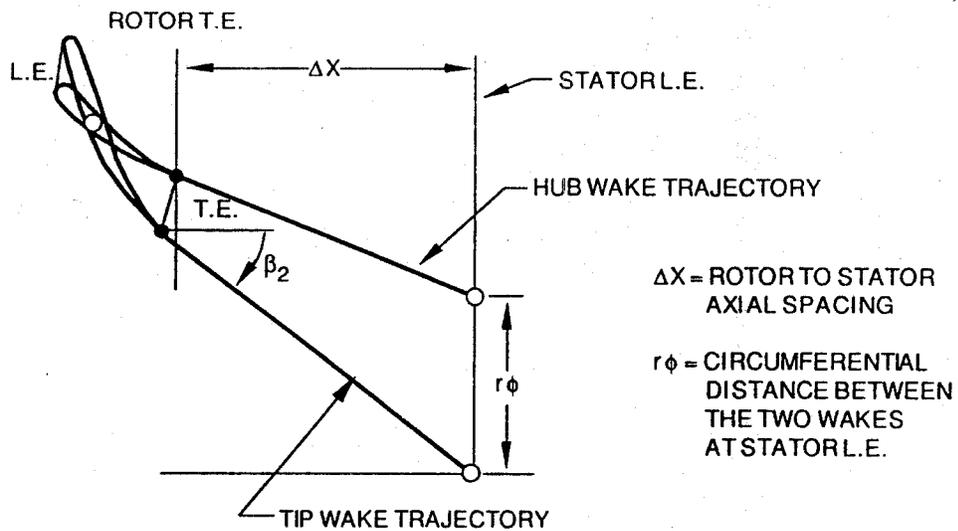
Thus, a parameter called the wake phase lag is used to set the number of radial variations. The phase lag is a form of reduced frequency which has the form:

$$\begin{aligned} \text{NRAD}_2 &= 2 \times \text{PI} \times (\text{No. of spanwise wake disturbances on the stator span}) \\ &= \text{Wake Phase lag relative to the hub.} \end{aligned}$$

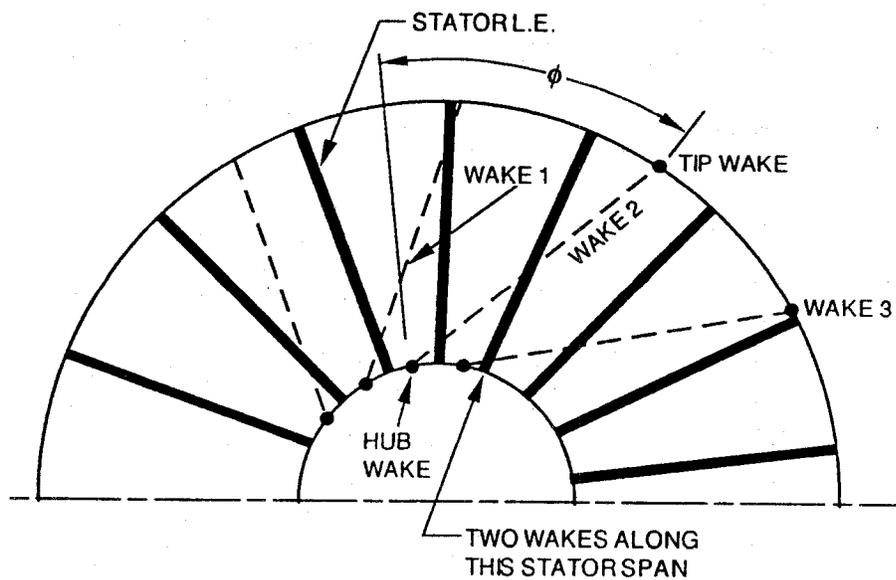
The required number of radial integration stations is now calculated by simply choosing the highest calculated value from the two NRAD criteria (either NRAD<sub>1</sub> or NRAD<sub>2</sub>). To insure reasonable accuracy, minimum values have been set based on the type of run. For a rotor wake/stator interaction without any vortices NRAD must be at least 11. To insure reasonably accurate vortex representation the minimum is raised to 21 when a vortex is calculated. This is done to deal with the evenly spaced radial integration stations utilized by the program. Due to the program’s structure one NRAD value is then employed corresponding to the highest harmonic being calculated.

To calculate NRAD for the rotor wake/core stator interaction a variation on this criteria was introduced. As was suggested before, the core stator only generates noise along its real span (see Section 4. and Figure 7). Therefore we need only integrate along the core stator span itself, i.e. we need not integrate over the entire inlet duct. So to determine NRAD for this case we simply take the value calculated for the total inlet duct and multiply it by the percentage of the total span which is occupied by the core stator. This criteria significantly reduces computational time without affecting program accuracy. For this case the minimum NRAD value is set to 7. The present maximum for NRAD is set at 79.

After formulating these criteria a battery of test runs were initiated using the APN and full-scale engine data input. Results indicated that the criteria were effective in giving accurate results.



(a) Cascade View



(b) End View of Wakes at Stator Leading Edge

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Figure 10 Wake Time/Phase Lag Due to Rotor Blade Twist

## 6. "COMPUTATIONAL NOISE"

In numerical analysis applications such as this program the potential exists for the computer to add noise of its own due to computer roundoff or truncation error. This is particularly true in the BBN/PW code for a rotor wake/core stator interaction. This is because many mode shapes concentrate themselves at the tip where the noise generated at the core stator is not a factor. To minimize this problem the program has been designed to detect very small numbers in the J-Bessel function subroutine so as to minimize computational noise. However, even with this improvement some computational noise is likely to occur when the J-Bessel function goes to zero. This computational noise is normally worse when the calculation of the critical mach number also does not converge (see Part 2, Section 4). The improvements made to the code have rendered computational noise insignificant for the Fan/FEGV interaction noise predictions and most Fan/core stator noise predictions. However, it does have an effect on Fan/core stator predictions where the expected noise is relatively low.

There are sometimes instances where judgement is required to ascertain if the generated noise for a particular radial mode is actually due to computational noise. An example of this occurs in a full scale engine (for example Figure 11) where a rotor wake/core stator interaction generates the  $m=38$  mode. Figure 11 illustrates the (38,0) and (38,1) modes as they are generated in the present code. In this situation the expected power levels for BPF for these modes are near zero dB. However, real predictions give power levels at BPF for these modes are 14dB and 81dB respectively. Note that the associated Fan/FEGV noise prediction for this case is much higher (closer to 120dB) and is not effected by computational noise. Both of the rotor/core stator answers, however, are due to computational noise.

Figure 11a shows the actual mode shapes. These mode shapes look quite correct with the mode shapes having zero value across part or all of the core stator span and a zero slope at the hub and tip. However, we need to look at the mode shape in the region where the core stator is located (Figure 11b). In Figure 11b it is seen that the (38,0) mode still is near zero accounting for the 14dB power level result. In the (38,1) mode case there is a "tail" near the hub which is not in fact at zero slope to the hub with error showing up in the third decimal place of the radial mode shape. This tail is due to the fact that both J-Bessel function and its derivative go to zero while the Y-Bessel function goes to minus infinity. The Bessel function calculation develops errors in calculating these results correctly and thus a "tail" develops in the results in the hub region. This 81dB result is representative of a worst case scenerio using the improved J-Bessel Function subroutine. The routine originally supplied with the BBN code (Ref. 2.) allowed computational noise at the core stator to rise as high as 120dB which is unacceptable when the real noise is at this level.

This type of problem shows up for high circumferential mode lobe numbers with low radial mode orders and is at its worst when a "critical mach number not converged" warning is seen in the printout. When this occurs the rotor wake/core stator results should be suspect for that mode and a radial mode plot should be made to check the results.

While these numbers add no noise to the total result they do mislead the user into incorrectly concluding that some tone noise was generated by this mode when in fact there was none.

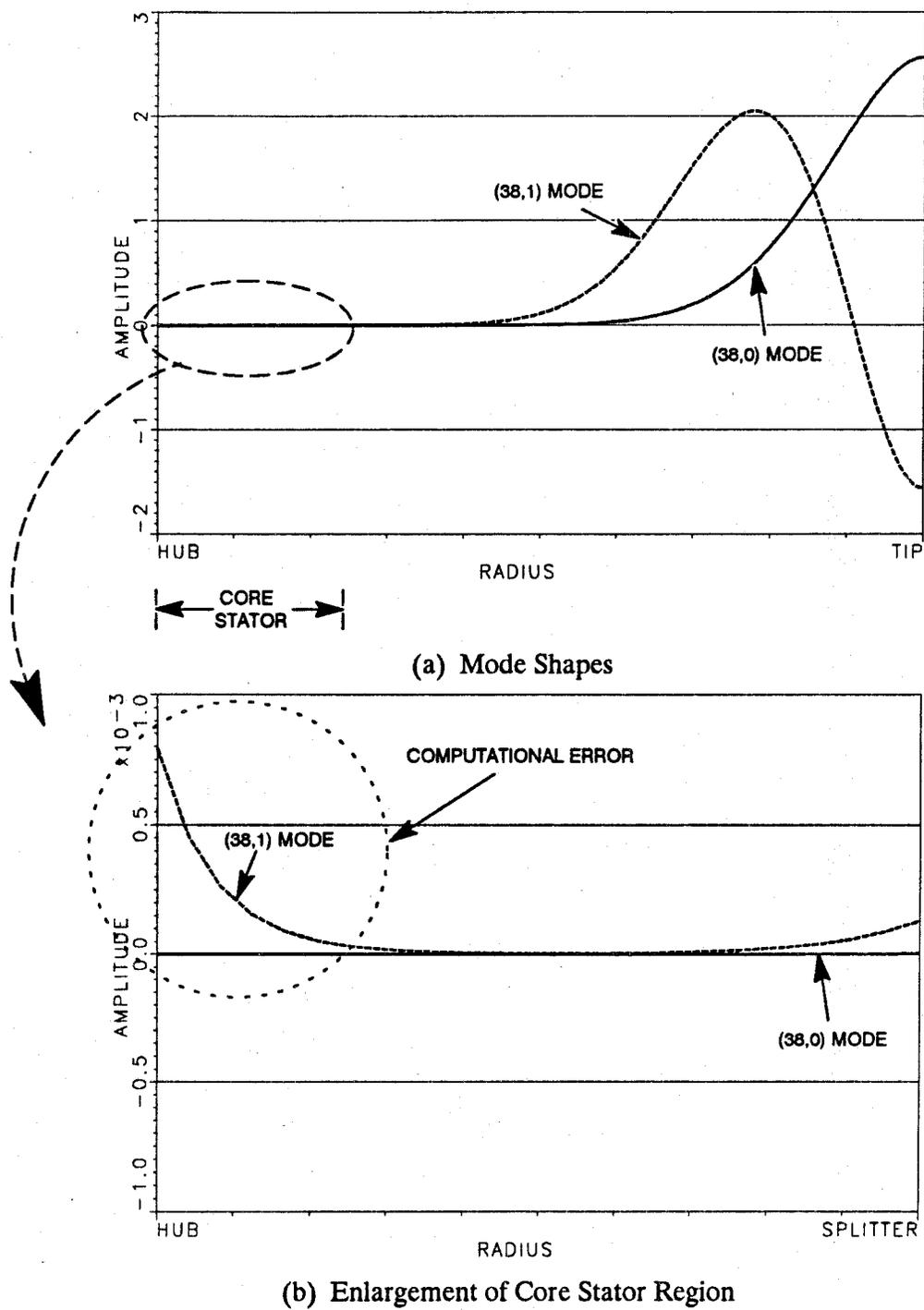


Figure 11 Radial Mode Shapes – Hub/Tip Ratio = 0.38

## 7. CONCLUDING REMARKS

Two NASA computer codes were combined and improved to form a new rotor wake/stator interaction code. Program capabilities include the ability to run noise predictions from the following noise sources:

- Rotor wake/stator interaction (in a low pressure compressor stage),
- Fan wake/core stator interaction,
- Fan wake/FEGV interaction (in a fan stage).

A semi-empirical tip vortex calculation and a partial hub vortex calculation are also available.

Finally, under certain circumstances the program will insert computational errors of its own giving rise to computational noise. Thus when running rotor wake/core stator interaction noise predictions, care should be taken to check mode power levels for this effect.

## **PART 2: USER'S MANUAL**

### **1. INTRODUCTION**

The BBN/PW code has been designed to calculate noise from the following sources:

- Compressor rotor wake/stator interaction.
- Fan wake/FEGV interaction.
- Fan wake/core stator interaction.

If desired, the program will also run the wake/vortex flow calculation. A tip vortex or preliminary hub vortex calculation may be run with the wake prediction.

Part 2 of this document discusses what is required to run this program including all program enhancements to date.

The program may be run in the workstation environment. About 10 minutes of time is needed to run a noise prediction on a Sun SPARC 2 Workstation for an average engine condition. However, a prediction of the only the wake runs extremely quickly. The namelist input is used in this program where multiple cases may be run by simply stacking one namelist input above another. The code presently requires geometry and performance parameters as a function of radius across the fan, FEGV, and core stator (if applicable).

## 2. INPUT REQUIREMENTS

The Rotor Wake / Stator Interaction Program uses Namelist input. It gives flexibility to the user in entering the data. It does not require all possible input be in the data file. Variables can be left out of the input file with ease. Thus minimal input from the user is required.

### 2.1 GENERAL NAMELIST INPUT

The following is a general description of how the input file for V072 is set up :

Title – this can be up to 80 characters in length and is the title for the case being run. If a title is going to be entered it must be input before the Namelist data. If no title is entered the program will use a default title based on the case being run.

The namelist data section of the input file is to be set up as follows :

Column 1 of each record must be blank.

All data must start in column 2

The first record of a namelist set of data must contain &INPUT The data may be entered starting on the same line as the &INPUT or on the next line. If it is to be entered on the same line as the &INPUT a blank space must separate the data from the &INPUT.

The data is to be entered separated by commas. As much data as fits can be entered on a single line and the order of the variables is irrelevant.

The form of the data is VARIABLE NAME = DATA VALUE or , ARRAY NAME = DATA VALUES (Each element separated by a comma),. The last record of a set of data must contain &END

Multiple cases can be input in the same data file. This is set up as if the cases were in separate files. Each case needs its own namelist input. Only those items that need to change from the previous case must be defined in the new namelist set. Once each case is defined they can be stacked on top of each other in the file. For more information regarding the set up of the input data file refer to the Appendix (Sample Input).

### 2.2 INPUT DESCRIPTION

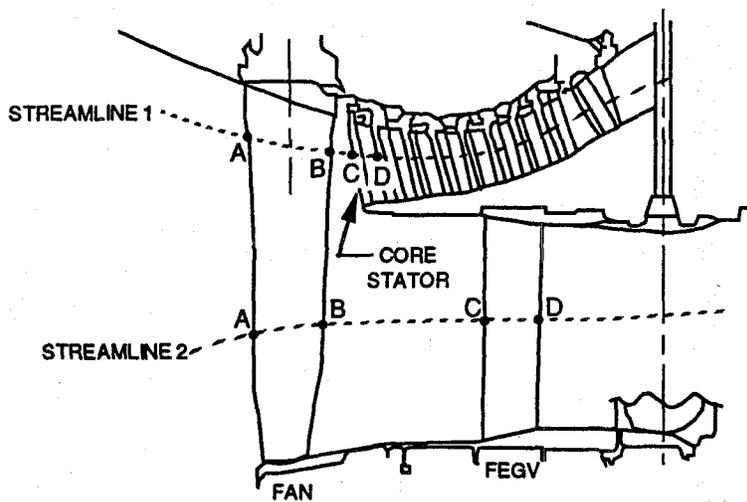
#### 2.2.1 Creating a Streamline Input

To obtain input to V072 we need to first transform our real engine geometry (Fig. 12a) into a constant area duct geometry (Fig. 12b). To obtain Figure 12b from Figure 12a, visualize each streamline like a “string” with geometry and performance varying along the “string.” Now pull the string so it is taught where the radius of the string from the engine centerline corresponds to the rotor leading edge radius of this streamline.

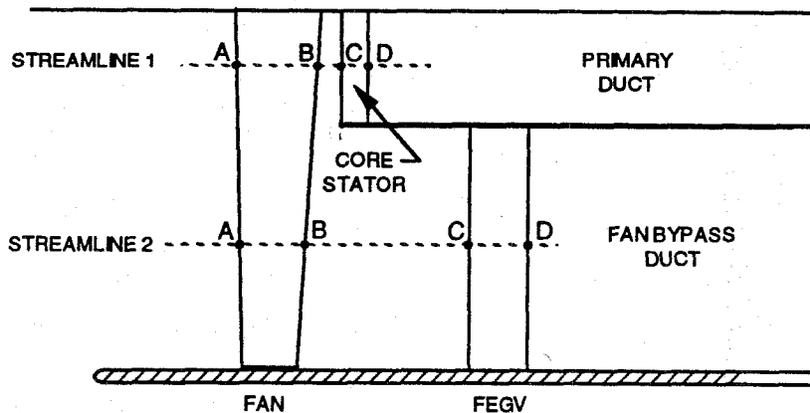
Thus, each streamline is located at the rotor leading edge radius to create the constant area duct. We then follow along each streamline back to the stator to obtain engine geometry and performance parameters.

For example:

Looking at Figure 12, streamline 2: to get from Figure 12a to 12b look at the streamline radius at point A in Figure 12a. This radius will be the radius of the streamline in the program. Therefore utilize geometry and performance at points A,B,C. Identify the rotor chord along point A to B and the stator chord from point C to D respectively (this is the aerodynamic chord). Do not use the axial chord. Use the aerodynamic chord as defined on a streamline. Use the stator stagger angle at an airfoil cross-section starting at point C. Identify the axial spacing as the streamline distance from points B to C.



(a) Full Scale Engine Geometry



(b) V072 Full Scale Engine Geometry

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Figure 12 Full Scale Engine Geometry Vs. V072 Representation

For more information on the choice of radial locations see Section 4. of Part 1 of this document. Note that if the radial change on the engine from the rotor leading edge to the stator leading edge is significant a program streamline radial location other than the rotor leading edge may be desirable.

### 2.2.2 Standard Input Data Units

#### Standard Input Data Units

- Lengths ---- Inches
- Rotor speed ---- RPM
- Temperatures ---- Degrees Rankin
- Densities ----  $\text{lb}_m/\text{ft}^3$
- Angles ---- Degrees

All air and stagger angles are defined relative to the circumferential direction.

### 2.2.3 Case Descriptive Input Parameters

IPRED – type of prediction

- = 0 Compressor rotor wake prediction only
- = 1 Rotor/Stator or Fan/FEGV interaction only (default)
- = 2 Fan/Core stator interaction only
- = 3 Both Fan/FEGV and Fan/Core stator interactions

NDATS – No. of streamlines where streamline information will be input for a rotor/stator or rotor/FEGV interaction (use when IPRED = 0, 1, or 3)

NDATC – No. of streamlines where streamline information will be input for a rotor/core stator interaction (use when IPRED = 2, or 3)

ICASE – The number of cases being run (default = 1)

NHT – The number of BPF harmonics where noise is being calculated (default = 3)

IWAKE – Chooses Wake width and velocity deficit correlations to be used

- = 1 Loaded fan wake profile (default)
- = 2 Linear rational function for rotor wake profile
- = 3 GE's New correlation

ISHAPE – Wake Tangential profile option

- = 1 Hyperbolic Secant profile
- = 2 Gaussian profile
- = 3 Loaded fan wake profile (default)

ITPVTX – Tip Vortex option

- = 0 Tip Vortex not included in calculation (default)
- = 1 Calculation includes a Tip Vortex

IHBVTX – Hub Vortex option

- = 0 Hub Vortex not included in calculation (default)
- = 1 Calculation includes a Hub Vortex

IPRINT – Print option

- = 0 Short output file (Does not print detailed wake profile and vortex information).
- = 1 Long output file (Prints wake profile details and vortex information).

IPLOT – Plot option

- = 0 Plotting file not created (default)
- = 1 Create plotting file.

**2.2.4 Scalar Geometry and Performance Input**

Variable Name	Needed as input for IPRED option:				Variable Type	Description
	0	1	2	3		
NBLADE	x	x	x	x	INTEGER	No. of rotor blades
NVANES	–	x	–	x	INTEGER	No. of stator vanes (or FEGV's)
NVANECS	–	–	x	x	INTEGER	No. of core stators
DDUCT	x	x	x	x	REAL	Outer duct diameter at rotor i.e.
N1	x	x	x	x	REAL	Uncorrected rotor speed
TS	x	x	x	x	REAL	Mass averaged static temperature; rotor t.e.
RHOS	–	x	x	x	REAL	Massed averaged static density; rotor t.e.
MAS	–	x	–	x	REAL	Mass averaged axial mach no.; FEGV (or stator) i.e.
MAC	–	–	x	x	REAL	Mass averaged axial mach no.; rotor i.e.

### 2.2.5 Distributing the Streamlines In V072

Once the streamline radii are located the geometry and performance may be obtained. Streamlines must include the wall streamlines and must be specified as follows:

IPRED	Number of Streamlines Being Input	Wall Streamlines Where Input Must Be Specified
0	NDATS	None
1	NDATS	Stator hub streamline Stator tip streamline
2	NDATC	Fan hub streamline Fan inner splitter dia. streamline
3	NDATC+NDATS	Fan hub streamline Fan inner splitter dia. streamline Fan outer splitter dia. streamline Fan tip streamline

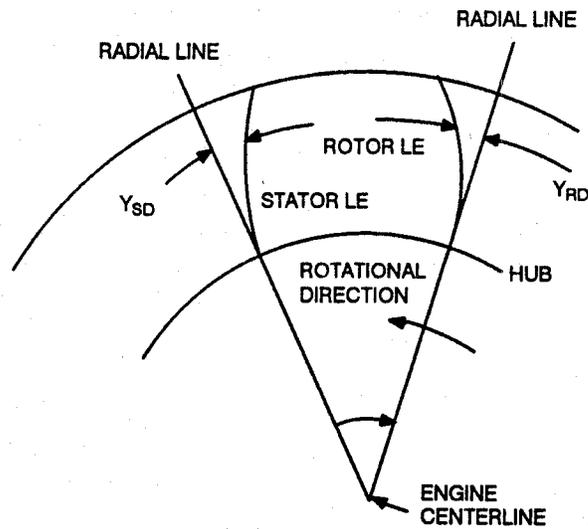
Note that all input radii must be specified starting at the inner most radius given above and ending with the outer most radius shown above.

### 2.2.6 Streamline Geometry and Performance Input

These parameters should be input at the number of streamlines described by the previous section (Section 2.2.5).

Variable Name	Needed as input for IPRED option:				Variable Type	Description
	0	1	2	3		
RADIUS	x	x	x	x	REAL	Radius of streamline; rotor l.e.
BROTOR	x	x	x	x	REAL	Rotor aerodynamic chord
XSPAC	x	x	x	x	REAL	Rotor t.e. to stator l.e. axial spacing
YRD	-	x	x	x	REAL	Non-radial variation; Rotor t.e. (see Figure 13)
BSTATR	-	x	x	x	REAL	Stator aerodynamic chord
YSD	-	x	x	x	REAL	Non-radial variation; stator l.e. (see Figure 13)
XSD	-	x	x	x	REAL	Axial variation; stator l.e. (see Figure 14)
ALPHCH	-	x	x	x	REAL	Stator stagger angle
BETA1D	x	x	x	x	REAL	Relative flow angle, rotor l.e.
BETA2D	x	x	x	x	REAL	Relative flow angle, rotor t.e.
OMEGA	x	x	x	x	REAL	Rotor loss coefficient, $\bar{\omega}$ (See Note 6)
MX	x	x	x	x	REAL	Axial mach no.; rotor l.e.
ACLS	-	x	x	x	REAL	Relative flow angle; stator l.e.
MRABS	-	x	x	x	REAL	Absolute mach no.; stator l.e.

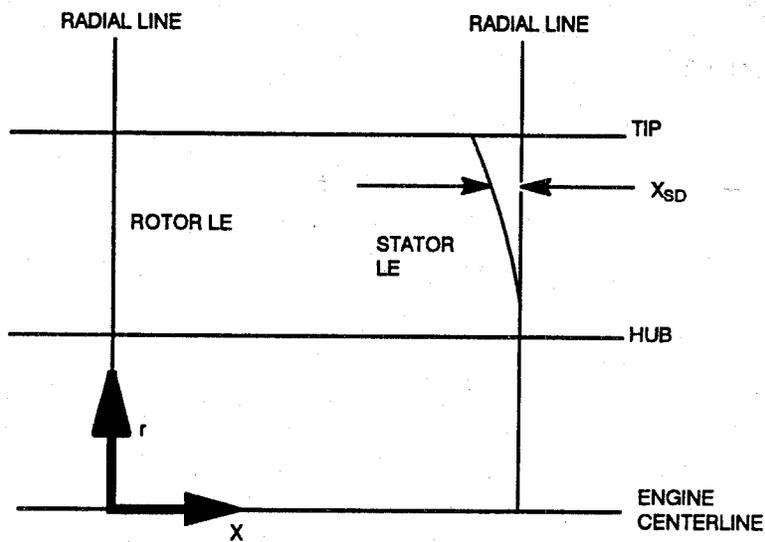
Schematic View of a Rotor Blade TE and Stator Vane LE Looking Down the Turbofan X AXIS, in Stator-fixed Coordinates



$Y_{SD}$  is positive in the direction opposite rotor rotation.  
 $Y_{RD}$  is positive in the direction of rotor rotation.

Figure 13 Definition of  $Y_{RD}$  and  $Y_{SD}$

Schematic View of a Rotor Blade TE and Stator Vane LE Looking Perpendicular to the Rotor Axis.



$X_{SD}$  is positive in the direction of reducing the axial spacing relative to the hub streamline.

Figure 14 Definition of  $X_{SD}$

### 2.2.7 Hub Vortex Parameters

Use Only When IHBVTX = 1. These are scalar quantities.

Variable	Variable Type	Units	Description
DHUB	REAL	INCHES	Rotor l.e. hub diameter
SBNH	REAL		Tangential distance of vortex center from rotor wake pressure side divided by the rotor pitch at the hub (default = 0.5)
BRHUB	REAL	INCHES	Hub rotor aerodynamic chord
MXHUB	REAL		Axial mach no.; rotor l.e. hub streamline
BETA1H	REAL	DEGREES	Relative flow angle ; rotor l.e. hub streamline
BETA2H	REAL	DEGREES	Relative flow angle ; rotor t.e. hub streamline

### 2.2.8 Tip Vortex Parameters

Use Only When ITPVTX = 1. These are scalar quantities.

Variable	Variable Type	Units	Description
TAUG	REAL	INCHES	Rotor tip clearance gap
SBNT	REAL		Tangential distance of vortex center from rotor wake pressure side divided by the rotor pitch at the tip (default = 0.5)
BRTIP	REAL	INCHES	Tip rotor aerodynamic chord
MXTIP	REAL		Axial mach no.; rotor l.e. tip streamline
BETA1T	REAL	DEGREES	Relative flow angle ; rotor l.e. tip streamline
BETA2T	REAL	DEGREES	Relative flow angle ; rotor t.e. tip streamline

## 2.2.9 Program Overriding Parameters

These are scalar quantities.

Variable Name	Needed as input for ipred option:				Default Value	Description
	0	1	2	3		
EC	-	x	x	x	0.0001	Convergence criteria to calculate $X_{mn}$ ( $k^*_{m\mu}$ in Tyler/Sofrin)
NRADS	-	x	-	x	*	No. of radial integration stations; Rotor/FEGV or Rotor/Stator interactions. Must be an odd no. (maximum: 79)
NRADC	-	-	x	x	*	No. of radial integration stations; Rotor/Core stator interaction. Must be an odd no. (maximum: 79)
NCHRS	-	x	-	x	*	No. of chordwise integration stations; Rotor/FEGV or Rotor/Stator interactions. Must be an even no. (maximum: 60)
NCHRC	-	-	x	x	*	No. of chordwise integration stations; Rotor/Core stator interaction. Must be an even no. (maximum: 60)

Note: Experience shows that Run Time  $\propto$  (NRADS) x (NCHRS)<sup>2</sup> and (NRADC) x (NCHRC)<sup>2</sup>

When the above parameters are set near their limits, runs of up to 1.5 hrs per case have been found to occur on a Sun SPARC2 workstation.

\* CALCULATED USING A CRITERIA CALCULATION IN THE PROGRAM. If this variable is used in a multi-case run, it must be input for all cases separately. Otherwise the code will automatically override.

## 2.2.10 Developmental Parameters

These parameters may be used to effect the wake harmonic magnitudes.

Variable Name	May be input for IPRED option:				Description
	0	1	2	3	
WTIV	x	x	x	x	Rotor inviscid velocity gradient/rotor wheel speed (negative value accounts for rotor loading) (default = 0.0)
BETAW	x	x	x	x	Wake flow angle variation parameter (default = 0.0)
VVTR	x	-	-	-	CRP parameter: rotor 2 fan speed / rotor 1 fan speed (default = 0.0)
WKEFAC	x	x	x	x	Multiplier for wake width correlation (WAKEWTH=WKEFAC*WAKEWTH) (default = 1.0)
VELFAC	x	x	x	x	Multiplier for velocity deficit correlation (VELDEF=VELFAC*VELDEF) (default = 1.0)

### 2.2.11 Notes On Input

1. **ISHAPE:** The wake profile shape is defined by the variable ISHAPE. The best value for this shape is a function of the streamwise spacing to chord (SSOC in the output file). The Loaded Wake profile (ISHAPE = 3) is best used for streamwise spacing to chords of less than 4. For streamwise spacing to chords of greater than 4 the Hyperbolic secant wake profile (ISHAPE = 1) is the best profile to use.
2. **RADIUS:** RADIUS defines the streamline radii which will identify the constant area duct to be utilized by the program. RADIUS has been defined at the rotor leading edge. However if the fan duct shows significant convergence or radius change from the rotor to the stator then it may be desirable to redefine the RADIUS at another axial location. See Section 5 of Part 1 of this document (Program Assumptions) for a more complete discussion of this parameter. Note: If RADIUS is defined at an axial location other than the fan i.e. then DDUCT must be set equal to the tip radius at the location used.
3. **MAS, MAC:** The mass averaged axial mach numbers, MAS and MAC, are utilized in the calculation of the cutoff ratio and are used to specify the nature of the duct acoustics. For a fan wake/stator or a fan wake/FEGV interaction MAS is specified at the stator leading edge where the noise is generated. For a fan wake/core stator interaction assume that the noise decays by an insignificant amount when it reaches the rotor leading edge so that MAC is used at the rotor leading edge. However, if the engine performance shows a need these values may be specified anywhere in the duct. Note that as MAS or MAC are increased, the number of propagating radial modes will increase.
4. **ALPHCH:** The stator stagger angle may be expressed using a number of different parameters. The method chosen here is to use the stagger angle defined as follows:

$$\text{ALPHCH} = \arctan \left[ \frac{\tan(\text{stagger}) + \tan(\beta_1^*)}{2} \right]$$

where:

stagger = angle the chord of the stator airfoil section makes with the circumferential direction (alpha chord)

$\beta_1^*$  = Stator leading edge metal angle relative to the circumferential direction

This angle is chosen because it is effectively the angle of the airfoil at the quarter chord point.

Stagger may be approximated by:

$$\text{stagger} = \arctan \left[ \frac{\tan(\beta_1^*) + \tan(\beta_2^*)}{2} \right]$$

where:

$\beta_2^*$  = Stator trailing edge metal angle relative to the circumferential direction

5. TAUG, SBNT, SBNH: These parameters are not readily available. However estimates of their values can be made. See Section 6.2 on "Vortex Parameter Information" for more information.
6. OMEGA= Rotor Loss Coefficient (see Reference 10) in the relative reference frame (fixed to the rotor) where:

$$\bar{\omega} = \frac{P_{o2_{ideal}} - P_{o2}}{P_{o1} - P_1} = \frac{\text{Ideal Total Pressure at Fan t.e.} - \text{Actual Total Pressure at Fan t.e.}}{\text{Total Pressure at Fan l.e.} - \text{Static Pressure at Fan l.e.}}$$

## 6.1 Other Input Hints

- N1 and TS are only used to calculate the rotor tip mach number.
- BROTOR, MX, BETA1D, BETA2D and OMEGA are only used in the rotor wake calculation.
- OMEGA is only used to calculate the rotor drag in the wake calculation. Drag is proportional to a value of OMEGA. However the wake profile is a weak function of drag. Thus only a reasonable estimate of OMEGA is needed.
- XSPAC is only used to determine the wake shape and determine the wake skew.
- MAS,MAC, YRD, YSD, XSD, ALPHCH, ACLS, MRABS are only used in the noise calculation program.
- YRD and YSD are used in the calculation of radial wake skew
- YSD and XSD are used to insure that the power levels are properly calculated at the stator leading edge, hub axial location in the duct. If either of these parameters is important then the noise will not be correctly integrated across the duct.
- BSTATR is utilized in the wake skew, vane pressure distribution and chordwise integration calculations.
- ACLS, ALPHCH are only used in the wake skew and vane pressure distribution calculations.
- MRABS is only used to calculate vane pressure distributions.
- RHOS is only utilized to redimensionalize the noise at the end of all other calculations.

## 2.3 VORTEX PARAMETER INFORMATION

### 2.3.1 Tip Vortex Notes

Reference 1. describes the tip vortex model which is a simple semi-empirical model. There are two important parameters in this model which are not easily determined:

SBNT = Circumferential location of the tip vortex relative to the pressure side of the wake of a nearby blade divided by the blade pitch.

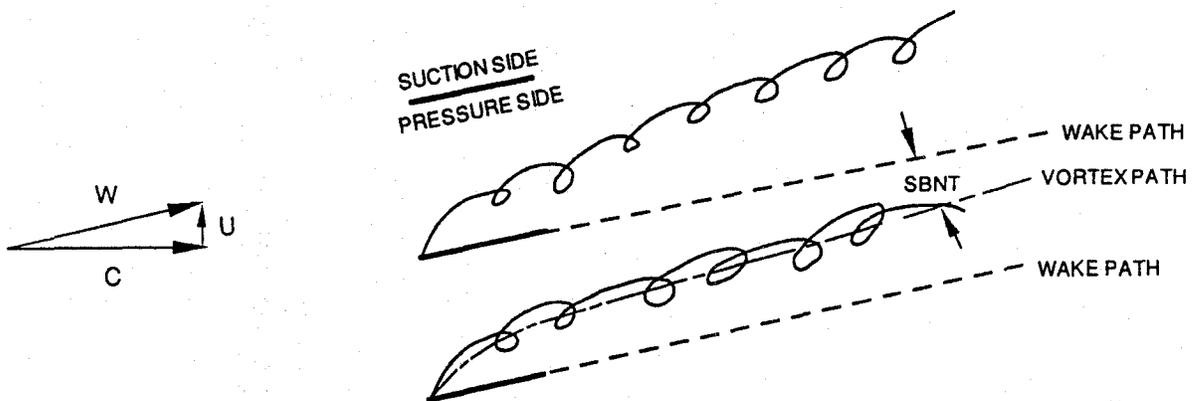
TAUG = Rotor blade tip clearance

TAUG is quite important as it determines the vortex strength and contributes to determining the vortex radius. A couple of notes:

- In a real engine TAUG varies around the circumference.
- In a real engine TAUG varies with engine condition.
- In V072 a constant TAUG is assumed at a given engine condition.

SBNT refers to the circumferential location of the tip vortex relative to the pressure side of the wake of a nearby blade normalized by the blade pitch (see Figure 15). We can explain the development of this parameter as follows:

Wakes from each blade are convected downstream along some path (Fig. 15). Near the tip, at or near the blade leading edge a vortex develops as a result of the interaction between the blade and tip leakage. This vortex convects along some path toward the stators (Fig. 15). As it convects it moves away from the suction side of the blade where it was generated and toward the pressure side of the neighboring blade wake.



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Figure 15 Tip Vortex Location, SBNT

SBNT is also never known nor can we estimate it. However we do know the effect of the placement of the vortex on the harmonic content of the stator upwash. If SBNT=0.5 then the vortex is half way between two wakes. Consequently, two velocity deficits are created per passage in the tip region, one from the vortex and the other from the wake. This will cause any tip generated 2BPF noise to dominate. If SBNT=0.0 then the vortex velocity deficit adds on top of the wake velocity deficit. This causes a rise in all harmonics where BPF noise > 2BPF noise > 3BPF noise. Reference 1 studies this effect in detail.

### **2.3.2 Hub Vortex Notes**

It is important to realize that the hub vortex model is only partially developed from the technical standpoint. Reference 1. will give details but essentially the empirical correlations for this vortex do not exist so the NASA program either uses tip vortex relations or it sets values equal to a constant.

Because of the preliminary nature of this option, extreme care should be exercised when it is used.

### 3. PROGRAM OUTPUT

#### 3.1 NOISE AND WAKE OUTPUT

The Rotor Wake / Stator Interaction program creates 3 output files. The Noise output file is a mandatory output file but the IPRINT input option allows for this file to be either a long output file or a short one.

The Eversman Radiation code output file is the second file. It outputs the real and imaginary part of each of the radial mode amplitudes in pound force per square inch for each propagating radial mode. This output may then be non-dimensionalized for input into the Eversman Radiation Code.

The Plot Data output file is the final output file and is optional. The user controls the creation of this file through the IPLOT input option. For information on the use of IPRINT and IPLOT refer to section on "Case Descriptive Input Parameters" of this manual.

The output files will be of the following format:

Output File	Output File Name	Output File Extension	What is in it
Noise output file	Same name as user's input file	v072out	Wake and noise output from the program including power levels and complex radial mode amplitudes (using radial mode shape as defined by Ref. 2)
Radiation output file	Same name as user's input file	raddata	Peak complex mode amplitudes (lb/in <sup>2</sup> ) normalized to the Eversman Radiation Code. To use this output in the radiation code non-dimensionalize it by $\rho c^2$ where $\rho$ = far-field, freestream air density, and $c$ = far-field, freestream speed of sound. Note: These are peak levels and not RMS levels.
Plotting output file (not used) output only output if IPLOT=1	Same name as user's input file	plotdat	Data for a plotting routine that was never completed

#### 3.2 NOISE OUTPUT FILE DESCRIPTION

The Noise output will be written to a file of the form: user input file name.v072out.

1. Listing of the user's input
2. Wake Characteristic Parameter Output as a Function of Radius
  - 2.1 Streamwise spacing / aerodynamic chord
  - 2.2 Airfoil streamline section drag coefficient
  - 2.3 Half wake width / rotor pitch
  - 2.4 Wake velocity deficit / Freestream relative velocity.

3. Hub Vortex Parameter Output (if IHBVTX = 1 and IPRINT = 1)
  - 3.1 Scalar output at the rotor i.e.
    - 3.1.1 Blade section lift coefficient at the hub
    - 3.1.2 Fraction of lift lost to the hub vortex
    - 3.1.3 Radius of the hub vortex core/hub blade pitch
    - 3.1.4 Streamwise velocity deficit of hub vortex core/ hub freestream velocity
    - 3.1.5 Circulation per unit span of hub vortex core (ft<sup>2</sup>/s)
    - 3.1.6 Angular velocity of hub vortex core/hub wheel speed
    - 3.1.7 Hub vortex tangential location/hub blade pitch
    - 3.1.8 Hub blade pitch
    - 3.1.9 Hub freestream relative velocity
  - 3.2 Array output as a function of Streamwise Spacing(relative to each radius) at stator i.e.
    - 3.2.1 Radius at rotor i.e. (in)
    - 3.2.2 Streamwise spacing/aerodynamic chord
    - 3.2.3 Hub vortex core radius/hub blade pitch
    - 3.2.4 Hub core velocity deficit/hub freestream velocity
    - 3.2.5 Radial distance of hub vortex from engine center line (in)
    - 3.2.6 Radial distance of hub vortex from engine center line normalized by the rotor tip radius
    - 3.2.7 Hub vortex circulation/span (ft<sup>2</sup>/sec)
4. Tip Vortex Parameter Output (if ITPVTX = 1 and IPRINT = 1)
  - 4.1 Scalar output at the rotor i.e.
    - 4.1.1 Blade section lift coefficient at the tip
    - 4.1.2 Fraction of lift lost to the tip vortex
    - 4.1.3 Radius of the tip vortex core/tip blade pitch
    - 4.1.4 Streamwise velocity deficit of tip vortex core/tip freestream velocity
    - 4.1.5 Circulation per unit span of tip vortex core
    - 4.1.6 Angular velocity of tip vortex core/tip wheel speed
    - 4.1.7 Tip vortex tangential location/tip blade pitch
    - 4.1.8 Tip blade pitch
    - 4.1.9 Tip freestream relative velocity
5. Array output as a function of Streamwise Spacing (relative to the radius) at stator i.e.
  - 5.1 Radius at rotor i.e. (in)
  - 5.2 Streamwise spacing/aerodynamic chord
  - 5.3 Tip vortex core radius/tip blade pitch

- 5.4 Tip core velocity deficit/tip freestream velocity
- 5.5 Radial distance of tip vortex from engine center line (in)
- 5.6 Radial distance of tip vortex from engine center line normalized by the rotor tip radius
- 5.7 Tip vortex circulation/span ( $\text{ft}^2/\text{sec}$ )
- 6. Velocity Profiles (if IPRINT = 1)
  - 6.1 Relative velocities fixed to the rotor at specified axial locations (ft/s)
  - 6.2 Absolute velocities fixed to the stator at specified axial locations (ft/s)
  - 6.3 Upwash velocities fixed to the stator at specified axial locations (ft/s)
  - 6.4 Harmonic Content of Rotor Wake Vortex Flow
  - 6.5 Wake Harmonic Magnitude
- 7. Noise Output
  - 7.1 Radial mode power levels (dB) for each Circumferential mode and BPF harmonic in the inlet and aft.
  - 7.2 Circumferential mode power levels (dB) for each BPF harmonic in the inlet and aft.
  - 7.3 Total power levels (dB) for each BPF harmonic in the inlet and aft.

#### 4. ERROR MESSAGES OUTPUT

The program will output a number of different types of error messages to signal possible problems with the program answers. The two important areas where this is done are during the various aspects of the radial mode shape calculation and during the matrix inversion of the stator dipole strength calculation. In the mode shape calculation errors, the problem will be identified along with the absolute value of the circumferential mode number,  $m$  and the radial mode number,  $\mu$  of the effected radial mode. In large part these errors signal where minor errors have occurred and in most cases the user should simply check the answers for the mode shapes for the modes where these errors occur to see that these errors are in fact insignificant.

There are three types of errors: NOTES, WARNINGS, and FATAL ERRORS.

- “NOTES” notify the user that a bessel function subroutine has calculated an answer which has gone to plus or minus machine infinity according to these subroutines. These errors are just there to inform the user of this fact. These errors do not in and of themselves signal a real problem.
- “WARNINGS” are more serious. They relate to one of two things: The critical mach no. (radial mode eigenvalue) calculation did not converge, or the stator dipole distribution matrix inversion is ill conditioned. In these cases the accuracy of the answers may be effected. Perhaps the least worrisome warning is when the critical mach number does not converge. Normally the critical mach number is correct to machine accuracy. However, the criteria is quite stringent and will sometimes cause this error. Note that when this error does occur it is important to check the radial mode shape and to check the radial mode power levels for the mode where this occurs. This is because while the critical mach number may be good, when this error occurs there is usually some computer roundoff error which will effect the radial mode shape. In most cases this error is much smaller than the noise which propagates from the important modes. This error is most likely to occur when the hub/tip ratio is less than 0.4 and seems to be the most significant in rotor/core stator interactions. See Section 6. of Part 1, the “Computational Noise” discussion.

If the stator dipole matrix distribution warning occurs it is important that the engineer and the programmer responsible for this program be contacted. This error indicates that the accuracy of this matrix inversion is poor. This error occurs because a value along the matrix diagonal is much smaller than one off the diagonal. This can effect the program error. This error has not occurred for the cases tried. However, an increase in the matrix condition number has been observed as the BPF harmonic frequency rises.

- “FATAL ERRORS” will cause the program to automatically end execution. They suggest a drastic problem with the input to one of the bessel function subroutines. It may also indicate that the matrix inversion routine (LINPACK) has detected a singular matrix. Under these circumstances the responsible program engineer and programmer should be contacted promptly to correct the problem.

## 5. SYSTEM EXECUTION

To execute the V072 system:

1. Insure that the v070\_v072 executable created in the v070sys/v070src/v072 subdirectory has been sourced.
2. Enter v070\_v072 on the command line in the directory where you have an input file. At this point the following message will occur:  

“The input file must be on your current directory”

“Enter the filename or carriage return (control d) to quit”
3. Enter the file name and press enter
4. The following output will be created:
  - 4.1 Output file with the superset name equal to the input file name with an extension v072out (e.g. if the input file was called “file1” the output file would be “file1.v072out”
  - 4.2 Output file with the superset name equal to the input file name with an extension raddata. This file has in it the input to the Eversman Radiation code.
  - 4.3 If IPLOT = 1, then another file would be created called by the input file name with an extension plotdat. This file would be used for plotting if there were a plotting routine.

A flowchart of how the computer program is given in Figure 16.



## 10. REFERENCES

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9. Goldstein, M. E., Aeroacoustics, McGraw Hill International Book Co., New York, 1976.
10. Lieblein, S., et. al., "Diffusion Factor For Estimating Losses and Limiting Blade Loadings in Axial-Flow-Compressor Blade Elements," NACA RME53D01, June 8, 1955.

## APPENDIX

Sample Input – This is the “test3” test case in the “ws\_test\_case” subdirectory

```
IPRED=3 TEST CASE
&INPUT
IPRED=3,
ICASE=4,IPRINT=1,IPL0T=0,
N1=2760.1,
NHT=3,WKEFAC=.5,VELFAC=.5
NDATS=5,NRADS= 9,NCHRS=8,
NDATC=4,NRADC= 7,NCHRC=6,
NBLADE=38,NVANES=72,NVANEC=80,
MAS=0.331,MAC=0.335,
DDUCT=92.510,
TS=564,RHOS=0.0770,
RADIUS=27.87,30.0,33.0,36.0,38.0,40.0,42.0,44.28,46.255,
XSPAC=12.704,12.734,12.719,12.725,12.760,12.948,13.251,13.692,14.028,
BROTOR=7.555,7.665,8.042,8.338,8.542,8.839,9.173,9.512,9.79,
BSTATR=4.52,4.538,4.563,4.563,4.562,4.563,4.561,4.487,4.462,
ALPHCH=74.368,74.926,75.547,75.862,75.859,76.453,77.41,75.362,74.846,
YSD=0,-0.126,-0.294,-0.465,-0.491,-0.601,-0.704,-0.648,-0.568,
YRD=0,-0.186,-0.412,-0.624,-0.772,-1.010,-1.352,-1.687,-1.900,
BETA1D=38.78,36.10,33.24,30.48,28.49,26.39,24.09,21.31,19.21,
BETA2D=61.23,57.53,53.66,49.91,47.47,43.73,38.41,32.61,25.75,
OMEGA=0.02317,0.05942,0.06431,0.07369,0.11269,0.09059,0.07378,
0.09270,0.21135,
MRABS=0.389,0.410,0.418,0.419,0.426,0.414,0.403,0.400,0.447,
MX=0.493,0.449,0.445,0.450,0.442,0.447,0.431,0.394,0.306,
ACLS=41.71,41.13,37.77,34.13,32.61,29.75,27.35,25.59,26.74,
XSD=0.0,0.010,0.080,0.092,0.094,0.094,0.095,0.031,0.0,
IHBVTX=0,SBNH=0.5,DHUB=55.74,BRHUB=7.555,
MXHUB=.493,BETA1H=38.78,BETA2H=61.23,
ITPVTX=0,SBNT=0.5,TAUG=0.01,BRTIP=9.79,
MXTIP=0.306,BETA1T=19.21,BETA2T=25.75
&END
IPRED=3 TEST CASE
&INPUT
NRADS= 9,NCHRS=8,
NRADC= 7,NCHRC=6,
IHBVTX=1,
ITPVTX=1,
&END
IPRED=3 TEST CASE
&INPUT
NRADS= 9,NCHRS=8,
NRADC= 7,NCHRC=6,
IHBVTX=0,
ITPVTX=1,
&END
```

```
IPRED=3 TEST CASE
&INPUT
NRADS= 9,NCHRS=8,
NRADC= 7,NCHRC=6,
IHBVTX=1,
ITPVTX=0,
&END
```

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<b>14. ABSTRACT</b> This report documents the improvements and enhancements made by Pratt & Whitney to two NASA programs which together will calculate noise from a rotor wake/stator interaction. The code is a combination of subroutines from two NASA programs with many new features added by Pratt & Whitney. To do a calculation V072 first uses a semi-empirical wake prediction to calculate the rotor wake characteristics at the stator leading edge. Results from the wake model are then automatically input into a rotor wake/stator interaction analytical noise prediction routine which calculates inlet aft sound power levels for the blade-passage-frequency tones and their harmonics, along with the complex radial mode amplitudes. The code allows for a noise calculation to be performed for a compressor rotor wake/stator interaction, a fan wake/FEGV interaction, or a fan wake/core stator interaction. This report is split into two parts, the first part discusses the technical documentation of the program as improved by Pratt & Whitney. The second part is a user's manual which describes how input files are created and how the code is run.					
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