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INTERACTION OF ROTOR TIP FLOW IRREGULARITIES WITH STATOR VANES AS A NOISE SOURCE

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INTERACTION OF ROTOR TIP FLOW IRREGULARITIES WITH STATOR VANES AS A NOISE SOURCE

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Abstract

The role of the interaction of rotor tip flow irregularities (vortices and velocity defects) with downstream stator vanes is discussed as a possible fan noise mechanism. This is accomplished by: indicating some of the methods of formation of these flow irregularities; observing how they would behave with respect to known noise behavior and; attempting to compare the strength of the rotor tip flow irregularity mechanism with the strength of the more common rotor wake-stator mechanism. The rotor tip flow irregularity-stator interaction is indicated as being a probable inflight noise source.

Nomenclature

A	constant for a given airfoil (eq. (1))
A_1	constant depending on profile drag of airfoil (eq. (9))
B	constant for given free stream conditions (eq. (11))
C_R	airfoil chord
P	pressure
r	radial coordinate measured from vortex center
v_r, v_θ, v_z	velocities in r, θ, z cylindrical coordinates
W	axial velocity defect $W_\infty - v_z$
W_∞	free stream velocity
z	axial coordinate from airfoil trailing edge
Γ_0	circulation in initial vortex
θ	circumferential angle
ν	kinematic viscosity
ρ	fluid density

Introduction

Recent papers in the area of fan noise (refs. 1,2) have indicated that the rotor-stator interaction is the dominant tone noise source for subsonic fans in flight and that as a result the Tyler Sofrin "cutoff" criteria is applicable. A fan which is designed to be "cutoff" would typically have its blade passage tone greatly diminished in flight, however, the harmonics of the tone would remain in the spectra. These remaining tones would also be controlled by the rotor-stator interaction mechanism and because of the importance a review of this noise generation mechanism was initiated.

The typical rotor/stator interaction has been viewed as the interaction of the rotor blade wakes with the downstream vanes. A schematic drawing of this generation mechanism is shown in Fig. 1(a).

Another possible rotor/stator mechanism is the interaction of the rotor blade tip irregularities (vortices and velocity defects) with the downstream stator vanes. The schematic representation of this mechanism is shown in Fig. 1(b). This same general mechanism has been shown to be a significant noise source for helicopter rotors. Here the tip vortex from one rotor blade strikes the next blade creating a noise source. The likelihood of this generating the most annoying blade slap helicopter noise has been shown in such papers as Refs. 3 through 5 and its role as a broadband noise mechanism has been indicated in Ref. 6. In fan stages the vortex has been discussed as a prime broadband rotor alone noise source by Longhouse, Ref. 7. The rotor tip irregularity-stator interaction noise mechanism in a fan stage is discussed in this report and the possible dominance of this mechanism is proposed.

The first step in this report is to list the manner in which the tip flow irregularities can be formed. This is followed by the possibilities of the mechanism as a noise source which is explored through a comparison of its behavior with known fan noise behavior. The final step is a comparison of the expected noise from the rotor wake stator and rotor tip irregularity stator mechanisms by inference from some existing data. For simplicity of notation the rotor tip irregularity-stator interaction is sometimes referred to as RT-S and the rotor wake-stator interaction as RW-S.

Possible Sources of Rotor Tip Irregularities

Secondary flows in turbomachines have been the subject of investigations by various authors. A number of these works are in Refs. 8 through 14. It is not the intent here to provide a review of the various secondary flows in a turbomachine, however, a number of the possible rotor tip irregularity sources are worth exploring. These generally fall into two classes; mechanisms which generate a rotor tip vortex and, those which result in displacements and accumulation of the boundary layer.

Vortex Generators

Two of the possible causes of rotor tip vortices (indicated as secondary flow generators by Hansen and Herzig, ref. 14) will be described here - namely blade end clearance and relative motion between blade tips and annulus walls. Blade end clearance can generate a rotor tip vortex by allowing a communication between the pressure and suction sides of a rotor blade. (Fig. 2(a) shows this mechanism.) A secondary flow is generated around the tip of the blade which in turn can create a tip vortex. It is likely that this vortex could also be formed by communication slightly downstream of the blade, even if no end clearance were present.

Figure 2(b) shows how the relative motion between the blade tips and the annulus wall can create a vortex. Here the relative motion of the blade exerts a scraping effect on the wall boundary layer. The effect is to impart a rolling motion to the boundary layer as it is pulled up against the moving blade, thus creating a tip vortex.

Boundary Layer Accumulation

Displacement and accumulation of the blade boundary layer can result from secondary flows in

STAR Category 71

the channel between two rotor blades. Figure 2(c) shows how this accumulation can occur. Here a combination of radial and circumferential secondary flows have resulted in an accumulation of the boundary layer near the rotor tip suction surface. The radial flows shown here may be caused by radial pressure gradients or by centrifugal effects. In rotors these radial flows are usually outward with the boundary layer accumulating at the tip and for stators the flows are inward with the accumulation near the hub (Ref. 14). The circumferential flows may be caused by the blade to blade pressure gradients. (Flow from the pressure surface of blade A to the suction surface of blade B, in Fig. 2(c).) The combined effects of radial and circumferential flows of boundary layer material result in an accumulation of the boundary layer, and therefore the velocity defect behind the blade, in one particular location.

Possibility As Noise Source

The mechanism by which rotor tip flow irregularities can create noise is the same as for the rotor wake mechanism. Namely, since each rotor blade has this region of poor flow trailing behind it, the interaction of these regions with the downstream stator blades create fluctuating velocities and air angles on the stator blades. These in turn produce stator lift fluctuations which create noise. The blade to blade repeatability of this region creates blade passage tone and its harmonics while the purely random parts of these regions become broadband noise generators.

In order to show the probability that the rotor tip irregularities interacting with the stators is a strong candidate for a noise source in a turbofan it is necessary to show how this mechanism fits with respect to known noise behavior. In addition, to show this mechanism (RT-S) is as strong as the rotor-wake stator mechanism (RW-S) it is necessary to show that the velocity fluctuations felt by the stator are as great from this mechanism (RT-S) as from the rotor-wake stator interactions (RW-S).

Comparison With Noise Behavior

The intent here is to show that the rotor tip irregularity-stator mechanism behaves in the same manner as known noise behavior. In particular two noise effects for the fan stage of turbofan engines have been observed. These are the inflight cutoff phenomena of Tyler and Sofrin (Ref. 15) and the effect of rotor-stator spacing (see Ref. 16).

Cutoff behavior. The "cutoff" phenomena has been observed for fan stages in flight (Refs. 1 and and 2) and it is therefore necessary to show that the proposed mechanism also would act in this same manner. In the proposed noise generation mechanism each rotor blade tip trails behind it a vortex and a velocity defect region. When this region strikes the downstream blade it creates pulsating sources on the stator vanes in the same manner as the rotor wakes do in the rotor wake-stator mechanism. Since each rotor blade exhibits this poor flow region, the phasing from vane to vane is the same for the RT-S mechanism as for the RW-S mechanism. Therefore the "cutoff" phenomena would be the same for the RT-S mechanism as for the RW-S mechanism.

One of the differences in the two mechanisms is that the rotor-wake stator (RW-S) mechanism involves the entire span of the stator in generating noise where as the rotor tip irregularity-stator (RT-S) mechanism involves only the tip region of the stator. This disturbance concentrated at the blade tips should produce a sound pressure level which is more concentrated at the tip than that of the usual wake mechanism. Another difference is that the vortex portion of the rotor tip irregularity has an additional spanwise variation that does not occur for a wake. Because of the swirling motion of the vortex a section at the top of the vortex would have a velocity in the opposite direction from a section at the bottom of the vortex (see Fig. 3). (A velocity defect, as in a wake, would have the same direction for the upwash velocity along the span.) This change from upwash to downwash in a very short spanwise distance on the stator vane may result in a more compact and possibly stronger noise source.

Spacing. Lowson (Ref. 16) has indicated the behavior of the fan blade passage tone noise as the spacing between the rotor blade and stator vane rows is increased (Fig. 4). (This figure is a portion of a figure presented in Ref. 17.) The upper curve in Fig. 4 is the 2 dB reduction in sound pressure level per doubling of distance presented by Lowson. The data points are also from Ref. 16. The lower curve is the behavior of the wake described in Ref. 17 with spacing wherein the wake defect is described as

$$\frac{W}{W_\infty} = \frac{A}{(Z/C_R + 0.025)^{1/2}} \qquad (1)$$

where

- W is the wake defect
- W_∞ is the free stream velocity
- A is a constant for a given airfoil
- Z is the distance downstream of the airfoil
- C_R is the airfoil chord

As can be observed from Fig. 4 the wake decay model and the noise behavior are in fair agreement.

It then becomes necessary to show that the rotor tip vortex and velocity defect model also lead to this good of an agreement with the noise behavior. Since the velocity defect occurring at the rotor tip is an accumulation of the boundary layer over other portions of the blade it is not hard to envision the velocity defect region as a large localized wake. If this tip wake decayed at the same rate as the main blade wake does, then the dependence of the noise source on spacing would also be the same as for the main rotor wake source.

The behavior of the tip vortex strength with spacing is not as easily envisioned and it is therefore necessary to present some model for the vortex and observe its behavior. The model chosen for the vortex is one that Dosanjh, et al. (Ref. 18) have presented based on work performed by Newman (Ref. 19).

Under the assumptions that:

1. The axial velocity defect and the circumferential velocity of the vortex are small compared to the free stream velocity.

2. The radial velocity in the vortex is very small compared to the free stream velocity and

therefore small compared with the circumferential velocity; and

3. The Reynolds number of the main flow is large.

The Navier-Stokes equations and the continuity equation were reduced to

$$\frac{v_\theta^2}{r} = \frac{1}{\rho}\frac{\partial P}{\partial r} \tag{2}$$

$$W_\infty \frac{\partial v_\theta}{\partial z} = \nu \left\{\frac{\partial^2 v_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial v_\theta}{\partial r} - \frac{v_\theta}{r^2}\right\} \tag{3}$$

$$W_\infty \frac{\partial W}{\partial z} = \nu \left\{\frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\frac{\partial W}{\partial r}\right\} \tag{4}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r v_r) - \frac{\partial W}{\partial z} = 0 \tag{5}$$

Then with the application of the appropriate boundary and initial conditions the solutions became

$$v_\theta = \frac{\Gamma_0}{2\pi r}\left[1 - \exp\left(-\frac{W_\infty r^2}{4\nu z}\right)\right] \tag{6}$$

$$v_r = -\frac{A_1 r}{2z^2}\exp\left(-\frac{W_\infty r^2}{4\nu z}\right) \tag{7}$$

$$W = W_\infty - v_z = \frac{A_1}{z}\exp\left(-\frac{W_\infty r^2}{4\nu z}\right) \tag{8}$$

where

Γ_0	is the circulation in the initial vortex
r	is the radial coordinate measured from the vortex center
z	is the coordinate distance from the airfoil trailing edge
v_θ, v_r, v_z	are the vortex velocities in the r, θ, z cylindrical coordinates
A_1	is a constant dependent on the profile drag of the airfoil

It is herein assumed that the circulation generated part of the vortex is dominant and therefore that v_θ is the largest velocity component. The behavior of this velocity, v_θ, with distance behind the airfoil is then of concern for comparison with the noise behavior with spacing. Furthermore, since this velocity, v_θ, is a function of the radial distance from the center of the vortex, the variation of the maximum value of v_θ with distance z is desired.

As per Dosanjh, et al., the derivative of v_θ with respect to r is set equal to zero to obtain the radius at which v_θ is a maximum. When this radius is resubmitted the maximum value of v_θ is

$$v_{\theta_{max}} = 0.638\,\frac{\Gamma_0}{2\pi}\sqrt{\frac{W_\infty}{4\nu z}} \tag{9}$$

Rearranging with the addition of C_R equation (9) becomes

$$v_{\theta_{max}} = 0.638\,\frac{\Gamma_0}{2\pi}\sqrt{\frac{W_\infty}{4\nu C_R}}\left[\frac{1}{(z/C_R)^{1/2}}\right] \tag{10}$$

Replacing the outside terms by a constant for a given airfoil with given free stream conditions

$$v_{\theta_{max}} = \frac{B}{(z/C_R)^{1/2}} \tag{11}$$

As can be observed the variation of the vortex velocity $v_{\theta_{max}}$ with spacing (eq. (11)) is the same as the variation of the wake defect (eq. (1)) with the exception of a small constant, 0.025, which occurs in the wake defect model. In essence the expected variation with spacing of the tip vortex model is consistent with the noise behavior. Recent work by Raj and Lakshminarayana (Ref. 20) has shown that the decay of the wake in a turbomachine may occur more quickly with distance than previously indicated. With this rapid a decay the rotor wake-stator mechanism would no longer appear to fit the noise data. This, if true, may leave the rotor tip vortex mechanism as the only mechanism that fits the noise decay that occurs with increased spacing.

Relative Strength of Two Mechanisms

The next step in establishing the plausibility of the rotor tip flow irregularity-stator interaction mechanism is an attempt to ascertain the relative strength of this mechanism with respect to the rotor-wake-stator mechanism. Some information is available that might indicate the strength of this mechanism. The first piece of information deals with the strength of the velocity defect with respect to the wake defect. The second deals with the distribution of noise in the duct. The third piece of information involves fluctuating pressure measurements on the stator vanes. All of the pieces of information, although circumstantial, give some evidence of the relative mechanism strengths.

Wake defect - tip defect comparison. The noise generated by the interaction of a velocity disturbance and a downstream blade is a function of the strength of the disturbance, the response of the blade to that disturbance, and the area of the blade over which the disturbance takes place. With the same set of downstream blades the larger the disturbance the more noise is generated. Exact measurements of the rotor wake strength and the rotor tip defect strength are not easily obtainable. However, some measurements of these quantities behind turbine nozzles (stators) are available in Ref. 21. Some of these measurement contours have also been published in Ref. 14 and one of these contours (Fig. 284, Ref. 14) has been replotted herein as Fig. 5(a). This particular contour is plotted because it shows, the most clearly of the contours, the wake defect region and the region where the boundary layer accumulation has occurred. It should be noted here that this is the velocity loss region behind a blade in a stationary cascade. Here, because there is no relative motion of the blade with respect to the wall and no tip clearance, very little in the way of a vortex flow appears to be present. The extra velocity defect at the blade end is then only caused by the accumulation of boundary layer as a result of secondary flows. Since this represents only the boundary layer accumulation, the strength of the disturbance region would be greater behind a moving blade because of the additional vortex region not present in this stationary case. As mentioned previously the typical radial flows are toward the tip for a rotor and toward the hub for a stator. The pattern for this stationary turbine nozzle is as shown in Fig. 5(b). The velocity defect area, shown here in Fig. 5(a) as being near the hub, would appear near the tip for the case of a rotor-blade.

In order to provide some comparison of the noise production of the wake mechanism and the velocity defect mechanism, Fig. 5(a) will be used to provide the strengths and spanwise extents of the two regions. The noise generated is assumed to be proportional to the product of the defect and its spanwise extent. It will be assumed that the region from the inner hub to 1.02 cm (0.4 in.) from the inner wall is the velocity defect region. The wake defect region is then from 1.02 cm (0.4 in.) to the boundary layer region on the outer wall or 5.34 cm (2.1 in.). The amount of loss, which is defined as unity minus the ratio of the local velocity squared to the inlet velocity squared, is only roughly given in percent ranges for various regions behind the blade. For purposes of calculation each region will be taken as the average of the percentages given for that region. In addition, since the region between blades has a certain loss range and the desired defect strength is the variation between the amount between blades and that behind a blade, the average value of the between blade region will be subtracted from the other regions. This results in the table given in Fig. 5(a). For example the percent loss range between blades, region 1, is 0 to 5% giving an average of 2.5%. The wake region loss range is 5% to 10% giving an average of 7.5%. The wake defect is then 7.5% - 2.5% or 5% average wake defect. The radial span of the wake region is from 1.02 to 5.34 cm (0.4 to 2.1 in.) giving a span of 4.32 cm (1.7 in.) or 78% of the total span. So the wake contribution would be 5% loss times 78% of the span or 390. The accumulated velocity defect region has 0.23 cm (0.09 in.) 4% span at 60% loss, 0.102 cm (0.04 in.) 2% span at 20% loss, 0.38 cm (0.15 in.) 7% span at 15% loss and 0.306 cm (0.12 in.) 5% span at 10% loss for a total of 435. The noise difference between the two mechanisms would be around 1 dB based on 20 times the logarithm of the ratio of the two numbers.

In addition to the turbine data, some loss numbers are available for the region behind a stator in a single stage fan. The performance data and a description of this fan stage are reported in Ref. 22. The local loss coefficient data for this fan were not completely presented in Ref. 22 but were available from this contract for computations. The loss coefficient profiles, defined as the difference in total pressure across the stator divided by the difference in total and static pressure upstream of the stator, are presented in Fig. 5(c). When the same calculation is done for this stator as was previously performed for the turbine nozzle the difference in predicted noise was a little over 1 decibel. Here however the wake defect was noisier whereas the velocity defect was noisier for the turbine case.

The previous examples are an indication that the rotor tip defect-stator interaction is approximately as strong (within 1-2 dB) as the rotor wake-stator mechanism. Based on 20 $\log_{10}$ of the ratio, approximately a 6 decibel noise reduction would then be expected to occur if the rotor tip defect-stator mechanism were removed. It should again be noted that these stationary blade row cases contained little or no contribution from a vortex. If the rotor tip vortex were as strong as the defect, then the noise from the rotor tip irregularities (defect and vortex) could be around 6 decibels greater than the rotor wake-stator mechanism noise. If it were then possible to remove both the defect and the vortex a noise reduction of about 9 decibels might be possible.

<u>In duct measurements</u>. The attempt in this section is to observe some existing in duct microphone noise measurements and to infer the relative strength of the two mechanisms, RT-S and RW-S. Before this is done however, it is necessary to digress and discuss some facility effects. Noise measurements on the Lewis outdoor fan noise test facility have been somewhat handicapped, as are most static test facilities, in that extraneous noise has been produced by the interaction of an inlet flow distortion or inlet turbulence with the rotor (Ref. 23). This inlet flow disturbance-rotor interaction typically controls the blade passage tone of fans tested on this facility (Refs. 23-25). However, on certain fan stages at certain speed points, the harmonics of the blade passage tone have been shown to be controlled by some other mechanism. This was indicated in Ref. 24 where an increase in rotor-stator spacing brought a reduction in the harmonics for the QF-5 stage. (The blade passage tone did not change with spacing.)

In the testing reported in Ref. 25, the harmonics of the blade passage tone were reduced in the QF-2 fan by replacing the original stator vanes with a set of long chord stator vanes. This harmonic reduction occurred at most speed points but the inlet distortion appeared to control the inlet hemisphere harmonic noise at 90% speed. Some in duct microphone measurements were made on this QF-2 fan and are partially reported by Woodward, et al. in Ref. 26. These measurements consisted of microphone traverses inside the fan ducting at two axial locations, one upstream and one downstream of the fan. The locations are shown in Fig. 6. The data were taken at 60% and 90% of fan design speed.

The purpose here is to use some of the QF-2 in duct measurements to infer the relative strengths of the RT-S and RW-S mechanisms. Since the blade passage tone is presumably controlled by inlet flow distortion and since the distortion affected the harmonics at 90% speed, the level of the second harmonic at 60% speed, was chosen for this comparison. Here at 60% speed, the level of the second harmonic appears to be caused by some rotor-stator interaction (RT-S or RW-S) since the noise responds to changes in stator chord. The in duct variation of this level may then indicate something about the relative strengths of the two mechanisms (RT-S, RW-S).

Woodward et al. (Ref. 26) have previously plotted the variation of the blade passage tone with radius for this data and Fig. 7 was made with Woodward's data by plotting the variation of the second harmonic with radius at 60% speed. As can be seen in Fig. 7 the noise level near the outside wall is considerably higher than elsewhere in the duct. This is true both in the inlet and exhaust ducts. Since the rotor tip irregularity-stator mechanism would produce most of its noise near the tip, as opposed to the rotor wake stator mechanism which would be more uniformly distributed hub to tip, this may indicate that the rotor tip irregularity mechanism is dominant. At least the hub to tip variation of the noise is consistent with that expected to be produced by the rotor tip flow irregularity-stator interaction.

Blade pressure measurements. Blade pressure measurements were taken as part of a program at NASA Lewis which is reported in Ref. 27. During this testing, pressure transducers were placed on both sides of selected stator blades and the signals were recorded. The lift fluctuation was determined at each location by taking simultaneously the difference in pressure across the blade at a given point. The sensor locations are shown in Fig. 8(a). An attempt is made here to compare the tip region (about 7% span from the tip) lift pressure fluctuations with those at some distance in from the tip (about 21% span). As previously mentioned, the blade passage tone is controlled by inlet flow disturbances which also affect the harmonics at 90% speed. Therefore, the harmonics at 60% through 80% speed are of interest. A plot of these levels, Fig. 8(b) shows that the lift fluctuations in the tip region are significantly greater than those further inboard indicating that the tip region is the prime noise location and adding support to the rotor tip irregularity-stator mechanism as the dominant noise source.

Concluding Remarks

It has been the intent of this paper to show the possible significance of the interaction of the rotor tip flow irregularities with downstream stator vanes as a noise source for a turbofan engine. This was accomplished by: indicating the method of formation of these flow irregularities; observing how they would behave with respect to known noise behavior and; comparing the strength of the rotor tip flow irregularity mechanism with the strength of the more common rotor wake mechanism. This latter comparison was based on some existing loss profiles to compare the velocity defects from the two mechanisms and by inferring the primary noise source from existing in duct microphone traverses and blade pressure measurements.

This report has indicated the probable significance of the rotor tip flow irregularity-stator interaction as a noise source. However, more work is needed in this area to accurately assess its importance. In addition, the existence of this potential noise source, while it may first appear to be an additional problem, could be an advantage in reducing fan noise. The seeming concentration of the noise source in a small region near the tip may make it more amenable to reduction. Because of the small area it may be possible to dissipate the region of flow irregularity quickly, possibly by some blade tip redesign or to remove it altogether, possibly by duct wall suction, without having any significant effect on fan performance. In any case this mechanism should be worthy of consideration in future fan source noise reduction attempts.

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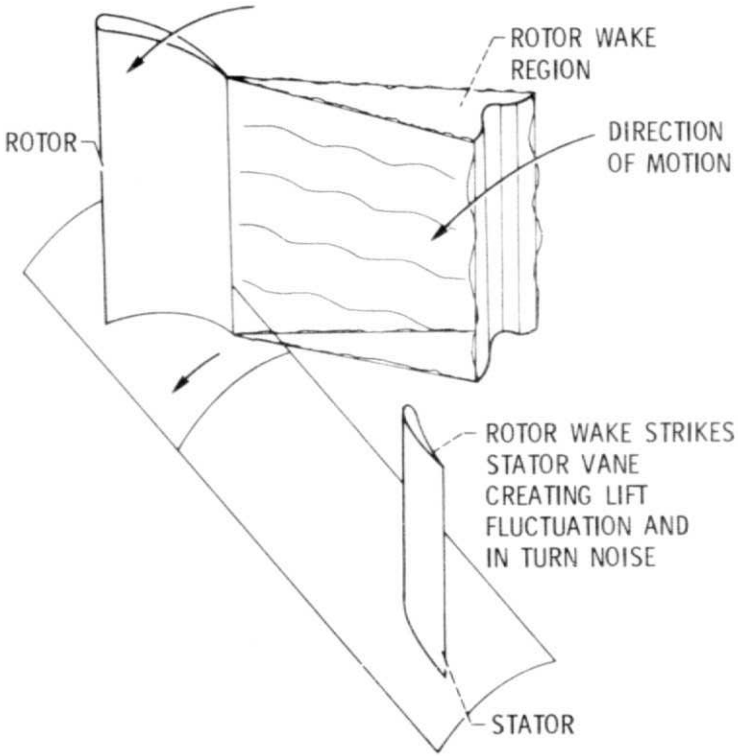
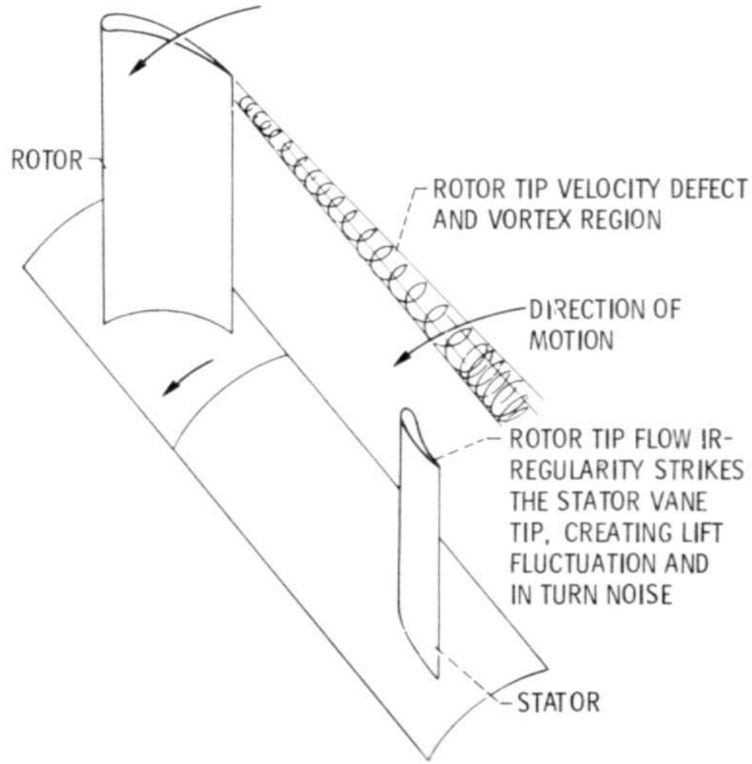


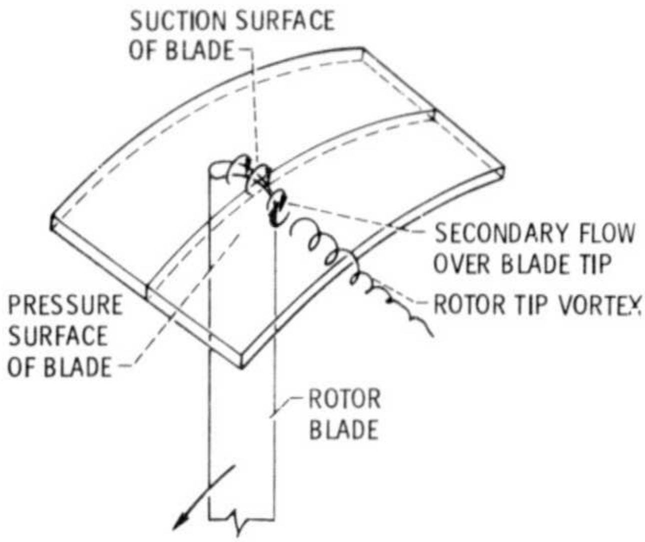
(a) ROTOR WAKE - STATOR INTERACTION MECHANISM.

Figure 1. - Noise mechanisms.



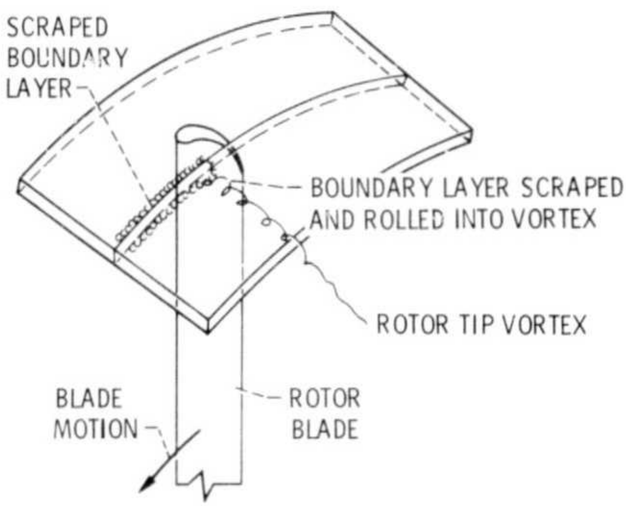
(b) ROTOR TIP FLOW IRREGULARITY - STATOR INTERACTION MECHANISM.

Figure 1. - Concluded.



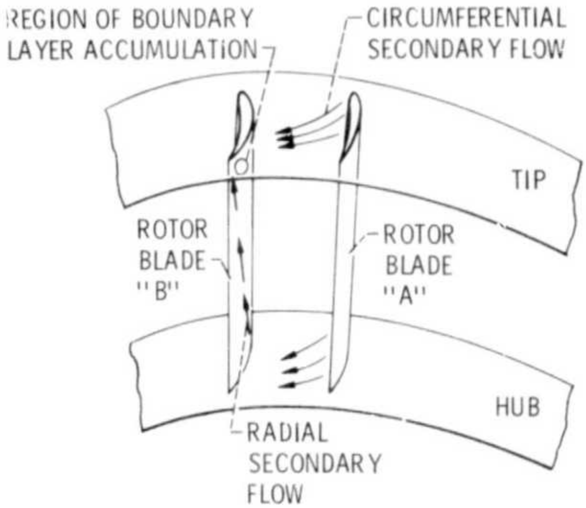
(a) BLADE TIP CLEARANCE VORTEX.

Figure 2. - Sources of rotor tip flow irregularities.



(b) BLADE MOTION VORTEX.

Figure 2. - Continued.



(c) BOUNDARY LAYER ACCUMULATION AT ROTOR TIP.

Figure 2. - Concluded.

E-9244

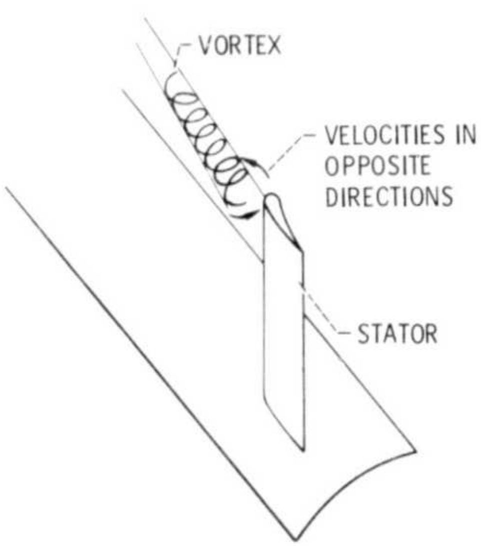


Figure 3. - Variation of vortex upwash.

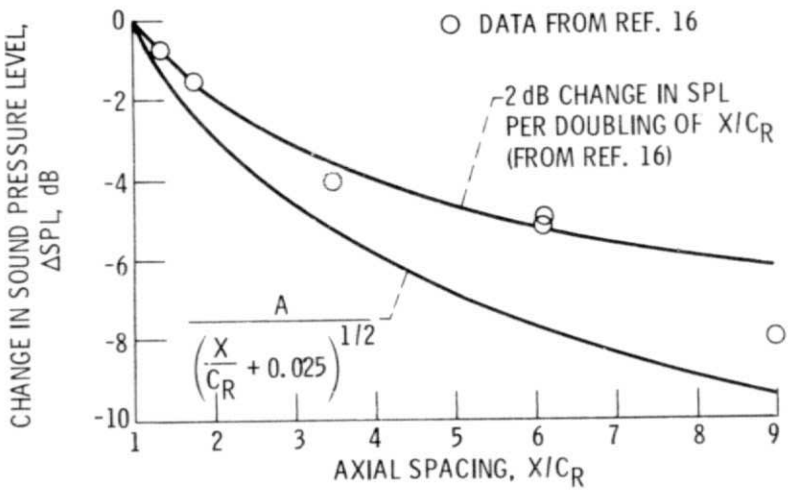
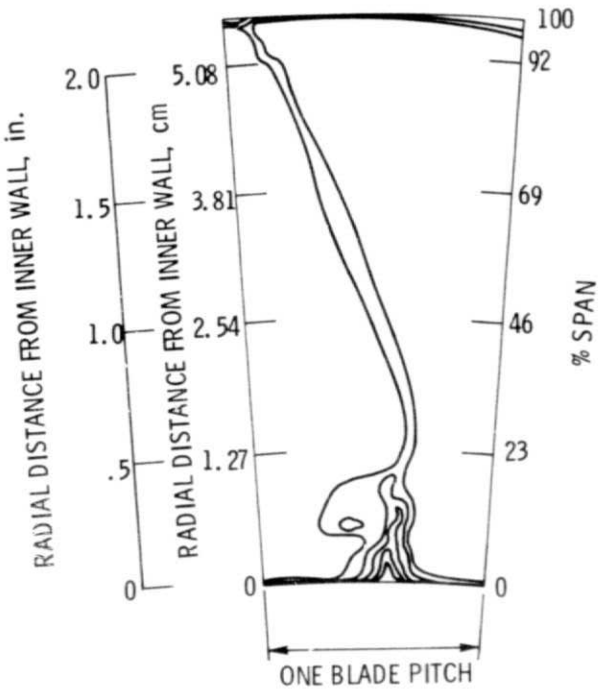


Figure 4. - Change in sound pressure level at blade passing frequency with spacing.

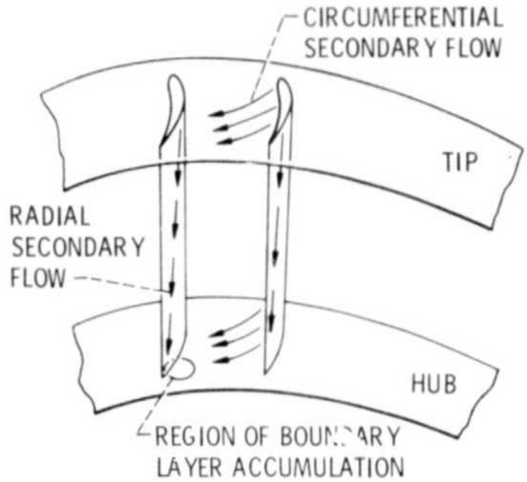


$$\text{LOSS} = 1 - \frac{(\text{LOCAL VELOCITY})^2}{(\text{INLET VELOCITY})^2} \text{ PERCENT}$$

REGION	LOSS RANGE, %	AVERAGE LOSS, %	AVERAGE LOSS - AVERAGE LOSS REGION 1, %
1	0 - 5	2.5	---
2	5 - 10	7.5	5.0
3	10 - 15	12.5	10.0
4	15 - 20	17.5	15.0
5	20 - 25	22.5	20.0
6	25 - 100	62.5	60.0

(a) KINETIC ENERGY LOSS CONTOURS FOR A TURBINE NOZZLE.

Figure 5. - Loss profiles.

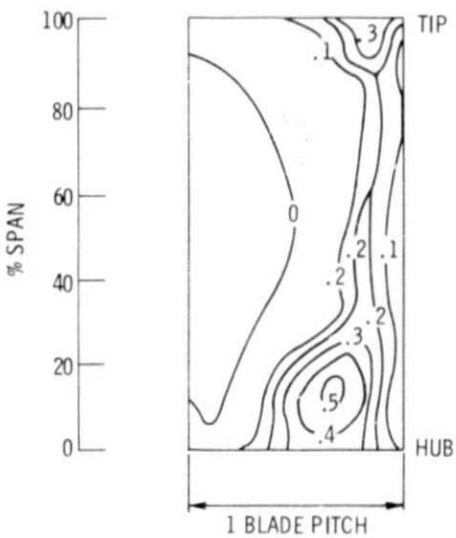


(b) BOUNDARY LAYER ACCUMULATION AT STATOR HUB.

Figure 5. - Continued.

E-9244

$$\text{LOSS COEFFICIENT} = \frac{\text{TOTAL PRESSURE UPSTREAM - TOTAL PRESSURE DOWNSTREAM}}{\text{TOTAL PRESSURE UPSTREAM - STATIC PRESSURE UPSTREAM}}$$



(c) LOSS COEFFICIENT PROFILE BEHIND STATOR (REF. 22).

Figure 5. - Concluded

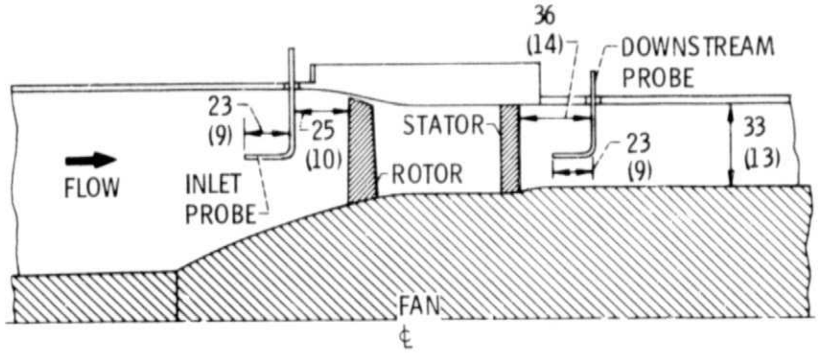


Figure 6. - Acoustic probe installation, cm (in.).

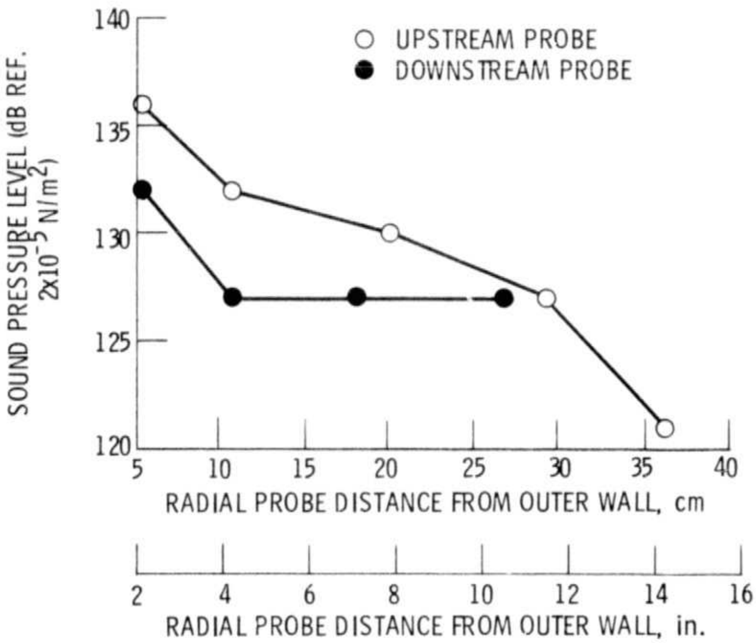
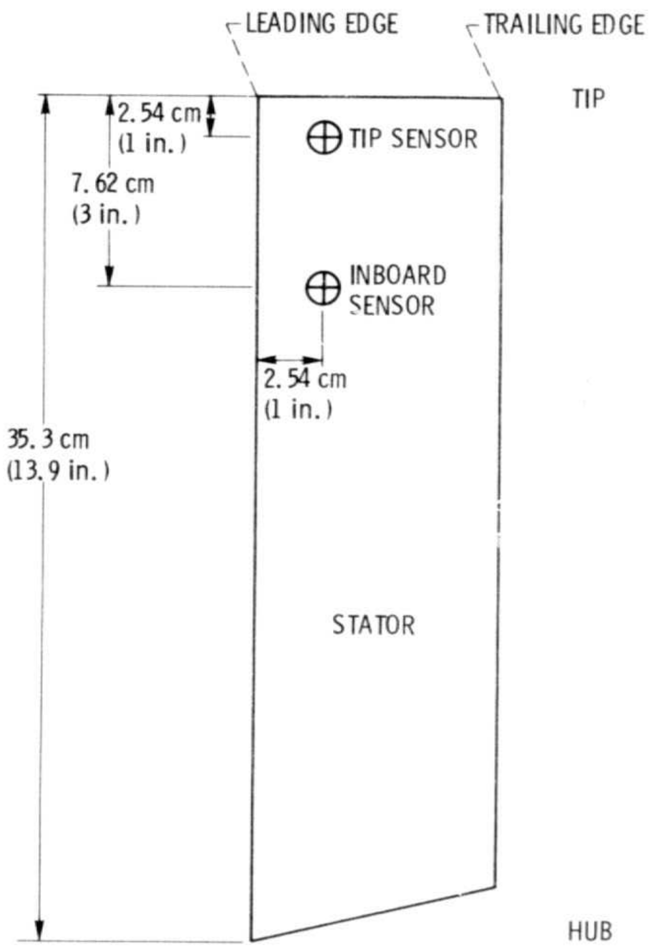
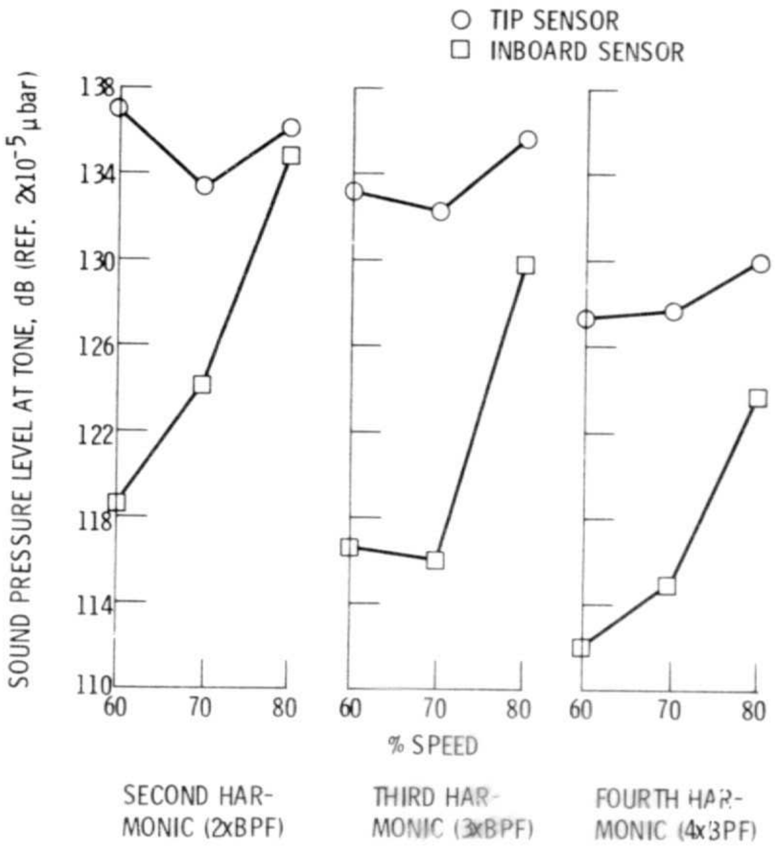


Figure 7. - Variation of second harmonic tone level with distance from outer wall 60% speed.



(a) SENSOR LOCATION.

Figure 8. - Lift pressure fluctuation on stator blade.



(b) PRESSURE FLUCTUATIONS.

Figure 8. - Concluded.