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Rotor Wake Characteristics Relevant to Rotor-Stator Interaction Noise Generation

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ROTOR WAKE CHARACTERISTICS RELEVANT TO ROTOR-STATOR

INTERACTION NOISE GENERATION

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Summary

Mean and turbulence wake properties at three axial locations behind the rotor of an aerodynamically loaded 1.2 pressure ratio fan were measured using a stationary cross film anemometer in an anechoic wind tunnel. Wake characteristics at four radial immersions across the duct at four different fan speeds were determined utilizing a signal enhancement technique. The shapes of the waveforms of the mean rotor relative and mean upwash velocities were shown to change significantly across the span of the blades. In addition, an increase in fan rotational speed caused an increase in the maximum wake turbulence intensity levels near the hub and tip. Spectral analysis was used to described the complex nature of the rotor wake.

Introduction

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One of the major contributions to the overall noise production by turbofans is rotor-stator interaction. One cause of this interaction noise is the fluctuating lift forces acting on the stator vanes as a result of the rotor wakes or tip vortices interacting with the stator.[1,2] The purpose of the present investigation is to experimentally study the variation of the mean and fluctuating properties of rotor wakes across the duct of an aerodynamically loaded 0.5 m diameter fan. The data resulting from this study could then be correlated with acoustic measurements[3] and be used as input for sound generation theoretical models.

A previous paper by Shaw and Glaser[4] reviewed experiments of other investigators and presented mean rotor wake properties in the tip and mid-span region behind the rotor blades in a stationary reference frame. In the present study, mean and turbulence properties of the rotor wakes in both the stationary and the rotor relative coordinate system were investigated at three axial stations downstream from the fan.

The present experimental program was part of a larger fan noise program in which fan noise characteristics were determined as a function of rotor-stator spacing, rotor and stator blade number, and with and without the effects of forward velocity. The experiments were conducted in the NASA Lewis 9x15-foot low-speed anechoic wind tunnel. The fan stage studied had 15 rotor blades, a design pressure ratio of about 1.2 at a tip speed of 213 m/sec (700 ft/sec). Wake characteristics were measured with a cross film anemometer oriented to sense the streamwise and upwash components of the rotor wakes. The wakes were measured at downstream distances of 0.54, 1.23, and 1.77 mean-radius aerodynamic rotor chords.

The data were analyzed to yield the magnitude and width of the wake defect of both the total relative velocity and the upwash velocity component. A comparison of the decay of the velocity defect of the rotor relative velocity with empirical correlations and data from previous investigators is made. The effects of radial immersion, forward velocity and downstream distance on the turbulence levels in the wake are also examined. Finally, a spectral analysis of the waveforms of the relative velocity and upwash velocity component is performed to yield the amplitude of the spatial harmonics of the wakes. In this form, the data should be useful as input to models of fan noise generation.

Apparatus and Procedure

Experimental Test Facility

The NASA Lewis 9x15 anechoic wind tunnel is located in the return loop of the 8x6 supersonic tunnel. The aerodynamic and acoustic properties of the low-speed section are documented in Refs. 5 and 6. The airflow in the test section is varied by control of both the tunnel drive motor speed and the position of the control doors located immediately upstream of the test section. The tunnel was operated both statically and with a free stream velocity of 41 m/sec.

Fan and Installation

The 50.8-cm diameter fan has 15 blades and 25 vanes. The vanes were positioned at three different mean-radius rotor blade chord spacings: 0.54 chord; 1.23 chord; and 1.77 chord. The spacings were based on a 7.7-cm midspan aerodynamic rotor chord. The fan design pressure ratio and work coefficient (change in tangential velocity normalized by tip speed) were 1.2 and 0.43, respectively. The aerodynamic performance of the fan is documented in Ref. 7.

A conventional low throat Mach number (0.60) flight inlet was used for the tests. The 1.46 contraction ratio inlet had a 2:1 elliptically contoured lip and a length of approximately 52.6 cm. Aerodynamic performance of the inlet can be found in Ref. 8. The installation of the fan in the wind tunnel is shown in Fig. 1. Shown in the photograph is a rotating microphone boom along with several aft microphones. The acoustic data from these microphones are not presented in this paper, but are reported in Ref. 3.

Instrumentation and Procedure

Rotor wake properties were measured with a cross film anemometer. Each film was 70 μm in diameter and 1.25 mm long. The cross film anemometer was located in the plane of the leading edge of the stator vanes midway between two vanes (Fig. 2) except for one series of experiments. In that series, the anemometer was located midway between two vanes but upstream of the stator leading edge plane. Since the measurements were all midway between vanes even when in the plane of the stator leading edge, any effect due to the proximity of the stators was expected to be small.

The following table lists the axial spacings of the anemometer and stator vanes from the rotor blades for each test condition.

Test series	Rotor-stator spacing (rotor chords)	Rotor-anemometer spacing (rotor chords)
1	0.54	0.54
2	1.77	1.23
3	1.77	1.77

Figure 3 shows schematically the film orientation and the fluctuating velocity across a wake behind a rotor blade as it appears to a stator vane. The following table lists typical values of the streamwise Mach number measured by the cross film probe and the probe set angles at 80 percent of design speed.

Immersion	Streamwise Mach number	Probe set angle
1.27 cm	0.35	28.9°
4.05 cm	.39	31.4°

The streamwise velocity changes magnitude as it fluctuates between the angles $\beta \pm \theta$. The cross film was oriented so that the mean streamwise velocity component into the stator would bisect the angles formed by the two films. The cross film had been calibrated for yaw angle before the test so that the fluctuating angle (θ) would be measured accurately. The orientation of the cross film was such that both the streamwise and upwash components of the flow entering the stator row were determined.

Measurements were made at several radial positions ranging from 9 percent of the span from the tip to 80 percent of the span. Data near the blade tip at 9 percent of the span from the tip (1.27 cm immersion) and at 30 percent of the span (4.05 cm immersion) at 80 percent design rpm are highlighted in this paper. The anemometer signals were linearized, summed and differenced and d.c. suppressed before being recorded on magnetic tape. A typical sample of the linearized signals is shown in Fig. 4. After linearization, the signals were digitized and analyzed with a computer program which utilized an ensemble averaging technique and Fourier transform analysis. Data averaging was done over 500 revolutions of the rotor and was triggered by a once-per-revolution signal generated by a magnetic pickup located on the rotor shaft and recorded on the data tape. Included in the program output were averaged waveforms through the wake, intensity levels and spectra of the upwash component and relative velocity.

Results and Discussion

The wake data were analyzed in terms of mean and turbulence properties and harmonic content. The differences in wake properties between a near tip probe radial immersion and an immersion of 30 percent of the span from the tip are emphasized. The effects of forward velocity and fan speed on the wake properties are also examined. A comparison of measured mean wake parameters with empirical correlations and data of other experiments is presented. As was pointed out in the Apparatus and Procedure Section, the data at 1.23 chords was obtained with the stator located at 1.77 chords, whereas the remaining data were obtained in the plane of the stator leading edge.

Wake Mean Properties

Figure 5 shows the mean rotor wake waveforms of the relative and upwash components of velocity across the span of the rotor blades at a rotor anemometer axial spacing of 1.23 rotor chords at 80 percent of design rpm with a tunnel velocity of 41 m/sec. Away from the tip, the velocity waveforms are similar in shape with a single velocity defect region behind each blade. From Fig. 5 it can be seen that the defect varies in its width and amplitude as a function of position along the span. The majority of the waveforms are asymmetric but similar from blade to blade at 80 percent design speed. However, near the blade tip at a probe immersion of 9.3 percent of the span, the waveforms are characterized by two regions of velocity change behind each blade. The complex nature of the tip waveforms reflects the complicated flow pattern in the blade tip region. The simple wakes and potential flows are complicated by interactions with the casing boundary flow as well as a number of secondary flows, for example, tip clearance flow, passage vortex flow, scraping vortex flow, etc. Some of these secondary flows are discussed by Dittmar,[2] Pillips and Head,[9] and Lakshminarayana and Ravindranath.[10] A tip vortex can be generated because of the clearance between the blade and the outer wall which allows communication between the pressure and suction sides of the blade thus resulting in a secondary flow. It could also be generated by the relative motion of the blade scraping the wall boundary layer and rolling it into a vortex. Since the radial component of the velocity field behind the blade was not measured, it is not possible to determine which region of the tip waveforms shown in Fig. 5 can be attributed to a tip vortex.

The effects of tip speed on the change in mean velocity in the wake at the closest rotor stator spacing are shown in Fig. 6. In order to display the rotor wake behavior, a wake magnitude parameter, $\Delta V_w/V_{free\ stream}$, where ΔV_w is the peak to peak value of velocity in the wake, was defined. For the upwash component, ΔV_w is normalized by the free stream value of the absolute streamwise velocity component, while ΔV_w for the relative velocity is normalized by the rotor relative free stream velocity. In the near tip region, the effects of fan speed are minimal. At probe immersions from near tip to midspan, the rotor relative velocity defects decrease with increasing fan speed. This trend is consistent with that observed by Lakshminarayana, et al.[11] Near the hub, however, both the rotor relative and the upwash velocity magnitudes show an increase with fan speed. The high levels of the wake magnitude parameter near the hub and tip reflect the large aerodynamic losses that occur in these regions.

For noise generation and other purposes, such as forced vibrations, one is interested in the decay characteristics of the wake as a function of downstream distance. Figures 7 and 8 examine the effects of rotor stator spacing on the rotor wake magnitude parameter at two fan speeds, 80 and 115 percent of design speed. To illustrate the effects of inflow turbulence and disturbances on the rotor mean properties, the wake magnitude parameter at 80 percent of design rpm is presented in Fig. 7 for a static tunnel flow condition ($U = 0$) and a forward velocity condition ($U = 41$ m/sec). Forward velocity reduces the turbulence and other inflow disturbances entering the inlet by reducing the stream tube contraction ratio and eliminating many sources of flow disturbances associated with the flow being drawn over the cowl and support structure from the aft direction. This "cleanup" of the inflow greatly reduced the noise generated by the fan due to the rotor interaction with inflow disturbances.[12,13] The effects of free stream turbulence on rotor wake properties were systematically studied by Kah and Lakshminarayana.[14] They found that a large reduction in inflow turbulence intensity resulted in a minimal change in the velocity defect.

Figure 7(a) presents the effects of downstream distance and forward velocity on the relative velocity and upwash velocity component at a probe immersion of 30 percent of the span from the tip. The wake magnitude parameter ($\Delta V_w/V_{free\ stream}$) for both velocity components decays with increasing downstream distance. The magnitude of the upwash component decays at a faster rate than that of the rotor relative velocity, but both velocities reach the same value at the farthest rotor stator spacing. Forward velocity lowers the upwash parameter at the close rotor-stator spacing but has a minimal effect on the rotor relative velocity.

As shown previously (see Fig. 6), the effect of increased fan speed is to lower the rotor wake magnitude near the mid-span region. This effect is observed in Fig. 7(b), which indicates lower values of the wake magnitude parameter at 115 percent of design speed than those measured at 80 percent. The wake magnitude decays much more slowly at 115 percent than at 80 percent of design speed. This effect of decrease in decay rate with increasing speed was also observed by Lakshminarayana.[11]

As discussed earlier, the tip rotor wake waveforms have a more complex shape than those at the other span positions. The schematics in Fig. 8 show that near the tip, the rotor wake waveform is characterized by two regions of velocity change behind each blade. Since one value of the wake magnitude parameter is not an adequate descriptor of the dual change in velocity indicated by the waveforms, two values of the wake magnitude parameter are presented for each waveform - one describing the change in velocity on the pressure side of the waveform and one for suction side (see schematic in Fig. 8). The wake magnitude on the pressure side of the waveform decays at a much faster rate than that on the suction side for both the relative velocity and upwash component. Between the first two downstream measuring stations, the magnitude of the upwash decays faster with forward velocity than with static tunnel operation.

Near the tip, the wake magnitudes at 115 percent of design speed are close to the same values as those at the lower fan speed of 80 percent rpm (Fig. 8(c)). Only one wake parameter for each waveform is plotted because the two regions of velocity change in each waveform now have merged to form one wide region of velocity change behind the rotor as shown in the schematic of Fig. 8(c). The values of the wake magnitude parameter for the upwash component are higher than those of the relative velocity for the first two rotor anemometer spacings. However, at the farthest downstream spacing, the wake magnitudes for both velocities are the same.

Another parameter commonly used to describe the wake is the wake width. The wake width is measured at the point where the wake velocity is half of its extreme value. Figure 9 shows the effects of downstream distance and forward velocity on the wake widths which have been normalized by the spacing between blades. Because of the complex shapes of the wake waveforms near the blade tip, only the widths of the wakes at the station 30 percent of the span from the tip were measured. At 80 percent of design speed, the wake widths of both velocities gradually increase with increasing downstream distance. The upwash component has a slightly higher wake width than the relative velocity. The effect of forward velocity is minimal. At 115 percent of design rpm (Fig. 9(b)) the wake widths are slightly greater than those at 80 percent rpm, however, the rate of increase of the wake width with downstream distance is nearly the same.

Comparison of Mean Properties with Empirical Predictions

The effect of rotor wakes on aircraft engine compressor and turbine performance has been a concern for many years. Several empirical relationships developed by investigators have been widely used to predict the velocity defect in the wake. A summary of these empirical correlations is given by Dittmar.[15] Perhaps the prediction of velocity defect most often used was developed by Silverstein for an isolated airfoil in 1939.[15] The velocity defect is predicted to be:

$$\frac{\Delta V_w}{V} = \frac{2.42\sqrt{C_D}}{\left(\frac{x}{c} + 0.3\right)} \tag{1}$$

where

ΔV_w	maximum difference from free stream velocity in the wake
V	free stream velocity
C_D	profile drag coefficient
x	downstream distance
c	rotor chord

In 1953 Spence[17] fit his data for a turbulent wake behind an airfoil with

$$\frac{\Delta V_w}{V} = \frac{0.1265}{\left(\frac{x}{c} + 0.025\right)^{1/2}} \tag{2}$$

From cascade investigations Lieblein and Roudebush[18] fit their data with

$$\frac{\Delta V_w}{V} = \frac{A_2\sqrt{C_D}}{\left(\frac{x}{c} + 0.025\right)^{1/2}} \tag{3}$$

where

$$A_2\sqrt{C_D} = 0.13$$

In 1979 Reynolds and Lakshiminarayana at Pennsylvania State University measured wake properties behind rotating blades with a triple wire anemometer.[19] Their velocity measurements of the defect of the relative velocity correlated well with the expression

$$\frac{\Delta V_w}{V} = C_D^{1/4}\left[B_5\left(\frac{s}{c} - \frac{s_0}{c}\right)^{-1/2} + B_6\left(\frac{s}{c} - \frac{s_0}{c}\right)^{-1}\right] \tag{4}$$

where

s streamwise distance
s_0 streamwise virtual origin

for the far wake region where $s/c > 0.25$:

$$s_0/c = -0.36, \ B_5 = 0.271 \ \text{and} \ B_6 = 0.0$$

In 1980, Ravindranath and Lakshminarayana performed a similar experiment behind a rotor with greater loading.[20] Their wake data in the axial direction correlated well with the following:

$$\frac{\Delta V_w}{V} = C_D^{1/2}\left[0.39\left(\frac{z}{\cos\beta_0}\right)^{-1} + 0.984\right] \tag{5}$$

for

$$0.2 < \left(\frac{z}{\cos\beta_0}\right) < 0.8$$

where

z axial distance from blade trailing-edge normalized by rotor blade chord
β_0 blade outlet angle

Figure 10(a) shows a comparison of the data measured in the present experiment with results predicted by these empirical equations. The empirical predictions were calculated using the profile drag coefficient approximated by Shepherd[21] to be

$$C_D = \frac{\overline{\omega}_p \cos^3\beta_\infty}{\sigma \cos^2\beta_1} \tag{6}$$

where

σ solidity
β_1 relative flow angle at rotor inlet
β_∞ $\tan^{-1}\left\{\frac{1}{2}(\tan\beta_1 + \tan\beta_2)\right\}$
β_2 relative flow angle at rotor exit
$\overline{\omega}_p$ profile loss coefficient

The values of the aerodynamic parameters used in this expression were obtained from Ref. 7 for a radial station 30 percent of the span from the tip at 80 percent of the fan design speed. Figure 10(a) indicates that the authors' data agree well with the empirical correlations of Spence, Lieblein and Reynolds. However, the correlations of Silverstein and Ravindranath overpredict the velocity defect. Although Silverstein's, Ravindranath's, and Lieblein's equations present the velocity defect to be a function of $C^{1/2}$ only Lieblein allows the constant A_2 to vary with the drag coefficient. The best prediction of the velocity defect, however, is based on Reynolds correlation with $C_D^{1/4}$. It should be noted that the expressions developed by both Reynolds and Ravindranath have been extrapolated beyond the downstream limits of the data used to construct them in order to make a comparison with present data. Figure 10(a) also shows a comparison of the authors' data with data measured by Ravindranath and Lakshminarayana[20] and Magliozzi, et al., at Hamilton Standard.[22]

Ravindranath and Lakshminarayana measured data behind an experimental rotor with a design speed of 1066 rpm at an operating flow coefficient (relative velocity/tip velocity) of 0.56. The data measured by Magliozzi, et al., was taken behind a 12 bladed rotor with a pressure ratio of 1.07 at a rotor speed of 6620 rpm. Although both sets of measured velocity defects are greater than measured in the present experiment, the measured 9x15 tunnel data does follow the trend of the other experimental results.

A comparison of the authors' measured wake widths with those predicted by correlations of Kemp and Sears, Reynolds and Lakshminarayana, and Ravindranath and Lakshminarayana is presented in Fig. 10(b).

In the far wake, Reynolds and Lakshminarayana[19] predict the wake width normalized by the blade spacing (δ/s_p) to be

$$\frac{\delta}{s_p} = C_D^{1/4}\left[0.735\left(\frac{s}{c} - 0.258\right)^{1/2}\right] \tag{7}$$

Ravindranath and Lakshminarayana[20] correlated their data in the far wake with

$$\frac{\delta}{s_p} = 0.5\sqrt{C_D}\left[0.833\left(\frac{z}{\cos\beta_o}\right) + 1.302\right] \tag{8}$$

In Ref. 23 Kemp and Sears used the following modified form of the wake width equation developed by Silverstein, et al.,[16]

$$Y = 0.68\sqrt{2}\, C_D^{1/2}\, c_h\left(\frac{x}{c_h} - 0.7\right)^{1/2} \tag{9}$$

where

- Y half width of the viscous wake
- c_h airfoil half chord
- x distance along airfoil measured from mid chord

The data in Fig. 10(b) agree well with the empirical correlations at the closest spacing but does not show the constant rate of increase that the correlations predict.

Wake Turbulence Properties

Figure 11 shows the turbulence intensity levels of both the relative and upwash velocities across the span of the rotor blades at a rotor anemometer axial spacing of 1.23 rotor chords at 80 percent of design rpm with a tunnel velocity of 41 m/sec. For the relative component the turbulence intensity is defined as the root-mean-square of the fluctuating velocity normalized by the local mean relative velocity. The root-mean-square of the upwash fluctuating velocity was normalized by the local mean streamwise velocity. From the near tip through the midspan region of the blades, the intensity levels of both velocities are nearly the same. At the immersion closest to the hub, the rotor relative intensity reaches nearly 10 percent in the wake compared to the upwash wake level of 7.2 percent. The free stream level of turbulence is nearly constant at about 1.5 percent at all probe immersions except near the tip where it shows a large increase to about 40 percent for both components.

The effects of fan speed on the maximum turbulence intensity levels in the wake at the close rotor stator spacing with a forward velocity of 41 m/sec are shown in Fig. 12. The levels of intensity in the wake are higher for the upwash (Fig. 12(b)) compared to the intensity measured for the relative velocity (Fig. 12(a)). As mentioned previously, the fluctuating upwash and relative velocities were normalized by streamwise and relative free stream mean velocities, respectively. In general, away from the hub and tip measuring stations, an increase in fan rotational speed was accompanied by a decrease in turbulence intensity level. This same trend was observed by Lakshminarayana, et al. for the relative tangential and axial velocity components in Ref. 11. In the near tip and hub regions, however, an increase in fan rotational speed from 60 to 115 percent of design speed brought a definite increase in the turbulence intensity levels of both components at the closest rotor-stator spacing. These high intensity levels occur in regions where the measured aerodynamic losses are high (Ref. 7) and secondary flows are prominent.

Figures 13 and 14 present the effects of downstream distance and forward velocity on the maximum levels of the upwash and relative turbulence intensities in the wake. Data is presented at both 80 and 115 percent of design speed to further examine the effects of fan speed on wake turbulence. To study the effects of forward velocity, that is, a reduced level of fan inflow disturbances including turbulence,[13] wake turbulence intensities are presented with both forward velocity (U = 41 m/sec) and static tunnel operating conditions (U = 0).

At a probe immersion of 30 percent of the span from the tip, it can be seen from Fig. 13(a) that the maximum intensity of the upwash component is at a higher level than that of the relative velocity. Forward velocity, which reduces the level of the turbulence to the rotor, also reduces the maximum wake turbulence level at the 0.54 c rotor-stator spacing. The decay rate for the upwash component between the first two downstream measuring stations is slightly greater for the static tunnel operating condition (high inflow turbulence) than for the forward velocity conditions. This trend is in agreement with Hah and Lakshminarayana's findings that the maximum turbulence intensity increases with an increase in free stream turbulence level, but decays faster at higher values of free stream turbulence intensity.[14] As can be seen in Fig. 13(a), there is little decay, even a slight increase in the rotor relative intensity between the first two downstream measuring stations.

At a higher fan speed of 115 percent of design rpm (Fig. 13(b)), the upwash intensity level decreases at about the same rate with increasing downstream distance as it does at 80 percent of design speed, but the overall levels of maximum wake intensity for the upwash component are slightly lower.

In the tip region of the blades (Fig. 14(a)) at 80 percent of design speed, the turbulence intensity levels for both the upwash and rotor relative velocities are slightly higher than they are at a probe immersion of 30 percent of the span (Fig. 13(a)). The decay rates of intensity for the two probe immersions are similar.

At the high fan speed of 115 percent of design rpm (Fig 14(b)) the near tip levels of maximum turbulence intensity are much higher than those in Fig. 13(b) at a probe immersion of 30 percent of the span from the tip. At the closest rotor-stator spacing, the upwash intensity increases from 8.8 to 13.0 percent while the relative intensity increases from 5.8 to 8.4 percent. The decay rate of the intensities at the higher fan speed is not as steep as the decay rate at 80 percent of design speed. Thus, the effect of increased fan speed on maximum turbulence intensity levels in the wake is more pronounced in the tip region of the blade.

Spectral Analysis of Rotor Wakes

The ensemble averaged waveforms were analyzed by Fast Fourier Transform methods to determine their harmonic content. Data from this analysis are more descriptive of the waveform than parameters such as the wake defect and wake width, especially for the complicated wake profiles observed near the tip. In addition, in this form the data are probably more useful for analysis of the noise caused by the wakes impinging on the stators. There is a direct frequency correspondence between the harmonics of the wake and the harmonics of the sound field generated in the wake-stator interaction.[3]

Typical spectra of the ensemble averaged wake velocities are shown in Fig. 15. The figure shows the spectra of the rotor relative and upwash velocities at 1.23 rotor chords downstream at 80 percent of design speed and at a probe immersion of 30 percent of the span from the tip. The measured velocities were normalized to a reference velocity of 3.05 m/sec and the spectra of the normalized velocity squared were computed in decibels.

Figures 16 to 18 utilize data from spectra such as these for the rotor relative and upwash velocities to examine the changes of spectral content with downstream distance and to compare the spectral content at two radial probe immersions all with a tunnel flow of 41 m/sec.

Figure 16 shows the harmonic content of the upwash and rotor relative components of velocity at 80 percent of design speed at a probe immersion of 30 percent of the span from the tip. The rotor relative component increases slightly at the blade passage frequency (BFF) and its second harmonic (2xBPF) between the first two downstream measuring stations while the third harmonic drops off slightly. At the closest rotor-stator spacing, the level of the BPF and its second and third harmonics are nearly the same. This same trend at the closest spacing is observed for the upwash component but at a slightly higher decibel level. The upwash component shows a nearly constant level at the blade passage frequency and its second harmonic between the first two downstream stations. In general, there is a sequential ordering of the harmonics of the blade passing frequency at all three downstream measuring stations for both velocity components.

In contrast to this sequential harmonic ordering at the 30 percent probe immersion, Fig. 17 indicates a nearly constant dominant level of the second harmonic between the first two downstream stations in the tip region at 80 percent of design rpm with a fall off at the blade passage frequency between these stations. The high levels of the second harmonic indicate the two oscillations in velocity for each blade gap which persist even to the farthest downstream measuring station (see sketches in Fig. 8).

Figure 18 shows trends of decay of the harmonic content for the upwash and relative velocities at 115 percent of design speed at a probe immersion of 30 percent of the span from the tip. Generally the harmonic levels of the relative velocity are higher than those of the upwash component. The increase in fan speed from 80 to 115 percent of design causes a higher level at the blade passage frequency and its second harmonic at the close spacing for the relative component but does not change the levels of the blade passage frequency and its second harmonic for the upwash component. Again a sequential ordering of the harmonic levels of the blade passing frequency is observed similar to that at the 80 percent design speed case.

Figure 19 shows that the levels at blade passage frequency and its harmonics decrease with increasing downstream distance for both the rotor relative and upwash velocities at 115 percent of design rpm at a near tip probe immersion. The blade passage frequency level is nearly 10 dB higher at the near tip immersion at 115 percent of design rpm compared to the 30 percent of span probe immersion. The effect of increasing fan rotational speed near the tip is to raise the level of the blade passage frequency and its harmonics. At the higher fan speed the amplitude of the blade passage frequency instead of its second harmonic dominates the spectra at all three downstream positions. These high levels at the blade passage frequency are indicative of the waveforms sketched in Fig. 8(c) showing that the two regions of velocity change behind the blade caused by the blade wake and secondary flow effects have now merged. Not only is the blade passing frequency amplitude dominant at the tip region at the higher fan speed, but the harmonic levels of the blade passage frequency now follow a sequential ordering at all three downstream measuring stations.

Summary of Results

An experiment was conducted to determine the mean and turbulence properties and the harmonic content of the blade wakes as a function of distance downstream of an aerodynamically loaded rotor. The effects of fan rotational speed and inflow turbulence were also studied.

The rotor wake mean velocities varied considerably in amplitude and width across the blade span from hub to tip. The mean wake waveforms near the tip are characterized by two regions of velocity change behind each blade at the lower fan speeds. These waveforms indicate that a velocity change due to the blade wake along with a velocity change due to a secondary flow phenomenon is present even at the farthest rotor-stator spacing. Above design speed only one wide wake in the tip region is observed indicating that the blade wake and secondary flow effects have merged.

The normalized wake magnitude decreases with increasing downstream distance from the rotor. In general, forward velocity has an inconsistent but minimal effect on the wake magnitude. The wake magnitude decays at a faster rate as axial distance is increased beyond 1.2 rotor chords. An increase in fan speed causes a large increase in the wake magnitude parameter near the hub. The width of the rotor wake gradually increases with increasing axial distance.

The measured mean rotor wake defects agree well with the data measured by other experimenters and the correlation developed by Reynolds where the wake velocity defect is a function of $C_D^{1/4}$.

The maximum turbulence intensities in the wake for the relative and upwash velocities decrease with increasing downstream distance.

forward velocity decreases the maximum intensity levels in the wake for both velocities at the 0.54 c measuring station. In general, an increase in the fan speed causes an increase in the maximum turbulence intensity levels near the hub and tip, but a decrease near the mid-span region.

Although only two components of velocity were measured in the present experiment, the data presented in this paper provides insight into the complex nature of the velocity components of the rotor wakes. The determination of the harmonic content of the rotor wake velocity profiles provides a key ingredient required for the analysis of fan tone noise generated by rotor-stator interaction.

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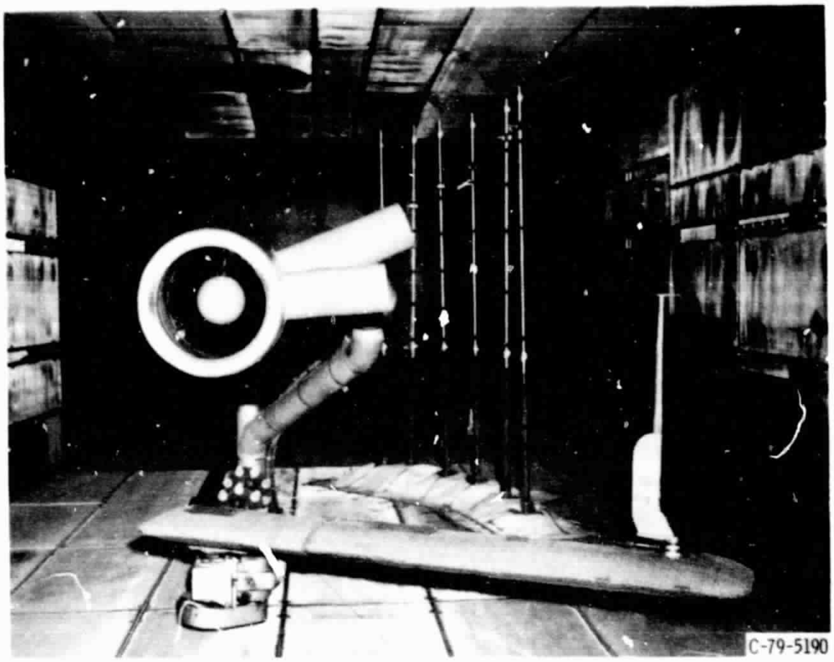


Figure 1. - Upstream view of fan simulator in tunnel.

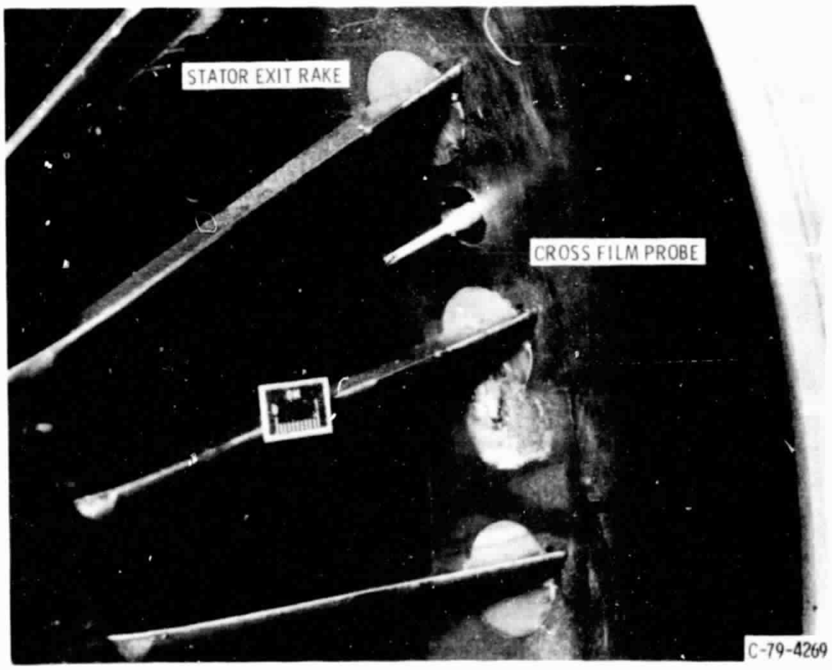


Figure 2. - Position of cross film relative to stator vanes.

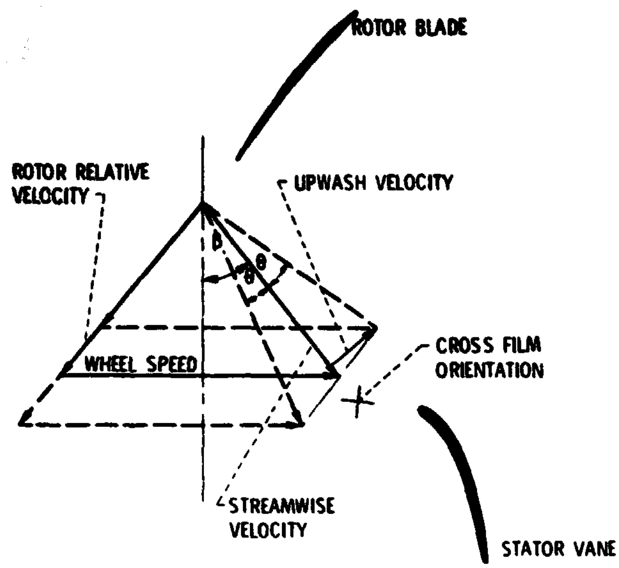


Figure 3. - Schematic of cross film orientation (β = probe set angle, θ = fluctuating angle about β).

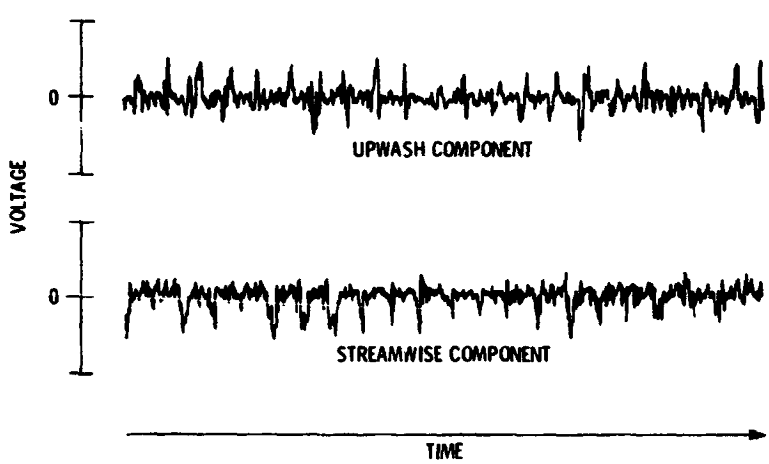
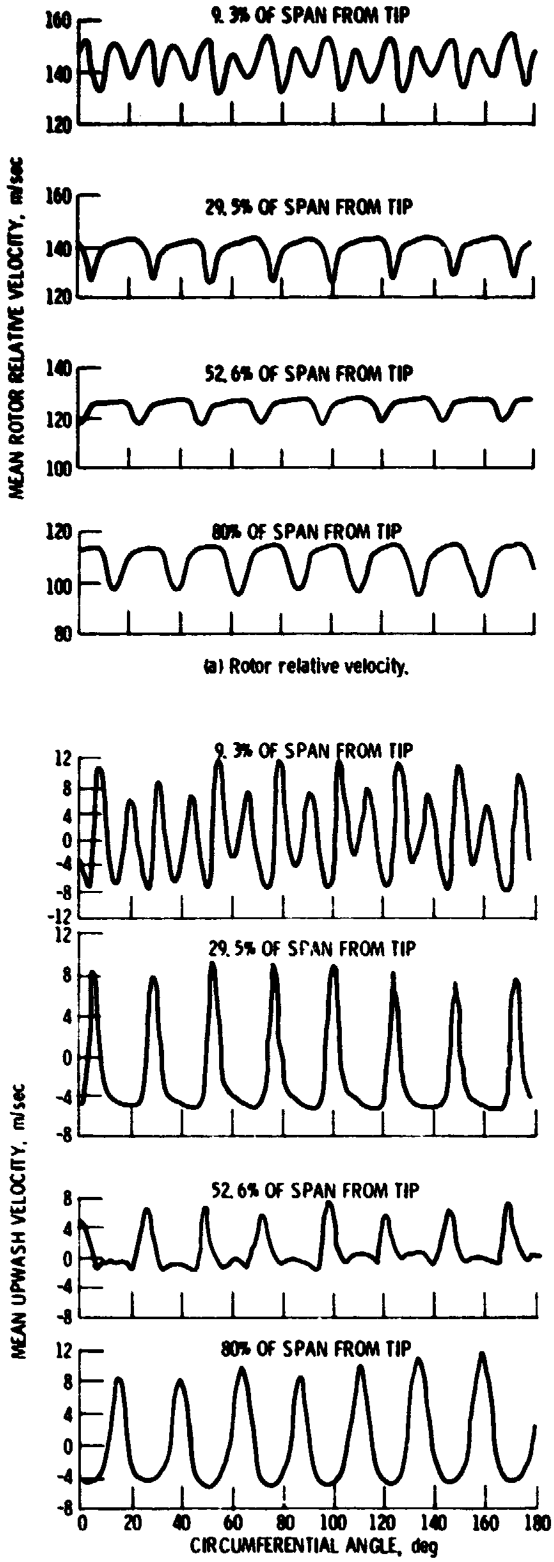


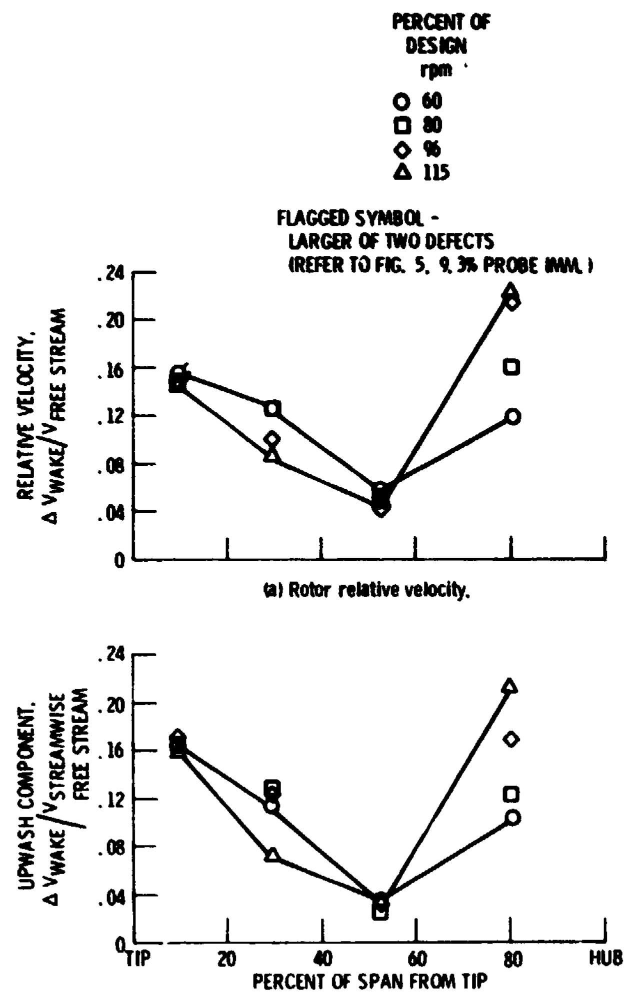
Figure 4. - Typical linearized voltage from cross film anemometer.



(a) Rotor relative velocity.

(b) Upwash component.

Figure 5. - Mean velocity across the duct at 80 percent of design RPM, U = 41 m/sec, 1.23 c spacing.



(a) Rotor relative velocity.

(b) Upwash component.

Figure 6. - Radial variation of the change in the mean velocity in the wake, 0.546 c spacing, U = 41 m/sec.

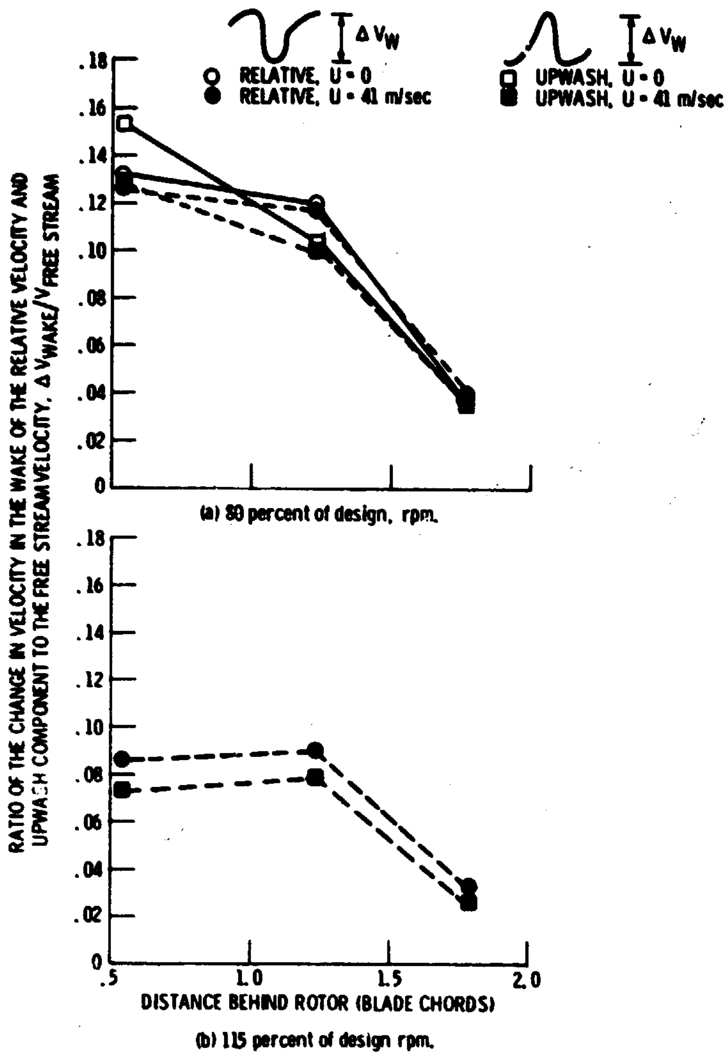
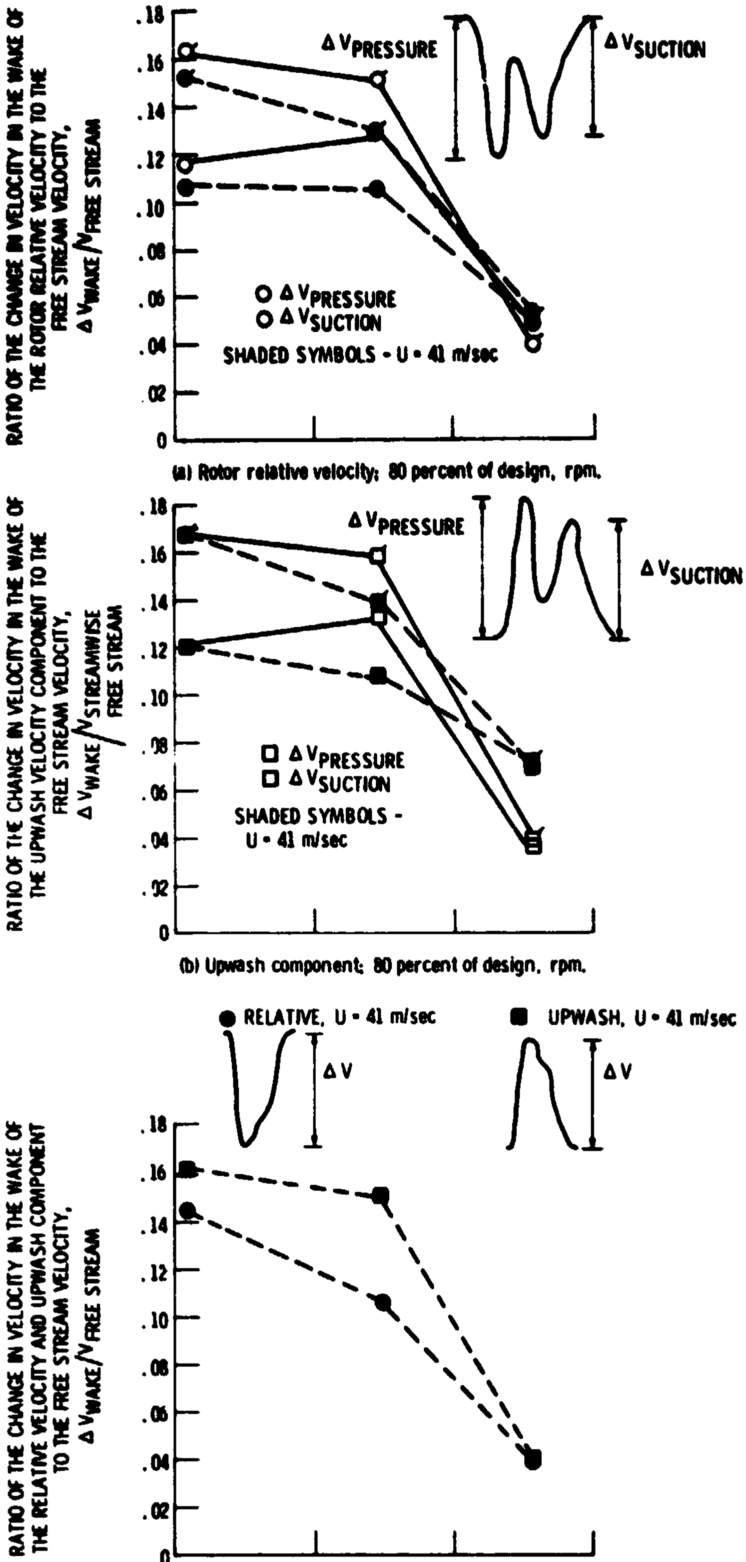


Figure 7. - Effect of downstream distance and forward velocity on the change in the relative velocity and upwash component in the wake at 30 percent of span from the tip.

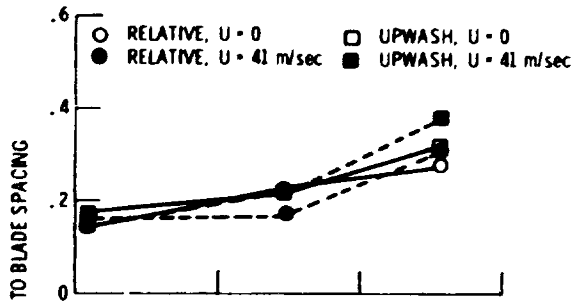


(a) Rotor relative velocity; 80 percent of design, rpm.

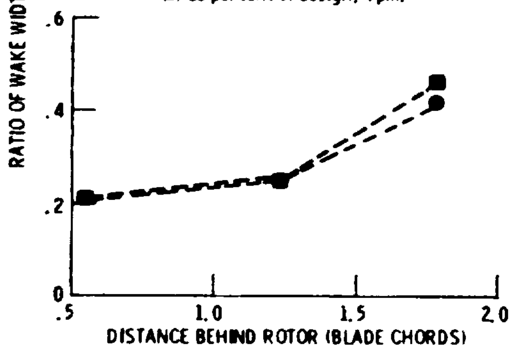
(b) Upwash component; 80 percent of design, rpm.

(c) Rotor relative velocity, upwash component; 115 percent of design rpm.

Figure 8. - Effect of downstream distance and forward velocity on the change in the velocity in the wake at 9.0 percent of the span from the tip.

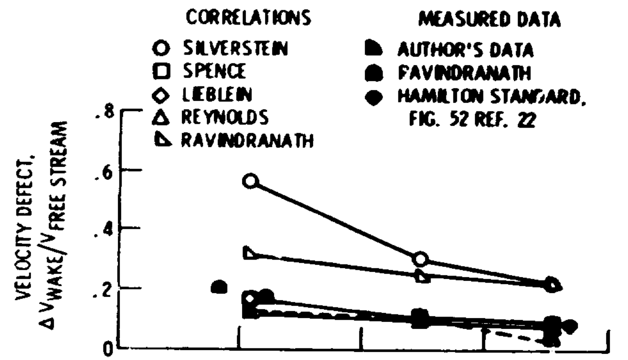


(a) 80 percent of design, rpm.

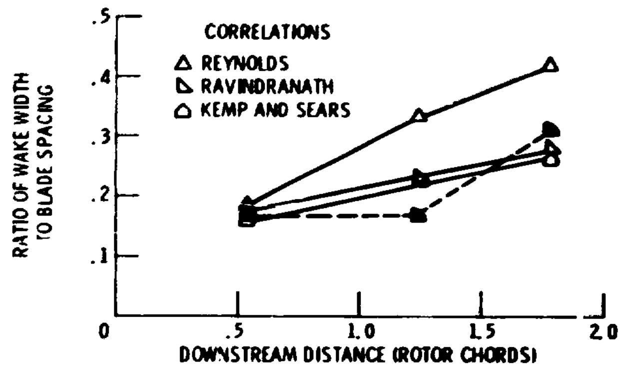


(b) 115 percent of design rpm.

Figure 9. - Effect of downstream distance and forward velocity on the width of the rotor wake at 30 percent of the span from the tip.



(a) Comparison of measured wake velocity defect in rotor relative system with correlations and other data, 30 percent of span from tip, 80 percent of fan design speed, U = 41 m/sec.



(b) Comparison of measured wake width in rotor relative system with correlations and other data, 30 percent of span from tip, 80 percent of fan design speed, U = 41 m/sec.

Figure 10.

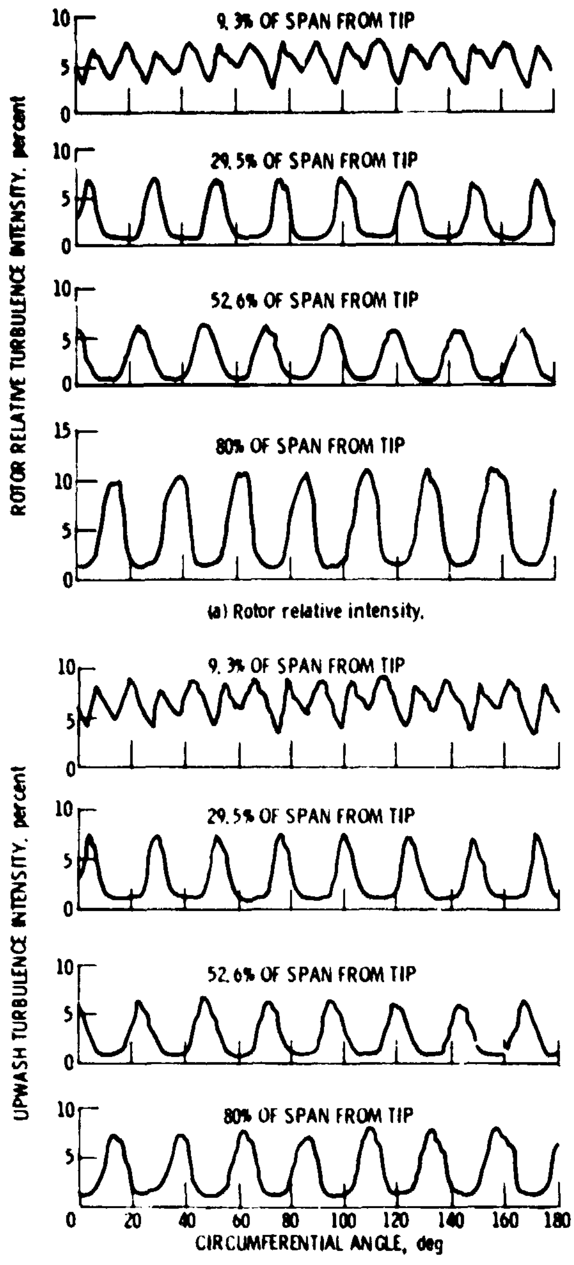


Figure 11. - Turbulence intensity across the duct at 80 percent of design, rpm, U = 41 m/sec, 1.23 c spacing.

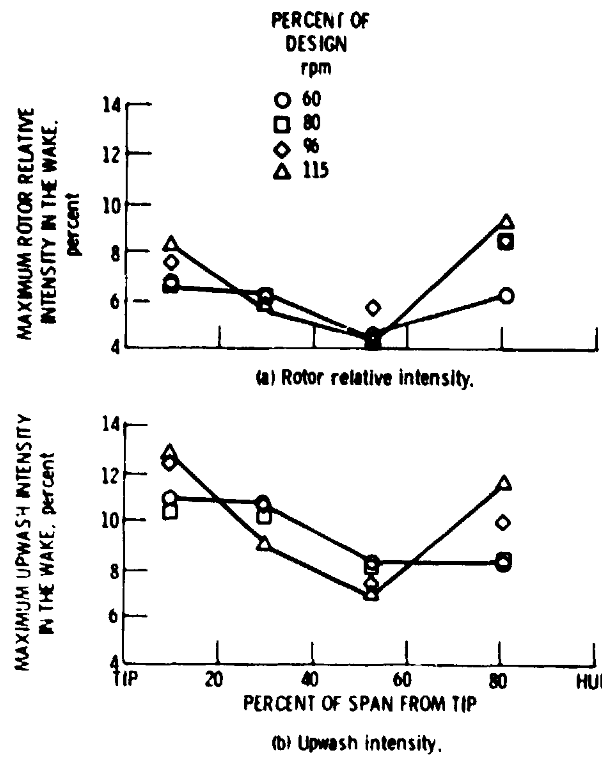


Figure 12. - Radial variation of the maximum intensity in the wake, 0.54 c spacing, U = 41 m/sec.

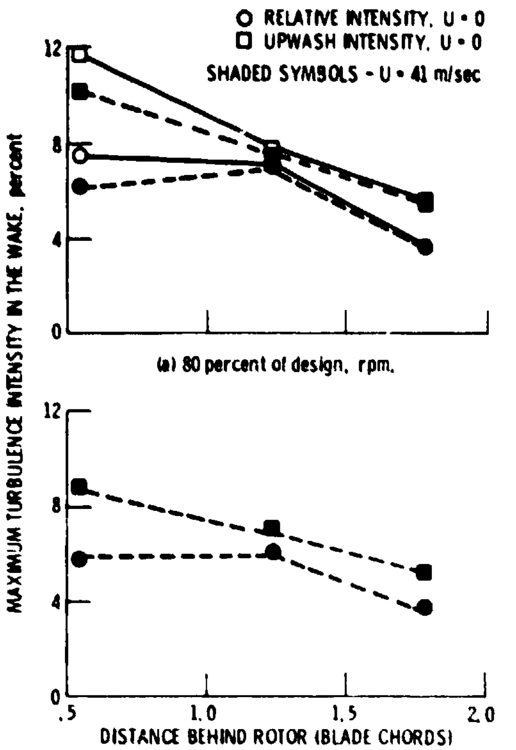


Figure 13. - Effect of downstream distance and forward velocity on the maximum relative and upwash turbulence intensity in the wake at 30 percent of span from the tip.

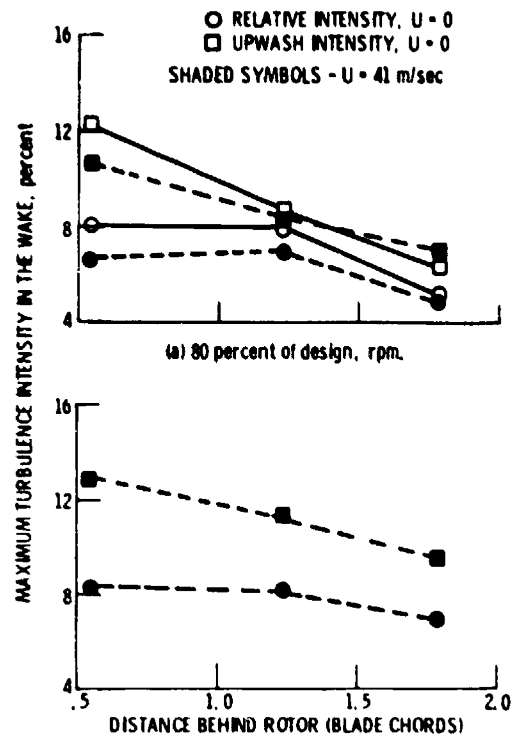


Figure 14. - Effect of downstream distance and forward velocity on the maximum relative and upwash turbulence intensity in the wake at 9.0 percent of the span from the tip.

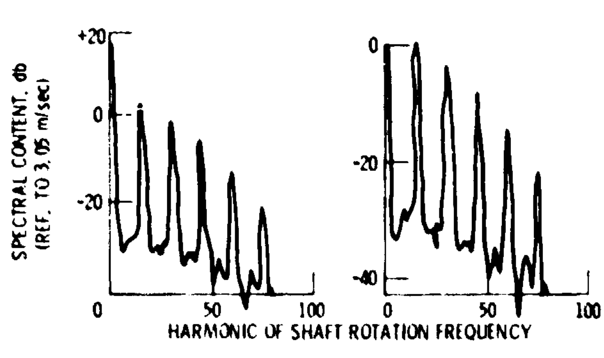


Figure 15. - Enhanced spectra of relative and upwash velocity at 80 percent of design rpm, 1.23 chord spacing, 30 percent of span from the tip, U = 41 m/sec.

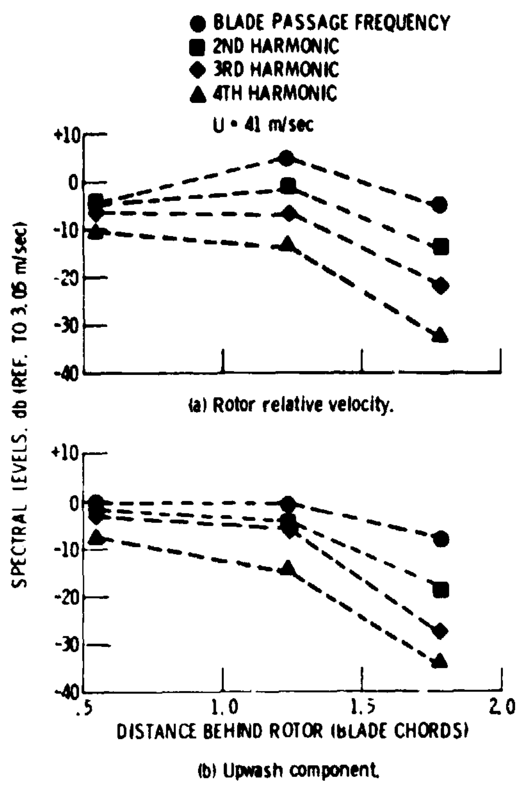


Figure 16. - Harmonic levels from ensemble averaged spectra. 30 percent of span from the tip, 80 percent of design rpm.

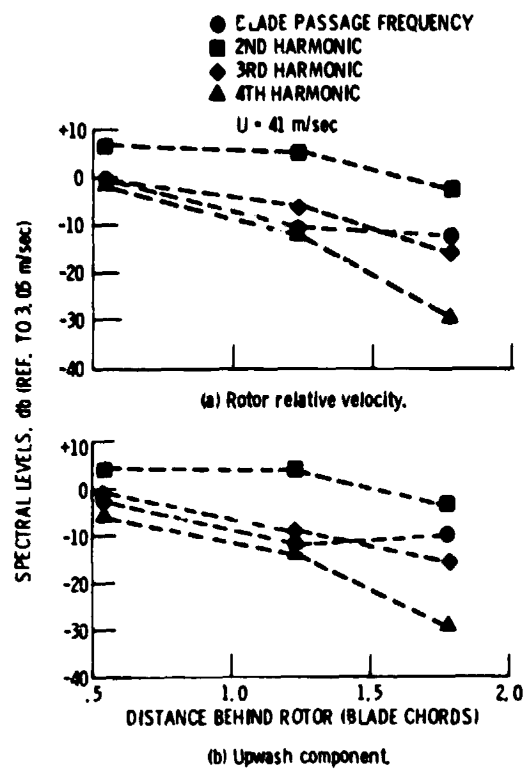


Figure 17. - Harmonic levels from ensemble averaged spectra. 9 percent of span from the tip, 80 percent of design rpm.

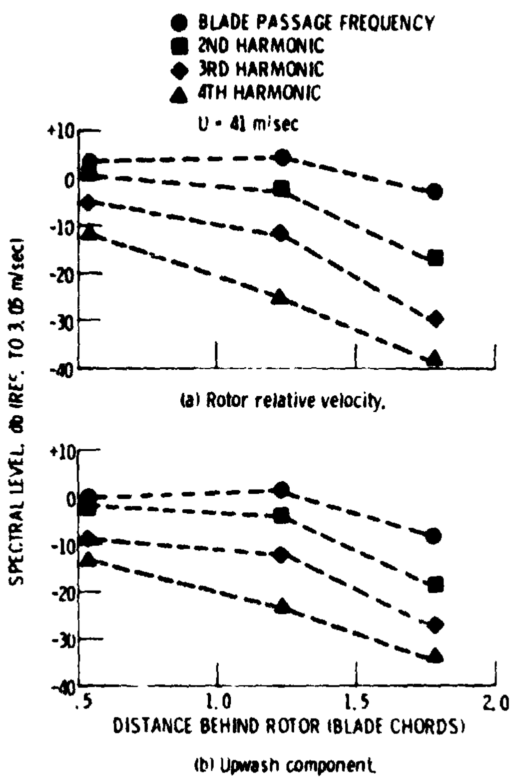


Figure 18. - Harmonic levels from ensemble averaged spectra. 30 percent of span from the tip, 115 percent of design rpm.

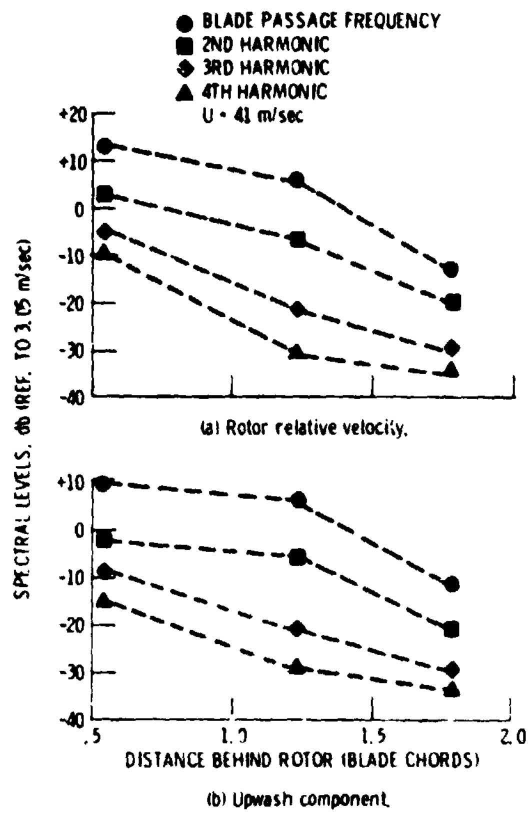


Figure 19. - Harmonic levels from ensemble averaged spectra. 9 percent of span from the tip, 115 percent of design rpm.