Sound Generated by a Single Cambered Blade in Wake Cutting

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The unsteady lift force on and the sound generated by an isolated cambered blade were measured in wake cutting, i.e., when subjected to periodic flow disturbances created by passing wakes. Depending on the orientation of the blade relative to the wake passage, significant difference was found in transient pressure signatures and in radiated sound. Furthermore, the sound field calculated from the fluctuating lift by Curle's formula did agree quite well with the measured value.

Nomenclature

A	= area of the blade, $A = bc$
A'	= normalized area of the blade, $A' = 4A/c^2$
a_0	= speed of sound
b	= effective span of the blade
c	= chord of the blade
C_L	= unsteady lift coefficient
$dA(\mathbf{r})$	= surface element on the blade at location $\mathbf{r}$
F_i	= surface pressure
q	= dynamic head, $q = \frac{1}{2}\rho U_0{}^2$
$\mathbf{R}$	= field vector
R'	= normalized value of the field vector, $R' = 2\lvert\mathbf{R}\rvert/c$
$R_\cdot$	= scalar distance between the field point and the surface element, $R_\cdot = \lvert \mathbf{R} - \mathbf{r} \rvert$
$\mathbf{r}$	= vector on the blade
$s(\mathbf{R}, t)$	= radiated pressure field
$s'(R', t')$	= normalized radiated pressure field
t	= time
t'	= normalized time, $t' = 2U_0 t/c$
U_0	= nominal velocity of the jet
α	= angle of attack
β	= angle between the wake and streamwise direction
ξ	= chordwise coordinate
Ξ	= normalized chordwise coordinate
ρ	= density of air

I. Introduction

UNSTEADY flows are major sources of sound generation. In turbomachinery, unsteady flows occur when the rotor blades cut through flow inhomogeneities, most typically the wakes of the guide vanes or those of previous stator blades. This way the blades are subject to a periodic flow disturbance. Transient pressure fluctuations are created on the surface of the blades, and the total integrated effect is a fluctuating lift and drag force. The farfield effect of the fluctuating pressure on the blade is a radiated sound that contributes significantly to the total noise of the machine.

Theoretically, the unsteady lift on a thin airfoil was first studied by von Karman and Sears.[1] Later, Curle[2] obtained a formula to calculate the farfield sound from the fluctuating pressure on a solid boundary. Recently, Naumann and Yeh,[3] as well as Atassi and Goldstein,[4] took the surface curvature of the cambered blade into consideration.

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Fujita and Kovasznay[5] investigated experimentally the fluctuating surface pressure on, and the sound radiated by, an isolated thin symmetric airfoil in a periodic flow disturbance created by passing wakes. One of the important results was the experimental verification of Curle's formula. In addition, new experimental techniques were established in order to deal with wake cutting problems in general.

Since turbomachinery blades with highly curved surfaces are in common use, the authors felt the necessity to include the cambered blade case. Consequently, the present work reports experimental results on surface pressure fluctuations and the farfield sound connected with a cambered blade subject to periodic flow disturbances, termed "wake cutting."

II. Experimental Configuration

The experiments were carried out in the open working section of a small wind tunnel.[5] The open working section is essentially a square jet with a nominal cross section of 30 cm × 30 cm and a centerline nominal velocity of $U_0 = 38$ m/sec (Fig. 1). The periodic flow disturbances were generated by passing circular cylinders (0.96-cm-diam aluminum rods) across the working section. The wake producing rods were mounted on a hub forming a large "pin-wheel" (total wheel diam. = 142 cm) rotating typically at 300 rpm, with its plane located at 6 cm downstream from the exit orifice of the square jet.

By use of rotating wake generators, the flow disturbances were not strictly two-dimensional, but helicoidal. On the other hand, the effect of "skew" wakes was established,[6] so that in the present study the configuration was deemed to be sufficiently two-dimensional to draw valid conclusions.

The acoustic echos from the laboratory walls were largely eliminated by installing acoustic baffles on all four sides of the working section; this created a box of about 180 cm in all directions except the downstream side, which was open, and the upstream side, which was closed by a solid wall representing an acoustic mirror. (The jet orifice that represented only 2.7% of area was neglected.)

The cross-sectional contour of the blade tested was generated from the NACA $a = 0.3$ mean line and NACA 64_1-012 basic thickness family.[7] The blade had a chord length of 9.7 cm and a total span of 45 cm extending well beyond boundaries of the jet. The blade was molded from a mixture of aluminum powder and Epoxy (Devcon F2). The leading edge of the blade was mounted at 14.5 cm from the jet orifice (or 8 cm downstream of the wake generating cylinders). The unsteady pressure was measured by a miniature electret transducer (ONERA model 2H222 type II) with a frequency response flat up to 3 kHz. The pressure transducers were flush-mounted at the five chordwise locations ($\xi/c = 0.0983$, 0.262, 0.45, 0.655, and 0.852, where c is the chord length and ξ is the chordwise coordinate) on both the highly curved suction side and the nearly flat pressure side. The farfield sound was measured by two B&K microphones (type 4133) located symmetrically at 76.2 cm from the blade.

The "raw" measured signal contains both a recurrent periodic component and random noise, largely caused by the turbulence. The "deterministic" portion, due to the periodic interaction of the wake and the blade, was extracted by the technique of "periodic sampling and ensemble averaging."[5]

III. Experimental Results

A. Definitions

In the two-dimensional wake cutting problem there are two important angles; the angle of attack α is defined as the angle between the mean flow direction and the chord, i.e., the line connecting the leading and trailing edges of the blade. The other angle β is formed by the downstream oriented wake axis and the mean flow direction. In the experiment, the angle α was changed by rotating the blade around its leading edge. The nominal value of β was measured at the center of the working section and it was 22° in all experiments. In case of an asymmetric blade there are, however, two different orientations possible relative to the wake axis. When the asymmetric blade is oriented so that an increasing α results in an increasing angle between the wake and the chord of the blade, then the orientation is defined as $\beta > 0$, and in the opposite case, it is defined as $\beta < 0$ (Fig. 2).

The nondimensional time was defined as $t' = 2U_0 t/c$ and $t' = 0$ was chosen when the axis of the wake passed the centerline of the blade. The origin of the chordwise coordinate is defined so that $\xi = 0$ at the centerline of the chord. The nondimensional coordinates is $\Xi = 2\xi/c$.

B. Farfield Sound

The farfield sound was measured extensively by two microphones placed symmetrically with respect to the plane formed by the centerline of the tunnel and the leading edge of the blade. The distance of each microphone from the center of the blade was 76.2 cm. Each microphone signal contains three components: first, the deterministic portion due to the interaction between the passing wake and the blade; second, another deterministic portion due to the interaction of the wake producing rod with the edge of the jet – this can be determined by repeating the same experiment but with the blade model removed – and third, a random signal largely caused by turbulence. This later random portion is suppressed by periodic sampling and averaging. The second portion can be subtracted by use of the result obtained without the blade, so that only the periodic deterministic portion due to wake cutting will remain. The sum of the two microphone signals was consistently small, indicating that the source (monopole) type of radiation was negligible. On the other hand, the difference between the two microphone signals was large, indicating that the radiated sound was primarily a dipole field in accordance with Curle's theory.

The sound signature was always measured with both orientations of the blade, i. e., for $\beta > 0$ and $\beta < 0$. In both cases, three values of the angle of attack were chosen: 5°, 10°, and 15°. Tests with tufts indicate that no steady flow separation occurred on the blade at any of these angles. The temporal variation of the dipole sound field is shown for all cases in Fig. 3. There was no significant difference in the sound signatures as long as β remained of the same sign. On the other hand, for a given angle of attack, the peak of the sound pulse was much smaller (in a ratio of about 2:3) for $\beta < 0$ than for $\beta > 0$.

C. Chordwise Pressure Distribution

The fluctuating surface pressure along the chord was measured at ten transducer positions distributed around the blade. The normal component force distributions (the component perpendicular to the mean flow) was calculated as the difference of the normal component of the pressure force measured on the two sides of the blade. The chordwise pressure distribution at different angles of attack and at given instants (relative to the passing wake) are given in Fig. 4. The pressure fluctuations were normalized with the nominal dynamic head $q = \frac{1}{2}\rho U_0^2$. A significant difference was observed in the distribution pattern between the cases of $\beta > 0$ and $\beta < 0$. For $\beta > 0$, the pressure pulse was positive at all stations. For $\beta < 0$, at a particular instant, the pressure varied between positive and negative values along the chord. The unsteady (a.c.) component of the pressure reading was always higher in the $\beta > 0$ case than in the $\beta < 0$ case. Furthermore, an interesting observation was made: the unsteady component of the measured pressure on the pressure (belly) side of the blade was of the same magnitude for both $\beta > 0$ and $\beta < 0$. On the other hand, the pressure fluctuation on the suction (back) side was much higher for $\beta > 0$ than for $\beta < 0$. The difference can be attributed to the fact that the suction side was a highly curved contour, whereas the pressure side is nearly flat.

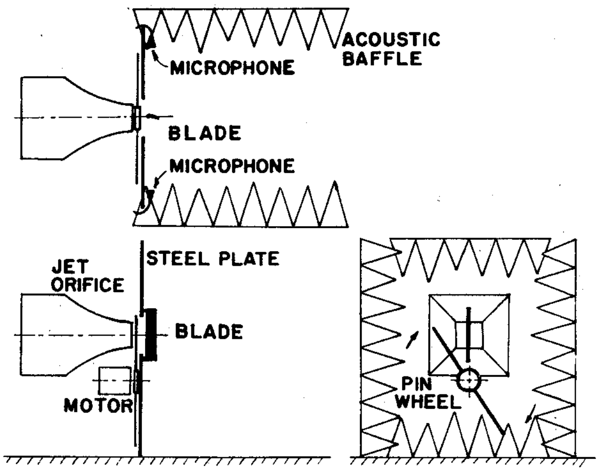

Fig. 1 Experimental facility.

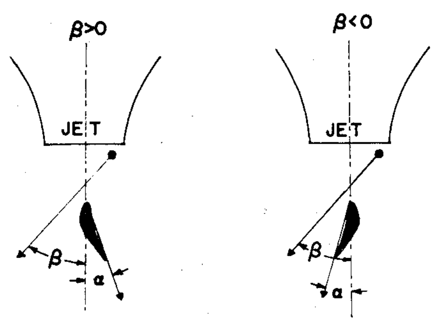

Fig. 2 The two wake orientations ($\beta > 0$ and $\beta < 0$).

D. Fluctuating Lift

The lift is defined here as the force component on the blade perpendicular to the mean flow direction. The instantaneous value of the pressure force at ten transducer locations was recorded, then was multiplied by the local geometrical factors (direction of the surface and distance between points), and it was integrated around the blade. The fluctuating lift coefficient was measured for the same set of angles of attack (5°, 10°, 15°) both for $\beta > 0$ and for $\beta < 0$ (Fig. 5). In general, the lift coefficient had a high positive peak near $t' = 0$, followed by slower oscillations. The peak value of the unsteady (a.c.) lift force for $\beta > 0$ was about twice as large as that for $\beta < 0$. In all measurements, there was a rapid change in dC_L/dt' near $t' = 1.5$ followed by a high pulse. After comparing the individual output signals from the transducer at different locations, one may conclude the pulse must be due to a temporary flow separation, and the transient flow disturbance (separation vortex) must be convected downstream from the

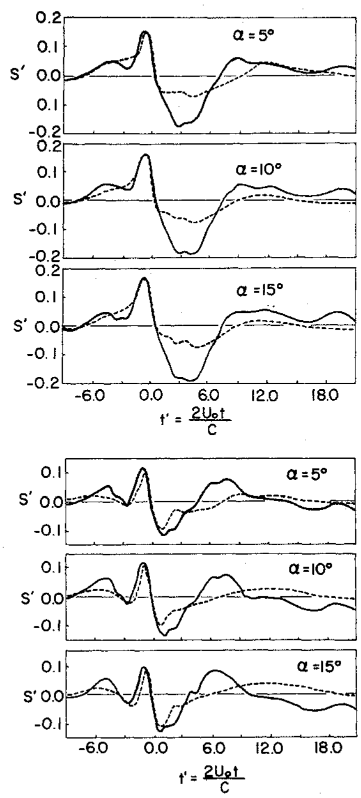

Fig. 3 Predicted and measured sound signatures: ——measured sound, ---predicted sound.

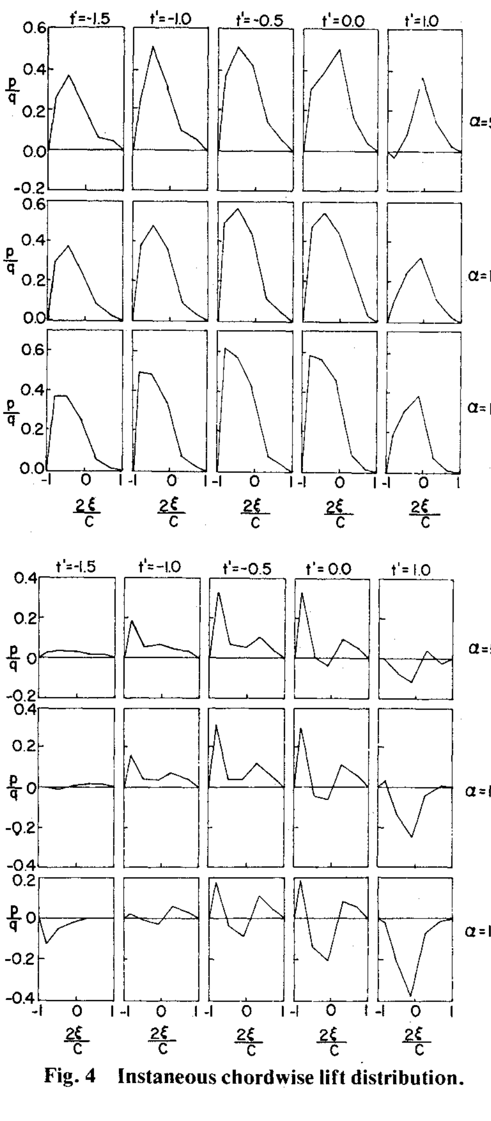

Fig. 4 Instaneous chordwise lift distribution.

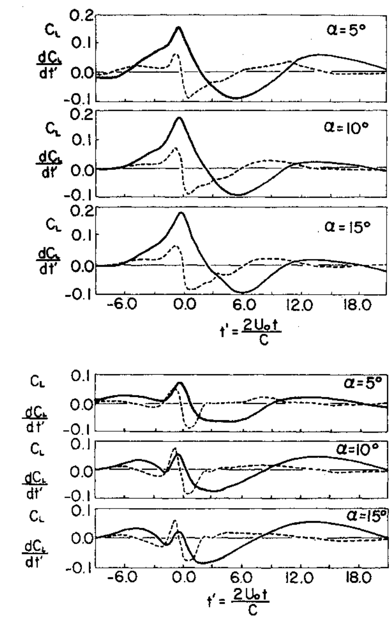

Fig. 5 Lift coefficient $C_L(t')$ and its time derivative dC_L/dt':—— $C_L(t')$, ---dC_L/dt'.

leading trailing edge by the mean flow. On the other hand, there was no significant difference in the peak values of dC_L/dt' for $\beta>0$ and for $\beta<0$.

E. Predicted Sound

By Curle's formula, the farfield sound generated by the blade can be predicted from the surface pressure fluctuations measured on the blade. The instantaneous pressure $S(\mathbf{R}, t')$ at a field point at $\mathbf{R}$ is

$$S(\mathbf{R},t) = -\frac{1}{4\pi}\frac{\partial}{\partial R_i}\int_A \frac{F_i[\mathbf{r}, t-(R_*/a_o)]}{R_*} dA(\mathbf{r}) \tag{1}$$

where F_i is the force per unit area at the location $\mathbf{r}$ exerted by the blade in the i directions ($i=1,2,3$), and $R_* = |\mathbf{R}-\mathbf{r}|$ is the scalar distance from the surface element dA ($\mathbf{r}$) to the field point $\mathbf{R}$, and a_o is the speed of sound. Assume that $|\mathbf{R}|^2/b^2 \gg 1$, where b is the effective span of the blade. In the present case, $b\approx 30$ cm, and the ratio $|\mathbf{R}|^2/b^2 \approx 2.50$. Curle's result can be further simplied[5]

$$S'(R',t') = (a_o/U_oR')\ C_L(t') + dC_L(t')/dt' \tag{2}$$

where

$$R' = 2|\mathbf{R}|/c \qquad A = bc$$

$$S'(R',t') = (4\pi R' a_o/A' U_o)\ S(R,t')$$

$$t' = 2U_o t/c \qquad A' = 4A/c^2$$

From the measured unsteady pressure on the blade, the predicted sound signature was calculated by use of Eq. (2), and the result is shown in Fig. 3. The magnitudes of the first positive pulse in the cases of $\beta>0$ and $\beta<0$ are different. They are in a ratio of about 3:2, in the same way as it was found in the measured farfield sound. According to Eq. (2), there are contributions to the sound field from both dC_L/dt' and C_L, but the second contribution, proportional to C_L, decreases relative to the first in the ratio proportional to $1/R$. This difference for the two configurations, $\beta>0$ and $\beta<0$, was caused mostly by the difference in the magnitude of C_L, the unsteady lift coefficient, and not by a difference of dC_L/dt'. We note that the peak values of dC_L/dt' are of the same magnitude, both for $\beta>0$ and $\beta<0$. For $R\to\infty$, this is the only term responsible for sound radiation. In general, the predicted sound level agrees well with the measured sound level during the wake passage both for $\beta>0$ and $\beta<0$. In the case of $\beta<0$, Curle's theory also gives a good account of the negative going pulse occurring at a later time ($0<t'<5$). For $\beta>0$, however, the predicted negative lobe ($t'>0$) is consistently smaller than that in the measured sound. The same discrepancy was observed earlier in some isolated cases on a thin symmetrical airfoil.[5] It appears that such a discrepancy becomes detectable whenever the peak value of C_L is significantly higher than the peak value of dC_L/dt', but unfortunately no rational explanation can be provided at this time.

IV. Conclusions

For a single cambered blade under periodic flow disturbances, much higher unsteady force fluctuations were found for $\beta>0$ than for $\beta<0$. Authors suspect that the highly curved suction (back) side of the airfoil has significantly different transient flow response under the two different wake orientations, $\beta>0$ and $\beta<0$. The unsteady (a.c.) force on the nearly flat pressure (belly) side of the blade remained about the same for the two different wake orientations. The measured sound level of an isolated nonsymmetrical blade under gusts was in a ratio of about 3:2 for $\beta>0$ and $\beta<0$. The radiated sound field, as predicted by Curle's formula, gave very good agreement with the measured sound, even when the existence of separation bubble propagating from leading edge to trailing edge was inferred from the detailed observations.

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