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LDV MEASUREMENTS OF THE UNSTEADY SHEAR LAYER ABOVE A RESONANT CAVITY

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Abstract

Flow past a wall mounted cavity can excite strong acoustic resonance in the cavity. The acoustic field in the cavity is coupled to the unstable shear layer at the mouth of the cavity. Flow visualization revealed that the flow in the shear layer is characterized by periodic formation of large-scale vortices and convection of these vortices downstream to the trailing edge. A LDV system was utilized to measure the periodic changes in the shear layer flow. A two step data analysis process was used to reconstruct the velocity field. The process consisted of phase conditioned averaging and a Fourier series approximation.

Nomenclature

U_0	free stream velocity
ρ	air density
c_p	pressure coefficient= $p_{rms}/(\rho U_0^2/2)$
d	cavity depth
f	fundamental frequency of the tone
f_n	natural frequency of the cavity
L	stream wise cavity dimension
U_r	reduced velocity = $U_0/f_n{*}L$
u	x-component of velocity
v	y-component of velocity
t	time
$\bar{u}$	averaged velocity
ϕ	phase
p_0^+	acoustic pressure, zero and increasing
p_0^-	acoustic pressure, zero and decreasing
p_{rms}	root-mean-square of acoustic pressure

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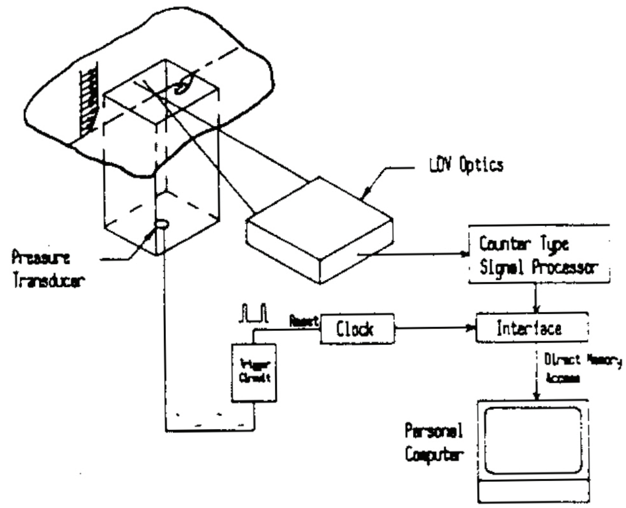

FIG. 1 FLOW SITUATION AND MEASURING EQUIPMENT

Introduction

Flow past a cavity can excite strong acoustic resonance in the cavity. The acoustic field is coupled to the unstable shear layer at the mouth of the cavity. Figure 1 shows this shear flow past the resonant cavity.

Feedback of the acoustic field to the shear layer occurs near the leading edge of the cavity. The approaching turbulent boundary layer separates from the wall and forms a shear layer which subsequently rolls up to form large-scale vortices. Due to the high amplitude of the acoustic pressure in the cavity, significant sound pressure levels can be generated or mechanical stresses induced in surrounding structures. Situations where this phenomenon occurs are commonly found in piping systems and bays in the fuselage of aircraft. The feedback mechanism which couples the acoustic field and the shear layer is yet to be discovered. The work reported herein resulted from on-going studies to characterize the feedback mechanism.

Flow visualization studies have revealed that the flow in the shear layer is characterized by a periodic formation of largescale vortices (1,2,3). These vortices are convected downstream to the trailing edge of the cavity. The vertical deflection amplitude of the shear layer during resonance is as great as 30% of the stream wise length of the cavity (L) (3,4). Due to such large distortions of the mean flow, the fluid interaction is highly non-linear and, therefore, theoretical approaches to the problem are difficult (5,6).

In order to investigate the feedback mechanism, the turbulent flow field in the vicinity of the mouth of the cavity must be measured and correlated to the acoustic pressure changes in the cavity. Hot-wire measurements have shown that the approaching boundary layer pulsates as a result of the periodic pressure gradient imposed by the resonating cavity (4). In portions of the shear layer, however, the flow direction changes periodically precluding velocity measurements with hot-wire probes.

To measure the flow in the shear layer, a laser doppler velocimetry system, which can track flow reversals, was utilized. To reconstruct the velocity field around the mouth of the cavity, the velocity signals were phase conditioned averaged and then approximated with a Fourier series.

LDV Setup

A standard one component LDV system was utilized. The system consisted of optics, a frequency shifter, a 2.27X beam expander and a 3 W Argon-ion laser. The focal length of the transmitting lens was 600 mm. The output power of the laser was 500 mW and the wavelength was 488 nm. The optics were rotated 90 degrees to measure the vertical velocity component. Propylene glycol was used in an evaporation/condensation type smoke generator to produce the seeding particles. A window made from 12 mm thick plexiglass was used for transmitting the laser beams into the wind tunnel.

The doppler burst signals were processed with a counter type signal processor, which converted the bursts into digital data. The digital data were then transferred via a specially designed interface to a microcomputer programmed for direct memory access. In addition to transferring the digitized Doppler burst data, the interface measured the phase of the Doppler signal relative to the oscillating acoustic pressure in the cavity. This was accomplished by resetting a clock each time the acoustic pressure in the cavity was zero and increasing (p_0^+). The Doppler burst signals were recorded for many cycles of pressure oscillation in the cavity.

Data Analysis

Specially developed software was used for data analysis. For each doppler burst, the velocity of the particle and the phase (referenced to the pressure in the cavity) were computed. The seeding particles were randomly distributed in the flow and therefore the Doppler bursts occurred at random times. In order to recreate the velocity waveform, the data was reduced using phase conditioned averaging and a Fourier series approximation technique.

Phase Conditioned Averaging

Phase conditioned averaging consisted of condensing the data of many acoustic pressure cycles into one equivalent cycle. The phase of each velocity sample was computed, referenced to zero and increasing acoustic pressure in the cavity (p_0^+). Thus, each of the many acoustic pressure cycles were automatically overlaid into a single equivalent cycle. Hence, the equivalent cycle has as many samples as all the original cycles combined. Figures 2a,2b show this process schematically.

The equivalent cycle was then divided into 256 intervals. The samples in each interval were weighted and averaged. Equation (1) defines this average.

$$\overline{u}_k = \frac{t_{Bi} * u_i}{t_{Bi}} \quad (1)$$

$\overline{u}_k$ = Weight averaged velocity in interval k of the equivalent cycle

u_i = velocity of seeding particle i in interval k

t_{Bi} = time for particle i in interval k to traverse measuring volume

This averaging is necessary in order to avoid velocity bias, which could otherwise occur because the probability (per unit time) of a particle entering the measuring volume depends on its velocity (7).

Fourier Series Approximation

A Fast Fourier Transform was performed on the averaged data. The FFT provided the magnitude and phase of the harmonic components which describe the velocity waveform. To eliminate noise in the data (due to turbulence and non-periodic fluctuations of velocity) only the first few harmonics of the FFT were retained. The magnitude and phase of these harmonic components were used as the coefficients of a Fourier series approximation of the actual velocity waveform. Therefore, the velocity for any given time can be estimated from this approximation.

A simple procedure was used to determine which harmonics were needed to approximate the original velocity waveform. The procedure consisted of sampling the velocity field at the same point in space for two separate time intervals. Both sets of data were phase conditioned averaged and then transformed to the frequency domain via a FFT. Next, the harmonic components of each set of data were compared. The harmonic components found to be comparable in magnitude and phase were retained. The harmonic components which did not correlate were ignored. This procedure was repeated for different points in space. Typically, the first four to six harmonics were found to correlate in magnitude and phase. The components at frequencies seven times the fundamental and higher were found not to correlate and were therefore ignored. Figure 3 shows the process for this comparison.

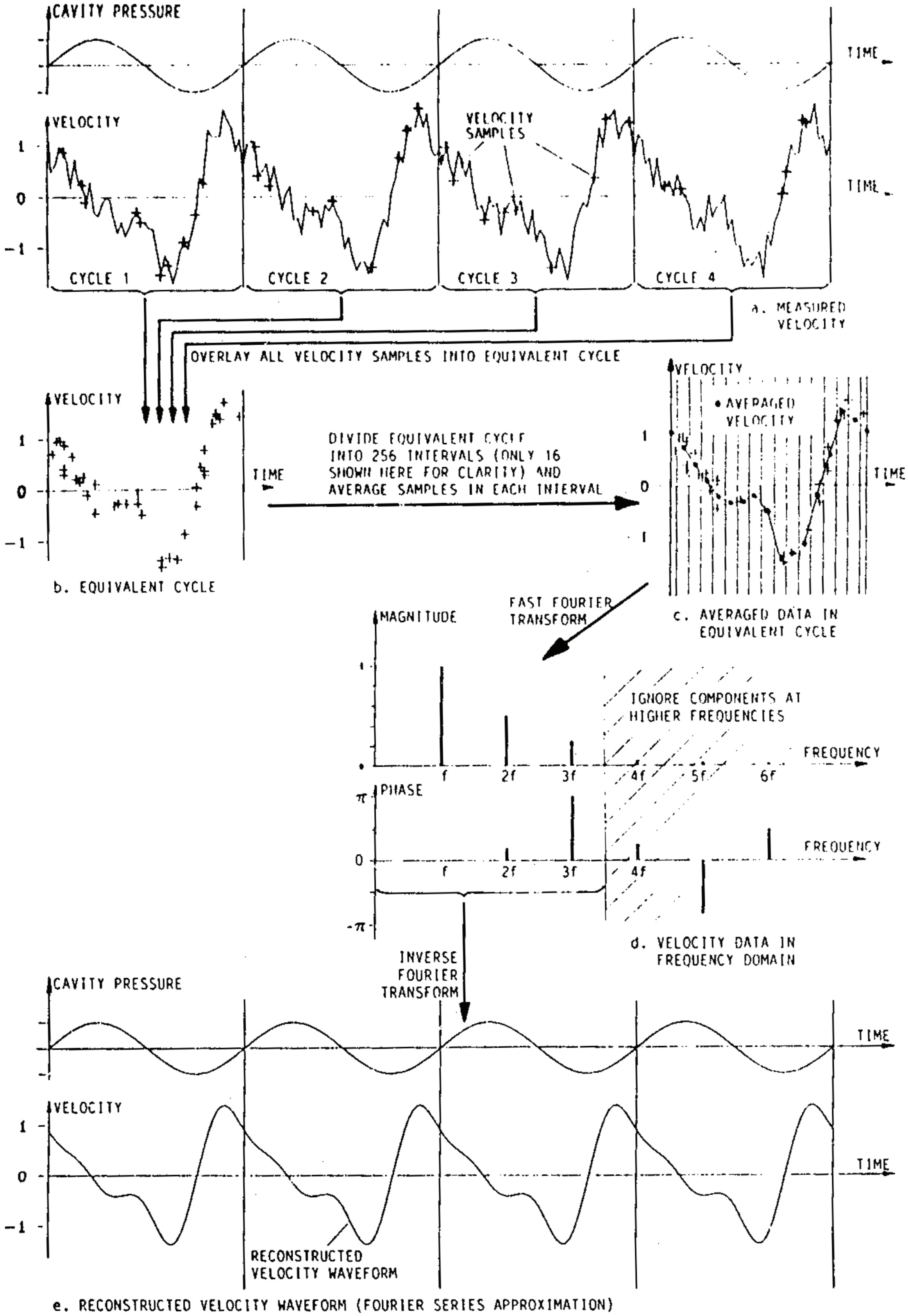

FIG. 2 PROCESS OF DATA ANALYSIS

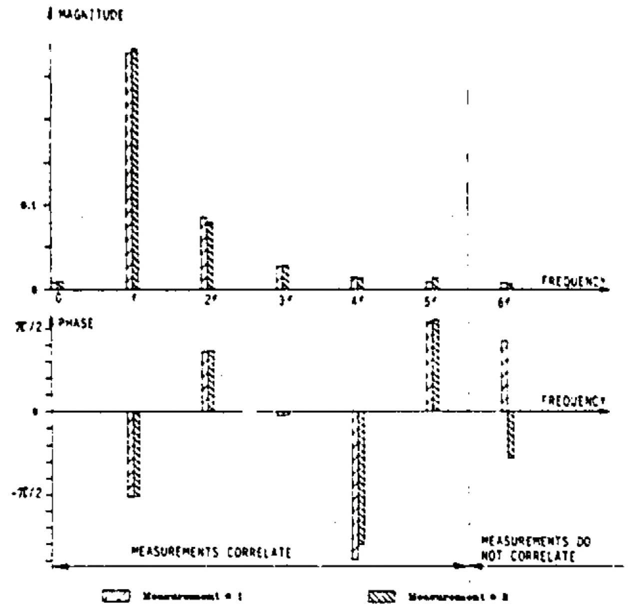

FIG. 3 COMPARISON OF THE HARMONIC COMPONENTS OF TWO MEASUREMENTS TAKEN AT THE SAME LOCATION IN SPACE

Measurements

At each measurement point, 4000 Doppler signals were recorded and analyzed. Typically 10,000 particles per second travelled through the measuring volume, with the seeding method used. Thus, each measurement took about 0.4 seconds which corresponded to 80 cycles of acoustic pressure oscillation.

Figure 4 shows one equivalent oscillation cycle of the vertical velocity component. The measurement was taken in the center of the cavity at the interface plane. Each dot represents one measured particle velocity. The solid line curve represents the Fourier series approximation of the velocity waveform; harmonics with frequencies up to 6 times the fundamental were used in the approximation.

Measured Velocity Profiles

Velocity profiles of the shear layer were measured at three points along the length (L) of the cavity. The locations of these points are shown in Figure 5. At each point the horizontal (u) and vertical (v) velocity components were measured. Figure 6 shows the profiles of the horizontal and the vertical velocities.

Leading Edge Figure 6a shows the u-velocity profiles near the leading edge of the cavity. The profile of the u-velocity component showed strong pulsations of up to 30% of the free stream velocity. The velocity in the profile was higher than average (the velocity profile was "full") when the pressure in the cavity was increasing and air was flowing into the cavity. On the other hand, when the cavity pressure was decreasing due to air flowing out of the cavity, the velocity profile was "shallow" (i.e., the velocity in the profile was less than average). This behavior matches the results of previous hot-wire measurements (4).

Figure 6b shows the v-velocity profiles near the leading edge of the cavity. Here the amplitude of the fluctuating v-velocity component was nearly 5% of the free stream velocity. When the pressure in the cavity was increasing the direction of the v-velocity was into the cavity. The direction of the vertical velocity was out of the cavity for decreasing cavity pressure.

Center of the Cavity Figure 6c shows the u-velocity profiles at a distance L/2 down steam from the leading edge. At this location the u-velocity fluctuations were larger (more than 50% of free stream velocity) than at the leading edge. When the pressure in the cavity was maximum the measured velocity profile was nearly uniform. At this point the shear layer was deflected far into the cavity, where no measurements were taken.

Figure 6d shows the v-velocity profiles at a distance L/2 down steam from the leading edge. The fluctuations of the v-velocity component at this location were up to 30% of the free stream velocity. The fluctuations of the vertical velocity were in phase with the fluctuations of v at the leading edge.

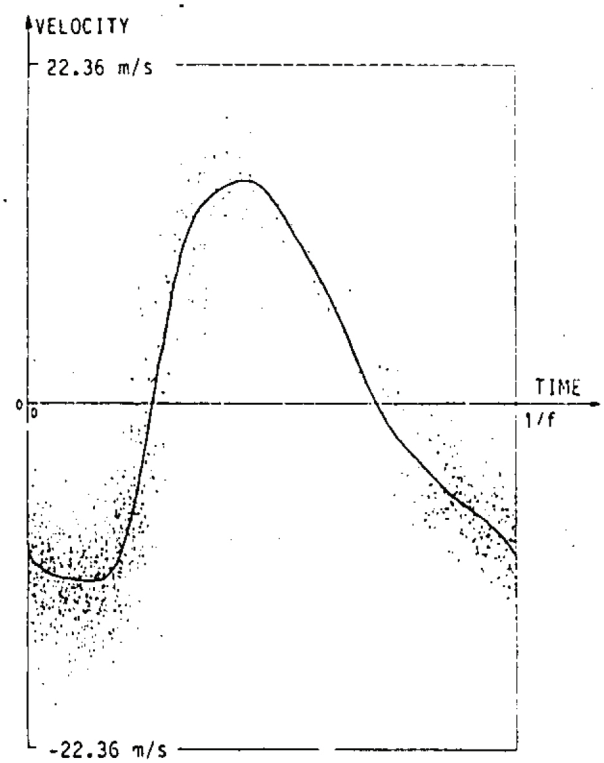

FIG. 4 EXAMPLE OF A VELOCITY WAVEFORM (VERTICAL VELOCITY COMPONENT, CENTER OF MOUTH OF CAVITY)

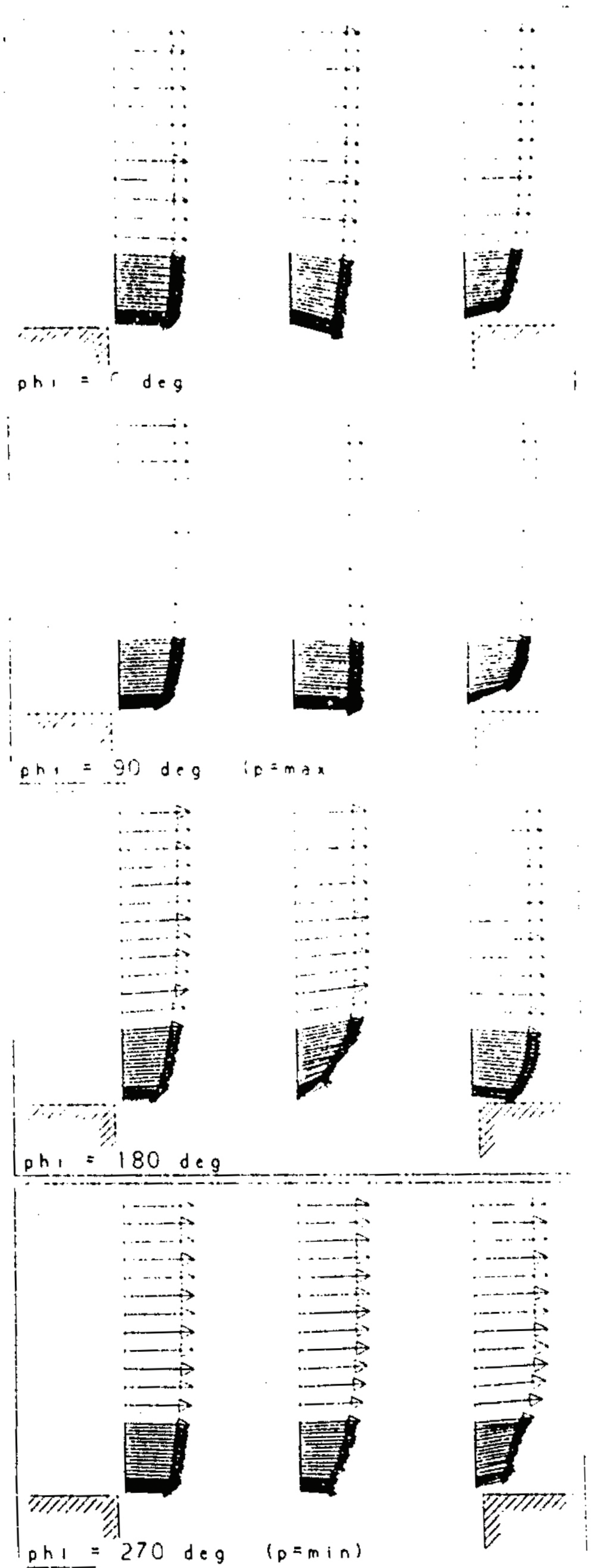

FIG. 5 VELOCITY DISTRIBUTION FOR DIFFERENT PHASE ANGLES IN PRESSURE CYCLE

Trailing Edge Figure 6e shows the u-velocity profiles near the trailing edge of the cavity. Here the velocity fluctuations in x-direction were about 30% of the free stream velocity. When air was flowing into the cavity (cavity pressure was increasing), the velocity profile appeared to be shallow. When air was flowing out of the cavity (decreasing cavity pressure), the velocity profile was full.

Figure 5f shows the v-velocity profiles near the trailing edge of the cavity. The fluctuations in the vertical velocity at this location were substantial (up to 30% of the free stream velocity). When the pressure in the cavity was maximum the vertical velocity was maximum, directed out of the cavity. A quarter of a cycle later (when the pressure was zero and decreasing), the v-velocity was maximum into the cavity. The impingement of the vortex on the trailing edge caused these abrupt changes in the v-velocity.

Conclusion

Laser Doppler Velocimetry is a powerful tool for measuring unsteady periodic flow. Large amplitudes of the fluctuating velocity and even flow reversals can be measured if the system is equipped with a frequency shifter. Special software is needed, however, to process and analyze the large amount of measured data and to filter out noise due to turbulence and non-periodic velocity fluctuations. The filtering was accomplished using a two step method consisting of phase conditioned averaging and Fourier series approximation of the velocity waveform.

The results presented in this report show that this LDV system is capable of measuring the flow field around the mouth of a cavity during flow-induced resonance. However, more measurements are required to characterize this flow field and to investigate the feedback mechanism.

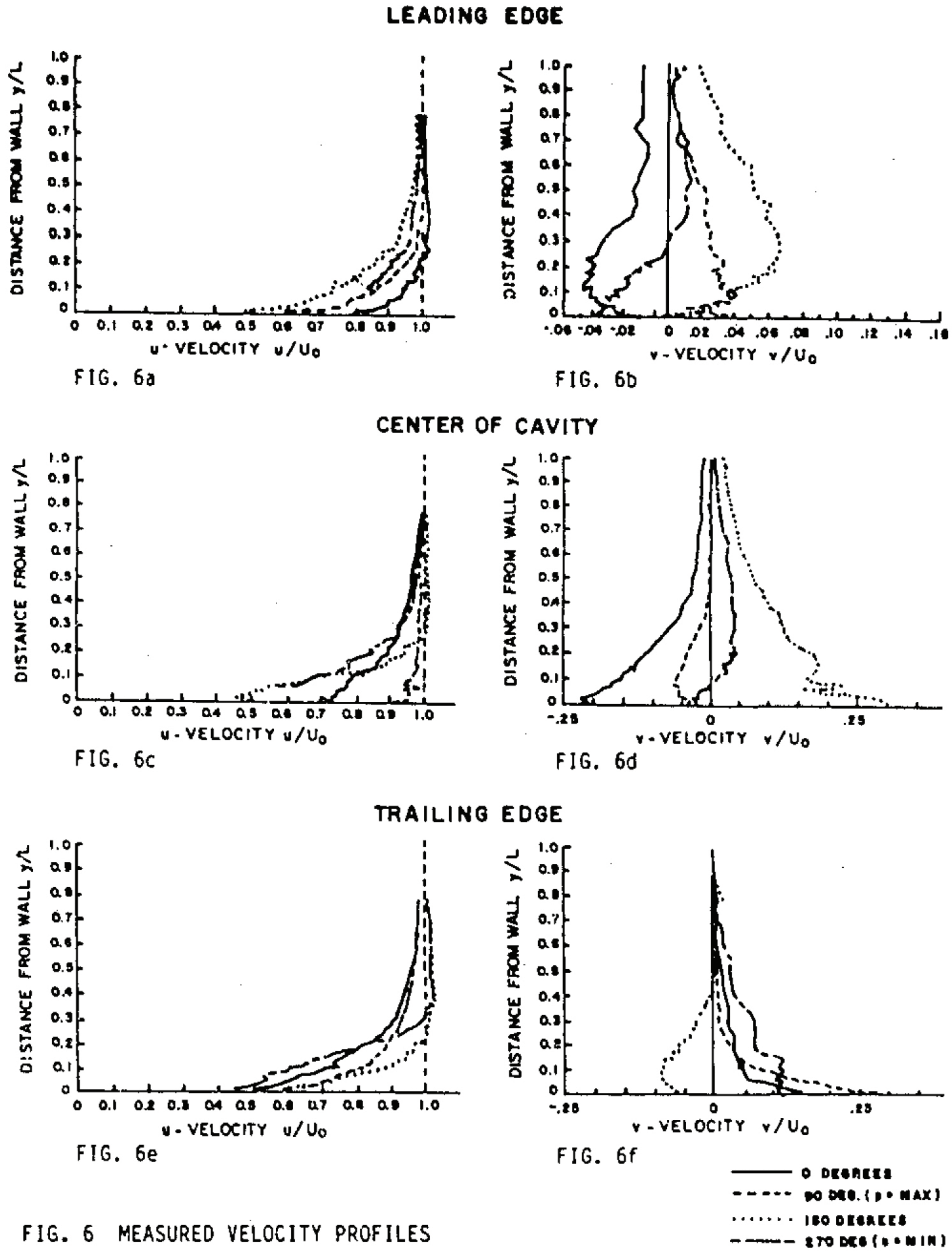

FIG. 6 MEASURED VELOCITY PROFILES

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