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NASA TM X-71524

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LASER DOPPLER VELOCIMETER MEASUREMENTS IN A TURBINE STATOR CASCADE FACILITY

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TECHNICAL PAPER proposed for presentation at
Laser Velocimetery Workshop
West Lafayette, Indiana, March 27-29, 1974

E-7919

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ABSTRACT

A laser Doppler velocimeter (LDV) developed for mapping the flow velocity downstream from a 32-inch diameter annular cascade of turbine stator vanes is described. The LDV measurements were taken in a plane located approximately 0.5 inch downstream of the trailing edges of the vanes. Two components of the mean velocity (axial and circumferential) were measured. The flow velocities were in the high subsonic range. The LDV optics are of the dual scatter type with off-axis collection of the scattered light. The electronics system is based on the measurement of the time interval corresponding to eight periods of the Doppler signal and has a range of 10 to 80 MHz. The LDV measurements are compared with previous measurements made with a pressure probe.

INTRODUCTION

The laser Doppler velocimeter (LDV) is a promising new diagnostic tool for use in turbine and compressor research for advanced airbreathing engines. Conventional diagnostic techniques, such as hot wire probes and pressure probes, have limitations because they perturb the flow being measured. The introduction of physical probes into transonic and supersonic flows is particularly undesirable as large changes in the flow can result. It is also very difficult to measure the flow velocities within a rotating blade row of a turbine or compressor using conventional probes because of mechanical and signal transmission problems. The LDV offers a method of measuring flow velocities without disturbing the flow and under conditions where conventional probes cannot be used. For instance, the flow field within a rotor passage of a low speed compressor has been mapped using an LDV by Wisler and Mossey.[1]

There are a number of points to consider when using an LDV for flow velocity measurements in turbomachinery. First, optical access must be provided so that all regions of the flow field to be mapped may be viewed. In many applications non-planar windows, which may disturb the optical path, must be used to avoid disturbing the flow. Because the LDV actually measures the velocity of micron size particles entrained in the fluid rather than the fluid velocity itself, the accuracy of the measurement is limited by the accuracy with which these particles track the fluid. The maximum allowable particle size and density depend on the details of the particular flow being investigated. Another consideration is that, in order to minimize the time required to map the flow region under study, means must be provided for rapid scanning of the flow field and for efficient data reduction. Frequently, artificially generated particles must be introduced into the flow in order to provide an adequate data rate. Finally the LDV must be designed to operate in a rather hostile environment which may include high acoustic noise levels, mechanical vibration, and varying temperatures.

In this paper an LDV system developed to study the flow downstream from an annular cascade of turbine stator vanes will be described. The flow velocities measured are in the high subsonic range (up to 900 ft/sec). Two components of the mean velocity (the axial and circumferential) were measured. The region mapped is in a plane located about 0.5 inch downstream of the trailing edges of the vanes. The optical system is of the dual scatter type with four input beams and has off-axis collection of the backscattered light. The electronics system incorporates a direct measurement of the Doppler frequency and has a range of 10 to 80 MHz.

DESCRIPTION OF CASCADE

This annular cascade of turbine stator vanes was designed for cooled-turbine aerodynamic studies[2]; however, in the LDV measurements reported here, solid vanes with no cooling air were used. The cascade consists of 72 vanes (5 degree spacing). Each vane has a 3.85 inch span and 2.47 in.chord. The tip (outer)diameter of the turbine is 31.9 inches, the hub-to-tip radius ratio is 0.76, and the mean radius solidity (ratio of chord to mean vane spacing) is 2.02. At the design point the mass flow rate is about 50 lbm/sec and the downstream-to-upstream pressure ratio at the hub is 0.56. An exhaust system is used to lower the downstream pressure and a wood bellmouth is used to guide ambient air into the cascade (figure 1). The axis of the cascade is vertical with the test section located about 10 feet above the floor of the test cell.

OPTICS AND TRAVERSING MECHANISM

The LDV used in this study (figure 2) is of the dual scatter type.[3] The beam from an argon ion laser (0.488 μm, TEM_{00}, 1 watt) is split into 4 equal intensity parallel beams. These beams are focused at a common point in the test region with a simple plano-convex lens (5 inch focal length). The use of a remotely controlled aperture plate to select two of the beams allows measurement of either the axial or the circumferential component of the velocity. The window is 1/8 inch thick plexiglass bent to conform to the inner surface of the test section wall. Thus the flow is not disturbed by the window. The window is, in effect, a cylindrical lens that changes the crossing angle of the pair of beams lying in the horizontal plane. Furthermore, the intersection point of these beams does not coincide with the intersection point of the pair of beams lying in the vertical plane. The magnitude of these effects is a function of the distance between the window and the probe volume. The crossing angle is about 0.25 percent larger for the pair of beams lying in the horizontal plane when the probe volume is near the window (the worst case). The maximum difference in the positions of the intersection points of the two pairs of beams is about 500 μm and occurs when the probe volume is at the greatest distance from the window (about 4 inches). Since both of these effects are relatively small for this particular configuration, no correction was applied to the data.

The crossing angle was found by direct measurement to be 4.70 ± 0.02 degrees. The number of "fringes" located between the $1/e^2$ intensity points was about 16 and the fringe spacing was 5.95 ± 0.03 μm. All four beams were polarized with their electric vector parallel to the plane of scattering.

Lenses L_1 and L_2 have two purposes: (1) to set the waist diameter of the beams in the probe volume to 100 μm (this was done by mode matching the laser cavity to the desired mode in the probe volume[4]), and (2) to insure that the waist positions coincide with the intersection point of the beams. The focal lengths and positions were chosen to simultaneously satisfy these two conditions. Failure to satisfy the second condition can result in the radii of curvature of the beams in the probe volume being so small that the proportionality "constant" relating the Doppler beat frequency and the flow velocity is actually a function of the location within the probe volume[5] (i.e., the fringe spacing is not constant).

The light scattered from the probe volume is collected by a lens system (f number 3.9) located 20 degrees off the axis of the incident beams. The off-axis light collecting optics reduce the effective length of the probe volume from 2.4 mm to about 0.8 mm (see figure 3). It also reduces the amount of light that is scattered from the hub of the cascade into the light collecting optics when the probe volume is close to the hub. The photomultiplier tube (PMT) is an RCA type 8645. A 350 μm aperture in front of the tube is positioned at the image point of the probe volume.

The laser and all the optics are mounted on a 2 ft x 4 ft x 1 1/2 in aluminum plate (figure 2). This plate rests on a second plate which rests in turn on a third plate that is stationary. The top plate is constrained to move only in the radial direction and the second plate is constrained to move in a circular arc whose center coincides with the axis of the cascade. Hence, circumferential surveys can be made at a constant radial position and the axial and circumferential components of the velocity can be measured. The range of travel is about 5 inches in the radial direction and about 8 degrees in the circumferential direction. The bottom stationary plate is supported by a rigid structure that is bolted to the floor of the test cell. There is no direct contact between the LDV and the cascade in order to minimize the vibration of the laser and the optics.

SEEDING

A necessary requirement for an LDV is a sufficiently large concentration of scattering centers (particles) in the fluid to achieve the desired data rate. Furthermore, the size of these particles must be such that they accurately track the flow. The initial tests were conducted with ambient dust particles as the scattering centers. In more recent tests an aerosol generator using a Laskin nozzle[6] was added to increase the data rate. The fluid used was a silicone oil (350 cs viscosity). The aerosol was injected into the air flow at the top of the bellmouth above the test region. A particle size analyzer was used to measure the distribution of sizes of the silicone oil droplets. Approximately 80 percent of the droplets with diameters greater than 0.5 μm had diameters less than 1.0 μm.

The largest particles that will accurately track the flow depend, in general, on the details of the flow field. A detailed study of the particle tracking problem for the cascade used in these tests was made by Maxwell.[7] The results of his study show that, for the region where these LDV measurements were made (0.5 inch downstream of the trailing edges of the vanes), the particles should have a diameter of 1.0 μm or less. This will insure that the difference between the magnitudes of the particle and fluid velocities will be less than 0.5 percent and the difference between the direction of the particle and fluid velocities will be less than one degree. To prevent large particles from biasing the velocity measurement a circuit (described below) was included in the signal processing electronics to disregard large amplitude signals (which, in general, correspond to large particles).

ELECTRONICS

The electronics system used to measure the Doppler frequency (range, 10 to 80 MHz) is based on a commercial (Hewlett-Packard) computing counter (with a time interval plug-in and a programmer). This instrument is able to measure time intervals with an accuracy of ± 1 nanosecond. This permits the measurement of a time interval equal to 8 periods of an 80 MHz signal to be made with an accuracy of one percent. Additional circuitry is necessary to condition the Doppler signal and to insure that only valid Doppler signals are used. A logic diagram of this circuitry (built from ECL integrated circuits) is shown in figure 4. The principle of operation is similar to that described by Iten and Mastner.[8]

The signal from the PMT is amplified and sent through a dividing network that splits the signal into two parts. One output of the dividing network contains the part of the signal with frequency components less than 10 MHz (the pedestal signal) and the other output contains the part of the signal with frequency components greater than 10 MHz. If the amplitude of the pedestal signal exceeds a preset level, a signal is sent to the computing counter. This identifies the corresponding Doppler frequency measurement as invalid.

The high frequency signal is sent through a high pass filter (5, 10, 20, or 40 MHz) to remove the remaining part of the pedestal and through a low pass filter (50 or 80 MHz) to reduce the shot noise. It is then applied to: (1) a limiter circuit that produces a square wave output with transitions at the zero-crossing times of the input signal, and (2) a Schmitt trigger with an adjustable threshold. Whenever the amplitude of the Doppler signal exceeds the threshold of the Schmitt trigger (e.g., at time t_o on figure 5) a short pulse is generated that resets the flip-flop. The next transition (with positive slope) of the limiter output (e.g., at time t_1) causes the flip-flop to change states. The resulting low to high transition of the output of the flip-flop is used to clock a synchronous divide-by-8 counter. Succeeding cycles of the Doppler input signal with amplitudes that exceed the threshold of the Schmitt trigger result in a repetition of the process of resetting the flip-flop and clocking the divide-by-8 counter.

The initial state of the divide-by-8 counter is chosen so that its output changes from a low state to a high state on the second pulse (at time t_2) and the tenth pulse (at time t_{10}) applied to its input. The computing counter measures the time interval $T = t_{10} - t_2$ (which is related to the Doppler frequency by $f_D = 8/T$).

Doppler signals are frequently encountered that have fewer than 10 consecutive cycles with amplitudes above the threshold of the Schmitt trigger. These may be caused by very small particles, by particles passing through the edges of the probe volume, or by noise. The following logic circuitry is employed to discriminate against these signals. The divide-by-8 counter is reset by every low to high transition of the output of the limiter if the flip-flop has not been reset; that is, every cycle of the input signal that does not exceed the Schmitt trigger threshold resets the divide-by-8 counter. Thus ordinary noise in the input merely causes a continual resetting of the divide-by-8 counter. If the input signal contains at least 2 consecutive cycles above the threshold of the Schmitt trigger, the output of the divide-by-8 counter switches to the high state and latch 1 is triggered. The next cycle of the input signal with an amplitude less than the Schmitt trigger threshold causes latch 2 to be triggered. The output of latch 2 is applied to the set input of the flip-flop. This forces the output of the flip-flop to remain in the high state until the circuitry is reset by the computing counter. Also, at the time that latch 2 is triggered, the divide-by-8 counter is reset so that the input to the computing counter is held in the low state. In order to allow the computing counter to complete its measurement cycle and to identify the measurement as erroneous, a pulse is applied to the computing counter input after a time delay (16 μs) that is much longer than any valid measurement. This permits identification of invalid measurements during the processing of the data.

In summary, a Doppler input signal with at least 10 consecutive cycles greater than a preset threshold will be divided by 8 and measured by the computing counter. A signal with only one cycle above the threshold results in an immediate resetting of the circuitry and no signal will be sent to the computing counter. A signal with less than 10 (but more than one) consecutive cycles above threshold will result in the computing counter measuring 16 μsec. Finally, signals with a pedestal amplitude that exceeds a preset threshold are identified so that they may be disregarded.

DATA PROCESSING

A programmer is used to control the computing counter and process the data. All time interval measurements greater than 10 μsec are disregarded as well as all measurements taken where the amplitude of the pedestal signal exceeded the threshold of the amplitude discriminator. The remaining time interval measurements are used to calculate the mean and standard deviation of one component of the flow velocity for a preset number of individual measurements. The maximum rate of making and processing these measurements is limited to approximately 150 per second by the computing counter. In addition, the following scheme is used to disregard all measurements that greatly differ from the expected mean velocity. The mean velocity $\bar{v}_{20}$ and standard deviation σ_{20} are calculated for the first 20 measurements. If σ_{20} is less than some preset fraction of $\bar{v}_{20}$ (e.g., 10 or 20 percent), then, for the remaining measurements, all of those with measured velocities greater than $3\sigma_{20}$ from $\bar{v}_{20}$ are disregarded. This feature was incorporated when initial tests showed that an occasional bad measurement (typically one out of several hundred) could cause an error in the mean velocity as great as 10 percent.

The programmer is also used to control the beam blocker that selects which component of the velocity is measured. The mean and standard deviation of the velocity are alternately measured for the axial and circumferential components. The results of these measurements, as well as the position of the movable plates and information about the number of rejected measurements, are recorded by a digital printer.

EXPERIMENTAL RESULTS

Figures 6, 7, and 8 show typical results for the magnitude and angle of the flow velocity calculated from the axial and circumferential velocity components. These are circumferential surveys taken at a constant radial position. The radial position is expressed as a percentage of the span of the vane with the hub at 0 percent and the tip at 100 percent. The flow angles were measured from the axial direction.

The dotted lines on the figures represent the velocity magnitude calculated from data taken by a survey probe used to measure total pressure, total temperature, and static pressure. Details on the probe measurements are given in reference 2. These measurements were taken at an earlier date and the vanes were not the same vanes as those used for the LDV measurements. Therefore, because of differences in the individual vanes and because of blockage of the flow by the pressure probe, the flow conditions were not necessarily identical for the two sets of data and detailed comparisons have limited validity. However, several observations may be made based on these results. The free stream velocities (approximately the region with a constant velocity profile), as determined by the LDV and pressure probe data, at the 7 percent and 35 percent positions are in good agreement (within about 2 percent) although at the 91 percent position they differ by about 4 percent. The dip in the magnitude of the velocity in the wake as measured by the LDV is usually not as great as that given by the pressure probe measurements. The larger dips in the velocity profile near the hub and the tip as compared to the 35 percent position are an indication of the higher losses due to the walls. The angle of the flow for the free stream ranged from 57 degrees near the hub to about 67 degrees near the tip. These values are in agreement with the flow angles reported in reference 2.

The number of individual measurements that are averaged to get each data point shown on the figures range from 200 to 800. The larger number of measurements were used in the wake where the distribution of the measured velocities was greater. The standard deviation of the individual measurements ranged from 3 to 5 percent of the mean velocity in the free stream region and from 15 to 20 percent in the wake. The percentage of the total number of measurements that were not used ranged from 75 percent to 95 percent. Finally, the measured velocities were not a sensitive function of the number of measurements rejected because of large pedestal amplitudes. This indicates that, in the region where these measurements were made, most of the particles present were accurately tracking the flow.

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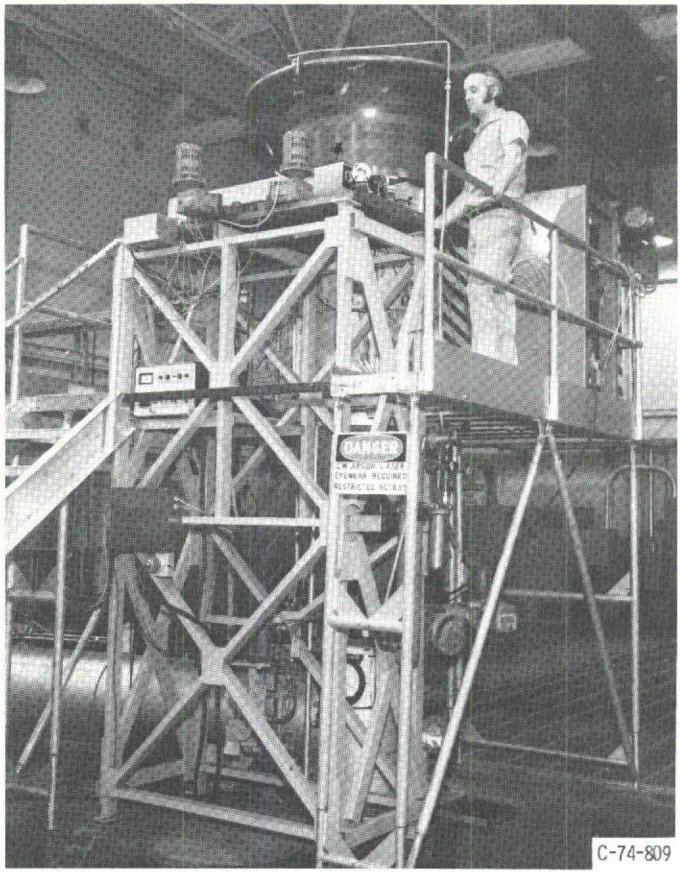

Figure 1. - 32 Inch diameter annular turbine stator cascade facility.

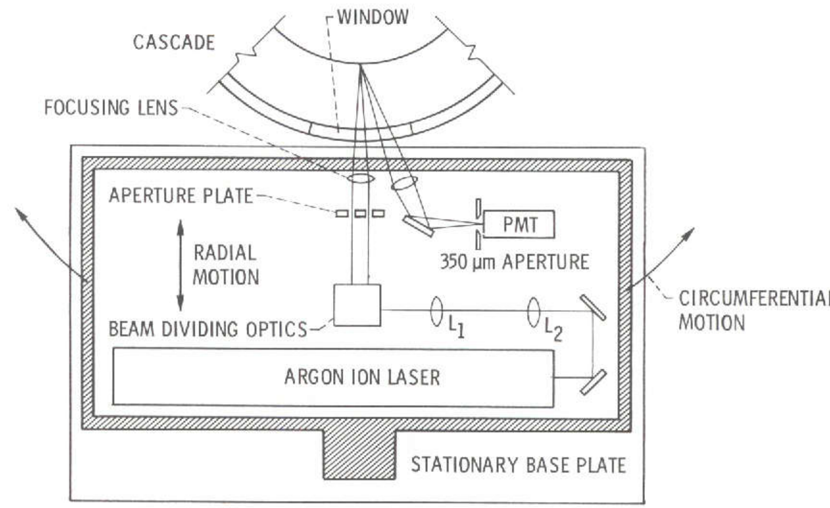

Figure 2. - Top view of optics and traversing mechanism.

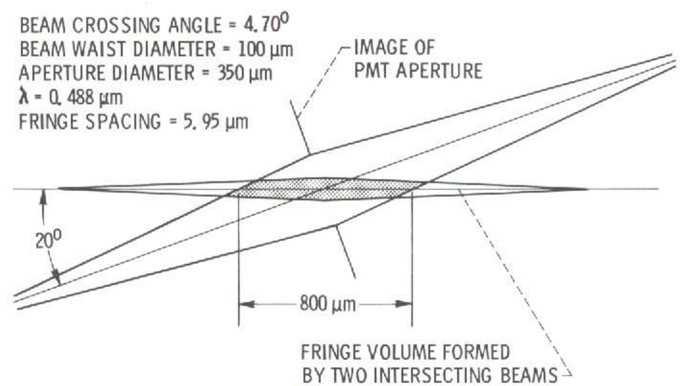

Figure 3. - Probe volume.

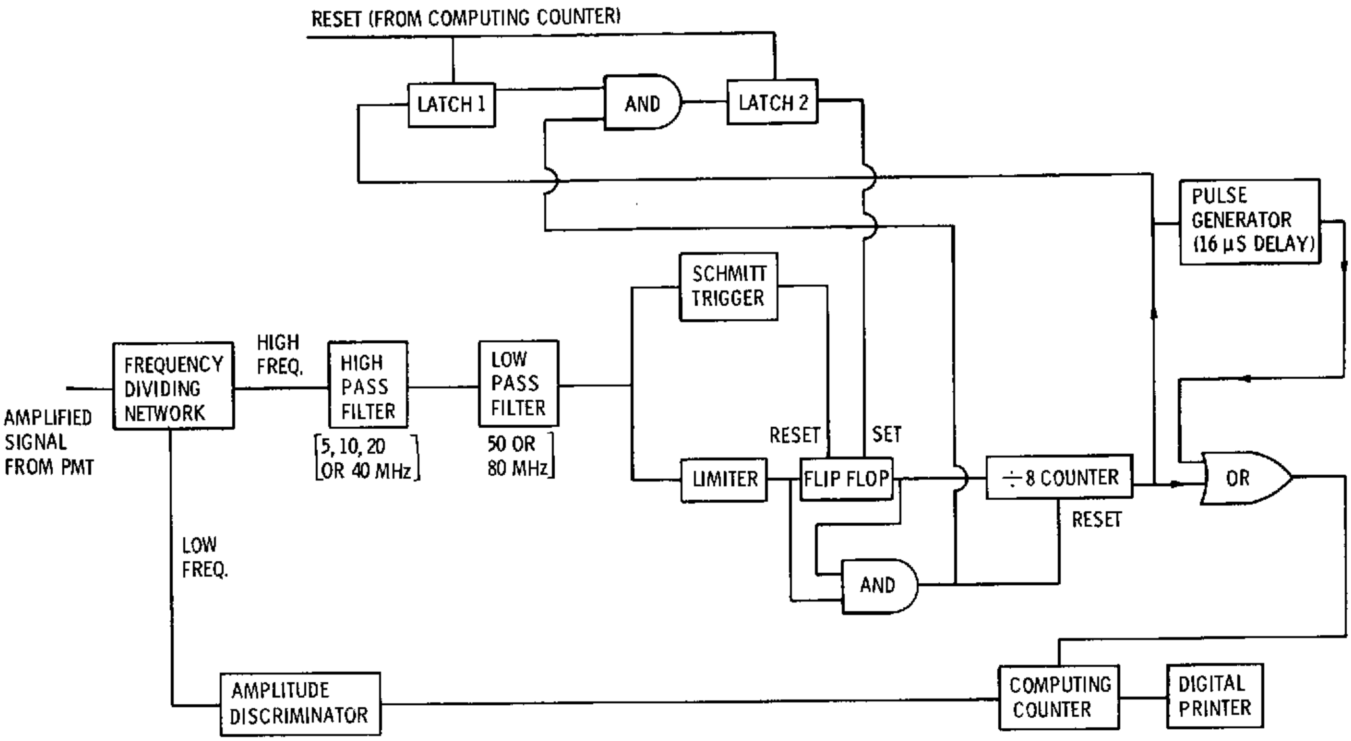

Figure 4. - Block diagram of signal processing electronics.

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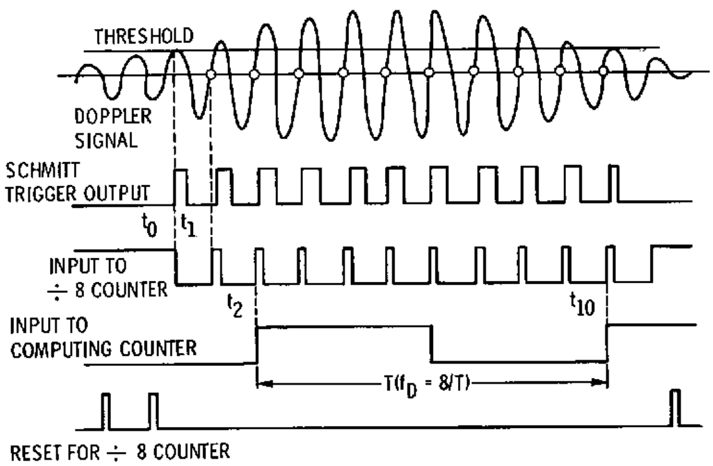

Figure 5. - Selected signals in signal processing electronics.

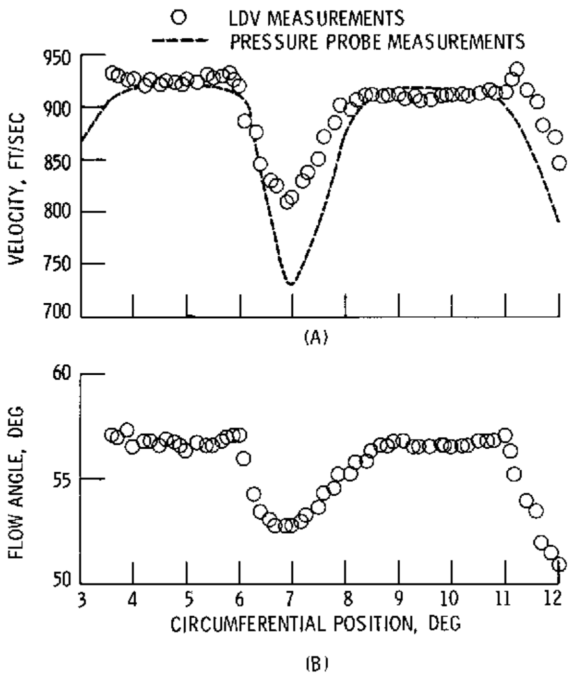

Figure 6. - Magnitude and angle of flow velocity at 7 percent position.

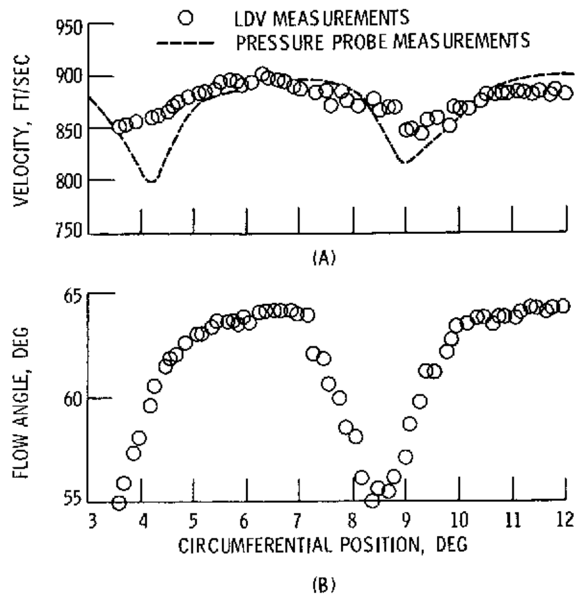

Figure 7. - Magnitude and angle of flow velocity at 35 percent position.

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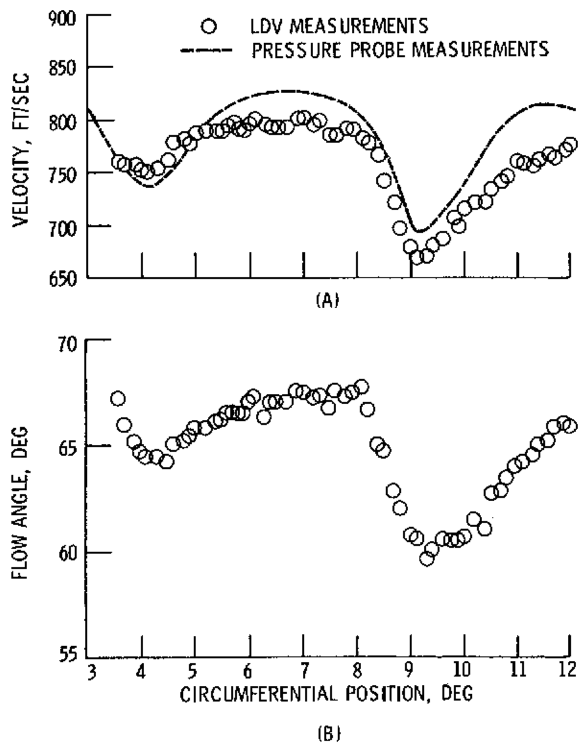

Figure 8. - Magnitude and angle of flow velocity at 91 percent position.