MEASUREMENT OF THE INSTANTANEOUS VELOCITIES IN A HELICOPTER ROTOR WAKE IN FORWARD FLIGHT*

H. Velkoff, H. Terkel, R. Navarro

Department of Mechanical Engineering
The Ohio State University
Columbus, Ohio 43210

1. ABSTRACT

Extensive velocity measurements have been made of the non-steady velocities in the wake of a model helicopter rotor operating at low advance ratios. The work utilized a model rotor operating in a wind tunnel. The measurement system consisted of using a "three-wire" hot film probe which was placed at many locations in the rotor wake. The outputs from the hot wires were sent through signal conditioning equipment, through an A/D converter to a minicomputer. Real time results could be portrayed at a monitor located at the test site and could also be stored for subsequent processing. The primary challenge for the work was the data handling, presentation, and formatting required.

The data operating system sampled data for 14 successive revolutions at 5° azimuth intervals for each of the three wires. The data could be presented as time-varying velocity components at each wake location, in the form of continuous traces, or it could be presented as a 2-D velocity component field in selected planes.

The results of the work indicate that specific wake vorticies are readily observable near the rotor tip regions in the wake. However, more deeply into the wake few clear indications of concentrated vorticity exist.

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2. INTRODUCTION

The need for detailed information on wake structure of the helicopter rotor arises both from a desire to obtain a better understanding of the physical nature of the wake and from the need to provide a sound data base against which descriptive computer algorithms of the flow can be compared. In both the above areas, basic nature and data base, only spotty quantitative information exists. A recent AGARD meeting on rotorcraft loads and the summary report point up the needs for an adequate data base (1). Although prior studies have been run and some are continuing, most have been directed towards obtaining average velocities at points in the wake. Flow visualization, both in hover and in forward flight, has revealed many interesting characteristics of the wake structure as well as forming a basis for various flow models such as the prescribed wake, circulation, and velocity coupled wakes. The flow visualization, of itself, cannot provide quantitative velocity field data.

Early measurements of the flow field used total pressure tubes (2). These results were very useful in demonstrating the nonuniformity of the time averaged flow. However, the instantaneous velocities, which are especially important for accurate loads calculations, were not measured. Hot-film anemometers have been used for rotor wake studies and reported in Refs. 3, 4, and 5. The results of Ref. 3 allowed the structure of a tip vortex to be defined for the hover conditions tested, whereas in Ref. 4 and 5 the averaged velocities at low advance ratios were measured. Photographic techniques have also been used. Ref. 6 and 7 show results from two investigations using Schlieren photography systems. Water and smoke studies using photography are presented in Ref. 8 and 9. Both of these methods are useful for flow visualization, but data reduction is somewhat difficult and accuracy is not high. The first demonstrated use of a Laser Doppler Anemometer (LDA) for rotor investigation was that in Ref. 10. In other recent work with an LDA, such as Ref. 11, instantaneous as well as time averaged velocities were measured. The laser system allows flow measurements to be made very close to the blade, and the vortex velocity distribution and core size were determined.

The purpose of this work was to develop the instrumentation and the experimental methods needed to measure the instantaneous velocities in the vicinity of a small helicopter rotor in a wind tunnel and to make measurements of typical flow fields. The measurements were made with a three dimensional hot-film anemometer. The data acquisition was done by DEC PDP 11/60 or VAX-80 minicomputers with a GENRAD Analog to Digital System. A three dimensional traverse system was used to traverse the anemometer probe throughout the rotor wake. The data were obtained under low advance ratio conditions where large wake distortion can take place.

3. BACKGROUND

In the flight of a helicopter, the lifting surfaces of the rotor deposit both shed and trailed vortices on the wake. The tip vortex is quite concentrated and tends to be a dominant feature of the wake. As the blades rotate through the air, they deposit the various vortices initially in spiral or cycloidal paths. Viewed from a body fixed set of coordinates, the resulting structure is non-steady and generally periodic. In hover, the blades tend to see a steady pattern except for the effects of fuselage or tail interference or vortex path instability or burst. The fixed system elements see a non-steady flow. In forward flight, both the blades and the fixed system see the non-steady effects of the rotor wake structure. At high flight speeds the magnitude of the induced vortices tend to be reduced except at the retreating tip, and the resulting structure often doesn't effect the rotor directly through vortex ingestion. At high speed the induced effects are reduced and the fuselage aft components see less of the complex, "turbulent" wake.

Conversely, the rotor wake at low advance ratios tends to roll up in the vicinity of the rotor and the fuselage. The wake is filled with the vortices trailed from the tip regions, the sheet structure and the root vortices. Portions of this wake can re-enter the rotor disk. Individual vortices may intercept or pass close to the lifting blades. Ever since the pioneering work of Schieman, it has been realized that proximity of a tip vortex can result in significant structural response in consonance with that vortex-blade "intersection".

Many models have been formulated to describe the rotor flow field, using variations of vortex models with prescribed and free wake as well as acceleration potential methods. In most cases the adequacy of the model has been checked using structural response data from model or flight test. Structural response involves many factors, including the integration of many effects as well as the airloads themselves. Thus correlation of analytical wake models with structural data, though useful, cannot truly provide the verification of the models actually desired.

To attempt to provide quantitative information in the complex low advance ratio region, and to provide a relatively simple configuration to model, this study was undertaken.

4. EXPERIMENTAL APPARATUS AND PROCEDURE

The Test Rig

The tests were conducted in a wind tunnel with a test section of 8 ft. x 4 ft. in The Department of Mechanical Engineering at The Ohio State University. The flow turbulence is reduced by means of 500,000 nested 1/8 inch diameter straws followed by a 2 to 1 contraction to the test section. The wind tunnel velocity is variable up to 75 ft/sec.

The tests were carried out on a teetering two bladed rotor with twisted blades. Details of the rotor are shown in Table 1.

Table 1. Details of the Rotor

Number of Blades	2
Rotor Radius, ft	1.25
Blade Chord, in	2.1875
Rotor Solidity $bc/\pi R$	0.0928
Root Cutout % R	12.08
Blade Taper Ratio	1
Coning Angle	0°
Blade Twist	8° (from 12.08% to 100% R)
I_B	0.004260 slug-ft^2
Airfoil Section	NACA 0012
Rotor Speed	2250 rpm

The rotor is driven by a variable speed electric motor. The speed is variable up to a maximum of 3000 RPM which results in tip speeds up to 400 ft/sec. The collective pitch and the rotor shaft tilt angle are variable but are constant for each case run.

Data Acquisition System

General Description

The data acquisition system consists of two basic subsystems:

1. the velocity measurement system and

2. the minicomputer and the A/D system.

The velocity measurement system is located at the wind tunnel on the first floor of The Mechanical Engineering building and consists of a three-dimensional hot-film probe connected to three constant temperature anemometer circuits. The probe is attached to a traverse mechanism positioned in the wind tunnel enabling the operator to locate the probe at the desired point in the tested volume.

The minicomputer and the A/D are located in the computer room (ADML laboratory) on the second floor of The Mechanical Engineering building. The operator interfaces the computer by means of an alphanumeric terminal. The triggering of the A/D is done from the wind tunnel by a special interface designed and built for this purpose. Figure 1 shows the interconnection of the entire system.

The Velocity Measurement System

The rotor induced velocities were measured by a three dimensional hot-film probe (TSI 1294-20-18 or 1294-60-18) connected to three DISA 55D05/102C constant temperature anemometer circuits with a SOLA 83-15-2216 power supply. In order to improve the frequency response of the hot-film anemometer a lead compensator was added to each channel. Because of the mode of operation of the A/D converter channels B and C had to be delayed, 6μ sec and 12μ sec respectively, in order that the computer would "see" the same angle of the rotor in time. The delay lines used were Allen Avionics 1000 ohms impedance 6μ sec B06P0Z01K. One delay line was used for 'B' and two 6μ sec delay lines in series were used for 'C' to create the 12μ sec delay. The output from the anemometer thru the delay lines was connected to three DANA 2210 DC amplifiers. In the latter phases of test the DANA amplifiers were replaced by three integrated circuit amplifiers to improve stability. Figure 2 shows the complete velocity measuring system including the lead compensators and the delay lines.

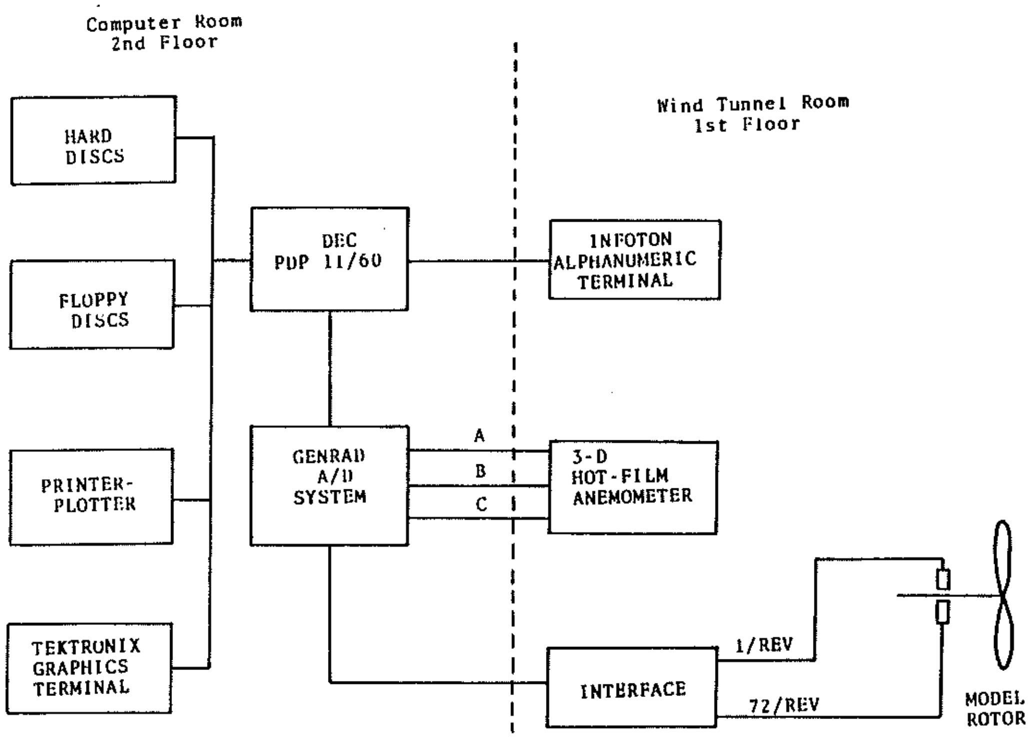

Figure 1. Block Diagram of the Entire Measuring System

Directional Sensitivity of Cylindrical Sensors

The basic hot-wire hot-film anemometer output is a voltage which is related to the fluid velocity approximately as:

$$E^2 = A + B\,U^{1/2} \qquad (1)$$

where U is the stream velocity, E is the voltage output and A, B are constants determined by the electronic circuit, the physical properties of the sensor and by the fluid properties.

If the fluid velocity is not perpendicular to the sensor, equation (1) does not hold, since the heat transfer from the sensor is reduced. A convenient way to overcome this problem is to define an "effective cooling velocity" as the perpendicular velocity which produces the same cooling effect as the actual, non-perpendicular velocity and to

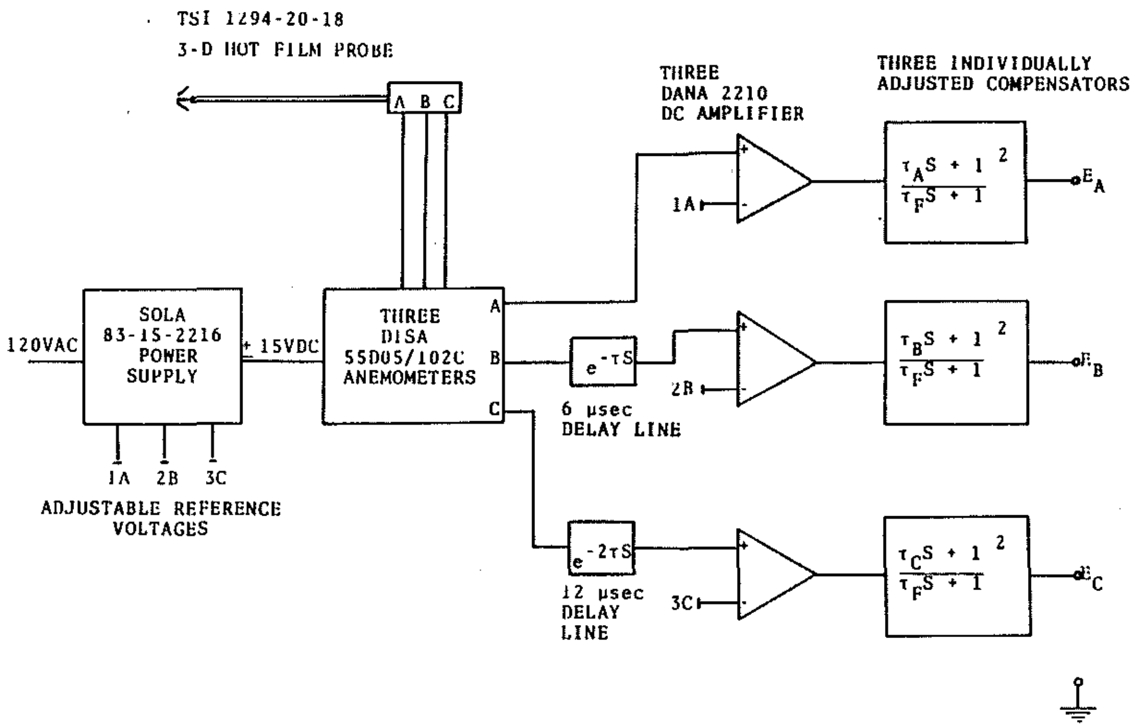

Figure 2. Block Diagram of the Anemometry

correlate it to the true stream velocity.

The relationship used in the initial part of the study is

$$V_{eff}^2 = U^2(\cos^2 \phi + k^2 \sin^2\phi) \qquad (2)$$

where:

V_{eff} is the effective cooling velocity normal to the sensor

U is the stream velocity

ϕ is the angle between the free stream and the normal to the sensor

k is a dimensionless constant

An alternate form was used in the latter phases and $V_{eff} = U \cos^m \phi$

The three dimensional probe consists of three orthogonal, cylindrical sensors. The effective cooling velocities of the three sensors are:

$$V_i^2 = U^2(\cos^2\phi_i + k^2\sin^2\phi_i) \qquad i = 1,2,3 \qquad (3)$$

The mean velocity becomes

$$U = \sqrt{\frac{\Sigma V_i^2}{2 + k^2}} \qquad (4)$$

The directional angles can be obtained from

$$\sin\phi_i = \sqrt{[1 - [\frac{V_i}{U}]^2]/(1 - k^2)} \qquad i = 1,2,3 \qquad (5)$$

The total velocity vector and its direction in the probe system of coordinates are thus delineated.

The above analysis is correct, provided that k^2 is the same for all three wires and that it is not a function of the wires' Reynolds number. At low Reynolds numbers this assumption will lead to erroneous results.

To overcome the above stated problem an iterative program was developed to account for the dependency of k^2 on Reynolds number, and specifically on the total velocity vector, U.

Extensive investigation on the influence of k^2 on U and ϕ_i showed that k^2 had a negligible effect on the calculations of U, and a significant influence on the angles. Thus, to simplify the iterations a constant value of k^2 (based on the average values of k_A^2, k_B^2, k_C^2)was used in calculating the total vector, and a local value of k_i^2 was used in calculating ϕ_i.

The probe used was a T.S.I. 1294-20-18 or 1294-60-18 hot-film probe. The three sensors are mutually perpendicular and inclined 54.74° to the probe axis. The spatial orientation of the probe in the wind tunnel is shown in Fig. 3, and the probe coordinate system is shown in Fig. 4, relative to the rotor coordinate system. The orientation of the probe is such that axis C lies in place X - Z and plane BOAD is perpendicular to the same plane. For this orientation we can perform the coordinate transformation knowing that:

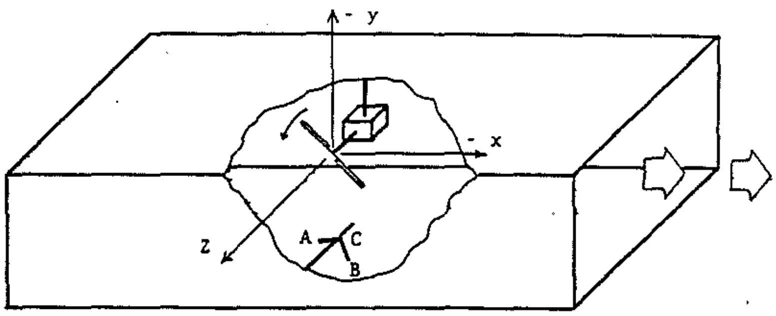

Figure 3. The Spatial Orientation of the Probe in the Wind Tunnel

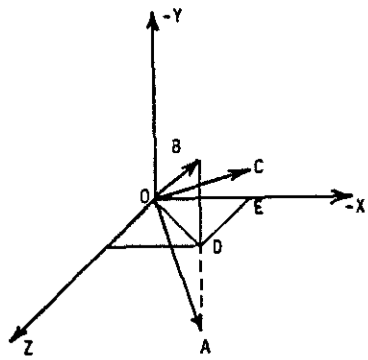

Figure 4. Probe Coordinate System Relative to Tunnel Coordinate System

$$\angle EOC = 35.26°$$

$$\angle EOD = 54.74°$$

$$\angle AOD = \angle BOD = 45.0°$$

Equations 3.13 through 3.16 define this transformation

$$V_x = 0.4082(U_a + U_b) - 0.8165U_c$$

$$V_y = 0.7071(U_a - U_b)$$

$$V_z = 0.57735(U_a + U_b + U_c)$$

The calibration of the three-dimensional probe consisted of two stages. The first was to obtain the voltage versus velocity curve for each sensor and the second was to determine the dependency of the yaw angle sensitivity constant k^2, on the total vector U. Since all calculations of the velocity were done by computer, a forth order polynomial was fitted to the calibration curves of each sensor. The effective velocities were calculated with this equation.

$$V_{eff} = E_4E^4 + C_3E^3 + C_2E^2 + C_1E + C_0$$

The constants of the polynomials were calculated by using the Method of Least Squares. The curve fit matched the experimental results within $\pm$ 0.4 ft/sec.

Directional Sensitivity Calibration

The purpose of this calibration was to determine the dependency of k^2 on the velocity vector. An extensive investigation done for this purpose revealed that k^2 is strongly dependent on the wire's Reynolds number where

$$Re = \frac{Ud}{\nu}$$

However, d and U are constant for each case, and R_e becomes a function of U alone. Therefore, k^2 was evaluated also as a function of U. For high Reynolds numbers, k^2 is nearly a constant. Thus, only by changing wire diameter (different probes) the values of k^2 would change even though the regime of velocity was not changed. For the TSI 1294-60-18 probe with 0.006 inches wire diameter, a single value of k^2 was adequate, similar to the method discussed in Ref. 12.

For the TSI 1294-20-18 probe, k^2 showed a strong dependency on the velocity (low Reynolds number due to small diameter). The correlation between k^2 and U was obtained experimentally. Then the data obtained was curve fitted so that the relationship $k^2 = f(U)$ could be used in the computer program.

The Minicomputer and the A/D System

The minicomputer, installed in The Department of Mechanical Engineering at The Ohio State University, provided the means of data acquisition for instantaneous velocity measurement.

The minicomputer is a Digital Equipment Corporation (DEC) PDP 11/60. It has a 256 KBYTES memory (RAM) and 64 KBYTES are available to the user. The PDP hosts graphics (Tektronix 4014-1) and alphanumeric (Infoton) terminals. The terminals are supported by a high speed Printronix Printer-Plotter and a Tektronix hardcopy unit. Data and program storage are provided by a dual floppy disc drive and two cartridge disc drives.

A GENRAD 4 channel Analog-to-Digital System (ADS) with sampling frequency up to 160 KHz was used for data acquisition.

The ADS is triggered by one pulse sent from an interface unit at the wind-tunnel. The ADS then samples the first channel and after 6μ sec the next one. The 6μ sec interchannel interval caused significant errors in our case, where the three digitized values had to correspond to the same instant in space and time. To overcome this problem Allen Avionics delay lines were used. Using these delay lines the analog signal B was delayed by 6μ sec, and the analog signal C was delayed by 12μ sec. The simultaneous triangular wave test conducted with the delay lines showed agreement between channels A and C within 0.26%, which is of the order of magnitude of the noise present in the long cable connecting the ADS to the wind tunnel.

The analog signals coming out of the constant temperature anemometer were connected by a 500 ft. cable required to get from the wind tunnel room, where the experiments were conducted, to the computer room. An analysis conducted on the significant frequency content of the wake at a typical point, showed that the significant frequency is contained in the region below 4000 Hz. Fortunately, this frequency was far below the frequency where the reactive elements of the cable became significant. This frequency of the cable was found to be around 20 KHz. However, the triggering signal was a square pulse of 1μ sec. This short duration makes the frequency content of the pulse on the order of magnitude of 1 MHz which is in the region where the reactive elements of the cable (capacitance and inductance) are significant. We found that the pulse is attenuated from 10 volts to about 5 volts. The triggering threshold of the ADS is 3 volts, thus the 50% attenuation of the signal did not cause any problem. An additional 0.6μ sec delay was observed, corresponding to an insignificant rotor rotation, and we concluded that the triggering process was reliable.

Data Acquisition Method

Prior to starting the data acquisition, the flight conditions for the rotor were set. This was done by adjusting the collective pitch angle, incidence angle, tip speed and wind velocity. Then the system was adjusted so that the response of the hot film and data output system would be flat up to about 4000 Hz.

The data collection was done in a predetermined systematic method, which was a three nested do loops, each for one coordinate. The x direction changed the fastest, then z, and last to change is y. Each case started at x - 28, y - 20, z = 12 and from this point on, the computer did the bookkeeping and instructed the operator how to proceed. The process was fully continuous from previous days (the data acquisition for one case might take about a week) with no information needed from the operator except defining the status of the new day, i.e. is the present data acquisition a continuation of previous session or not? If the answer was yes, the computer instructed the operator where to locate the probe, and if the answer was no, the computer instructed the operator to locate the probe at the initial point. Once the data collection started the computer would tell the operator when to change holders and warn him when the probe got into the area in which the rotor is too close to the sensors.

Using the assumption that the wake is periodic for each and every rotor revolution the data collected was averaged at every five degrees increment for 14 revolutions. For this case the ADS had to be triggered each time the blade had passed five degrees of rotor revolution. At a tip speed of 300 ft/sec the sampling frequency is about 2750 Hz which is not a sufficient sampling frequency for a fine-grain wake reproduction. Thus, we have to keep in mind that the values measured are discrete values at five degrees increment of rotor rotation. The five degrees increment triggering signal was supplied by an interface designed and built for this project.

The data were collected by the computer in real time with the ADS.

The inputs to the interface of the ADS were:

a 1/REV pulse from a magnetic proximity pickup indicating ψ = 0, and 72/REV pulses from a second magnetic proximity pickup indicating five degrees increments in rotor rotation. The output from the interface was one pulse at each five degree increments for 15 revolutions.

The ADS was initiated by the software, but the digitizing process started only after the operator signaled, from the interface, that the probe was at the correct location. Then, the ADS was triggered every five degrees.

After the digitizing process was completed, the computer averaged the data for every five degree increments for 14 revolutions. The three average voltages were transformed into wind tunnel coordinates in the manner previously described. These velocities and the probe location were temporarily stored in an encoded way, on the computer's hard discs, until the case was completed.

The numerical values of the velocities and their location were stored on floppy discs and could be displayed on any terminal or printed out by high speed printer. However, the vast amount of "numbers" associated with each case (1188 points x (72 x 3 numbers per point) = 256608 "numbers" for velocity presentation) made the use of data visualization a necessity.

For data visualization the TEKTRONIX 4014-1 graphics terminal was used. This terminal has a refresh mode of operation and animated pictures of any plane (xy, yz, zx) as the rotor passes by were created. In addition, graphs of velocity vs. rotor position, or velocity vs. probe location could be obtained by using the plotting routines available.

Measurement Error Analysis

Probe error was evaluated experimentally. The probe was installed on the probe holder in the calibration nozzle rig so that all the sensors were inside the core of uniform velocity. Then the velocity of the jet was set to velocity values between 10 and 70 ft/sec, and the probe was rotated as to achieve different combinations of ϕ_i. The velocity was varied in steps of 10 ft/sec and combination of the directional angles were set at each velocity. The anemometer's analog voltages were connected to the ADS in the usual way, and the velocities were read from the terminal. These velocities were then compared with the actual velocities determined using the velocity calibrator's calibration curve. The results showed an average error of 1 ft/sec and an angular error of $\pm 1°$.

The probe was also checked in the wind tunnel. The magnitude of the measured velocity was within 1% of the stream velocity. A constant 5° error relative to the X axis for all the points measured and for the whole velocity range was corrected for in the transformation equation. An extensive investigation was done and revealed that the velocity error due to tunnel wall and probe vibration at the sensor is less than 1%.

The tunnel speed is believed to be accurate to within 2%, rotor speed to within 2%, blade angle to within $\pm .5$ degrees and the probe positions to less than ± 0.1 inches.

5. TEST RESULTS AND THEIR PRESENTATION

Because of the enormous amount of information that could be obtained for even a single test condition, data presentation was a primary concern at the onset of the work. It has remained so. Factors involved include:

(a) the desire to provide understanding of the nature of the flow

(b) the need to quantify the results so that they can be of some use to analysts

(c) the recognition that the flow at each point in the wake is changing instantaneously and continuously. The velocity at a point is a 3-D vector which changes in time, which from a presentation viewpoint is a 4-D vector.

The ability to provide understanding and to provide quantitative data is frustrated by the enormously large amount of data which could be obtained. An automated system will produce such vast quantities of data, which could be completely beyond human understanding if tight bounds are not placed onto the test and the data acquisition. Similar situations were seen in the initial useage of strain gage output where many, many gages were used and literally miles of oscillograph tapes resulted for every helicopter flight test use.

In the initial set up of the system presented herein, many presentation systems were considered. Several were tried. It was believed that visualization could help the understanding of the physics of the flow. Presentation of velocity vectors which varied in time in a manner analogous to "streak lines" could be useful in conjunction or in comparison with smoke visualization pictures. Of several possibilities a technique was utilized of presenting the 2-D components of vectors on selected planes through the wake. The vectors would be presented as "frozen-in-time" at 5° azimuth intervals. Computer preparation of the plots would be made and in presentation on a monitor, could be stepped in 5° increments. The variations with time of any or all the selected points could then be observed as the sequence stepped around the azimuth.

Another technique tried, provided isometric surface plots of velocities. For each plane selected, a single component of the velocity could be presented as arising from that plane and the resulting surface drawn in by the computer. The most useful presentation for this graphical scheme seemed to be the depiction of downwash velocities, V_z, on horizontal planes below the rotor.

Still another technique considered in some detail was the presentation of velocities emanating from a plane, typically a vertical plane perpendicular to the tunnel axis. The velocities would arise from a point and be shown relative to a reference perpendicular. The vectors would be seen as to move as pointers and would be equivalent to a tuft grid except that not only would direction be seen but variation in magnitude as well.

While the foregoing presentations are descriptive in nature, to provide a more quantitative view, information could be provided in a time sequence at a given point or a plane, or it could be in a position sequence for selected instants in time (azimuth). If one were to provide velocity data at any point, then it would be necessary to provide either a curve for each of the three components of velocity versus azimuth, or a detailed listing of the components at each azimuth position. As discussed in the section on velocity measurement, such a listing would require 256,000 items of averaged data.

The presentation of data accomplished to date has concentrated on the plots of time varying curves of velocity components at selected points and the presentation of planes of 2-D vectors in the planes through the use of computer graphics.

Typical plots of the components of velocity versus time are presented for a flight condition with the following parameters.

Blade Tip Speed ft/sec	300
Advance Ratio	0.06
Collective Pitch, (75% R)	8
Rotor Shaft Tilt Angle, degrees	8

Figures 5, 6, and 7 present data from points in a plane located just aft of the rotor, at Z/R = -1.07, or 7% of the rotor radius aft of the rotor tip. The point p_{028} refers to a position X/R = 0.27 or 27% of the radius laterally on the retreating side, and a Z/R of 0.2 which is a point .2 R below the reference plane through the rotor center, parallel to the tunnel "floor" and would be perpendicular to the shaft axis if the shaft axis inclination were zero degrees. At this point, X/R = -1.07, X/R = 0.27 and Z/R = 0.2, the probe should be immersed in the "wake" from the rotor, yet it should not be in the immediate proximity to the blade tips which should pass above it. These figures illustrate that some 1p and 2p is present. The 2p would imply the presence of a "disturbance per blade" and as will be noted from the next sequence of figures was probably the influence of trailed vortices. Further examination of the figures does not reveal significant nonsteadiness that might be associated with a complex vortex filled wake. At Z/R positions lower than 0.2, the velocities show even less excursion. Yet if one examines Figure 14 of reference 13, it can be seen at these positions, X/R = -1.07, X/R = .25 and Z/R = 0.2, 0.4, 0.6, that the probe is located in the heart of the downwash field and should respond to all significant velocity fluctuations. Throughout the velocity field except near the blade tips, large excursions of the

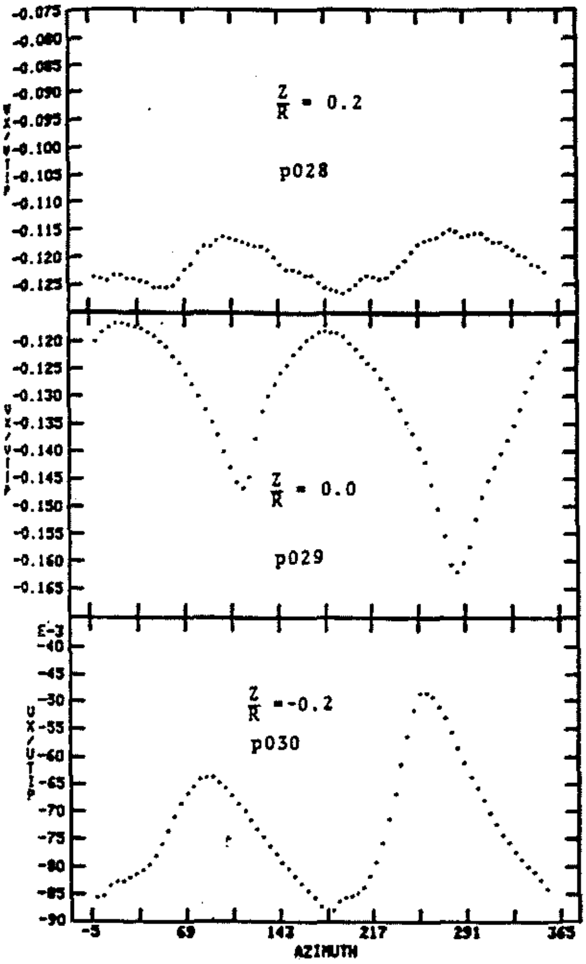

Fig. 5. Stream Velocity Variation with Azimuth for $\frac{X}{R} = -1.07$ $\frac{Y}{R} = 0.27$

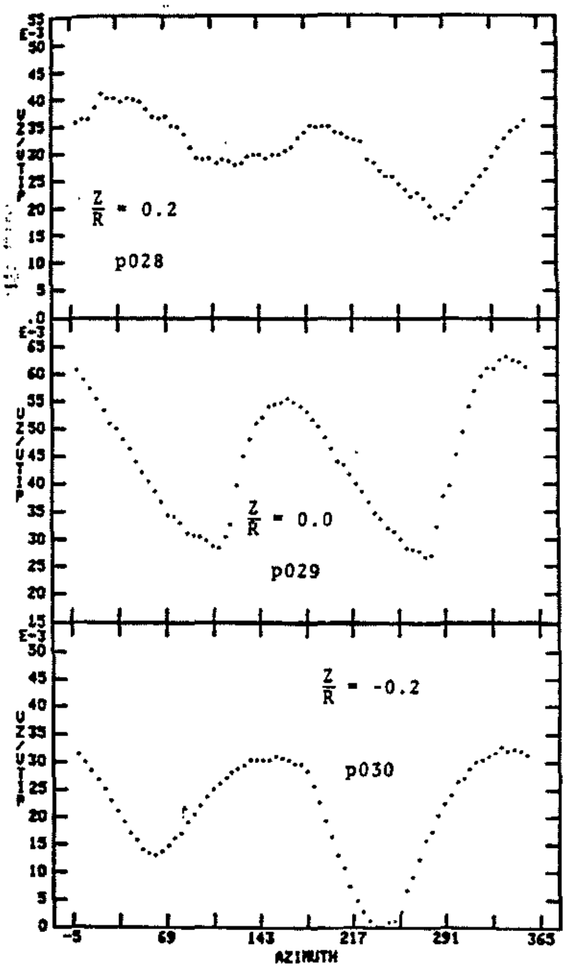

Fig. 6. Normal Induced Velocity Variation with Azimuth $\frac{X}{R} = -1.07$ $\frac{X}{R} = .27$

velocity vectors are not apparent.

If one next considers a location in close priximity to the blade tip one can indeed see strong indications of localized vortex actions. Figures 5, 6, and 7 also present data for a point just above the previous point, at the position X/R = -1.07, Y/R = 0.25, and Z/R = 0.0 p_{029}. This point is in the reference plane and is about an inch and a half below the tip path plane at the rear. The two per rev oscillation

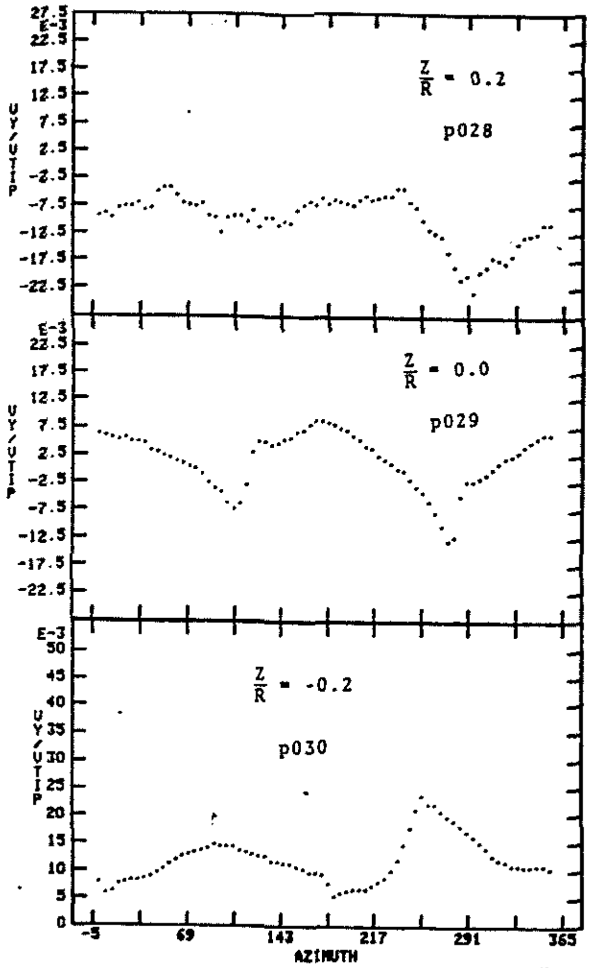

Fig. 7 V_y Velocity Variation with Azimuth for $\frac{X}{R}$ = -1.07, $\frac{Y}{R}$ = .27

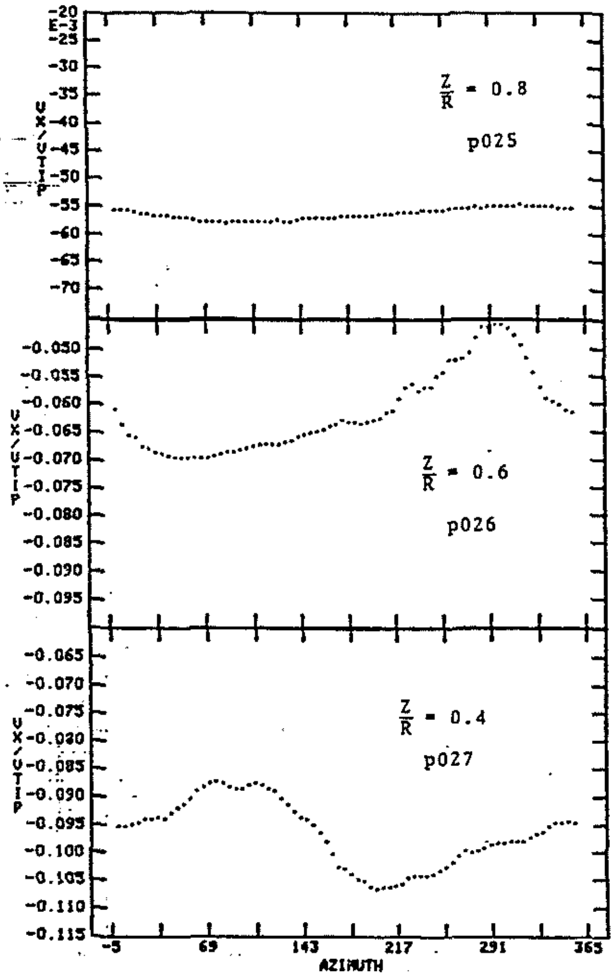

Fig. 8. Stream Velocity Variation with Azimuth fo X/R = -1.07 and Y/R = 0.27

can be clearly seen in all three of the traces. This is attributed to the passage of vortices which were newly created at the tips of the blades at the rear of the disk.

Point p_{030} illustrates the situation for the point at Z/R = -0.2 which is slightly above the reference plane.

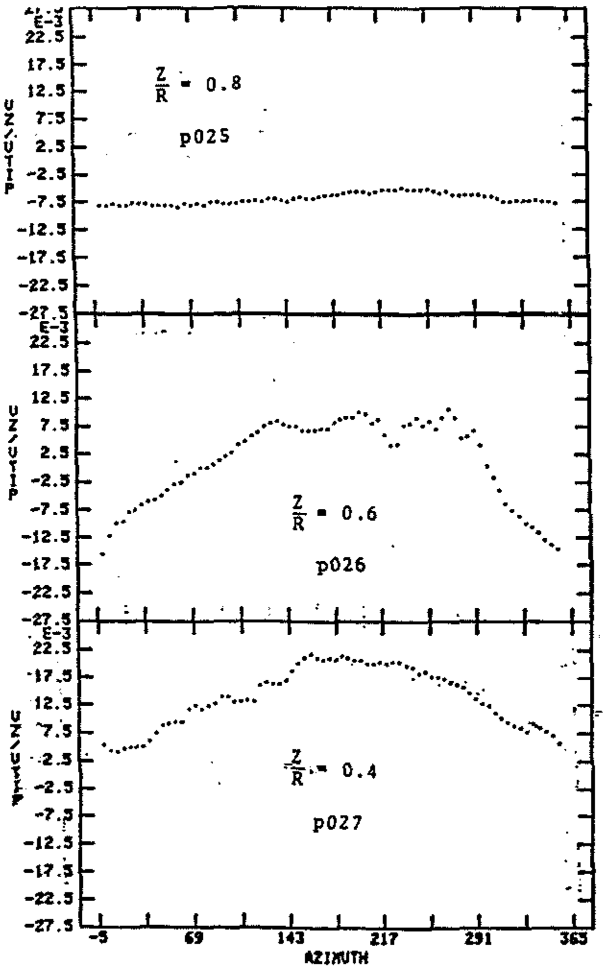

Fig. 9 Normal Induced Velocity Variation with Azimuth
X/R = -1.07 X/R = .27

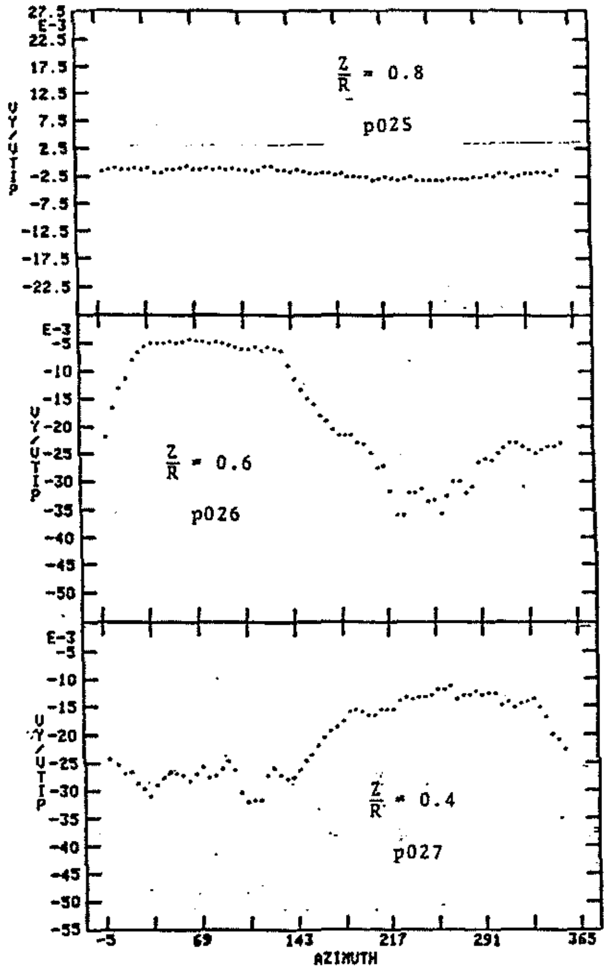

Fig. 10 V_y Velocity Variation With Azimuth
Y/R = .27 X/R = -1.07,

Figures 8, 9, and 10 present data at locations further below the rotor plane at X/R = -1.07, Y/R = 0.27 and Z/R = 0.8, 0.6 and 0.4. At Z/R = 0.8 the probe output indicates that the probe is located below the wake in a relatively undisturbed region. At Z/R = 0.6 a once per rev variation can be seen and some higher order oscillations can also be seen when the reference blade is between 200 and 300 degrees. For Z/R = 0.4 some higher order disturbance can be seen both at 0-145° and 220-325° azimuth positions.

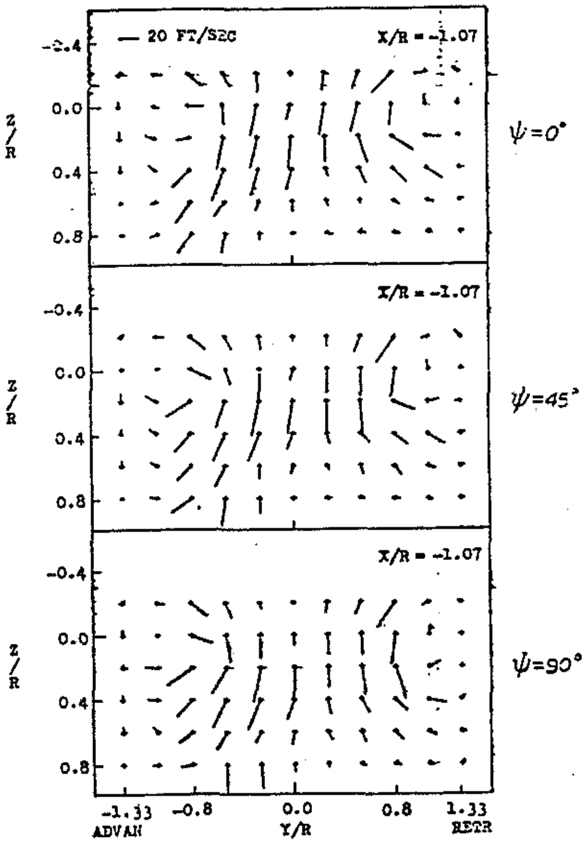

Figure 11. Y-Z Vectors for X/R = -1.07 at Several Azimuth Angles.

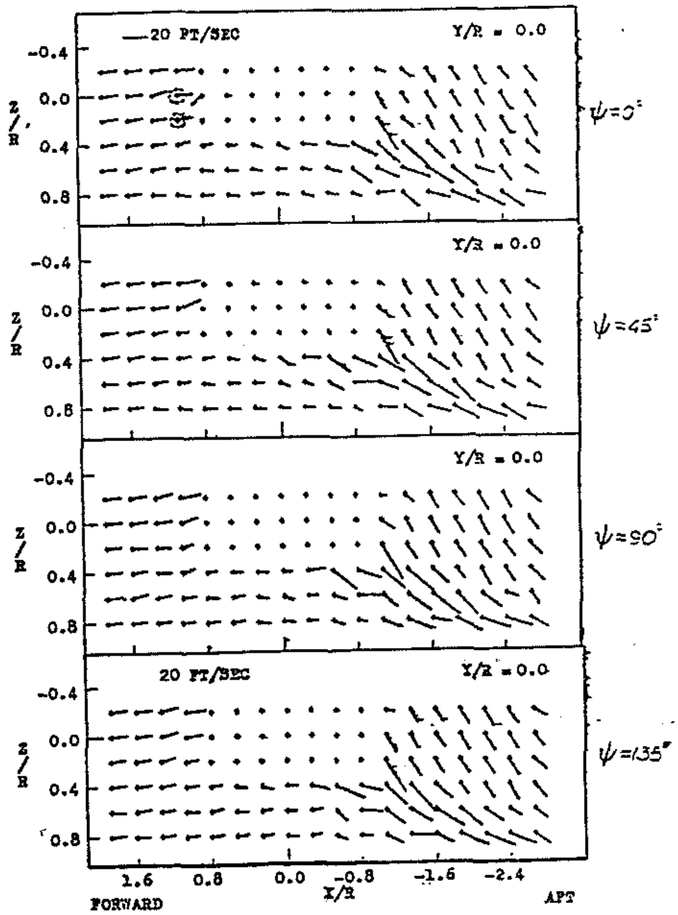

Figure 12. X-Z Vectors for Y/R = 0.0 at Several Azimuth Angles

The pictorial representations of the 2-D vectors in planes are identical in appearance to the figures shown in reference 13. Samples of these are shown for three orthogonal planes in Figures 11, 12, and 13 for some typical azimuth angles. Even when considering a complete azimuthal set for any given plane, it is difficult to see significant differences in the velocity fields as the rotor rotates. A motion picture film of the various planes of vectors was prepared based upon the computer graphics developed under this project.

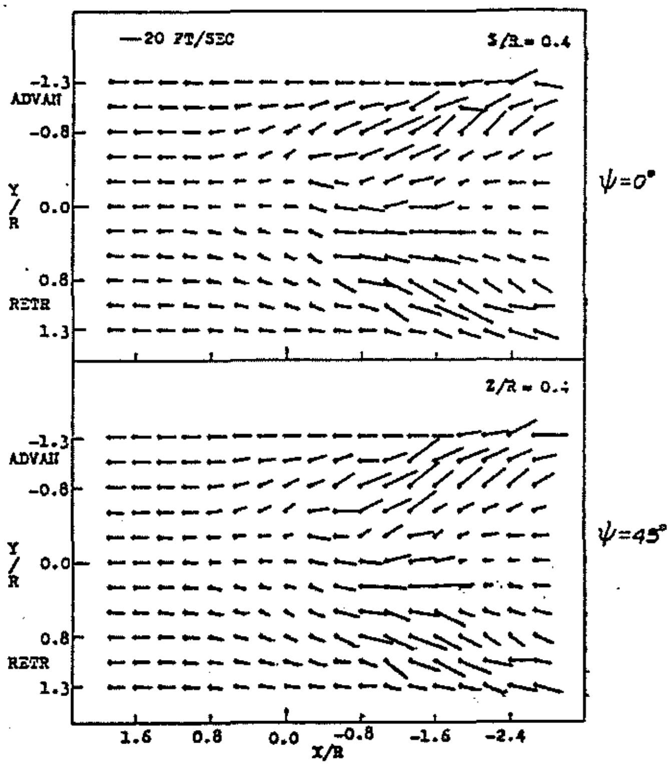

Figure 13 X-Y Vectors for Z/R = 0.4 for Several Azimuth Angles

6. CONCLUSIONS

The instrumentation system and the data processing methods developed were found to be quite effective in the measurement of instantaneous velocities in the wake of a model rotor. The computer based data handling system was able to acquire and reduce vast quantities of data in an efficient manner. It proved possible to automate most of the data-handling and the data presentation. The actual conduct of the test was performed manually although the interactive feature allowed the computer to guide the operator in setting probe positions as required by any test condition.

Although the study started with the fundamental question, "How can the vast quantity of information best be portrayed?", and although considerable effort was directed towards presentation techniques, it is believed that this fundamental question remains. Because of this, the request made in AGARD AR-189 is repeated, that is - it is recommended that a group of concerned rotary wing analysts and experimentalists be convened for the purpose of defining as precisely as possible the type of data and format which would be most useful.

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