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Use of a Four-Hole Cobra Pressure Probe to Determine the Unsteady Wake Characteristics of Rotating Objects

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This paper investigates the wake characteristics of rotating and static objects, typical of US Navy ship emitters, using a four-hole Cobra Probe. The Cobra Probe has the ability to measure unsteady 3D velocity. An in-situ calibration was performed and compared to manufacturer specifications. Agreement between the in-situ and manufacturer calibrations led to a practical assessment in a 3D turbulent flow field. The assessment provided insight into the wake of rotating and static objects, and further explored limitations and advantages of the Cobra Probe for subsonic wake flows.

I. Introduction

The Experimental Aero-Physics Branch at NASA Ames Research Center conducts a variety of fluid mechanics, aerodynamics, acoustics, and instrumentation development programs, using wind tunnel and water channel facilities at the Fluid Mechanics Lab (FML). A US Navy-sponsored project currently underway at FML investigates the aerodynamic wake characteristics of various ships, as a means of improving safety for aircraft operating in the ship vicinity. One subtask of this project is the experimental determination of wake characteristics downstream of rotating electronic emitters, such as planar radar arrays. Review of existing instrumentation revealed that the Cobra Probe (Turbulent Flow Instrumentation, Inc; TFI) might prove useful in a wind tunnel effort to document flow speed and direction characteristics in the complicated three dimensional unsteady wakes that occur downstream of rotating arrays. Before starting the actual wind tunnel effort, a short investigation of the Cobra Probe's adequacy for such efforts was conducted. This paper reviews the results of that investigation, and provides some practical insight gained from use of the Cobra Probe for measurements of three-dimensional unsteady wakes.

II. Cobra Probe Overview

The Cobra Probe was first proposed by Shepherd[1] for mean flow measurements and further developed by Hooper and Musgrove.[1-4] The Cobra Probe is a multi-hole pressure probe which has the ability to simultaneously measure three unsteady orthogonal velocity components in subsonic flows. Unlike many other pressure probes, it is able to resolve unsteady velocity components because its pressure transducers are located in close proximity to its pressure sensing ports. The Cobra Probe is capable of measuring not only mean or time-averaged flow properties, but also time-varying or turbulent flow properties at a practical range of frequencies. The Cobra Probe provides a variety of parameters during each measurement; these include 3D velocities, flow angles, turbulence statistics, Reynolds stresses, and static pressure.

The design of the Cobra Probe is shown in Fig. 1.[3] There are typically 3 probe sizes and 3 pressure transducer ranges available. Pressure transducer ranges are from 1 to 7 kPa and provide velocities from 2 to 100 m/s. The exact velocity range of the Cobra Probe is dependent on the pressure transducer range, density of the fluid, pressure at the Probe's reference pressure port and electrical noise. The probes in use at FML employ 2 kPa pressure transducers, which provide a useable speed range between 3 and 80 m/s. Prior studies have shown that the Cobra Probe is

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accurate to at least 1500 Hz[2], and is relatively stable with temperature (minimal thermal drift within 10° C of calibration temperature). The Cobra Probe comes with its own data acquisition and reduction software, and has user-selectable sample duration and sampling rate. Data files are stored in binary format, but the software includes a conversion routine to create ASCII data files. The Cobra Probe's compactness and ease of use makes for a portable instrument that can be used with a laptop or desktop computer through available data acquisition cards.

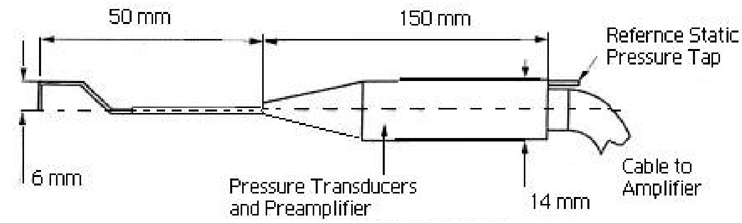

Figure 1. Cobra probe. (adapted from Chen et al.)

Figure 1 depicts the type of probe in use at FML. This probe is configured with 0.4 mm diameter pressure tap holes and a 2.6 mm diameter head. Being a four-hole pressure probe, the Cobra Probe has a flow acceptance cone with a 45° half angle. As a result, some flow situations require the probe to be rotated. The probe's design allows for 360° rotation about the shaft axis without changing the measuring position; this feature is important in swirling flow.[2] The lower portion of the probe is J-shaped, for which the probe is named, and houses four pressure taps. It has a truncated pyramid-shaped head with a center face oriented perpendicular to the probe centerline and three faces oriented at 45° to the center face. Each of the four faces has its own pressure port. The Cobra Probe measures pressures at each of the four ports and compares them to a table of calibration data generated by the manufacturer. The associated speed, pitch and yaw angle for the four pressures are interpolated in the table of calibration data. Additionally, the static pressure is determined during the same interpolation.

III. Manufacturer's Calibration

Before conducting an in-situ calibration of the probe, the manufacturer's calibration procedures were reviewed. The following section describes the manufacturer's calibration of the Cobra Probe. The content of this section was derived from the TFI Cobra Probe User's Guide.[5] The probe was shipped fully calibrated. The manufacturer calibrates each Probe in a steady flow of low turbulence for a range of pitch and yaw angles within the 45° cone of acceptance. This was done by mounting the Probe on a pitch and yaw traverse with the Probe head located in the core flow of a wind tunnel. Pressures from each of the four taps in the Cobra Probe head were measured over the entire operating range of the Probe; calibrations are generally performed over the range ±48° for pitch and yaw in 4° increments. Sample calibration data consisting of the four hole-pressures versus pitch and yaw angle are presented as contour plots, depicted in Fig. 2.[5] Data from Fig. 2 can be combined to form calibration surfaces, which include measurements from all the calibration points. Thus, a calibration surface is simply a two dimensional plane that contains non-dimensionalized calibration data for a Cobra Probe, such as shown in Fig. 3.[5] Each calibration surface is generated by calculating non-dimensional ratios consisting of pressures from the Cobra Probe head and points that covered the operating pitch and yaw range. Calibration surfaces for pitch angle, yaw angle, total pressure, and static or dynamic pressure are then used to calculate the instantaneous three-dimensional (3D) velocity vector and static pressure.

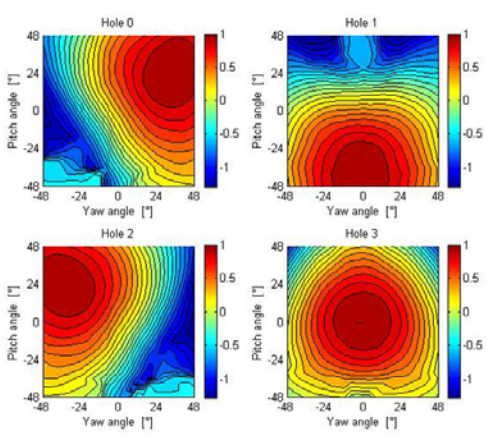

Figure 2. Sample Calibration Hole Pressures.[5]

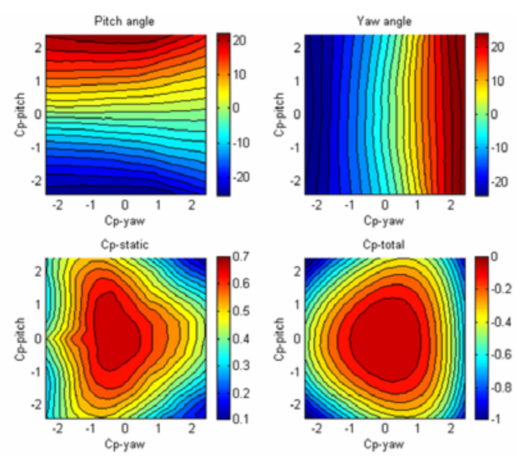

Figure 3. Sample single-zone calibration surfaces.[5]

To improve the accuracy of the probe, multiple calibration surfaces are sometimes needed. The Cobra Probe has several calibration surfaces that are dependent on the measured velocity and flow angle. Flow angles less than ±24° in both pitch and yaw require a single-zone calibration surface. Single-zone surfaces are very accurate near 0° pitch and yaw. Flow angles between ±24° and ±45° use multi-zone calibration surfaces. Multi-zone calibration surfaces use several surfaces, which are selected depending on flow angle.

The manufacturer conducts the process described above for each Cobra Probe. The results of this process show the Cobra Probe to be accurate within approximately ±0.5 m/s and ±1° pitch and yaw, in flows of up to 30% turbulence intensity, at frequencies exceeding 1500 Hz.[4] Even at turbulence intensities above 30%, the Cobra Probe still remains relatively accurate.[5]

IV. In-situ Calibration

To confirm the usefulness of the Cobra Probe for the US Navy rotating wake project, in-situ calibrations were performed on a probe used in the Navy project for comparison with the manufacturer's results. For the in-situ calibration, data were sampled in an empty low turbulence wind tunnel at speeds between 0 and 15 m/s, using a sample rate of 312.5 Hz for 12.698 seconds duration. Sampling parameters were chosen to guarantee statistical convergence of spectral data and to ensure the acquisition of sufficient spectral content. The three parameters considered in the calibration were speed, direction, and frequency. Pitch calibration was assumed to follow similar trends as yaw, and thus was not conducted.

An in-situ speed calibration was conducted during two separate wind tunnel runs, each conducted at 0 to 15 m/s of wind speeds. The first of these wind tunnel runs was used to compare the speed indicated by the Cobra Probe with the reference speed indicated by a high accuracy pressure transducer (± 3 cm/s) attached to the wind tunnel's static pressure taps located at the tunnel inlet. The second run compared the speed measured by the Pitot-static probe with the same high accuracy wind tunnel reference speed. For each calibration run, the appropriate probe was centered in the test section as wind tunnel speed was increased from 0 to 15 m/s, in approximate increments of 1.5 m/s. Figure 4 depicts the speed calibration results for one Cobra Probe. As can be seen in Fig. 4, velocity measured by the Cobra Probe was similar in both magnitude and trend as for the Pitot-static probe. Figure 5 depicts the same data, plotted nondimensionally against the Pitot-static speed. Figure 5 shows that the Cobra Probe indicated speed gradually becomes less accurate as tunnel speed is decreased. Note that in Fig. 5 there are upper and lower dashed lines that represent the manufacturer's 0.5 m/s measurement uncertainty. Note that Fig. 5 includes a vertical line at 3 m/s, which represents the manufacturer's lower stated speed limit. Therefore, as can be seen from Fig. 5, the Cobra Probe fell within the manufacturer's 0.5 m/s uncertainty for all speeds greater than the 3 m/s lower limit.

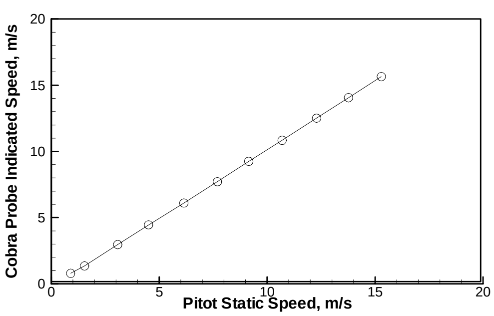

Figure 4. Accuracy of Cobra Probe compared to Pitot -static probe.

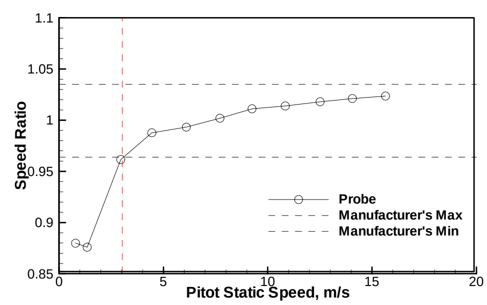

Figure 5. Nondimensional speed vs. Pitot-static speed. Red line shows lower speed limit (3 m/s).

An in-situ direction calibration was conducted by mounting the Cobra Probe on a yaw table on the bottom of the wind tunnel floor. The Probe was rotated in yaw by a computer-controlled floor mounted yaw table through a range of ±45° in 2° angular increments. Zero degree references were obtained at the beginning, middle, and end of the calibration to ensure repeatability and check for hysteresis effects. Figure 6 depicts the direction calibration results. As can be seen in Fig. 6, strong correlation exists between the flow yaw angle detected by the Probe and the geometric yaw angle. As expected, for flow angles that exceed the probe acceptance angle of 45°, the Probe returned values of zero for speed. Investigation of Fig. 7 reveals that the indicated flow yaw angle was within 1° of the geometric yaw angle for all but the most extreme angles tested, which fell within manufacturer's uncertainty. It is significant to note in Fig. 7 that directional accuracy decreases as the yaw angle nears ±45°. As a further investigation of direction effects, an investigation of the axial component of velocity predicted by the Cobra Probe was conducted. The axial component of flow (defined as the U component of flow by the Cobra Probe software; this is actually the component of velocity along the probe head centerline) should vary with the cosine of the probe's geometric yaw angle. Since the Cobra Probe computes flow components by using interpolated mean and direction data, it was desirable to compare the predicted axial velocity to the actual axial wind tunnel velocity. Figure 8 shows that the axial component measured by the Cobra Probe does decay with the cosine of yaw angle. Additionally, the axial component decreases by approximately 4% in either direction. The difference between the theoretical axial component and the actual axial component is very small (2% or less) as can be seen in Fig. 9.

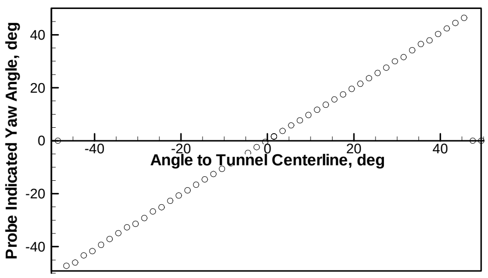

Figure 6. Comparison of Cobra Probe indicated and measured tunnel yaw angle

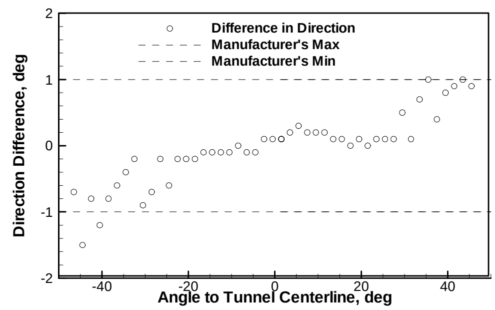

Figure 7 Difference in Cobra Probe indicated direction.

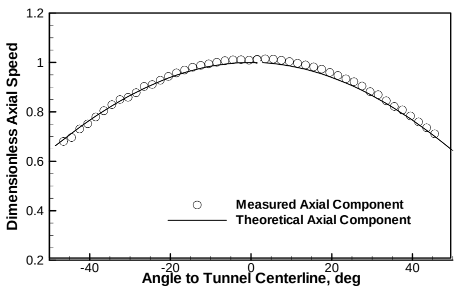

Figure 8. Change in axial velocity with yaw.

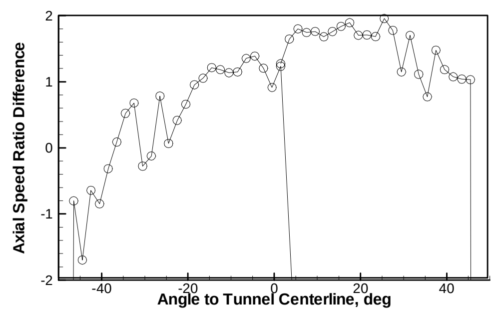

Figure 9. Difference in theoretical and actual axial velocity.

An in-situ calibration in frequency was conducted by comparing measured frequencies with predicted (Strouhal) frequencies in the wake of two circular cylinders. Initial reference frequencies were obtained in the wake of a 3.2 cm diameter (aspect ratio of 19.2) cylinder, while subsequent frequencies were obtained in the wake of a 8.9 cm diameter (aspect ratio 6.8) cylinder. In each case, a single Cobra Probe was located downstream of the frequency generating device and the resulting primary wake frequency was obtained from the computed velocity spectra. The tunnel was operated at speeds ranging between 0 and 15 m/s to generate a range of wake velocity frequencies in the vicinity of the Cobra Probe. Figure 10 depicts the results of the frequency calibration effort. Note from Fig. 10 that the frequencies measured by the Cobra probe do match the Strouhal frequencies predicted for a 2D circular cylinder, with an assumed Strouhal number of 0.2. The in-situ calibrations showed very close agreement (less than 5% error, which is less than experimental uncertainty associated with the predicted frequencies) between predicted and actual frequencies over the range from 10 to 100 Hz. This is in consonance with the manufacturer's findings, depicted in Fig. 11, which shows the dimensionless amplitude response for the Cobra Probe for a range of frequencies between 0 and 2500 Hz.[2] Hooper and Musgrove[2] discuss the convention that amplitude ratios greater than 0.4 represent desirable frequency response characteristics. Using this convention, inspection of Fig. 11 shows the Cobra Probe to have desirable frequency response characteristics at frequencies less than 1500 Hz. This is in good agreement with the findings in the in-situ calibration, which focused on lower frequencies in the range of interest of the ongoing US Navy experiment.

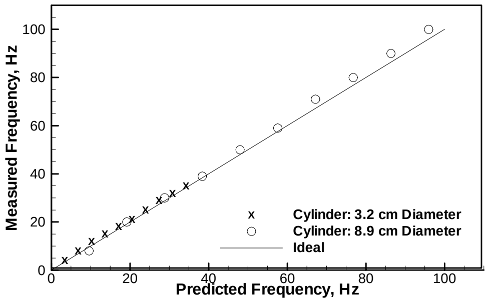

Figure 10. Comparison of measured and Predicted frequencies.

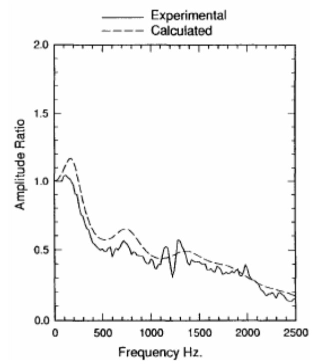

Figure 11. Amplitude response for a 0.5 mm tap Cobra Probe. [2]

V. Experimental Results

A. Background

The in-situ calibration results compared favorably with the manufacturer's calibration results for speed, direction, and frequency. To further explore the capabilities of the Cobra Probe, it was decided that a practical evaluation in a 3D turbulent flow field might also be beneficial.

As discussed previously, there is an ongoing effort at FML to investigate the aerodynamic wake characteristics of rotating objects aboard US Navy ships, and their corresponding effects on shipboard anemometer sensors. It is virtually impossible for shipboard personnel to determine how accurately an anemometer's speed and direction indications represent free stream conditions. Uncertainty about the validity of an anemometer's wind indications poses significant safety implications for shipboard flight operations. Any improvement to the validity of anemometer sensor indications will produce immediate shipboard safety benefits, and is the motivation behind this current airwake investigation.

Because of the unsteady wake characteristics of such flows, a sensor capable of discriminating unsteady frequencies accurately is essential. Previously discussed calibration efforts of the Cobra Probe confirmed it to be a good candidate sensor for use in such flows, and thus the practical assessment of the Cobra Probe was conducted as part of the ongoing ship aerodynamic effort. The following section describes the results of the practical assessment.

B. Experimental USN Procedure

The ship airwake measurement effort is currently being conducted in the 1.2 x 0.8 m wind tunnel at FML. The indraft wind tunnel has a contraction ratio of 9:1 with four screens and inlet honeycomb, which produce a free stream turbulence level of approximately 0.1% in the middle of the test section. Immediately above the test section is an enclosed plenum which houses three-axis automated traversing equipment. The test section was enclosed on all sides by clear Plexiglas panels to allow observation of objects inside. Three Cobra Probes were arranged laterally, (1.8 cm spacing) as shown in Fig. 12, and the entire Cobra Probe assembly was then suspended vertically from a mount connected to the traversing gear in the plenum.

Figure 12. Three Cobra Probes. Probe head is circled in red.

Various thin plate objects that represent US Navy radar arrays were mounted on a vertically oriented shaft protruding from the tunnel floor. Each shaft was connected to an AstroFlight 040 Cobalt DC electric motor which was mounted beneath the tunnel floor, and powered by a Sorenson 33V/33A power supply. Varying the power supply voltage allowed control of the shaft rotation rate. An optical tachometer was employed to determine rotation speed. The Cobra Probe assembly was sequentially traversed throughout a 3D volume downstream of the thin plate objects to collect wake data.

Various objects were investigated during the experiments. Each object represented approximate 1/50 scale models of typical US Navy shipboard electromagnetic emitters, such as a radar array. Each object was made of 3.2 mm thick aluminum and included square, rectangular, trapezoidal and circular shapes. A variety of porosities were also investigated, but in this paper, only results of the solid 76 x 76 mm square shaped object will be discussed. To replicate full scale tip speed ratios, each object was rotated at a rate of 300 ±20 rpm. Uncertainty in this measurement is due to the suboptimal speed control of the motor, which created the potential of undetected variations in rotation rate.

The 76 x 76 x 3.2 mm shape was mounted in the geometric center of the 1.2 x 0.8 m test section and this created a maximum blockage ratio of 1.56% and thus blockage corrections were not performed.

For the practical assessment, the wake characteristics behind each object were measured by the Cobra Probe assembly. The free stream speed was 14 m/s for the entire assessment. The Cobra Probe assembly was laterally traversed at two distances downstream of the object. All data investigated in the practical assessment was acquired at the same height above the tunnel floor as the object centroid (40 cm).

The data presented in this paper correspond to nondimensional downstream distances of X = 0.75D and 2.66D, where D is the 76 mm object diameter. Data were acquired laterally, within a range of approximately 30 cm (Y= 4.0D) of both sides of the object centroid. Lateral data collection intervals were 1.8cm, the same as the Cobra Probe lateral spacing, which facilitated repeated measurements. Although three probes were used to collect data, the measurements acquired by each were effectively identical at each point in space and thus, the remainder of this paper will only address the results from the center probe.

C. Results

To demonstrate the usefulness of the Cobra Probe in a flow of practical significance, Figs. 13-23 depict the wake characteristics of the 76 x 76 x 3.2 mm. object. In addition to empty tunnel data, Figs. 13-23 depict wake measurements acquired for the object in both static and rotating (about its vertical axis) conditions. Sampling parameters were chosen to guarantee statistical convergence of spectral data and to ensure the acquisition of sufficient spectral content. Each symbol depicted in Figs. 13-23 represents the mean of 13 seconds of data collected at a sampling rate of 312.5 Hz at a free stream speed of 14 m/s.

Figures 13 and 14 depict the variation of mean downstream (U) velocity component for lateral traverses conducted at 0.75D and 2.66D downstream of the object centroid, respectively. In both figures, at distances more than 10 cm outboard of the object, the measured U component approximates empty tunnel conditions. Similarly, at distances less than 10cm outboard of the object the measured local speed decreases dramatically for both static and rotating cases. Inspection of Fig. 13, which is 0.75D downstream of the object, reveals that the U component for the static case decreases to 10% of the empty tunnel speed within 1D of the object centroid, whereas the rotating case decreases to 60% of the empty tunnel speed at the same lateral locations. In comparison, Fig. 14 depicts the same conditions 2.66D downstream. Figure 14 shows similar trends for both static and rotating cases as Fig. 13, but the magnitudes of the velocity defect are much less. Figure 14 reveals that for all lateral locations exhibiting a velocity defect, the magnitude of that velocity decrement is much less at 2.66D aft then that at 0.75D. Figures 13 and 14 suggest there is little or no significant indications of wake presence at lateral locations more than approximately 2D from the centerline of the object for distances either 0.75D or 2.66D downstream of the object.

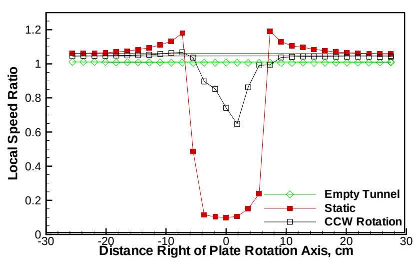

Figure 13. U velocity component 0.75D downstream of object.

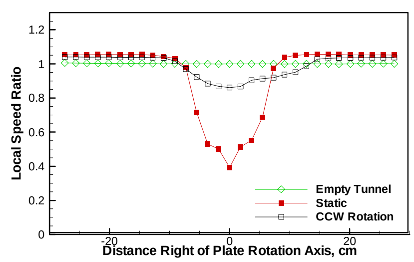

Figure 14. U velocity component 2.66D downstream of object.

Figures 15 and 16 depict the variation in turbulence intensities at 0.75D and 2.66D, respectively. As expected, the turbulence intensity (TI) magnitudes follow the inverse trend of the U velocity component magnitudes; when mean velocity decreases, turbulence intensity increases. Fig. 15 represents data collected 0.75D downstream of the object, and reveals that the maximum turbulence intensity for the static case is 40%, which is higher than the manufacturer's suggested optimal usage range of 30%, whereas the rotating case has a maximum TI of 30%, which occurs directly downstream of the object. In comparison, Fig. 16 depicts the same conditions 2.66D downstream. Figure 16 shows similar trends for both static and rotating cases as Fig. 15, but the TI magnitudes are much less. Figure 16 reveals that for all lateral locations exhibiting a turbulence intensity increment, the magnitude of that turbulence intensity increment is much less at 2.66D aft then there is at 0.75D. All turbulence intensities located 2.66D downstream of the object are less than the 30% recommended TI, except at the centerline of the static object, which is has a TI comparable to the 40% TI value measured at 0.75D downstream of the object. Since the object that will be studied in future experiments will be rotating and measurements will be taken at least 2.66D downstream, the data depicted in Fig. 16 provide confidence in the Cobra Probe when used for measurements within the wake.

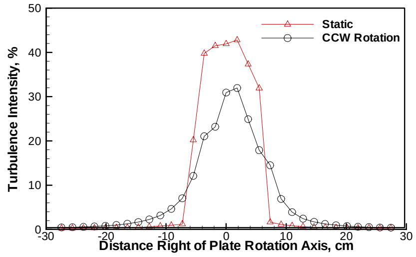

Figure 15. Turbulence intensity 0.75D downstream of object.

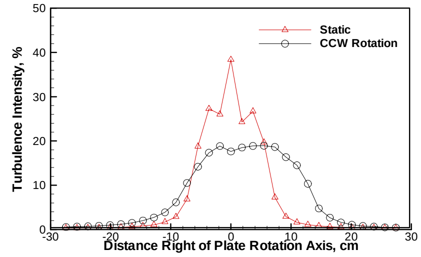

Figure 16. Turbulence intensity 2.66D downstream of object.

Figures 17 and 18 depict the variation of percentage of good data at 0.75D and 2.66D, respectively. The Cobra Probe software has the ability to display the percentage of good samples that were acquired during each data sample. The percent good samples indicated the percentage of samples that simultaneously fell within the 45° acceptance cone half angle and exceeded the 3 m/s minimum speed. A low data acceptance value in turn would suggest erroneously low mean values for that sample, providing the user an idea of the trustworthiness of the data collected. Thus, a low value of percentage of good data that occurs on either Figs. 17 or 18 signifies less confidence in all other parameters recorded during that sample. In both Figs. 17 and 18, at distances more than 76 mm outboard of the object, the percentage of good data points is approximately 100%. Similarly, at distances less than 76 mm outboard of the object the percentage of good data points decreases dramatically for static and rotating cases. Inspection of Fig. 17 reveals that the percentage of good data 0.75D downstream of the static object within 1.0D laterally of the object centroid decreases to approximately 20%. Additionally, the rotating case has approximately the same percentage of good data points as the static case. Comparison of Fig. 17 with Fig. 13 (U velocity component) reveals that points in the immediate wake of both the static and rotating object have similar low percentage of good points despite the fact that only the static case is operating at speeds below the minimum speed range. The mean values associated with the rotating case in Fig. 13 all exceed the Cobra Probe's 3 m/s minimum speed requirements, although Fig. 17 shows that the percentage of good points in this same region decreases dramatically. A possible cause for this example of high mean speed, but low percentage of good points could be the fact that flow at those points exceeds the 45° acceptance cone half angle. Although not presented in this paper, measurements of lateral and vertical flow velocities confirm that the flow in this region did in fact exceed the 45° acceptance cone half angle. In comparison, Fig. 18 depicts the same conditions at 2.66D downstream. Figure 18 shows similar trends for the static case as Fig. 17, but the magnitudes are much less. The rotating case is far enough downstream to guarantee operation in a speed range that exceeds its 3 m/s minimum capabilities, thus the majority of data points are good (greater than 90% percentage good points). Figures 17 and 18 suggest that the Cobra Probe is not optimal for measurements in environments containing exceptionally low speeds or high angularity, such as near wake and recirculating flows. However, when it is used, it does provide confidence in the accuracy of all parameters collected during the sample.

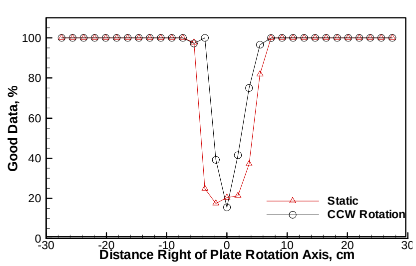

Figure 17. Percentage of good data 0.75D downstream of object.

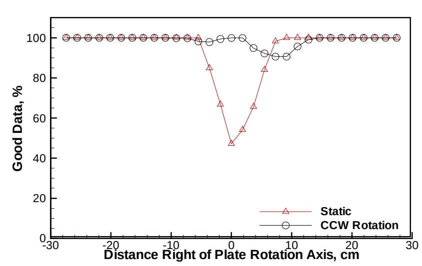

Figure 18. Percentage of good data 2.66D downstream of object.

In addition to mean velocities, flow angles, and turbulence statistics, the Cobra Probe also automatically measures and computes all six components of Reynolds stresses (three normal, three shear) during each sample. As an example of this, Figs. 19 and 20 depict the lateral variation of Reynolds $\overline{u'v'}$ shear stress at 0.75D and 2.66D downstream, respectively. The $\overline{u'v'}$ Reynolds shear stress component is very low for the static object at 0.75D, but very large for the rotating object at both 0.75D and 2.66D. To further emphasize one of the advantages of the Cobra Probe, Fig. 21 depicts all six components of Reynolds stress acquired at a location that roughly corresponds to the shear layer approximately 1D laterally and 2.66D downstream.

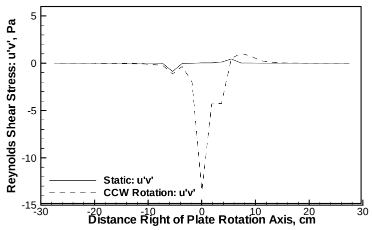

Figure 19. Reynolds shear stress ($\overline{u'v'}$) 0.75D downstream of object.

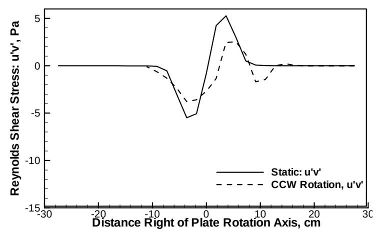

Figure 20. Reynolds shear stress ($\overline{u'v'}$) 2.66D downstream of object.

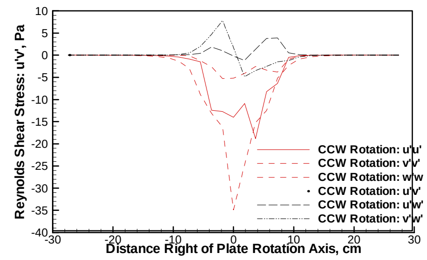

Figure 21. Six components of Reynolds stress at 2.66D downstream of object.

An additional quality of the Cobra Probe is its ability to document unsteady data. Figures 22 and 23 depict power spectral density (PSD) results at 0.75D and 2.66D downstream, respectively, at two lateral locations. The two locations are positioned directly downstream of the centroid (0.0D) and at 3.3D laterally outboard of the centroid, a position that is assumed to be free stream and therefore relatively unaffected by the wake of the object. Although at both downstream locations, spectral evidence of the static object wake is limited to elevated PSD amplitudes at a broad range of frequencies, spectral evidence of the rotating object wake is manifested by a series of large peaks, which occur at 1 per rev (~5 Hz), 2 per rev (~10 Hz), and *n* per rev frequencies. It is interesting to note that the highest amplitude occurs at the 2 per rev frequency vice the 1 per rev frequency. This can be explained by considering a rotating flat plate, which has two edge passings for every one rotation. Of particular interest to the US Navy aerodynamic project is the fact that the 2 per rev spike is evident not only directly in the wake of the object, but also far outboard of the object's centroid, in an area that might otherwise be assumed free of wake effects. This implies that a ship's anemometer located in an area far outboard of a rotating emitter might still be able to detect the emitter's presence simply by analyzing the spectral content of the locally measured velocity. The unsteady measurement capabilities of the Cobra Probe can directly facilitate better understanding of fluid flow near anemometers on ships.

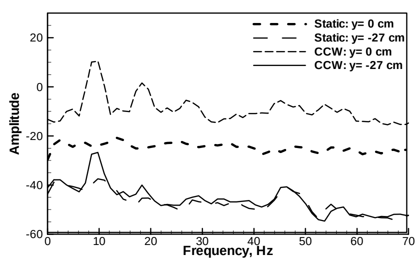

Figure 21. Frequency response 0.75D downstream of object.

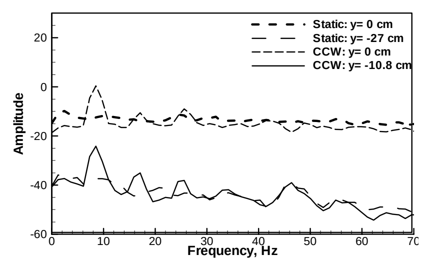

Figure 23. Frequency response 2.66D downstream of object.

D. Assessment of the Cobra Probe

The Cobra Probe facilitated insight of a variety of fluid mechanic parameters during the practical assessment. Its ability to provide unsteady 3D velocity components, turbulence intensities, Reynolds stresses, and power spectral data was evident during the experiment and gave a better picture of the object's wake characteristics. As described in the preceding paragraphs, the Cobra Probe's minimum speed requirement is less than desirable for certain applications, such as in low speed flows. There are other traits of the Probe that are less than desirable for measurements in certain flow conditions involving low speed and highly recirculating flow. The limited acceptance cone angle of ±45° can become problematic when looking at recirculating flow: In instances such as this, the Cobra

Probe must be rotated to acquire data. The Cobra Probe's lack of a practical centerline reference makes it difficult to align the probe with the tunnel centerline. Researchers at FML manually adjust the probe until yaw and pitch angles are zero; but this can be a time consuming process. The Cobra Probe is relatively expensive, approximately $12,000, and may not be suitable for experiments with limited budgets. Additionally, the Cobra Probe's maximum practical frequency (approximately 1500 Hz) is far below that of other unsteady sensors, such as hotwires.

Despite the potential limitations of the Cobra Probe, there are many advantages to using the Cobra Probe when making unsteady 3D velocity measurements in flows. First of all, the Probe has the ability to provide 3D measurements due to its four holes, which allow for a flow acceptance cone angle of ±45°. Because of the relative proximity of its pressure transducer to its pressure tap, or measurement location, it can measure instantaneous data, thereby providing time history data, unlike many current pressure sensor devices. This facilitates fast response time and the ability to resolve unsteady frequencies up to 1500 Hz. Furthermore, unlike many typical somewhat cumbersome unsteady pressure sensing devices, the Cobra Probe is easy to use. The Cobra Probe requires nothing more to operate than a PC and an A/D data acquisition card. Since the pressure transducers are remote from the pressure taps, they are mechanically protected and can operate in both industrial and laboratory conditions, providing a robust instrument. The Probe has a small head, thus providing minimal flow intrusion, whereby maintaining flow integrity. Each probe measurement produces unsteady 3D speed, direction, turbulence statistics, Reynolds stresses and local static pressure, which is a substantial amount of information.

VI. Conclusions

The Cobra Probe is a 3D unsteady pressure sensor device that is designed to operate in subsonic, incompressible flow conditions. The Cobra Probe was calibrated in the wind tunnel for speed, direction and frequency and found to be within the manufacturer's quoted accuracies. In-situ and manufacturer calibrations confirmed the Cobra Probe to have accuracies within 0.5 m/s and 1° in pitch and yaw for frequencies below 1500Hz. When employed in a fluid flow of interest to the US Navy, the Cobra Probe facilitated improved understanding of the complicated flow in the wake of rotating and static objects. The probe's ability to indicate the percentage of the data that falls within a known range of accuracy facilitated improved understanding of other measured parameters, especially in regions of low speed or high angularity, such as in recirculating or near wake flows. Like most pressure probes, the Cobra Probe cannot indicate very low speeds. Additionally, the use of four holes constrains the probe to an acceptance cone of ±45°. The finite distance between pressure transducers and pressure sensing taps creates a maximum useable frequency of approximately 1500 Hz. Despite these limitations, the advantages of the Cobra Probe for use in subsonic flows are many, most significant of which is its ability to measure 3D instantaneous velocities. Additional advantages include its robustness, temperature insensitivity, ease of use, and compatibility with PCs. The Cobra Probe provides a variety of fluid mechanic parameters that present insight to the fluid mechanics of the flow, but also help the user evaluate the validity of data acquired at each measurement. The Cobra Probe will be employed in future subsonic wake efforts at FML, including the ongoing rotating emitter wake effort for the US Navy.

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