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COMMENTS OF PROPULSION COMMITTE OF 22nd ITTC

In the main the Guide for the Use of LDV of 1996 is acceptable. A caveat on the use of LDV measurements and blade surface pressures calculated from measured velocities in the LE and TE region was added

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Guide For The Use Of LDV

1. PURPOSE OF PROCEDURE

Guide for the use of LDV for the collection of data suitable for validating numerical calculations

2. GUIDE FOR THE USE OF LDV FOR THE COLLECTION OF PROPULSOR DATA SUITABLE FOR VALIDATION OF NUMERICAL CALCULATIONS

2.1 Introduction

Laser Doppler Velocimetry (LDV) was first used to measure flows about marine propellers by Min (1978). Since then, the primary motivation for using LDV has been the validation of prediction tools, such as lifting surface, panel methods and RANS codes. As part of the validation, complex flow details have been measured, which have been used to develop empirical models within the various calculation methods.

The Committee's task was to develop a guide for the use of LDV for the collection of data suitable for validating numerical calculations. The data required for the validation of typical prediction methods are as follows:

1. Description and accuracy of test configuration
2. Measured flow field
3. Derived quantities
4. Uncertainty of measured data

The LDV measures velocity only, which can be compared against calculated velocity, but the quantities of real interest are pressures and forces which can only be indirectly calculated. Therefore, derived quantities are often calculated from the measured velocity field, such as blade pressure distribution, spanwise circulation, section drag coefficient, wake vorticity, and tip vortex core pressure. Derived quantities have been most useful in the validation of potential based methods, and have provided appropriate empirical models to account for viscous effects. Generally, LDV measurements are time consuming and expensive, therefore careful selection of velocity regions to be measured has to be made to maximised data usefulness. Various measurement techniques will be reviewed and assessed. Measurement uncertainty will be discussed, noting that the various uses of the data can each require varying degrees of accuracy.

2.2 Field Point Velocities

Field point velocities are considered the most fundamental type of measurement. In its simplest form, it includes measurements made upstream and downstream of the propeller. They have been used for validation of lifting surface codes and panel codes. This work was initiated at MIT by Min (1978), and continued by Kobayashi (1981), Kerwin (1982) and Yang (1988). These measurements included time average and blade to blade dependent flows using phase averaging. The phase averaging technique was refined by Jessup (1984) to very high angular resolution of 8192/rev. Most researchers have various phase averaging techniques with resolutions of typically 200/rev which is sufficient to validate non-viscous regions of the flow. The researchers above demonstrated the ability of the lifting surface and panel codes to predict accurately the upstream propeller flow. The downstream flow predictions were mixed due to the details of the viscous blade wake, tip and hub flow which are not properly modelled. In some cases the downstream wake model could be adjusted to produce reasonable predictions with the global flow, excluding the blade wake and tip vortex core regions.

2.3 Measured Downstream Tangential Velocity And Derived Circulation

When operating in uniform inflow, the propeller's spanwise circulation distribution can be derived from the measured time average tangential velocity downstream of the propeller. This was shown by Kerwin (1982), and Wang (1985) and has been a useful measurement to evaluate the radial loading distribution of the propeller. The formula is:

$$\frac{\Gamma}{2\pi RV}=\frac{1}{Z}\left(\frac{r}{R}\right)\left(\frac{\overline{V}_r}{V}\right) \qquad (2.1)$$

where Z = blade number.

Jessup (1989) evaluated the derived circulation. with and without the inclusion of the tangential velocity in the blade wake. The blade wake can be seen in the tangential velocity, V_T/V, of Figure 2.1, occurring at a blade angle of 85 degrees. at the 0.76 radius. Better agreement with lifting surface and panel methods was obtained when the wake was included, increasing the measured circulation. Generally, the measurement is made as close to the propeller as possible to avoid consideration of the wake contraction. Tracking the mean flow trajectory from the propeller mid-chord to the measurement plane would more accurately establish the radial distribution of circulation, but would require accurate radial velocity measurements including measurement passages through blade surfaces.

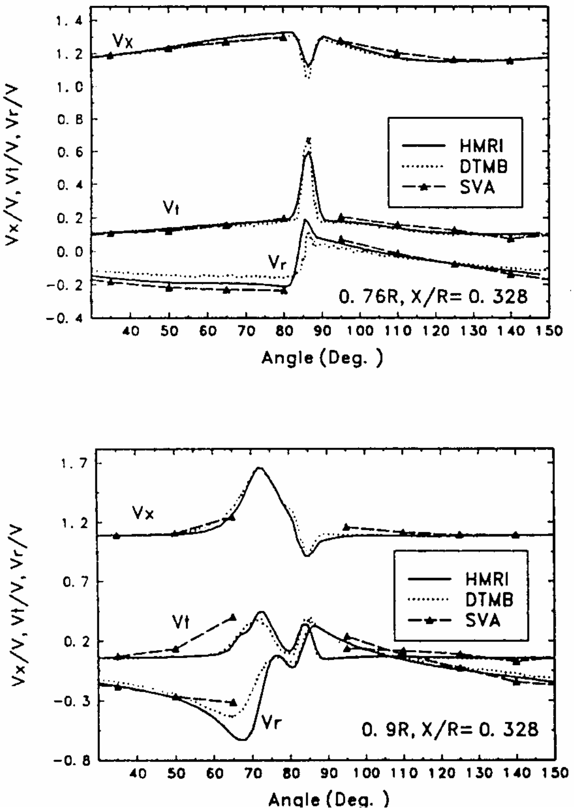

Fig. 2.1 Comparison of LDV Velocity Down-Stream of Propeller VWS 1464 (DTMB 4119)

Jessup (1989) observed that in some cases upstream swirl inflow should be considered in calculating the downstream circulation. Potential theory dictates that the upstream circumferential average tangential velocity induced by the propeller should be zero. Actual measurements have shown that some residual upstream tangential velocity occurs, presumably due to tunnel effects or propeller viscous effects (Stanier, 1994). Best correlation with prediction was obtained when the. upstream residual tangential velocity was subtracted from the downstream tangential velocity before computing the net propeller circulation. An alternative is to use measured nominal tangential velocity at downstream plane.

Some care is required in obtaining an accurate time average tangential velocity measurement due to possible uneven distribution of measurements over one revolution of the propeller. Also, large variations in velocity close to the blade trailing edges can result in filter biasing, occurring when the Doppler signal band pass filters are set too close to the extremities in the velocity measurement. A more accurate approach, demonstrated by Jessup (1989), is to initially phase average the velocity on blade angular position and then obtain the average velocity for all angular positions.

2.4 Propeller Wake Measurement And Derived Blade Section Drag

Observations of the blade viscous wake, first by Min (1978), led others to measure the wake in detail to determine the wake trajectories and blade section drag coefficient. Min tracked the trajectory of the tip vortex, determining it's pitch and radial trajectory. Both Jessup (1989) and Hoshino (1990) tracked the blade vortex wake to determine the wake pitch for use in lifting surface and panel method calculations. Jessup used two approaches to track the wake, the first merely tracked the measured angular position of the wake centre with downstream axial distance. The second method used the velocity average at the two edges of the blade wake deficit. Both methods were reasonably consistent and are shown in Figure 2.2 compared to a lifting surface model and the blade geometric pitch. Hoshino calculated the wake pitch from the circumferential average velocity in the downstream wake.

Kobayashi (1981) first performed the momentum integrations of the measured blade wakes to derive the blade drag coefficients. Kobayashi also differentiated the closely spaced velocity profiles to arrive at the vorticity field in the blade wake. Later, Jessup (1989,1994) performed similar but more detailed measurements. The influences of laminar and turbulent flow can have strong effects on the section drag, with very large drag occurring near the hub and tip vortex flows. Figure 2.3 shows measured drag for Propeller 4119.

The primary purpose of the measurement is to arrive at a better understanding of the blade drag component which is required as input to potential based panel and lifting surface methods. Therefore the radial distribution of drag is important. Measuring very close to the blades decreases the influence of wake contraction, but increases the uncertainty of the assumption of constant pressure through the wake. The near-wake correction of Squire and Young (1938) was used by Jessup (1989,1994) with some success. It should be noted that the passage of the blade wake through the stationary measurement volume, occurs at an oblique angle to the streamwise velocity in the moving blade frame of reference.

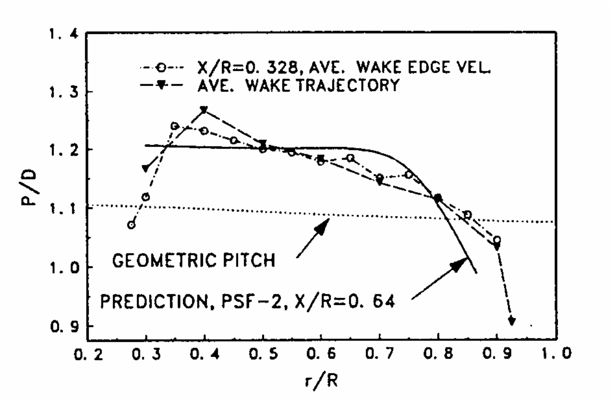

Figure 2.2 Measurement of downstream wake of Propeller 4119 by Jessup (1994).

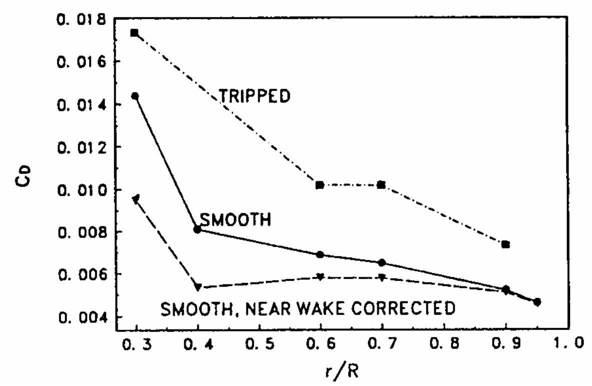

Figure 2.3 Measured Blade Section Drag for Propeller 4119 by Jessup (1994).

2.5 Blade Boundary Layer Measurements And Derived Blade Surface Pressure Distribution

Blade boundary layer measurements are a further refinement of the blade wake measurements. The LDV optics system must permit the rotation of the optical axis so that the blade streamwise measurement can be made in a direction tangent to the blade surface. Also, blade geometry must permit access of the transmission beams to the blade surface, which generally requires simple constant pitch propellers with no skew and rake. Jessup (1984, 1989,1994) performed these measurements on DTRC Propeller 4119. Resolution of the boundary profiles has limitations over large stationary model configurations. Generally, 5-10 points are measured near the leading edge, and 30-80 points are measured at the trailing edge at 0.7R blade chord Reynolds Numbers of 1 million. Limited radial boundary layer data were measured by Jessup. This measurement required the LDV optical axis to be oriented in the blade nose-tail line direction, requiring a complex optical configuration within the water tunnel test section.

The blade surface pressure distribution can be derived from the total boundary layer edge velocity measured at a number of locations on the blade surface, as shown in Figure 2.4. This was performed by Jessup (1984) initially with only the streamwise component and later (1989) with both streamwise and radial components of blade surface velocity for DTMB Propeller 4119. With the propeller operating in uniform inflow, Bernoulli's equation can be used to calculate pressure. As with the boundary layer measurements, a relatively constant pitch propeller is required. When the boundary layer is thick, the chordwise position of the measurement requires spatial correction since the boundary layer traverse is not made perpendicular to the blade section pitchline. Also, it is known that for thick boundary layers, the pressure at the edge of the boundary layer is an approximation of the pressure at the wall.

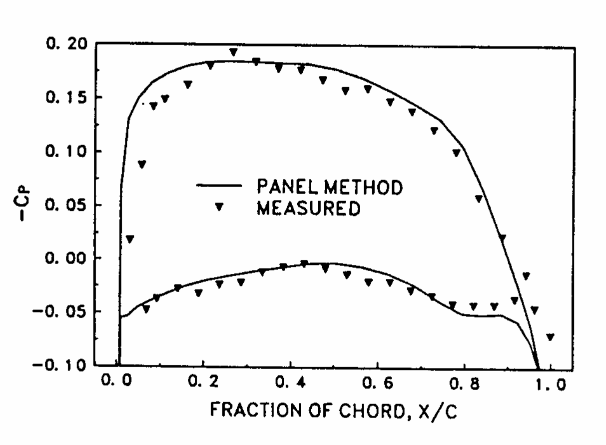

Figure 2.4 Derived Blade Section Pressure Distribution for Propeller 4119 at 0.7R by Jessup (1984).

2.6 Root Flow Measurements

The propeller root region is of interest due to root and hub vortex cavitation, and drag contribution. Wang (1985) measured the time average flows downstream of the blades along the fairwater, tracking the hub vorticity. Jessup (1989) measured the downstream hub flow about Propeller 4119, showing complex hub vortex flow. The other area of interest in the flow is the blade passage. Unfortunately the area is very hard to measure due to the proximity of the LDV measurement volume to the hub surface and the signal noise created by the optical axis oriented directly toward the hub surface. A possible technique to permit this measurement is the adaptation of holes or grooves in the hub surface in which the beams will penetrate. This will reduce flare from the surface, but also causes a near surface flow disturbance which must be accounted for.

2.7 Propeller Tip Vortex Measurements, Derived Core Pressure And Vorticity

Tip vortex flow details are of interest for improving the prediction of blade tip loading and tip vortex cavitation. Quantities of interest are the induced drag, vortex core size, velocity distribution, vorticity, trajectory and roll up physics. Early researchers identified the complex nature of the tip vortex from field point velocity measurements.

Kobayashi and Bugenhagen (1985) obtained the tip vortex structure using a single phase averaged three component measurement passing directly through the tip vortex core of DTRC Propeller 4119. Representing the velocity field in the moving co-ordinate system of the tip vortex core, velocity distribution resembled a typical tip vortex of an isolated wing. A core pressure was derived from the outer potential flow and inclusion of a simple viscous core model, and was correlated to limited tip vortex inception data. Jessup (1989) measured a more complete map of the tip vortex flow about Propeller 4119 and derived the vorticity distribution of the vortex showing typical vortex rollup structure.

Oshima (1994) made detailed tip vortex velocity measurements downstream of two propellers for the purpose of validating a tip vortex inception prediction method. Oshima found that the tip vortex circulation strength was proportional to the blade circulation at 0.95R. This provided a relatively simple prediction method using McCormick's (1962) empirical method.

The primary difficulty with the tip vortex measurement is the requirement of measuring all three components with a relatively small measurement volume. Jessup (1989) attempted this with a standard two component lens system with a third component fibre optic probe with its axis oriented parallel to the vortex core axis. Unfortunately the probe performance was not well matched to the two lens optics components. Most accurate results were obtained performing two sets of non simultaneous two component measurements at the side and top of the propeller disk. To obtain an accurate description of the vortex and nearby blade wake, data samples averaged at 512 points/revolution at 10 radial locations should be sufficient. At an axial location 30% downstream of the propeller, the radial measurements should be centred on the vortex core and extend ±7.5% of the tip radius.

2.8 LDV Measurements On Hydrofoils

Related LDV measurements on hydrofoils provide some insight to possible future propeller measurements. Much of this work was motivated toward understanding propeller flows. but for simplicity, was conducted on foil geometry.

Recent work has been performed at MIT, measuring steady and unsteady flows about 2-D hydrofoils. Lurie (1993) described these experiments in which a large foil (chord=0.46 m) was tested in a 0.51 m x 0.51 m square test section. Two component velocity measurements were performed in a rectangular contour about the foil to obtain steady and unsteady lift and drag performance. The foil boundary layer was also measured. Unsteady flow was created with small oscillating foils mounted ahead of the large foil. Phase average velocity measurements were performed relative to the small foil oscillating frequency, similar to phase averaging utilised on propeller LDV measurements. This work was extended to cavitating foils most recently by Brewer and Kinnas (1995). Unsteady foil measurements were also performed by Hart (1994) using a rectangular planform foil with oscillating angle of attack. Removal or attachment of a Plexiglas end plate permitted both 2-D and 3-D flow configurations.

Numerous 3-D foil measurements have been performed to study tip vortex flows. Billet (1987), Arndt and Dugué (1992), Fruman et al. (1992, 1993), and Yamaguchi et al. (1995) have measured tip vortex on elliptical and swept planform foils, deriving vorticity and correlating the velocity distributions to simple Rankine models, with a primary interest in cavitation. Also, Falcao de Campos (1991) measured flow about a similar elliptical foil. Problems associated with these measurements were in some cases attributed to vortex wandering, causing a smearing of the velocity measurements and a reduction in the maximum velocity about the core. This problem has not been identified by propeller flow researchers, perhaps due to the different orientation of the vortex core axis relative to the free-stream tunnel velocity.

2.9 Conclusions

Laser Doppler Velocimetry is a useful diagnostic measurement tool for the validation of propeller numerical calculations and investigation of specific propeller. flow features. A guide has been presented describing measurement techniques required to perform code validation. Numerous types measurements have been reviewed in an instructional sense, including general field measurements. blade circulation, boundary layer, tip, root juncture, and wake flow. These measurements have been used to validate potential flow procedures. Limited validations of propeller blade RANS methods have been performed. Further advancements in full viscous flow calculations will require more detailed measurements including turbulence quantities.

3. PARAMETERS

3.1 Parameters to be Taken into Account

Description of test configuration
Accuracy of test configuration
Measured flow field
Derived quantities
Uncertainty of measured data

3.2 Recommendations of ITTC for Parameters

None

4. VALIDATION

4.1 Issues Related To RANS Code Validation

Validation of RANS codes applied to propeller flows commenced in recent years, with special requirements imposed on the measured data. The primary advance in the application of RANS to propeller flows is the potential to model the viscous flow aspects, including tip, root and wake flows. Unfortunately, to model the flow details requires accurate measurement of the inflow conditions, blade flows, transition, turbulence quantities and the flow details. These measurements are far more detailed and extensive than the quantities that were typically measured to validate lifting surface and panel codes.

Jessup (1989) measured the flow about DTRC Propeller 4119 with the intent of documenting the flow sufficiently for RANS code validation. Extensive measurements of upstream, downstream, detailed root and tip, and blade boundary layer measurements were obtained. Items not fully measured were near wall boundary layer data, turbulent Reynolds Stress quantities and comprehensive blade to blade flow within the blade passages.

Stem et al. (1994a) presented a RANS solution and comparison with the Propeller 4119 measured data. Reasonable correlation with the measured results was shown, but Stem suggested that more detailed boundary layer measurements would be required especially at the leading edge, root and tip regions. Also, improved turbulence data would be required. Advanced LDV processors are now available that can process data in difficult regions and more easily measured cross turbulent quantities that require simultaneous measurement processing on three components.

4.2 Issues Related To Unsteady Flows Due To Spatially Varying Inflow

LDV measurements about propellers in spatially varying inflow have severe limitations due to the required magnitude of data and difficulties in measuring the entire disk space. Generally, stationary shaft or hull geometries block the LDV transmission beams in part of the flow domain. Unreported work at DTMB has overcome this problem using axisymmetric model configurations that permit rotation about the propeller shaft centre with LDV position fixed to obtain a circumferential traverse about the propeller disk. A better approach by Fry (1995) describes a sophisticated LDV system utilising small diameter probes inside an axisymmetric hull, measuring just upstream of the propeller providing a full circumferential traverse.

4.3 Accuracy

The early Propeller LDV work (1978-1990) treated measurement accuracy only briefly, see Fry (1985). With the advent of propeller RANS solvers and code validation requirements, there has been increased interest in documenting the uncertainty associated with LDV propeller measurements. During the benchmark LDV measurements conducted at CSSRC in Wuxi, by the 20th ITTC Propulsor Committee (1993, see Propulsor Committee report discussions), as discussed earlier, measurement accuracy was investigated. Also, Jessup (1994) summarised earlier work (1989) and presented a detailed error analysis of the measurements about Propeller 4119. Fry (1995) also presented a detailed error analysis of small probe LDV systems used with submarine models. The various areas of uncertainty are listed below:

1. Test configuration, inflow, propeller rpm
2. LDV positioning accuracy
3. LDV velocity measurement accuracy
4. Propeller model manufacturing accuracy

The test configuration accuracy was checked in two of the above efforts. Although simple uniform inflow tests were configured, significant non-uniformities were observed that require consideration when the flow field was calculated. The complex submarine model configuration required careful consideration of model orientation to the freestream direction and effects of support struts.

LDV positioning accuracy is initially straightforward, obtained from the traverse manufacturer's specification, but degrades when considering the optical axis normality to the tunnel window and the axial tunnel velocity. Measurable objects in the tunnel can be used to calibrate the LDV measurement volume (mv) position. Jessup (1994) found that typical traverse resolutions of 0.025 mm degraded to around accuracy's of 0.5 mm relative to a global reference point in the tunnel. The CSSRC researchers obtained a position accuracy of 0.1 mm to 0.5 mm. Jessup (1994) made an important distinction between global and local accuracy. Local relative flow structures such as the tip vortex, are measured with the initial traverse resolution, as long as the set of measurements are made sequentially. The same argument applied to the specified resolution of the shaft angular position measurement.

The accuracy of the LDV velocity was determined by velocity calibrations and flow dependent effects of turbulence, signal to noise ratio (SNR), and velocity gradients. Rotating wheel calibration and physical measurement of the transmission bean angle are used to measure the calibration factor between Doppler frequency and velocity to typical accuracy of 0.2%. High turbulence increases errors due to velocity bias and sample size limits, each on the order of 4%. Processor error due to SNR is typically 1 % using counter type processors. Jessup (1994) calculated total uncertainty of 1.2%. in low turbulence regions and 6% in typical turbulent regions such as the blade viscous wakes. The CSSRC tests established uncertainties of 3% for axial velocity, but included were effects of positioning errors in regions of large velocity gradients and uncertainties in the advance coefficient.

The manufacturing accuracy of the test model is an obvious consideration. Jessup (1994) measured the model geometry, best fitting the results to a pitch and thickness error relative to the design geometry. These differences were analysed for performance to establish the deviation in pressure distribution and loading. The measured model geometry should be used in further validation calculations.

For both efforts discussed, the ASME Guide to Uncertainty Analysis, PTC-19.1-1985 (1990) was used. Although presented as a clearly defined procedure, its application is somewhat subject to interpretation. Also, each individual type of measurement, such as general field point velocity, tip vortex measurement, blade boundary, layer, wake turbulence, etc. requires an individual uncertainty analysis with consideration of each type of error. A proper uncertainty analysis, including determination of the gradients of the specified quantity of interest to the various error parameters, requires significant effort, which must be weighed against the required accuracy of the specified quantity of interest.