

Naval Surface Warfare Center Carderock Division

West Bethesda, MD 20817-5700

NSWCCD-80-TR-2016/029

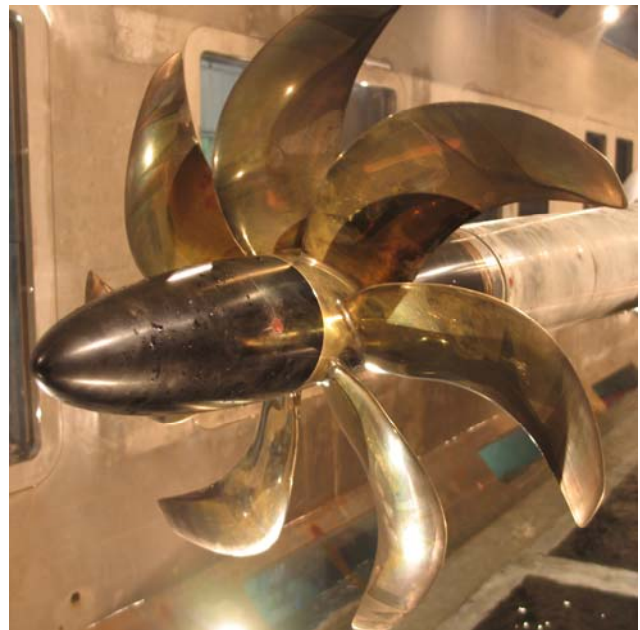
October 2016

Naval Architecture and Engineering Department
Technical Report

DEFLECTION MEASUREMENTS ON PROPELLER 5503 IN AHEAD AND CRASHBACK

by

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NSWCCD



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1. REPORT DATE (DD-MM-YYYY) 14-10-2016		2. REPORT TYPE FINAL		3. DATES COVERED (From - To) May 2010 to Oct 2016
4. TITLE AND SUBTITLE Deflection Measurements on Propeller 5503 in Ahead and Crashback		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Swithenbank, Susan B.		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER 10-1-5800-324		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NAVSEA Carderock Naval Surface Warfare Center Carderock Division (Code 873) 9500 Macarthur Boulevard West Bethesda, MD 20817-5700		8. PERFORMING ORGANIZATION REPORT NUMBER NSWCCD-80-TR-2016/029		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Ki-Han Kim Office of Naval Research One Liberty Center 875 North Randolph Street, Suite 1425 Arlington, VA 22203-1995		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT Propeller 5503 was tested in ahead and crashback in the Navy's Large Cavitation Channel (LCC) in February and April of 2009. The deflection of the blades was measured using defocused particle image velocimetry. Comparisons were made between the measured deflection and predictions. The test achieved good correlation with predictions for loading up to 900 RPM in ahead design operations, however no meaningful data was able to be collected in the crashback condition due to high unsteadiness in RPM.				
15. SUBJECT TERMS Propeller, Crashback				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		
			SAR	12+vi
			19a. NAME OF RESPONSIBLE PERSON Susan B. Swithenbank	
			19b. TELEPHONE NUMBER (include area code) 301-227-5775	

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SYMBOLS, ABBREVIATIONS, AND ACRONYMS

BDM	Blade Deflection Measurement
CalTech.....	California Institute of Technology
CMM.....	Coordinate-Measuring Machine
D.....	Diameter
DPIV	Defocused Particle Image Velocimetry
J.....	Advance Coefficient
K_Q	Torque Coefficient
K_T	Thrust Coefficient
LCC.....	Large Cavitation Channel
n	Shaft Rotational Speed
NSWCCD	Naval Surface Warfare Center, Carderock Division
ONR	Office of Naval Research
Q	Torque
R_n	Reynolds Number
RPM	Revolutions per Minute
T	Thrust
V	Velocity

ADMINISTRATIVE INFORMATION

This work was performed at the Naval Surface Warfare Center, Carderock Division, West Bethesda, MD 20817 and was sponsored by the Office of Naval Research (ONR) under the direction of Dr. Ki-Han Kim (ONR 331). The work was performed by the Propulsion Branch, Code 873 at Naval Surface Warfare Center, Carderock Division. This analysis was performed during the summer of 2010 under funding provided through the ONR Alternate Material Propulsor Program Work Unit 10-1-5800-324.

ACKNOWLEDGEMENTS

The author would like to acknowledge Jesse Geisbert who conducted the experiments, Steve Neely for providing the predicted deflections, and Dr. Gharib and his students at CalTech for their analysis of the position data.

SUMMARY

Propeller 5503 was tested in the ahead and crashback conditions in the Navy's Large Cavitation Channel (LCC) in February and April of 2009. In addition to thrust and torque measurements, the deflection of the blades was measured using defocused particle image velocimetry (DPIV). The deflections measured with respect to the stationary blade were compared with predictions in ahead operations. The test achieved good correlation with predictions for loading up to 900 RPM in ahead design operations, however no meaningful data was able to be collected in the crashback condition due to high unsteadiness in the system.

BACKGROUND

Propeller 5503 was designed by the Naval Surface Warfare Center, Carderock Division (NSWCCD) in conjunction with AIR Fertigung-Technologie GmbH & Co., in Germany in 2008. This effort was funded by an Office of Naval Research (ONR) Foreign Comparative Technology initiative. The propellers were tested in the ahead operating condition in February 2009 and in ahead and crashback operations in April 2009. Testing in April included DPIV data taken to measure the deflection of the blades under operation.

The propeller is a 24-inch (0.6096 m) diameter and has 7 blades. Propeller 5503 was manufactured as a mono-block Nickel-Aluminum-Bronze (NAB) geometry with moderate skew and rake which does not resemble any fleet design. The design condition for Propeller 5503 is given in Table 1. The propeller drawing and the values of K_T and K_Q in ahead and crashback are in Appendix A. Propeller 5503 is shown in the LCC test section in Figure 1.

Table 1. Design condition for Propeller 5503

Value	English Units	Metric Units
Torque Coefficient(K_T)	0.212	0.212
Thrust Coefficient ($10K_Q$)	0.317	0.317
Diameter (D)	2.00 ft	0.6096 m
Shaft Rotational Speed (n)	1360 rpm	1360 rpm
Ship Velocity (V)	26.29 ft/s	8.013 m/s
Thrust (T)	3452.6 lb	15358 N
Torque (Q)	1052.2 ft-lb	1426.6 N-m
Advance coefficient(J)	0.580	0.580
Reynolds Number (R_n)	33.67×10^{-5}	33.67×10^{-5}



Figure 1. Propeller 5503 in LCC test section.

Description of Facility

Large Cavitation Channel (LCC)

The William B. Morgan Large Cavitation Channel is located in Memphis, Tennessee. It is the world's largest high-speed, variable pressure water channel. It allows for model experimentation to measure submarine and surface ship power, efficiency, and propeller noise in a controlled but realistic environment. The LCC is a vertical plane, recirculating, 1.4 million gallon, variable-speed, variable-pressure channel. It has a contraction ratio of 6:1, aeration/deaeration system, filter system, temperature control, low turbulence (0.1%), and can reach steady speeds up to 59 ft/s (17.98 m/s). The test section has a cross-sectional dimension of 10 feet (3 m) by 10 feet (3 m) and a 43 feet (13 m) working length. Pressure in the LCC test section can be varied from less than atmospheric (0.5 psia (3.45 kPa)) to four times atmospheric pressure (60 psia (413.7 kPa)); the latter being the equivalent of water approximately 100 ft (30.48 m) deep. It has an electric motor capable of outputting 14,000 hp (10.444 MW) of power to drive an 18 ft (5.49 m) diameter fixed pitch, seven-bladed axial flow impeller with a nine-bladed stator.

Open Water Dynamometer (OWD)

The open water dynamometer, (OWD), is similar to that of a strut mounted submarine or torpedo model, but with the propeller on the upstream end of the assembly. The LCC OWD has a nominal body diameter of 26.0675 inches (662.0 mm) and a maximum overall length of 20.96 feet (6.389 m) to the propeller centerline. It is designed to use the existing LCC standard large model motors in a tandem configuration with no gear reduction. The current configuration is capable of operating to 3000 RPM and at torque levels of approximately 1000 lb-ft (1,356 N-m). The Thrust Torque Sensor (TQS) series of LCC dynamometers are installed in the drive shaft-line to measure propeller thrust and torque.

Crashback

The crashback condition is both a hydrodynamically and structurally complex condition to analyze. The propeller loading during crashback has a time-average component, but is dominated by large unsteady events [1]. Part of the unsteadiness is broadband, while a portion of the unsteadiness is at low frequency and can contribute to propeller unsteady forces during crashback. The unsteadiness also results in the most extreme propeller blade loading conditions.

The crashback condition is dominated by the interaction of the free stream flow field with strong recirculation driven by the local propeller-induced velocity. The local propeller-induced velocity pushes the fluid against the incoming free stream flow, shown in Figure 2. The vortex ring created in this condition is unsteady even in the idealized conditions of a water tunnel. Extreme flow unsteadiness and the varying degrees of blade surface flow separation make prediction of individual blade forces extremely difficult.

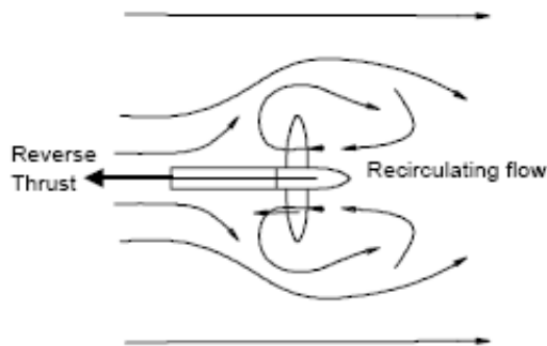


Figure 2. Crashback condition.

Tracking the deflection of blades operating in the crashback condition can be used to help validate fluid structure interaction tools for use in designing and structurally certifying propellers.

OPEN WATER DATA

In Figure 3, the torque and thrust curves for Propeller 5503 in the ahead condition are shown. There were two sets of testing done. The open water testing was conducted in February. This test was conducted with varying roughness on the blade¹. In April, the blade deflection measurement (BDM) tests were conducted. There was no roughness for the BDM testing. Ahead open water predictions were made for Propeller 5503 at NSWCCD using PSF10.

Propeller 5503 was tested in crashback in the LCC at 50 psia (344.7 kPa) centerline and 60 psia (413.7 kPa) centerline. All of the crashback testing was conducted during the April test window with no roughness. For the crashback test, the propeller was reversed on the shaft. Centerline pressure was increased to suppress cavitation which can have an adverse effect on the

¹ Data are documented in a report of higher classification.

propeller's performance. The cavitation also obscured the pictures used for the blade deflection measurements. Open water experimental data is presented in Figure 4.

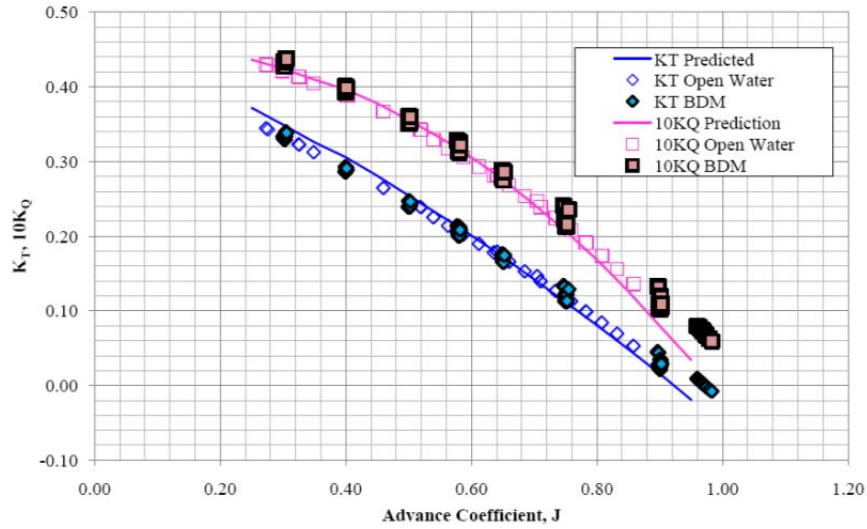


Figure 3. Propeller 5503 ahead quadrant open water.

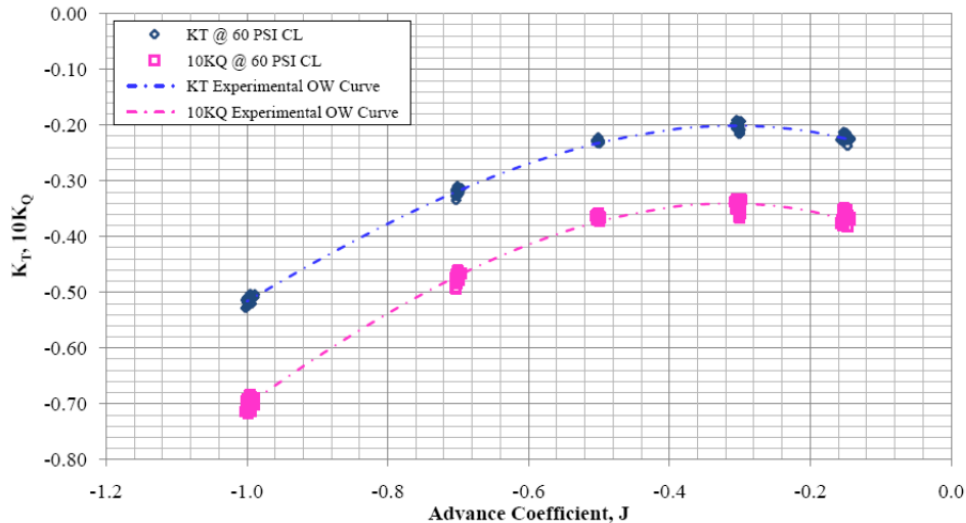


Figure 4. Propeller 5503 open water crashback results data.

DPIV DATA ACQUISITION

The data acquisition system used for the DPIV was a single, three pin-hole camera mounted outside the cavitation channel [2]. White dots were painted on the blades of the propeller and later located using a coordinate measuring machine (CMM). A calibration plate was affixed at the propeller plane prior to testing for calibration of the DPIV system. The propeller was first run in the ahead condition, then crashback, and finally stationary pictures were taken.

Figure 5 is a picture of the defocusing lens concept used for this project, which involves taking a single exposure picture through three apertures. Figure 6 shows an example of the pictures taken by the three pin-hole camera, where each triangular group of points represents a single point distorted by the triple aperture. The change in these points relative to each other and the reference correlates to their movement in space.

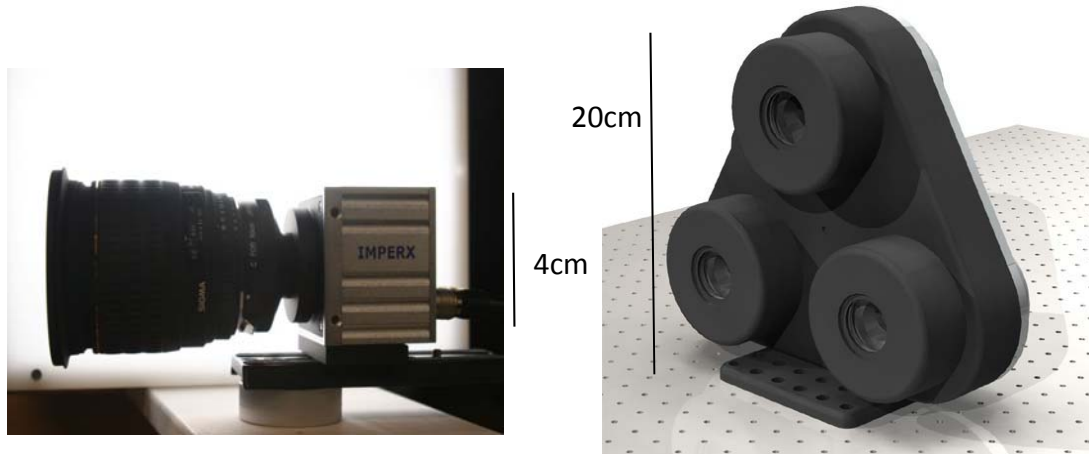


Figure 5. CalTech defocused lens hardware.

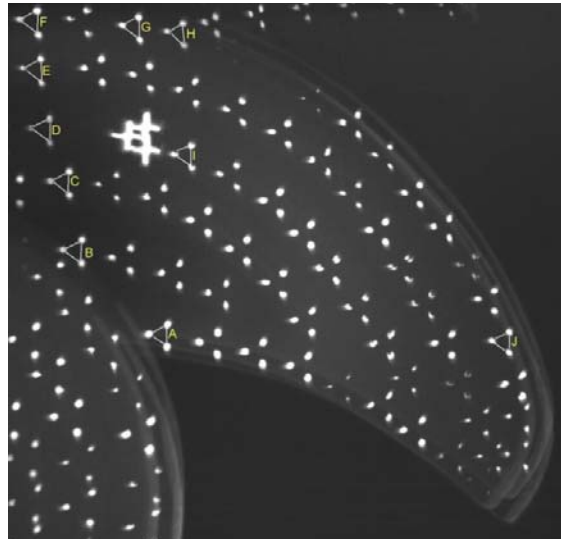


Figure 6. Example picture from three pin-hole camera used to determine point deflections.

From the pictures of the dots taken by the camera, the x-, y- and z-locations were determined using defocused camera technology being developed at CalTech. Data was acquired during both ahead and crashback conditions. CalTech post-processed the data and provided the x, y, and z location of each of the dots on the blade that were visible for the run. Not all points could be determined for each picture during each run. One issue discovered with the defocused technology is a “warping” of the data associated with the lens curvature, which increased error from the center of the picture to the edges. Because the camera was focused such that the mid-

section of the blade was in the center of the photograph, the root section was nearest the edge of the photograph and the highest warping happened there. This resulted in target locations which did not match the original blade design surface. Also, points at the hub or blade root were not captured due to blade overlap and image size.

The DPIV system required the use of a calibration plate, placed at the location of the propeller plane in the test section, to provide known locations for the calibration of the DPIV post-processing tool. DPIV data was taken over a range of advance coefficient (J) values for both the ahead and crashback quadrants. The propeller was finally photographed while stationary in the tunnel as an additional calibration, and the locations of the points were measured using a CMM.

DEFLECTION DATA

Analysis

For the ahead condition, the design advance coefficient of 0.58 was analyzed. For crashback, an advance coefficient of -0.50 was analyzed. Multiple measurement photographs were taken for each blade and each condition and each set of data placed the blade at a different origin in the photograph. The first step was aligning all the points such that there could be a point-to-point comparison of the data to determine the deflection.

The data was processed to be a list of x-, y- and z-coordinates by CalTech. The x-direction is spanwise from the center of the blade root; the y-direction is chord-wise at the root of the blade; the z-direction is in the direction of the shaft. First, each of the processed points was categorized as to which other points were the same point from a different point in time. An average of these points was taken to determine the average location of the points on the blade. Because of the need to average these points, only the steady component of deflection is being analyzed.

To align the different RPM runs, the points that were approximately 3.14 inches to 3.93 inches (80 to 100 mm) from the tip of the blade were chosen as references; these points are the as close to the root as without significant warping from the camera, were most consistently seen in the rotating data, and should have had the least deflections. Because of the optics of the camera causing warping, the points nearer the root had higher uncertainty, and due to problems with the calibrations, the bias uncertainty also could not be determined. To align the points from 3.14 inches to 3.93 inches (80 to 100 mm) from the tip, the points were only allowed to move in the propeller plane: translate in the x-, y-, and z- planes and rotate in the θ_z . The alignment was constrained in θ_x and θ_y so as not to change the deflection. A least-square fit optimization was used to align the data points that were 3.14 inches to 3.93 inches (80 to 100 mm) from the tip. Once the points were aligned, the difference from the stationary data in the z-coordinate was determined.

Figure 7 is an example of what the points look like after the alignment. The points on the left side are the points that are being used to align the points. The least squares error optimization was used on these points to minimize the distance between the different runs. The points nearest the tip, near the bottom right, are expected to be the most different from the stationary. This difference is the deflection due to operational forces.

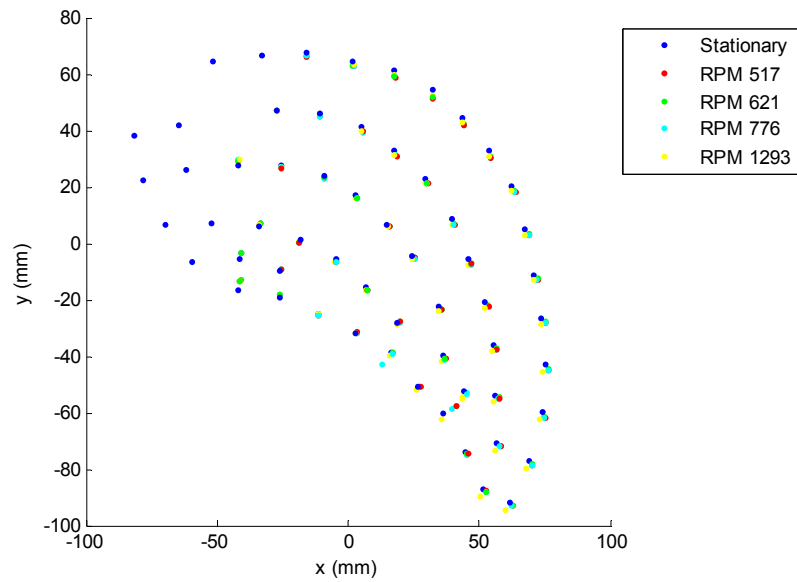


Figure 7. Points after aligning as seen from the x-y plane for Propeller 5503 in ahead.

During the crashback, the shaft torque was unsteady; this caused the RPM to vary by small amounts. The variation in RPM caused the camera to lose synchronization with the propeller. The lack of synchronization would put the propeller blade in a different position in each picture; this caused some of the alignment issues. In crashback, the dynamometer also had significant side forces which caused the dynamometer to move. This movement could have caused additional uncertainty in the data acquisition by moving the propeller hub in addition to the blade deflections.

Figure 8 shows the points in the propeller plane for Propeller 5503 in crashback for over 100 different images. Near the root, (upper left of figure), there was less variation in the x-, y-, and z-locations of the points which made alignment possible. Near the tip, (lower right of figure), there was significantly more scatter in the data, which is assumed to be caused by movement of the tip during the large load variations introduced during crashback.

The reference points at the root in Figure 8 are not all located on top of each other because a least squares fit was done to align the reference points and minimize the displacement error of multiple points. The reference points at the root were not always the same distance apart which causes some of the uncertainty in location.

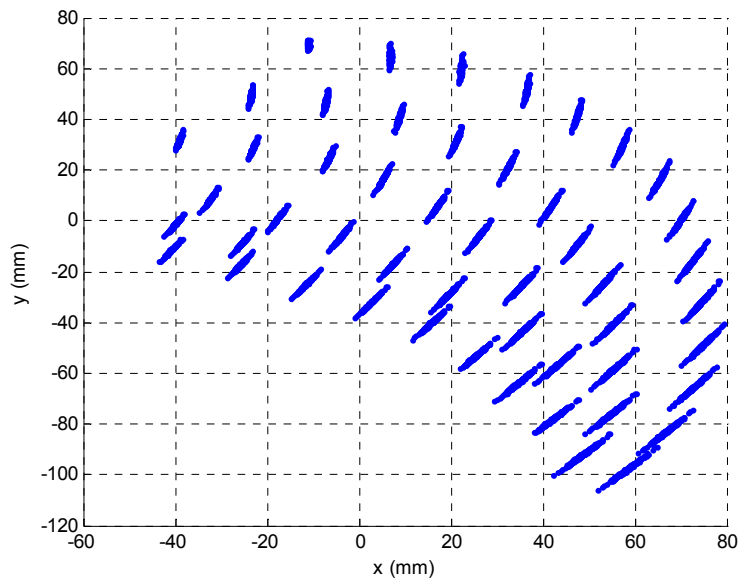


Figure 8. Point cloud after alignment for propeller 5503 in crashback at 500 RPM.

Results

Figure 9 shows the tip deflection for Propeller 5503 in the ahead quadrant. The tip deflection was measured as an average of the points within the last twenty millimeters on the blade. On average this was three points. Since the tip deflection is an average and not taken at the true end of the blade, the measured tip deflections are expected to be slightly lower than the predicted deflections. At the lower RPM, the deflections are similar to the uncertainty. The predictions were made by coupling NASTRAN [3] with PSF10 [4] and follow the quadratic behavior expected from a linear elastic material at a single advance coefficient.

Due to the high uncertainty associated with the crashback DPIV alignment data, the crashback results are not reliable. Figure 10 shows the tip deflections of Propeller 5503 in crashback. All of the deflections in crashback are less than the uncertainty. The uncertainty in the crashback condition is greater than the value of the deflection; this is discussed in greater detail later in the report.

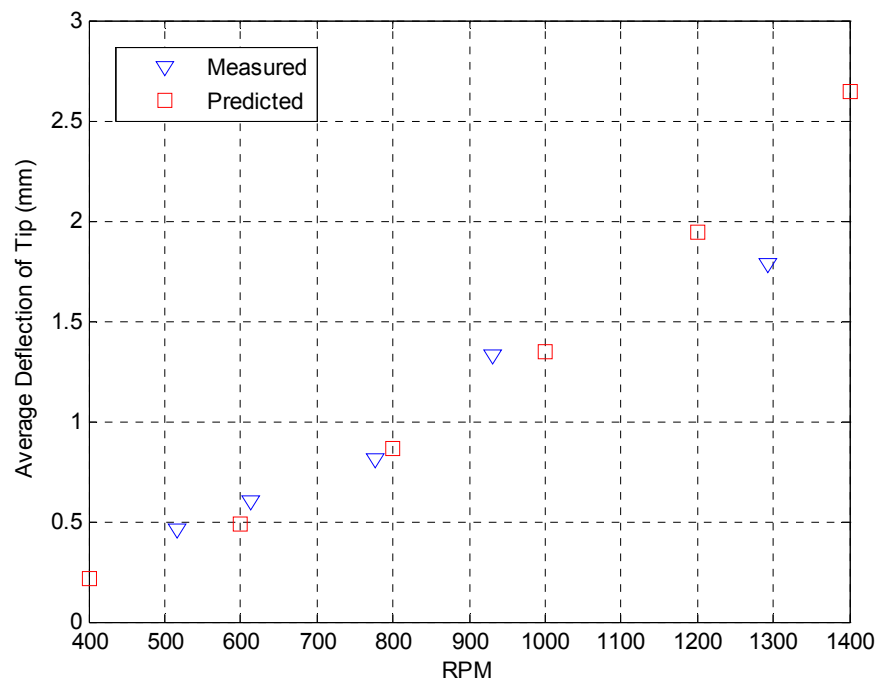


Figure 9. Tip deflections for Propeller 5503 in the ahead quadrant.

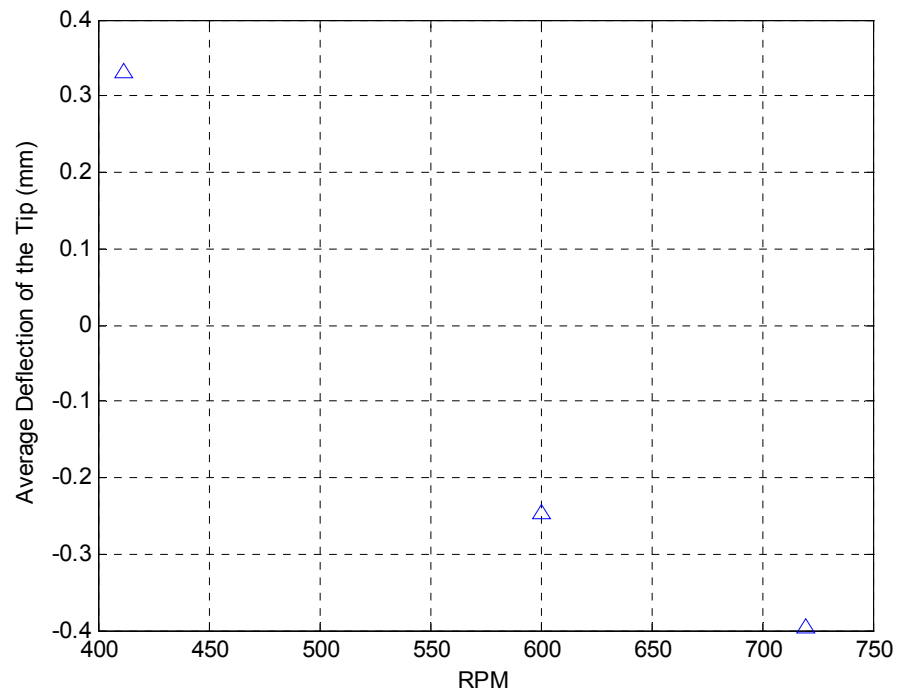


Figure 10. Tip deflections of Propeller 5503 in crashback.

Uncertainty

The uncertainty of these calculations is difficult to quantify. There is the uncertainty of the data acquisition system, the data processing method, and the analysis method as well as the variation of the position of the blade itself. The total of these causes uncertainty in the locations of the points and the deflections.

One significant problem with this methodology is that the highest uncertainty due to the data acquisition system is the location of the points nearest the root where the blade deflections are least. Because the camera was focused such that the mid-section of the blade was in the center of the photograph, the root section was nearest the edge of the photograph where, due to the optics of the lens, there was some warping of the picture at the edges which led to a higher uncertainty near the root of the blade. The calibration plate images were intended to address this issue, but did not appear to have a sufficient effect.

Since each point is an average of all the pictures, the standard deviation of that location tells the variation in that location from picture to picture. For the ahead condition the standard deviation of the location is expected to be low. In Figure 11, the standard deviation of the location after alignment is plotted versus the x-location on the propeller for Propeller 5503. The three plots represent the x-direction standard deviation (top), the y-direction standard deviation (middle) and the z-direction standard deviation (bottom). Refer to Figure 7 above for x (mm) locations referred to in Figure 11.

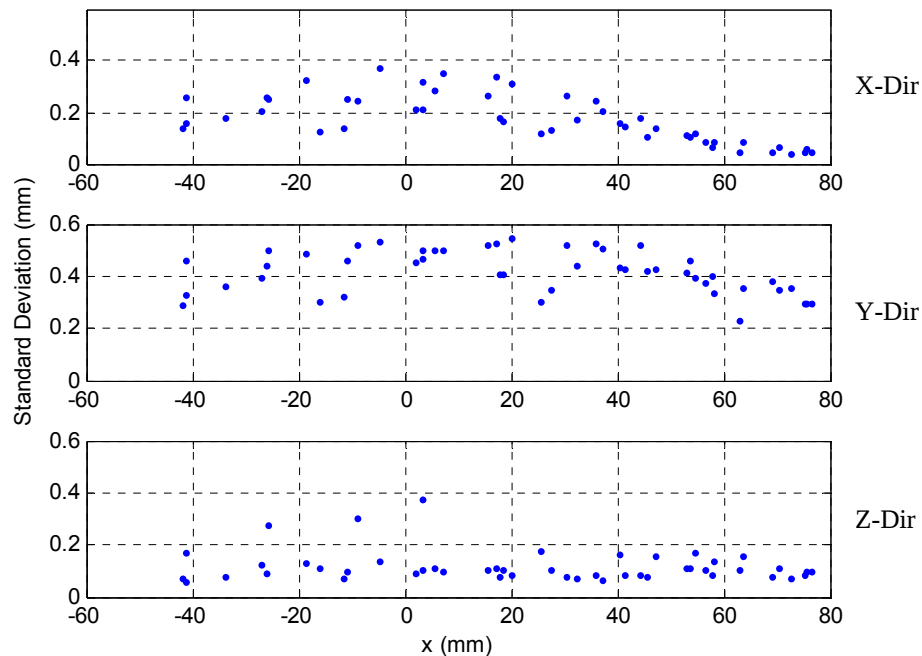


Figure 11. Standard deviation of deflections for Propeller 5503 in ahead at 500 RPM.

The standard deviation of the tip area is lower for all directions than the root area. This confirms that the uncertainty is higher near the root. Since the points nearest the root were used

to align the data, the uncertainty of the alignment and the deflections is also affected. The uncertainty in the z-direction is the lowest, while the uncertainty in the y-direction is the highest.

Figure 12 is the standard deviation of the location is plotted versus the x-location on the propeller for Propeller 5503 in crashback. The x- and y-locations in crashback (Figure 8) have significantly higher standard deviation than the ahead results (Figure 7); the standard deviation is shown in Figure 11. The standard deviation in the z-direction is similar to the ahead case, which is unexpected. Crashback is an unsteady phenomenon which causes unsteady motions of the propeller and would be expected to cause greater unsteadiness in point locations near the tip.

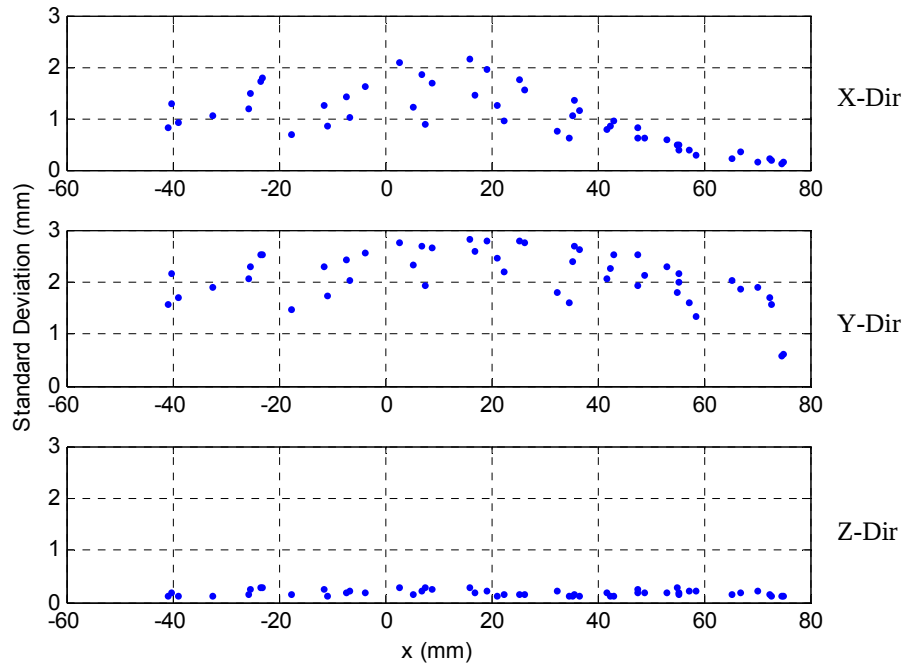


Figure 12. Standard deviation of deflections for Propeller 5503 in crashback.

The larger standard deviations in the x- and y-directions could be from errors and uncertainty in the alignment of the data as well as the warping effects from the camera. The relatively low standard deviation of the z-direction can be deceiving, because while the x- and y-directions can rotate through a 360° arc, the z-direction is constrained by the shaft, and the total measured deflections were less than two millimeters. This is true in both ahead and crashback, but the standard deviation in the x- and y-direction in the crashback condition was significantly larger than in the ahead condition.

Assuming an average standard deviation in all directions of 0.5 mm, the 95% confidence interval would be 1 mm for a standard distribution. Knowing the chord of the blade at 70% radius is approximately 11.5 mm, the uncertainty would cause an uncertainty in the pitch of 1° . The predicted pitch change in ahead at the tip was less than 0.2° for Propeller 5503. Magnitudes that small are indistinguishable from the uncertainty; therefore the pitch change of the blade cannot be determined from this data, either ahead or crashback. The uncertainty is less in ahead, however it is still greater than the predicted magnitudes.

CONCLUSIONS

The current deflection analysis shows good correlation for the ahead propeller conditions at RPM less than 900. At RPM higher than 900, the increasing trend is still there, but the measured deflection does not match the predicted data as well.

The DPIV system displayed sufficient ability to track an array of points in three-dimensional space in a continuous manner; however greater test planning integration is required to meet the needs of the test objectives. For future testing, the following recommendations should be considered:

- Better calibration data should help significantly reduce the uncertainty of the data. The calibration data from this test was neither good enough to remove the warping of the optics of the lens nor to definitively determine the uncertainty of the measurements.
- A better focus for the camera with more points towards the root would help to align the data.
- Better stationary data, including points at the tip, would improve calibration of the data and increase fidelity in the data.
- A propeller with fewer blades would allow greater visibility at the root and more consistency in points captured.
- Direct activation of the camera based on a shaft index would improve the ability to capture the blade of interest in the same rotational position and improve accuracy.

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4. Kerwin, J.E. and Lee, C.S. "Prediction of Steady and Unsteady Marine Propeller Performance by Numerical Lifting Surface Theory." *SNAME Transactions* 86 (1978).

APPENDIX A: Propeller Characteristics**Table A-1. K_T and K_Q in Ahead Operations**

J	K_T	$10K_Q$
0.3	0.333	0.421
0.35	0.312	0.406
0.4	0.291	0.388
0.45	0.268	0.369
0.5	0.245	0.349
0.55	0.222	0.326
0.6	0.197	0.301
0.65	0.172	0.275
0.7	0.146	0.246
0.75	0.118	0.214

Table A-2. K_T and K_Q in Crashback Operations

J	K_T	$10K_Q$
-0.3	-0.201	-0.341
-0.4	-0.208	-0.348
-0.5	-0.231	-0.373
-0.6	-0.268	-0.414
-0.7	-0.317	-0.470
-0.8	-0.376	-0.538
-0.9	-0.443	-0.616
-1.0	-0.515	-0.702

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