The Effectiveness of Guards in Mitigating Propeller Strikes

Introduction

Boaters have long faced the risk of injury by accidental contact with boat propellers. For many years there have been a host of claims and counterclaims relating to means of mitigating this risk. Since as early as 1988, the U.S. Coast Guard has commissioned a number of projects involving study of propeller injury accidents and potential means to mitigate the risk of injury.

The common thread throughout the work is that there is no universal solution to the problem. Except in very limited applications, the extremely large number of potential combinations of hull form, propulsion type and size, operating environment, and boating activities have made it impractical to establish a clearly defined means for a boat or engine manufacturer to eliminate the risk of injury while providing the product that the customers want to buy. This project is an effort to produce a workable system for evaluating propeller injury mitigation devices, specifically propeller guards. It should be noted that this analysis is principally intended for recreational boating. Further, this analysis was intended to evaluate the mitigation of propeller strikes involving people, and not entanglement with non-human objects, marine life, or damage to the lower unit.

Initially, it was envisioned that a summary product of this effort would be an evaluation matrix to be used by consumers as a guide in propeller guard selection. This matrix is not intended to be a design test standard, a law, or a regulation. The matrix is intended for use by manufacturers of propeller guard devices, other testing entities, and the consumer to evaluate guarding products in a way that allows comparison with other products on an "apples-to-apples" basis. Individual tests are designed to produce repeatable results. Specific result-oriented criteria have been established where subjective evaluation is required. The output of these evaluations may be cataloged such that a boater could conveniently research available products to determine what products might be available to allow reducing the risk of propeller injury in his or her particular circumstances. Propeller guard manufacturers might include these results on the packaging and advertizing material for their products. Finally, the matrix is intended to be dynamic. It should be subjected to periodic reviews and updates as needed.

Over time, many different groups and individuals have contributed to this evaluation protocol. They range from victims and victim advocate groups through government organizations and law enforcement personnel to boat and equipment manufacturers as well as manufacturers and designers of propeller guard devices. Throughout development of the protocol, many formal and informal opportunities have been available for interested parties to provide technical input. This final draft will be subjected to a peer review by interested parties. The results will be reviewed and appropriate edits will be completed before the final version is delivered to the U.S. Coast Guard.

Background

Working closely with the American Boat and Yacht Council (ABYC) and the U. S. Coast Guard Office of Auxiliary and Boating Safety, CED Investigative Technologies, Inc. (CED) was asked to perform testing and analysis of commercially available propeller guards designed for use in the recreational boating industry. The foundational work leading to the creation of a propeller guard evaluation matrix consisted of three phases. Phase I of this study consisted of an analysis of the human factors involved in propeller strikes; CED's report dated June 5, 2009 documented that effort. Phase II of the propeller guard analysis involved on-water propeller guard performance testing conducted by MacNeil, Akers and Goudey; that effort was documented by Propeller Guard Performance Test Protocol, Propeller Guard System Evaluation by Richard Akers and Clifford A. Goudey (Goudey-Akers) in a report dated January 2, 2009. Goudey-Akers has been included in Appendix A. Phase III of the overall propeller guard study consisted of full scale tank testing that was conducted at Center for Research and Education in Special Environments (CRESE) located at the State University of New York at Buffalo located in Buffalo, New York. CRESE testing was conducted during two segments, the first during July 19 through 23, 2010 and the second during December 14 through 16, 2010. Commercially available propeller guards were mounted on an outboard engine and video was used to record the effectiveness of these guards when the engine was operated at various speeds.

Based on the testing and analysis conducted during these three phases, a framework for an evaluation matrix was created. This matrix framework was discussed during a webinar hosted by ABYC on December 12, 2011 and input was solicited from interested parties. On January 6, 2012, the U.S. Coast Guard Office of Auxiliary and Boating Safety announced an accident mitigation workshop to be held at the Miami Boat Show on February 16, 2012. The propeller guard evaluation matrix will be discussed at this workshop.

Discussion

After an analysis of the work performed in Phases II and III, the basic framework for an evaluation matrix was created. The matrix consists of three principle categories: (1) performance based speed and maneuverability, (2) ease of installation, and (3) effectiveness. Each of these categories will provide a rating such that by using a summary of all the individual ratings, a consumer can be guided in selecting an appropriate propeller guard. Finally, the matrix would offer three types of commercially available propeller guards that a consumer could purchase: cage guard, ring guard, and concentric guard. Figure 1 represents a suggested evaluation matrix; specific ratings for this matrix would be based on individual testing as outlined below in this report.

Propeller Guard Evaluation			
	Cage	Ring	Concentric
Performance Speed Maneuverability	 good good	 best better	 better best
Ease of installation	good	best	better
Effectiveness	Best (boarding)	Limited (wake/trawl)	Blunt force (15 mph)

Figure 1 – Evaluation matrix

<u>Performance - Speed</u>

The specific steps to be taken to determine the effect of a propeller guard on the boat's speed will be in accordance with the protocol outlined by Goudey-Akers. A complete discussion of the Preparation and Test Conditions for speed testing is contained in Section 1.1 of Goudey-Akers; similarly, Safety is discussed in Section 1.2. The entire Goudey-Akers protocol should be read and understood before conducting any testing related to this matrix.

Experienced operators should be used when conducting any testing relating to this matrix. For emphasis, the Cautionary Note contained in Goudey-Akers is reprinted below:

Cautionary Note: These series of tests often discover off-design characteristics and/or dangerous conditions before, during and after maneuvering. Care must be taken to gradually increase speed and execute the maneuvers at multiple lower speeds in order to gain a feel for the behavior. Even with extensive low-speed testing, higher speeds may result in unexpected and spontaneous reactions either with or without the device installed. Use caution and experience to determine when or if the testing should be discontinued.

For clarity in completing testing related to this matrix, the specific section of Goudey-Akers dealing with the analysis of a boat's speed has been reprinted below.

"2.2 Speed vs. RPM Test:

This is a straight-line speed test used to quantify any change in speed as a result of adding a propeller guard.

Preparation and condition:

The boat shall be prepared as above.

Procedure:

1. With the outboard/sterndrive in forward, head directly into the wind at idle RPM. Once the speed has stabilized, note the RPM, the speed, and the fuel flow.
2. Increase outboard/sterndrive RPM to the first integer multiple of 500 RPM, achieve stabilization and again, note RPM, the speed, and the fuel flow.
3. Repeat Step 2 in 500-RPM increments until the outboard/sterndrive reaches maximum RPM. Run a final test at maximum RPM.
4. If the wind speed is greater than 5 MPH, repeat Steps 1, 2 and 3 heading downwind.

Measurements:

- Outboard/sterndrive RPM (noted for each increment).
- Boat speed (a displayed value from the differential GPS display).
- Fuel consumption rate (displayed or logged values from the test instrumentation).
- Zero-speed pitch angle of boat (displayed or logged values from the test instrumentation, taken at the beginning of the test).

- Pitch angle at each RPM.

Quantitative Results:

The speed during each test condition is manually recorded based on the GPS displayed speed value or calculated during post processing by averaging a steady-state portion of the recorded data or based the recorded position data using distance traveled divided by time.

The fuel consumption rate under each test condition is calculated during post processing by averaging a steady-state portion of the recorded fuel flow values.

Static pitch angle under each test condition is calculated during post processing from a steady-state portion of the recorded pitch values. The zero-speed pitch is subtracted from each static pitch angle so as to compensate for the slight change in bow-up moment by adding a propeller guard mechanism.

For each parameter, the performance metric is the percent difference between the results with the propeller guard compared to without the propeller guard. A convenient way of portraying the speed vs. RPM results for a specific trim setting is to plot the results as shown in Figure 1.

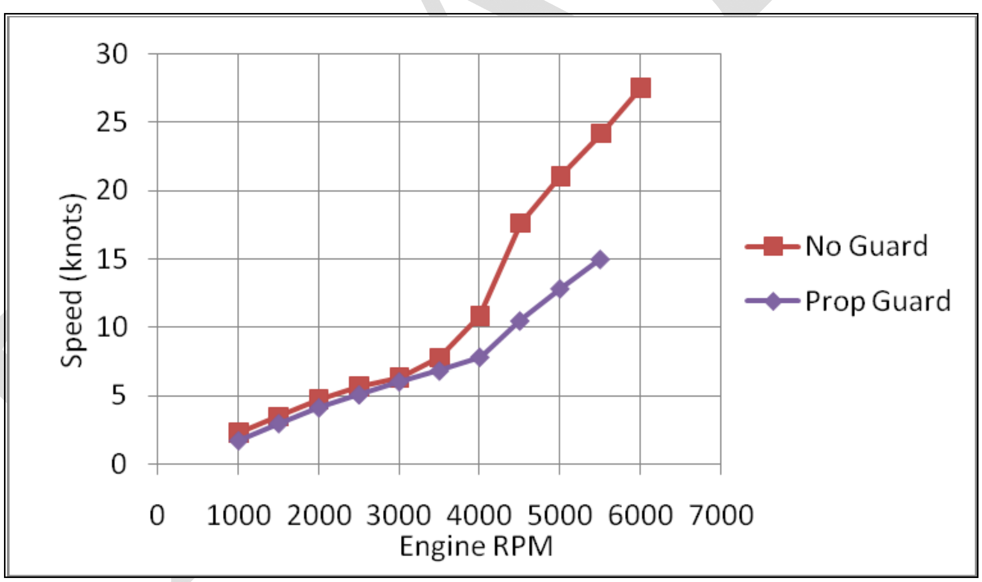

Figure 1. Sample plot of speed vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

A convenient way of portraying the pitch vs. RPM is to plot the results as shown in Figure 2. Plotting Fuel Usage/Second vs. RPM, as shown in Figure 3, can portray fuel consumption.

In addition to assessing the safety implications of a propeller guard installation, an important measure of boat performance is speed vs. power. In the absence of an outboard/sterndrive torque measurement, a useful surrogate for power is a combination of RPM and fuel consumption.

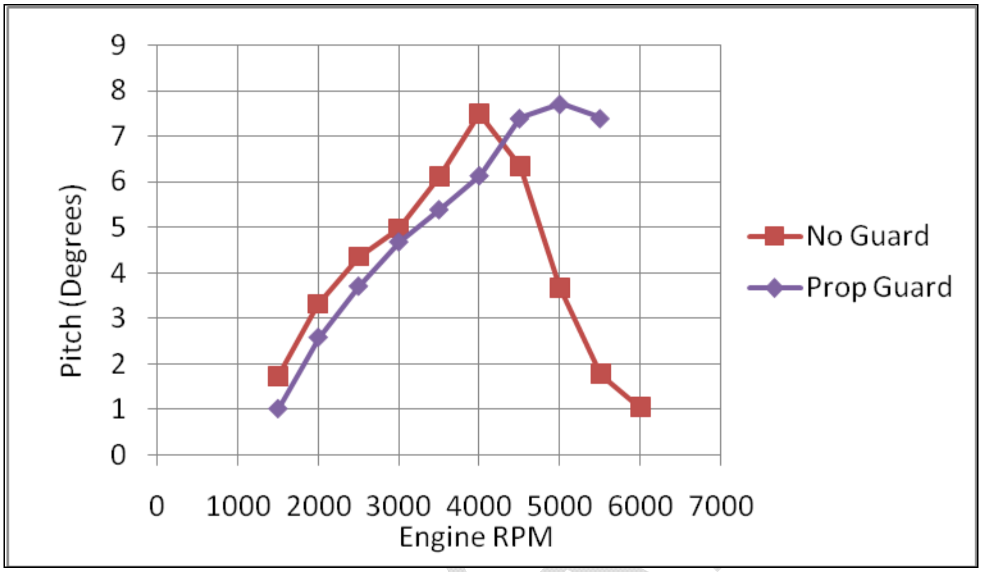

Figure 2. Sample plot of pitch vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

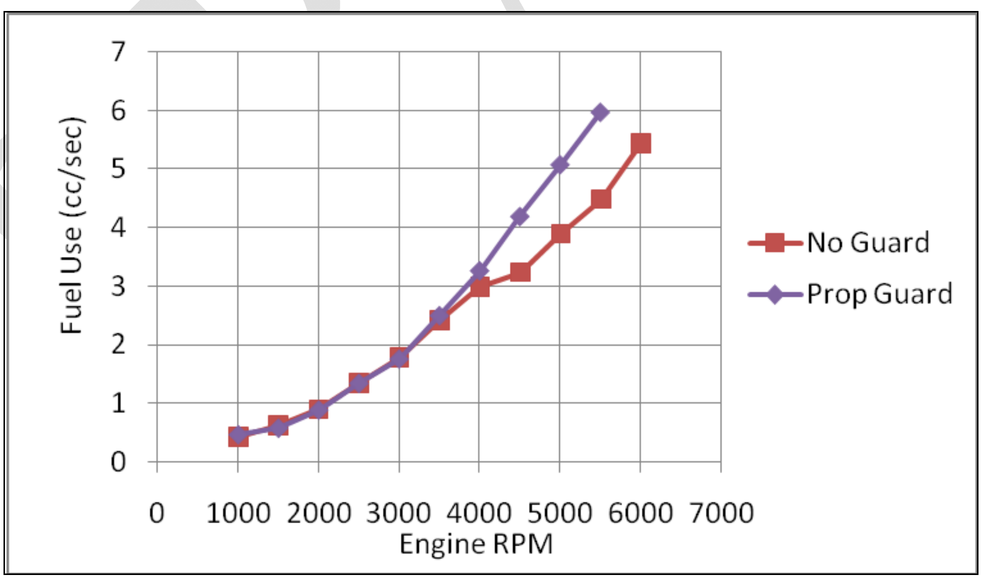

Figure 3. Sample plot of fuel consumption vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

In addition, fuel efficiency is an important measure of boat performance. Therefore, the data gathered from this test sequence can be combined to reveal the fuel consumption implications of operating with or without a propeller guard. For each RPM setting, the speed and the fuel consumption data should be combined to yield nautical miles per gallon for each test condition by using formula 1.

$$NMPG = \frac{MPH}{GPM \times 60} \qquad (1)$$

This result can be plotted to reveal the fuel efficiency trend over the range of RPM tested as shown in Figure 4.

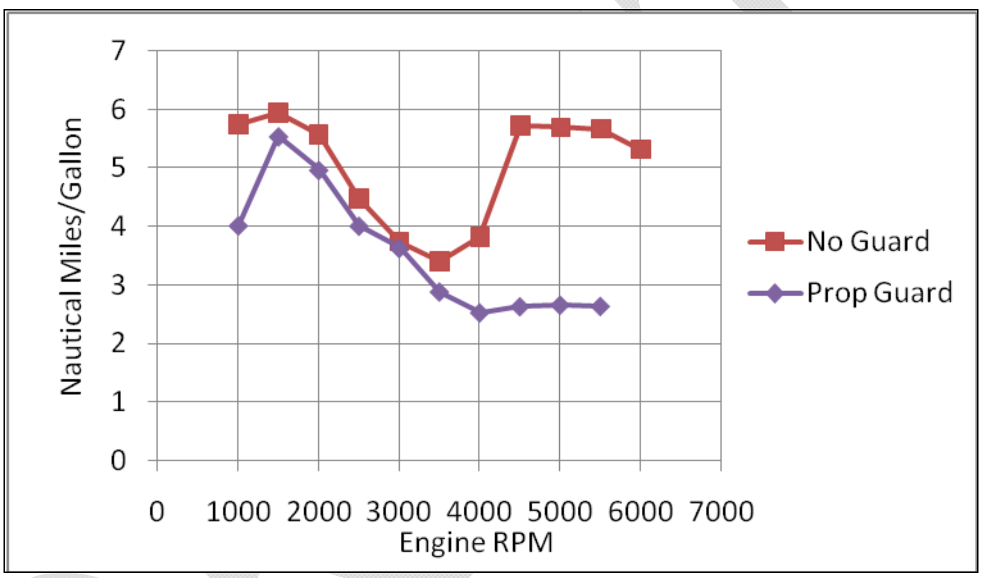

Figure 4. Sample plot of fuel efficiency vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default."

The summary metrics for the Speed vs. RPM tests are:

- The average of the percent differences in speed over the full range of RPM settings.
- The percent difference between top speeds with and without the propeller guard.
- The average of the percent differences in fuel consumption over the full range of RPM settings.
- The average of the percent differences in nautical miles per gallon over the full range of RPM settings.
- The percent difference in maximum pitch angle over the full range of RPM settings." (Goudey-Akers, Section 2.2).

Following the Goudey-Akers procedures reprinted above, a speed rating can be determined. When determining the rating for speed, a degradation greater than 25% relative to an unguarded propeller would receive a rating of 'Good', a degradation of between 10% and 25% would receive a rating of 'Better', and a degradation less than 10% would receive a rating of 'Best'. Since there are a large number of combinations of potential hull forms and power, the manufacturer would have to state that the rating was based on testing using a particular hull form and engine.

Performance - Maneuverability

The protocol used to measure the difference between maneuvering with and without a propeller guard was presented in Goudey-Akers. Those procedures will be used to rate maneuverability. When assessing the results of the Goudey Akers testing for maneuverability, a biomechanical evaluation was used to assign a rating. Again and for clarity, the specific section of Goudey-Akers dealing with the analysis of a boat's speed has been reprinted below:

"2.5 Maneuverability Tests:

Cautionary Note: These series of tests often discover off-design characteristics and/or dangerous conditions before, during and after maneuvering. Care must be taken to gradually increase speed and execute the maneuvers at multiple lower speeds in order to gain a feel for the behavior. Even with extensive low-speed testing, higher speeds may result in unexpected and spontaneous reactions either with or without the device installed. Use caution and experience to determine when or if the testing should be discontinued.

The maneuverability test provides a performance comparison as the boat follows a serpentine path resulting from alternating port and starboard helm commands. The test measures the ability of the boat to turn in response to specified helm inputs. The current should be less than 0.25 MPH. The wind should be less than 10 MPH.

Three maneuverability test speeds are selected to represent low speed, medium speed and high-speed operation. These should be selected based on the results from straight-line speed vs. RPM tests described above. The high-speed operation should be selected to be the "test speed" defined in section 2.3 above. The low speed should correspond to a "no-wake" speed that provides positive steering. The medium speed should be the average of the high and low speeds. The maneuverability tests are intended to compare the maneuverability at these three speed settings, not necessarily at equal RPM settings.

NOTE: The medium speed is the average between high and low speeds, and this may cause a problem if it happens to fall in the hump speed range. It is difficult to operate a planing hull boat so as to stay at the hump speed, as the boat will tend to speed up or slow down to avoid this speed. In this case the medium speed should be increased slightly from the average of the high and low speeds so as to achieve low-speed planing operation.

For each selected speed setting identify a corresponding RPM setting for each trim setting and with and without a propeller guard. That RPM setting is used throughout each serpentine run, though the speed will likely change during the tests. The steering position sensor is recorded during these tests for the purpose of verifying that the helm commands were properly executed within the specified time limit. If low test speeds result in the crossing of the test boat's earlier wake, disregard any roll data from that run.

Preparation:

The boat is prepared as described in section 1.1.2 above.

Procedure:

1. Set the outboard/sterndrive RPM for the first low-speed setting. Steer a course in the intended direction of the test sequence. Identify the helm position that provides a constant heading. Mark that helm position with a piece of tape or other means. Note that this "amidships" mark is likely to change at different outboard/sterndrive speeds and should be determined for each speed setting.
2. Once at a steady speed, turn the steering wheel 360˚ to starboard or the limit of rotation, which ever is less. Execute this helm command in less than 1 second.
3. Hold the wheel at that position until the boat has turned 90° relative to its original heading. It may be necessary to adjust the throttle setting during the turn in order to maintain the specified outboard/sterndrive RPM.
4. Once at 90˚ from the original course quickly turn the wheel to port 720˚ (two full turns) or until the limit of rotation is reached, whichever is less. This

rotation of the wheel should be accomplished in less than 2 second.

5. Complete a 180˚ course change and once at 90˚ from the original course quickly turn again.
6. Repeat steps 4 and 5 until the boat has gone through six complete half-turns. During the entire series of turns, adjust the throttle to maintain the specified outboard/sterndrive RPM. A diagram of the desired track is presented in Figure 9.
7. Document any anomalies such as propeller ventilation during turns. If any instabilities or difficulty in controlling the boat is experienced, the test should be aborted, and the anomalies recorded.

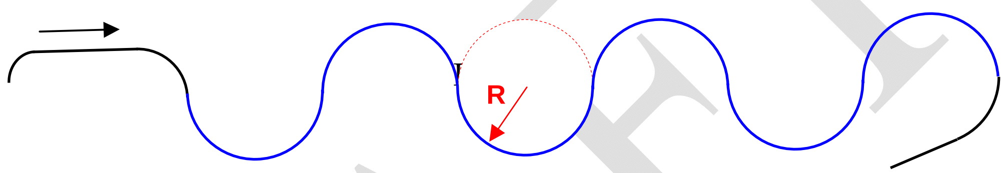

Figure 9. A diagram of the desired track like for the maneuvering test.

<u>Measurements</u>:

- Pitch and roll angles. Use only the data recorded during the 180˚ turns (blue portion of Figure 9) and when the boat does not encounter its own wake.
- Speed and position from GPS.
- Steering Wheel torque. Use only the data recorded during the series of 180˚ turns.
- Outboard/sterndrive/lower unit deflection.

<u>Quantitative Results</u>:

Calculate the following metrics for each trim condition and speed:

- The extreme and the average of the port and starboard roll angles during the serpentine run.
- The maximum and the average of the port and starboard steering wheel torques during the serpentine run.
- Plot the track of the serpentine run and graphically determine the turning radius for each of the 180˚ turns (blue portion shown in Figure 9).
- The steering position for each of the turns and the time required to execute the helm shift. This is defined as the time from the start of the steering event to the finish of the steering event.

The steering position data should be reviewed to ensure that the helm positions during the 180˚ turns are held to within 1˚ of the prescribed position and that the helm is shifted to within the prescribed time constraints. The following metrics are used to compare the maneuverability performance.

- The percent difference in extreme port and starboard roll angle over the three turns.
- The percent difference in average port and starboard roll angle over the three turns.
- The percent difference in extreme port and starboard steering wheel torques over the three turns.
- The percent difference in average port and starboard steering wheel torques over the three turns.
- The percent difference in port and starboard turning radii averaged over the three turns.” (Goudey-Akers, Section 2.5).

There are currently very few codes, standards or design guidelines regarding maximum allowable steering torques (or forces) during operation of a boat. Rather, most manufacturers design their steering systems to achieve the desired performance or “feel” based on small test groups or customer feedback. Substantial variations in steering force may be chosen depending on such factors as anticipated use, operating environment and expected operator demographics. Relatively “heavy” steering may be desirable in some applications, while minimal effort may be desirable in others. This testing is not intended to dictate that a manufacturer alter their designed steering force, but rather to assess whether the addition of a guard significantly alters the steering relative to the manufacturer’s design intent and, if so, to ensure that the addition of a guard does not introduce a condition wherein excessive steering effort is required by the operator. Accordingly, three key outcomes will be addressed from this portion of the maneuverability testing: (1) determine the degree to which the addition of a guard alters the steering effort relative to the unguarded condition (original design intent), (2) ensure that the addition of a guard does not increase the required operating force to an extent that exceeds typical human performance capabilities or comfort limits, and (3) determine the degree to which the addition of a guard alters the amount of steering input.

From the testing in Section 2.5 of the Goudey-Akers proposal (Maneuverability Tests), measures of peak torque will be available from each 180-degree turn for each test condition. The average of these peak torque measurements can be statistically compared for a guarded versus unguarded condition to determine whether the addition of a guard significantly alters steering effort. The exact statistical test to be used cannot be determined prior to data collection, but it is likely that a simple two-group comparison test will suffice (an independent t-test or Mann-Whitney test, depending on whether the data is normally distributed). If a significant difference is detected ($p<0.05$), then the guard will be rated “good”. If a marginal difference is detected ($p<0.15$), the guard will be rated as “better”. If no significant difference exists ($p>0.15$), the guard will be rated as “best”. [Note: The magnitude of the standard deviation in each group must be carefully considered when using this method. For example, if a guard produced an unstable steering condition, the resulting torque measurements might have a large standard deviation, thus preventing the statistical test from detecting a difference between the guarded and unguarded conditions (thus resulting in a rating of “best”); however, such a condition would be indicative of undesirable performance behavior and the corresponding guard should not be given a favorable rating. Conversely, groups with very small standard deviations can produce detectable statistical differences in situations where the mean torque requirements are not substantially different between the groups.]

Under no circumstances should the addition of a guard create a condition wherein excessive steering effort is required by the operator. A combination of biomechanical test data, industry standards, and government standards suggests that difficulties may be experienced by some operators if a steering force greater than 150 Newtons is required [NASA Man-systems Integration Standards, Chapter 4, Human Performance capabilities; SAE J1511 – Steering for Off-Road, Rubber-Tired Machines; European Directive 70-311-EWG and 70-311-EEC]; for a nominal steering wheel size of 14", this force corresponds to an approximate torque of 27 N-m. Such a value is consistent with the ABYC recommendations that a torque exertion of no more than 20 foot-pounds (27 N-m) be required at the steering wheel to attain 90% of the steering arm travel [ABYC Standards, P-17 (Mechanical Steering Systems), P-18 (Cable Over Pully Steering Systems for Outboard Engines), P-22 (Steering Wheels)]. If the addition of a guard significantly increases the steering effort relative to the unguarded condition (i.e., if the rating from above is either "better" or "good") and any peak torque measurement under the guarded condition exceeds 27 N-m, then a rating of "fail" will be assigned to the guard.

As was the case when assigning a rating for speed, since there are a large number of combinations of potential hull forms and power, the manufacturer would have to state that the rating was based on testing using a particular hull form and engine.

Ease of Installation

In determining the rating criterion for ease of installation, testing and analysis determined that time of installation and installation difficulty (represented by the need to use a power tool) should be used to determine the rating. Figure 2 represents the rating criterion for ease of installation.

			Power tool required?		
			No	Yes	
		< 1hour	best	better	
Installation time					
		> 1 hour	better	good	

Figure 2 – Installation rating criterion

Effectiveness

Testing conducted at CRESE during Phase III explored three principle speeds: (1) planing – 15mph, (2) wake speed/trawling – 5mph, and (3) boarding – idle and reverse. Video was used to document the effectiveness of various commercially available propeller guards when presented with a simulated human limb located at various distances from the centerline of the engine. An analysis of the CRESE testing was conducted to determine the number of test sample strikes or lacerations during each speed presentation. This analysis is summarized in Figure 3. The percentages in Figure 3 are the percentage of lacerations per test. For instance, there was not a single strike with a cage guard at 5 mph while 54% of the 5 mph runs resulted in strikes for the ring guard.

	Speed			
	BOARDING		**WAKE ZONE/TRAWLING**	**PLANING**
Guard	**rev**	**0**	**5**	**15**
Cage	0%	0%	0%	0%
Concentric	71%	30%	0%	20%
Ring	90%	75%	54%	54%
UNGUARDED	100%	50%	40%	13%

Figure 3 – CRESE testing summary

Using the CRESE testing analysis, a rating criterion was established for the effectiveness of a propeller guard in mitigating propeller strikes. The ratings are presented in Figure 4.

	Speed			
Guard	BOARDING		WAKE ZONE/TRAWLING 5	PLANING 15
Cage	best		best	blunt force
Concentric	better		best	blunt force
Ring	limited		limited	blunt force

Figure 4 – Effectiveness rating criterion

The use of the word "limited" was thought to be a better choice than "good", as the use of the word "good" might imply no injury potential. CRESE testing indicated that the severity of injury was reduced in certain instances, although not eliminated. Limited would be defined as some degree of protection was provided in some but not all cases.

The analysis revealed that although the CRESE testing showed blunt force trauma for speeds of 15mph for all the guards that were tested, this result was not a disqualifying factor in choosing a propeller guard. In other words, merely because blunt force trauma was exhibited, the partial protection provided at lower speeds could not be discounted. As an analog, a boat owner may value the limited protection of a guard during a boarding scenario as an effective means to mitigate propeller strikes and accept the potential for blunt force trauma at greater speeds. Therefore, based on the CRESE testing, it was agreed that for speeds of 15mph, the rating would be indicated "blunt force trauma".

Conclusion

The potential means to mitigate the risk of injury from accidental contact with boat propellers has been studied by the U. S. Coast Guard since as early as 1988. While no universal solutions exists for this problem, propeller guards have been shown to offer limited protection under certain conditions with particular hull types and engine combinations and are one method of mitigating this risk of injury.

An evaluative matrix can assist boat and engine manufacturers with a workable system to evaluate propeller guards. This study offers a means to create such a matrix and describes specific steps to be taken when evaluating propeller guards.

Other mitigation methods should be studied to extend the opportunity of mitigating injury from propeller strikes. These methods can include training, the use of alert technology, and even modifications to boat layout such as the location of boarding ladders.

Appendix A

Propeller Guard Performance Test Protocol

Propeller Guard System Evaluation

Authors: Richard Akers & Clifford A. Goudey

Date: 01/02/2009

Scope:

This protocol is designed to evaluate the essential safety consequences of installing a propeller guard on an outboard or sterndrive powered boat. This protocol is not intended to apply to other types of propulsion systems. The term “propeller guard” refers to rings, cages, nozzles, shrouds, fins and other devices intended to reduce the likelihood of unintended contact with the propeller.

1 Procedures

Notes On Testing Devices: As with performance testing of any small boat, caution should be exercised in the conduct of all test procedures with and without propeller guards installed. Certain boats and certain boat and outboard/sterndrive combinations can exhibit erratic behavior, particularly at higher speeds. Tests should be performed starting at the lowest RPM setting and working incrementally up from there. This rule is especially important when changing outboard/sterndrive or outdrive trim settings - always return to the lowest RPM setting and proceed up the sequence. The helmsman should not continue with a test sequence if a dangerous condition is noted. In all cases, merely abort the test and note the reason.

In the test procedures below, a single outboard/sterndrive is assumed, though these procedures are applicable to boats with more than one outboard/sterndrive. When testing boats with multiple outboard/sterndrives the following assumptions apply:

1. The outboard/sterndrives are identical in horsepower, propeller diameter and pitch, and either with or without identical guards installed
2. The test RPM should be identical for each outboard/sterndrive.
3. The steering alignment of the outboard/sterndrives is parallel over its full range. Alternatively, the steering alignment of the outboard/sterndrives should be set according to the manufacturer’s specifications.
4. The trim settings of all outboard/sterndrives are identical.

1.1 Preparation and Test Conditions

1.1.1 Personnel:

To execute the testing described in this document, a minimum of two people must be in the boat. This team may at their discretion choose to add personnel to the boat, as long as the same personnel are present for the entire series of testing.

Helm – This person must operate the boat and make the appropriate decisions to continue or discontinue test runs based on his or her observations and past experience. The helm operator should have a minimum of 100 hours experience driving similarly configured and powered boats.

Technician – This person will be directing the test procedure and instructing the boat operation to synchronize the maneuvers with the data logging process. This person must be able to operate the sensor and data logging systems and also verify that data has been recorded.

1.1.2 Boat Condition:

These tests are comparison tests, so the absolute loading condition of the boat is not as critical as when the absolute performance of a boat is being determined. The crucial point is repeatability and a weight tolerance within 1% of gross boat weight should be maintained. The following aspects of the boat should be considered:

Fuel Tank(s) – There must be an accurate way of measuring the fuel on board. The same amount of fuel must be aboard at the beginning of each series of tests. Logically this should be done coincident with the addition, removal, or changing of a propeller guard. Document the method of determination.

Capacity – The boat should not be overloaded or in its lightest condition. Since identifying safety issues is one of the motivations for the development of this protocol, these are less likely to be revealed as the boat is made heavier. Therefore, the minimum complement needed to perform the tests (two persons) is the preferred loading. More important is the consistency of loading and placement among the six test conditions. Document the load and its positioning.

Water Tanks/Live Wells/Bilge – These items should be empty.

Canvas/Covers/incidentals – Items such as Bimini tops, fire extinguishers, fish finders, anchors, dock lines, fenders etc. shall be in their normal positions for an underway condition, and those positions shall be held consistent throughout the testing series.

If the boat is fitted with trim tabs that are not required for normal operation, they should remain in the up (unused) position for all tests. If a boat requires trim tabs for acceptable performance (e.g. planning) then that position shall be used throughout the test and documented in such a way that a future test could achieve the same position.

1.1.3 Propulsion Equipment:

Outboard/Sterndrive Mounting Height – The boat manufacturer's recommendations shall determine the vertical position for mounting the outboard outboard/sterndrive. All tests shall be conducted in that position.

Boat bottom, outboard/sterndrive, and propeller shall be clean and in a like-new condition.

1.1.4 Propeller:

The propeller shall be chosen such that the outboard/sterndrive is operating as close as possible to the middle of its operating range as specified by the outboard/sterndrive manufacturer. The propeller shall remain the same for each test. If it is desirable to install a propeller with a different pitch and/or diameter, the complete series of tests shall be performed with that change, both with and without a propeller guard installed.

1.1.5 Console Indicators:

RPM – The boat should be equipped with a tachometer for each outboard/sterndrive. The tachometer should have an accuracy of +/- 100 RPM and a repeatability of +/- 10 RPM. The tachometer should be in clear view of the helmsman and of a sufficient size for easy reading. If the tachometer accuracy is suspect it should be calibrated or replaced.

Outboard / Sterndrive Trim Indicator – A control panel remote trim indicator is convenient but not necessary for these tests. If present, the outboard or sterndrive trim controls and indicators shall be calibrated by measuring the angle between the propeller shaft (usually also the anti-ventilation plate) and the keel line of the boat. An accuracy of +/- 1˚ is required as indicated in Table 2. The keel line is the normally straight run of the bottom of the lowest portion of the hull over the stern-most half of the boat.

- A "default" trim setting would have the propeller shaft parallel to the keel line.
- An "in" trim setting has the lower unit pulled in toward the transom 6˚ from default, directing the outboard/sterndrive thrust down. If the outboard / outdrive trim system hits a built-in stop before reaching 6˚ in from "default", then the stop will determine the "in" trim setting
- An "out" condition has the lower unit pushed out 6˚ from the "default" condition, directing the outboard/sterndrive thrust upwards.

In determining these trim settings, measure the angular difference between the keel line and the propeller shaft in degrees. The use of an electronic level or a dial angle indicator is suggested. In the case of boats with multiple engines, the trim indicators shall be calibrated on each outboard or sterndrive.

If the boat is not equipped with a trim indicator for each outboard or sterndrive, then they can be adjusted manually prior to each test. Precise visual markings may be used to provide a repeatable trim position. Alternatively, suitably sized gage blocks can be fabricated in plastic or wood to act as stops to ensure the "in", "out", and "default" conditions are consistent throughout the test series.

1.2 Safety:

The following safety equipment is required while performing these tests:

1. USCG-approved PFD's are to be worn at all times during the tests.
2. An approved emergency lanyard stop switch is to be used at all times.
3. VHF radio communications to a manned shore station.

4. Safety equipment normally required for the boat's operation, e.g. flares, horn, fire extinguisher(s), etc.

2 Tests

2.1 Test Conditions:

1. Testing shall be conducted on calm water (wave or wake height <6”) with the wind speed below 10 MPH.
2. The wind speed, direction and the wave conditions shall be recorded.
3. The current should not exceed 0.25 MPH measured by GPS or other means.
4. The procedures in the following sections are executed six times, over a range of three propulsion system trim settings, and with and without the propeller guard system installed.

	Propeller Guard	
Propulsion Trim Setting	**Not Installed**	**Installed**
Trim Setting 1 (“In”)	Test 1	Test 4
Trim Setting 2 (“Default”)	Test 2	Test 5
Trim Setting 3 (“Out”)	Test 3	Test 6

Table 1. Test Conditions.

2.1.2 Measurement Accuracy:

Each test has a section entitled "Quantitative Results" in which a set of measurements is described. Table 2 lists the types of measurements that will be collected during these tests and the required accuracy of each measurement. Not all measurements are required for every test. Refer to individual test descriptions to see which measurements are required.

In Table 2 there is a column labeled "Suggested Sensor." The specific sensors noted in that column are not required by the protocol. It is up to the test technician to choose test equipment that can take measurements of parameters in the desired units with the desired accuracy and sample rate.

2.2 Speed vs. RPM Test:

This is a straight-line speed test used to quantify any change in speed as a result of adding a propeller guard.

<u>Preparation and condition:</u>

The boat shall be prepared as above.

Procedure:

5. With the outboard/sterndrive in forward, head directly into the wind at idle RPM. Once the speed has stabilized, note the RPM, the speed, and the fuel flow.
6. Increase outboard/sterndrive RPM to the first integer multiple of 500 RPM, achieve stabilization and again, note RPM, the speed, and the fuel flow.
7. Repeat Step 2 in 500-RPM increments until the outboard/sterndrive reaches maximum RPM. Run a final test at maximum RPM.
8. If the wind speed is greater than 5 MPH, repeat Steps 1, 2 and 3 heading downwind.

Measurements:

- Outboard/sterndrive RPM (noted for each increment).
- Boat speed (a displayed value from the differential GPS display).
- Fuel consumption rate (displayed or logged values from the test instrumentation).
- Zero-speed pitch angle of boat (displayed or logged values from the test instrumentation, taken at the beginning of the test).
- Pitch angle at each RPM.

Table 2. Protocol parameters to be measured

Parameter	Desired Units	Digitally Logged	Suggested Sensor	Desired Accuracy	Max. Time between Samples
Speed	MPH	Yes	Differential GPS	+/- 0.25 MPH	1 second
Outboard / sterndrive speed	RPM	No	Tachometer	+/- 10 RPM	N.A.
Acceleration	Gs	Yes	Accelerometers	+/- 0.01 G	0.1 seconds (with 10Hz, 2nd order low-pass filter)
Turning radius	Feet	Yes	Tracking GPS	+/- 8 inches	Post processing based on 1-second position track
Pitch	Degrees	Yes	3-Axis Inclinometer	+/- 2 degrees	0.1 seconds
Yaw	Degrees	Yes	3-Axis Inclinometer	+/- 2 degrees	0.1 seconds

Parameter	Desired Units	Digitally Logged	Suggested Sensor	Desired Accuracy	Max. Time between Samples
Roll	Degrees	Yes	3-Axis Inclinometer	+/- 2 degrees	0.1 seconds
Steering angle	Degrees	Yes	Angle sensor	+/- 1 degrees	0.1 seconds
Steering torque	Foot pounds	Yes	Strain gage load cell	+/- 1% full scale	0.1 seconds (with 10Hz, 2nd order low-pass filter)
Outboard / sterndrive Trim	Degrees	No	Protractor, digital level or dial angle indicator	+/- 1 degrees	N/A
Fuel consumption	GPM	Yes	Fuel flow meter	+/- 1% full scale	1 second
Tow line tension	Pounds	Yes	Strain gage load cell	+/- 1% full scale	0.1 seconds (with 10Hz, 2nd order low-pass filter)

Quantitative Results:

The speed during each test condition is manually recorded based on the GPS displayed speed value or calculated during post processing by averaging a steady-state portion of the recorded data or based the recorded position data using distance traveled divided by time.

The fuel consumption rate under each test condition is calculated during post processing by averaging a steady-state portion of the recorded fuel flow values.

Static pitch angle under each test condition is calculated during post processing from a steady-state portion of the recorded pitch values. The zero-speed pitch is subtracted from each static pitch angle so as to compensate for the slight change in bow-up moment by adding a propeller guard mechanism.

For each parameter, the performance metric is the percent difference between the results with the propeller guard compared to without the propeller guard. A convenient way of portraying the speed vs. RPM results for a specific trim setting is to plot the results as shown in Figure 1.

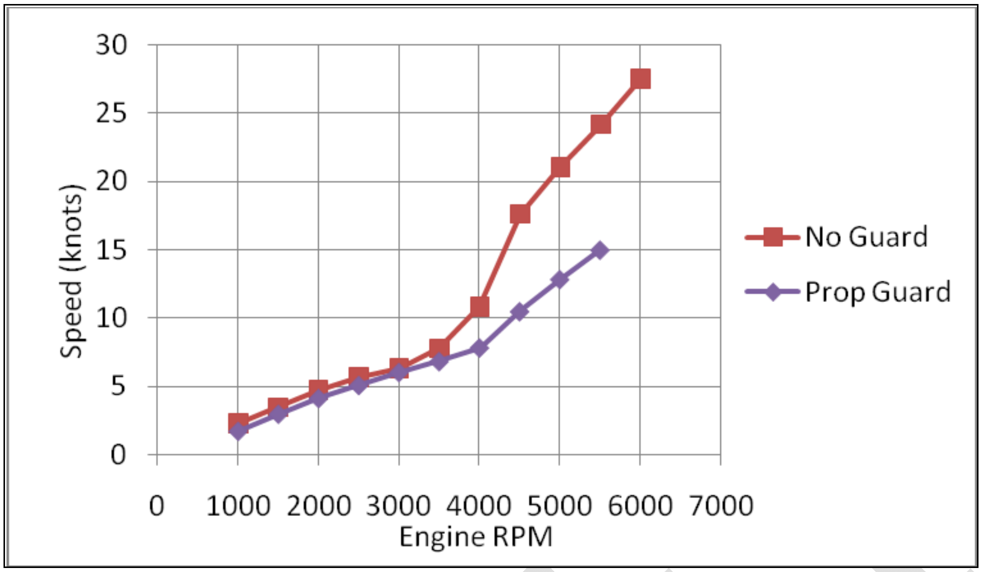

Figure 1. Sample plot of speed vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

A convenient way of portraying the pitch vs. RPM is to plot the results as shown in Figure 2. Plotting Fuel Usage/Second vs. RPM, as shown in Figure 3, can portray fuel consumption.

In addition to assessing the safety implications of a propeller guard installation, an important measure of boat performance is speed vs. power. In the absence of an outboard/sterndrive torque measurement, a useful surrogate for power is a combination of RPM and fuel consumption.

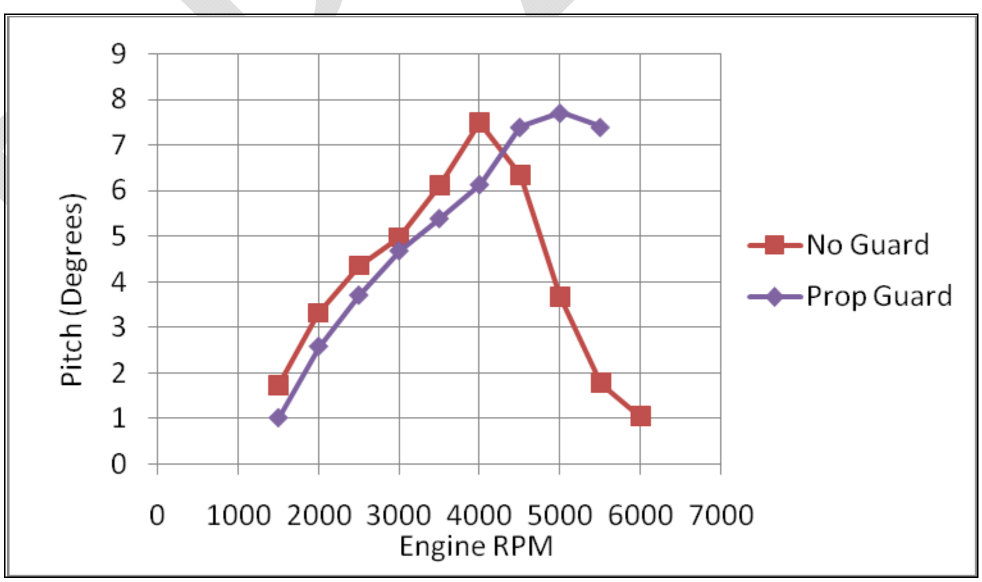

Figure 2. Sample plot of pitch vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

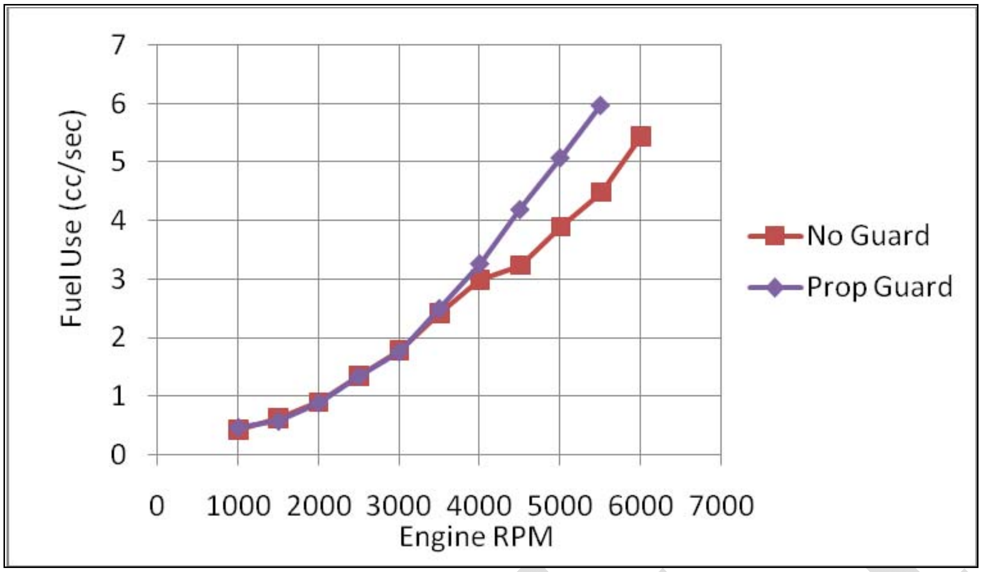

Figure 3. Sample plot of fuel consumption vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default".

In addition, fuel efficiency is an important measure of boat performance. Therefore, the data gathered from this test sequence can be combined to reveal the fuel consumption implications of operating with or without a propeller guard. For each RPM setting, the speed and the fuel consumption data should be combined to yield nautical miles per gallon for each test condition by using formula 1.

$$NMPG = \frac{MPH}{GPM \times 60} \tag{1}$$

This result can be plotted to reveal the fuel efficiency trend over the range of RPM tested as shown in Figure 4.

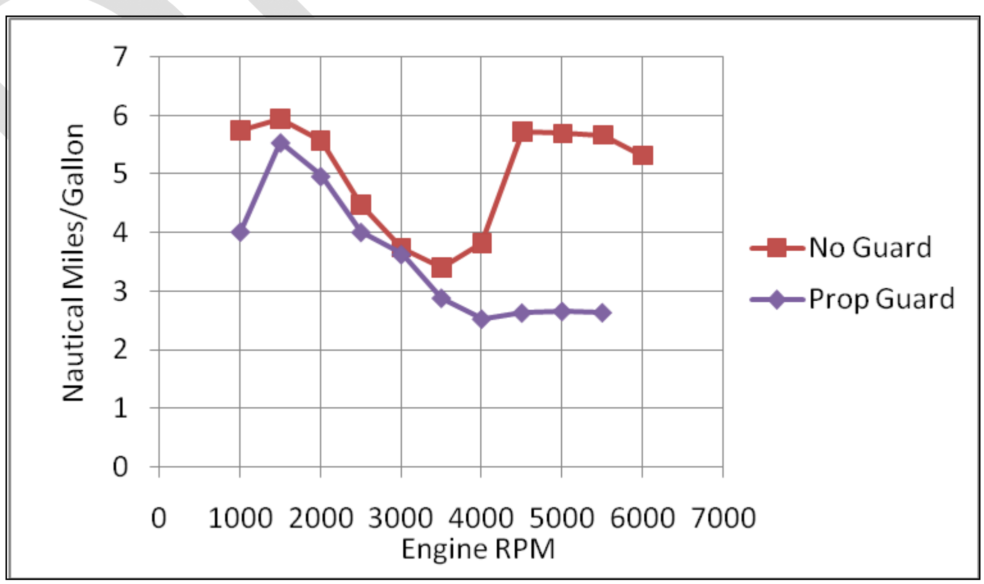

Figure 4. Sample plot of fuel efficiency vs. RPM, both with and without a propeller guard, outboard/sterndrive trim "default."

The summary metrics for the Speed vs. RPM tests are:

- The average of the percent differences in speed over the full range of RPM settings.
- The percent difference between top speeds with and without the propeller guard.
- The average of the percent differences in fuel consumption over the full range of RPM settings.
- The average of the percent differences in nautical miles per gallon over the full range of RPM settings.
- The percent difference in maximum pitch angle over the full range of RPM settings.

2.3 Acceleration/Deceleration:

This straight-line test is used to quantify any change in acceleration or deceleration as a result of adding a propeller guard. In addition to pure acceleration measurements, we are also interested in the pitch angle the boat assumes during acceleration or deceleration as it has implications on the forward visibility from the helm. These tests are conducted from a standing start, accelerating to top speed in all test conditions. However, in determining the acceleration implications of an installed propeller we compare only the data from the comparable portions of the two conditions.

Preparation and condition:

The boat shall be prepared as described in section 1.1.2 above.

Procedure:

1. Advance the throttle(s) full-forward position to the throttle stop in less than 1/2 second. Accelerate until boat reaches top speed (speed stays within 0.5 MPH for at least 2 sec.).
2. Reduce the throttle(s) to an idle position in less than 1/2 second. Decelerate until the speed of the vessel drops below 1.0 knot.
3. Repeat Steps 1 and 2, on a reverse course.

Measurements:

- Engine RPM at beginning and end of run and at top speed (noted for each increment).
- Boat speed (displayed value from the differential GPS display).
- Acceleration in forward direction.
- Time to reach specified boat speed (determined in post processing from the GPS position data).
- Pitch angle of boat (logged values from the test instrumentation).

Quantitative Results:

Top speed is determined from displayed GPS speed for each trim setting, with and without the propeller guard. A sample plot of top speed is shown in Figure 5.

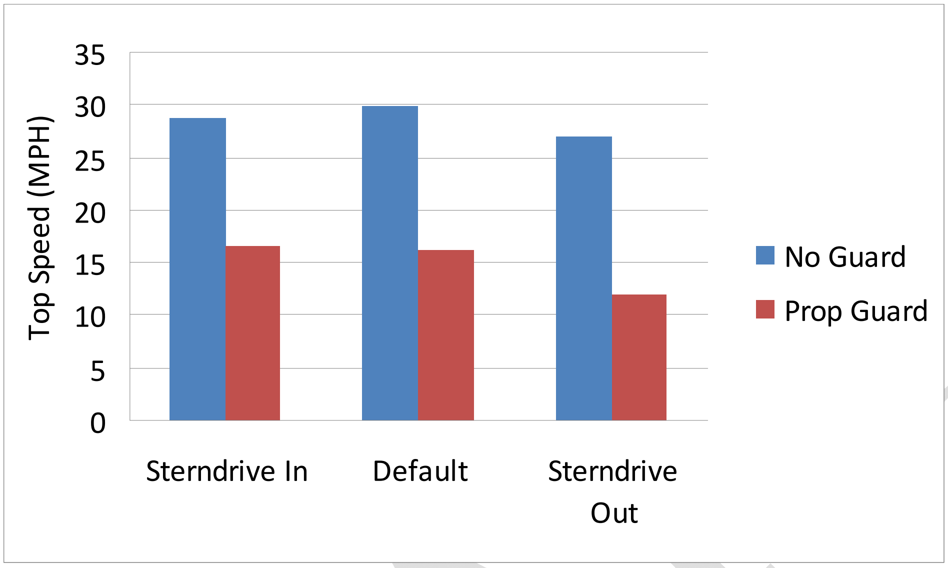

Figure 5. Top speed versus trim conditions. The "test speed" for each trim setting is 90% of the top speed, both with and without a propeller guard.

The "test speed" for each trim setting will be the slower boat's top speed for that trim setting. The "test speed" value determined here will be used in subsequent analysis.

A convenient way of portraying the test speed for all trim setting is plotting the times in a bar graph as shown in Figure 6. The percent difference in time with and without the propeller guard is used as a metric for each trim setting.

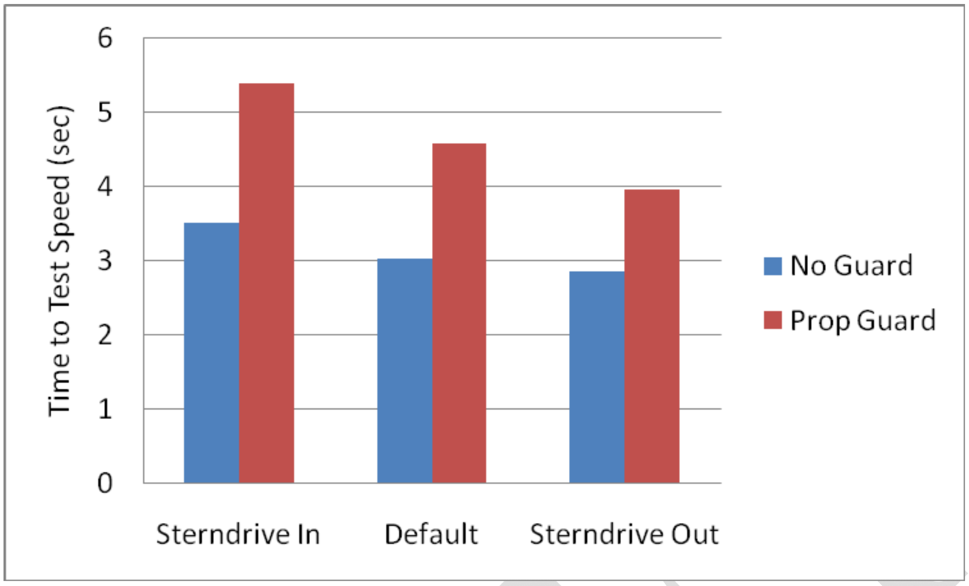

Figure 6. Sample plot of time to "test speed" for all trim settings, both with and without a propeller guard.

A convenient way of portraying the pitch results is a plot of pitch vs. time, with the average and maximum noted as in Figure 7.

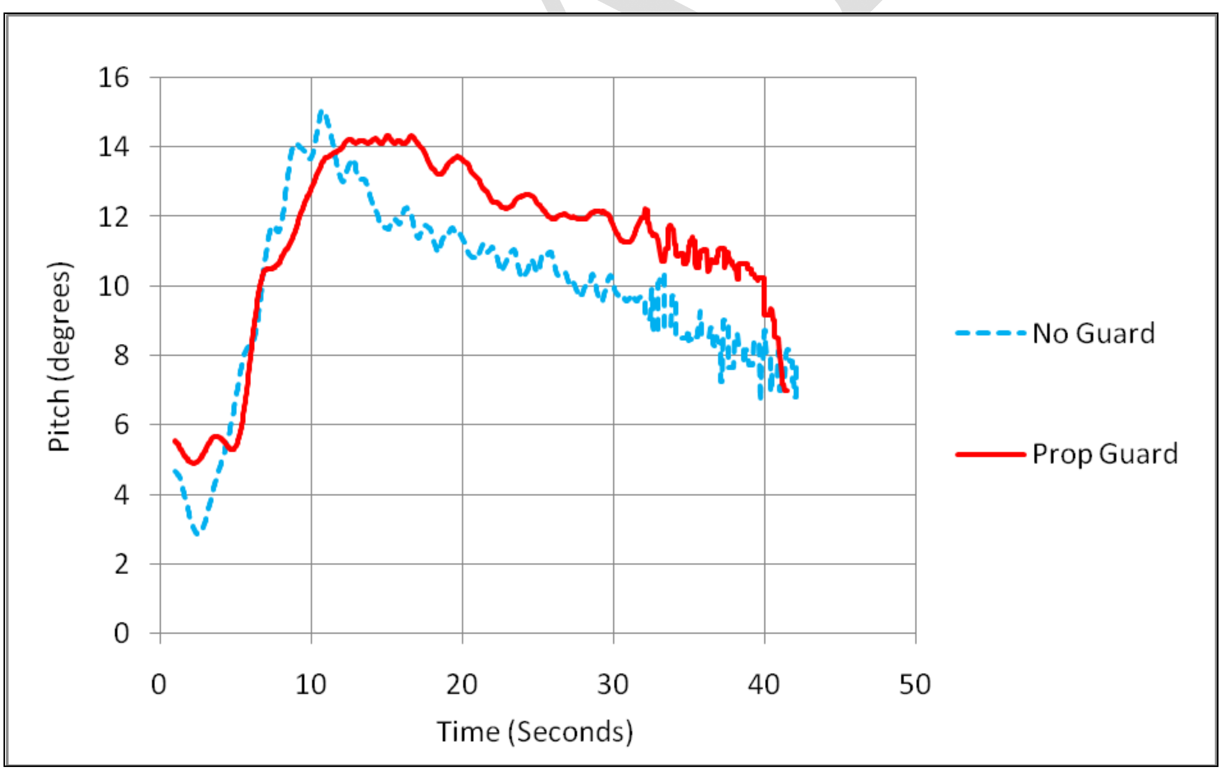

Figure 7. Sample plot of pitch angle, both with and without a propeller guard, for "default" trim.

The summary metrics for the Acceleration/Deceleration tests are:

- The time to accelerate from zero to test speed is determined for each test condition.
- The distance to stop shall also be measured and compared between the two boat conditions.
- The acceleration data collected under each test condition is averaged from the start of the run to the test speed. The percent difference in average acceleration with and without the propeller guard is used as a metric for each trim setting.
- The maximum pitch for each test condition is extracted from the pitch angle data. The percent difference in maximum pitch with and without a propeller guard is a metric for this parameter.
- To determine the broader impacts of a propeller guard on pitch angle under each test condition the values are averaged from the start of the run to the test speed.

2.4 Bollard Test:

This test measures the static thrust delivered by the outboard/sterndrive at zero speed. This corresponds to the initial thrust available for acceleration and what is available to pull a skier out of the water. This test is done only for one outboard/sterndrive trim setting where the propeller is parallel to the boat's keel line, the "default" trim position.

To minimize shallow water effects, this test should be conducted in depths that exceed the smaller of 1/2 boat length or 10 feet. The current should be less than 0.5 MPH. The wind speed should be less than 10 MPH.

A towing line of adequate strength should be used in this test. For safety sake, the line should have a breaking strength that exceeds the larger of:

- Twice the weight of the vessel under test, or
- Twice the product of the total installed outboard/sterndrive horsepower times “30 lb. per advertised horsepower.”

For example, consider vessel weighing 3,500 lb. equipped with an outboard/sterndrive rated at 350 BHP. The towing line should have a rating above the larger of 2 x 3,500 lb = 7,000 lb, or 30 lb/HP x 350 BHP = 11,500 lb. In other words, the towing line rating should exceed 23,000 lb.

In addition to adequate strength, a towline with a minimal amount of stretch is preferred to prevent surging during the tests. This can be met in several ways including; 1) oversized line to minimize fiber stress, 2) parallel-strand construction to minimize stretch due to rope geometry, and 3) the selection of line made of a high-modulus fiber. A further preference is a towline that floats to keep it in view during the test and to reduce the risk of propeller entanglement or snagging on debris on the bottom.

Two options are recommended; 1) a double-braid line with a parallel Spectra® or dyneema core, or 2) a 5-times oversized combination of polyethylene or polypropylene with polyester. Suitable commercial products include Sampson Rope’s Amsteel Dyneema Single Braid, New

England Ropes’ SpecTwelve Spectra Single Braid Line or EnduraBraid Dyneema Double Braid, or Spectra® 12-Strand by Pelican Rope Works.

Depending on the configuration of the test boat tow points, a means of controlling the yaw and the sideways movements of the boat may be required such as a towing bridle with equal legs that are at least half the length of the boat or lines port and starboard to fixed objects or pre-positioned anchors. Care is needed to keep these control lines perpendicular to the bollard test direction to prevent their influence on test measurements.

Preparation:

A towing line should be chosen that is between 4 and 8 times the length of the test vessel. The line should have proper spliced termination at each end to preserve its strength. The line should be attached to the test boat using towing fittings supplied by the manufacturer for towing and should be selected to meet the above requirements regarding tow line strength. A towing bridle may be used to distribute the load to two tow points and assist in controlling yaw. The height of any tow point above the resting waterline should not exceed 25% of the boat's maximum beam. If there is any doubt regarding the adequacy of the test boat attachment point(s), a suitable attachment to the lower unit of the outboard/sterndrive should be provided.

The fixed end of the towing line should be secured to a location on the shore or on a pier that can withstand the above-specified loads. The line from the test vessel to the load should be kept as level as possible by matching the heights of the two attachment points. Do not use a mooring the float that could be pulled under. Do not use a USCG navigation aid.

Procedure:

1. Set the outboard/sterndrive speed to idle RPM in gear. Once the boat position has steadied, increase the RPM setting to the first integer multiple of 500 RPM.
2. After the boat has steadied, holding the RPM setting for approximately 10 seconds, then gradually increase the throttle setting to the next integer multiple of 500 RPM.
3. Repeat Step 2 until maximum RPM is reached.

Measurements:

- Outboard/sterndrive RPM noted for each increment.
- Tension in the towing line.

Quantitative Results:

The bollard test data both with and without the propeller guard is averaged for each RPM setting. The percent difference in average bollard pull with and without the propeller guard is used as a metric for each RPM setting. A summary result for this test is the average of the percent differences over the full RPM range. If a test condition does not allow the attainment of certain RPM settings, those percent differences are not available for inclusion in the summary result.

It is useful to plot the data from the bollard test to reveal the effect of the propeller guard as shown in Figure 8. In this figure, towline tension is plotted vs. time. The RPM increments should be apparent if adequate field notes are recorded.

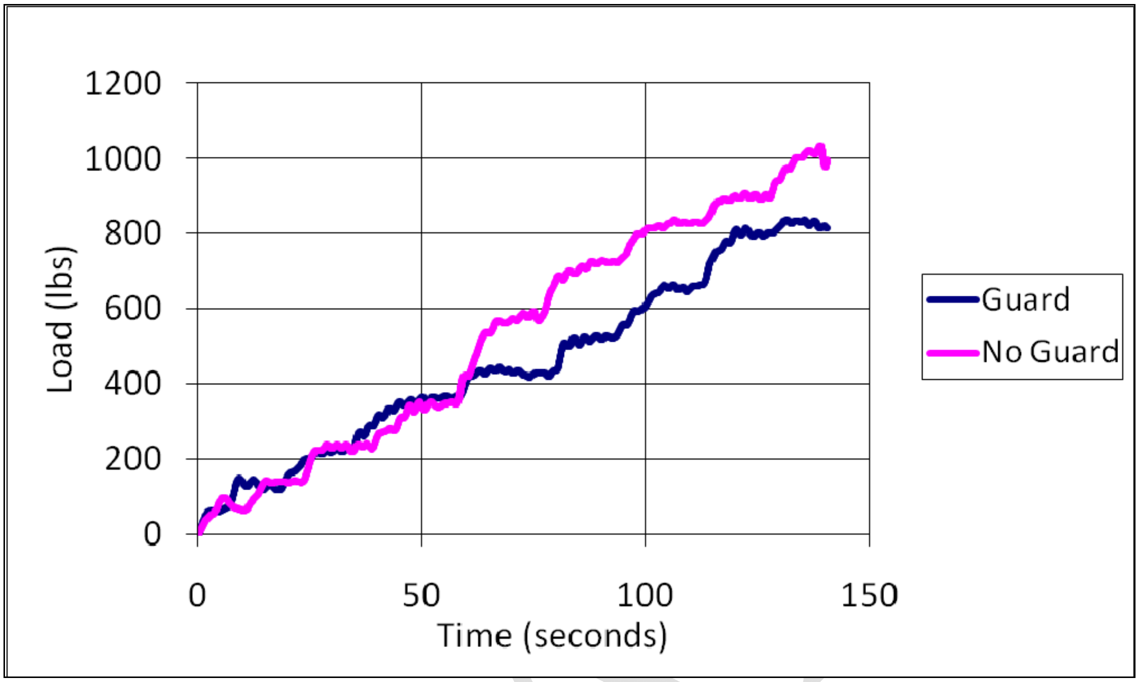

Figure 8. Sample plot of bollard pull with and without a propeller guard, for "default" trim in 500-RPM steps.

2.5 Maneuverability Tests:

Cautionary Note: These series of tests often discover off-design characteristics and/or dangerous conditions before, during and after maneuvering. Care must be taken to gradually increase speed and execute the maneuvers at multiple lower speeds in order to gain a feel for the behavior. Even with extensive low-speed testing, higher speeds may result in unexpected and spontaneous reactions either with or without the device installed. Use caution and experience to determine when or if the testing should be discontinued.

The maneuverability test provides a performance comparison as the boat follows a serpentine path resulting from alternating port and starboard helm commands. The test measures the ability of the boat to turn in response to specified helm inputs. The current should be less than 0.25 MPH. The wind should be less than 10 MPH.

Three maneuverability test speeds are selected to represent low speed, medium speed and high-speed operation. These should be selected based on the results from straight-line speed vs. RPM tests described above. The high-speed operation should be selected to be the "test speed" defined in section 2.3 above. The low speed should correspond to a "no-wake" speed that provides positive steering. The medium speed should be the average of the high and low speeds. The maneuverability tests are intended to compare the maneuverability at these three speed settings, not necessarily at equal RPM settings.

NOTE: The medium speed is the average between high and low speeds, and this may cause a problem if it happens to fall in the hump speed range. It is difficult to operate a planing hull boat so as to stay at the hump speed, as the boat will tend to speed up or slow down to avoid this speed. In this case the medium speed should be increased slightly from the average of the high and low speeds so as to achieve low-speed planing operation.

For each selected speed setting identify a corresponding RPM setting for each trim setting and with and without a propeller guard. That RPM setting is used throughout each serpentine run, though the speed will likely change during the tests. The steering position sensor is recorded during these tests for the purpose of verifying that the helm commands were properly executed within the specified time limit. If low test speeds result in the crossing of the test boat's earlier wake, disregard any roll data from that run.

Preparation:

The boat is prepared as described in section 1.1.2 above.

Procedure:

8. Set the outboard/sterndrive RPM for the first low-speed setting. Steer a course in the intended direction of the test sequence. Identify the helm position that provides a constant heading. Mark that helm position with a piece of tape or other means. Note that this "amidships" mark is likely to change at different outboard/sterndrive speeds and should be determined for each speed setting.
9. Once at a steady speed, turn the steering wheel 360˚ to starboard or the limit of rotation, which ever is less. Execute this helm command in less than 1 second.
10. Hold the wheel at that position until the boat has turned 90° relative to its original heading. It may be necessary to adjust the throttle setting during the turn in order to maintain the specified outboard/sterndrive RPM.
11. Once at 90˚ from the original course quickly turn the wheel to port 720˚ (two full turns) or until the limit of rotation is reached, whichever is less. This rotation of the wheel should be accomplished in less than 2 second.
12. Complete a 180˚ course change and once at 90˚ from the original course quickly turn again.
13. Repeat steps 4 and 5 until the boat has gone through six complete half-turns. During the entire series of turns, adjust the throttle to maintain the specified outboard/sterndrive RPM. A diagram of the desired track is presented in Figure 9.
14. Document any anomalies such as propeller ventilation during turns. If any instabilities or difficulty in controlling the boat is experienced, the test should be aborted, and the anomalies recorded.

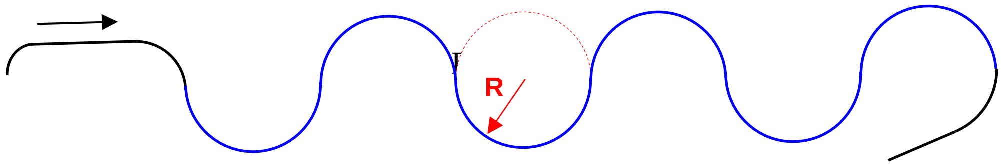

Figure 9. A diagram of the desired track like for the maneuvering test.

Measurements:

- Pitch and roll angles. Use only the data recorded during the 180˚ turns (blue portion of Figure 9) and when the boat does not encounter its own wake.
- Speed and position from GPS.
- Steering Wheel torque. Use only the data recorded during the series of 180˚ turns.
- Outboard/sterndrive/lower unit deflection.

Quantitative Results:

Calculate the following metrics for each trim condition and speed:

- The extreme and the average of the port and starboard roll angles during the serpentine run.
- The maximum and the average of the port and starboard steering wheel torques during the serpentine run.
- Plot the track of the serpentine run and graphically determine the turning radius for each of the 180˚ turns (blue portion shown in Figure 9).
- The steering position for each of the turns and the time required to execute the helm shift. This is defined as the time from the start of the steering event to the finish of the steering event.

The steering position data should be reviewed to ensure that the helm positions during the 180˚ turns are held to within 1˚ of the prescribed position and that the helm is shifted to within the prescribed time constraints. The following metrics are used to compare the maneuverability performance.

- The percent difference in extreme port and starboard roll angle over the three turns.
- The percent difference in average port and starboard roll angle over the three turns.
- The percent difference in extreme port and starboard steering wheel torques over the three turns.
- The percent difference in average port and starboard steering wheel torques over the three turns.
- The percent difference in port and starboard turning radii averaged over the three turns.

Appendix 1: Discussion

Quantifying the performance of a small craft can be broken down into several components:

- Straight-line speed vs. power
- Straight-line acceleration vs. power
- Deceleration in neutral
- Maneuverability
- Ride quality
- Fuel consumption
- Off-design performance in the above categories

For the purposes of determining the performance consequences of a propeller guard, some of these parameters are more important than others. For example, ride quality changes from a guard installation is likely to be a secondary factor.

In the development of a reliable test protocol that can be generally applied to a range of boats and power units, it is important to minimize the significance of the operator's skill, strength, and nerve to both eliminate possible bias in the results and to provide repeatability.

A1 Defining Performance:

A1.1 Straight-line speed vs. power

The resistance of a boat is the force required to move it through the water at a given speed. This resistance will vary with load condition. Resistance of a complete "boat system" is a function of its hull form, propulsion system, and its propeller guard system if installed, and the interaction between the three. The resistance of a boat system determines its maximum speed and its fuel economy at a given speed. Common units of speed include knots, miles per hour, feet per second, and meters per second. Since a direct measure of power is difficult to obtain, outboard/sterndrive RPM and/or fuel flow rate is commonly used as its surrogate.

A1.2 Straight-line acceleration and deceleration

According to the USCG Navigation Rule 8 (f), "A vessel which, by any of these rules, is required not to impede the passage or safe passage of another vessel shall, when required by the circumstances of the case, take early action to allow sufficient sea room for the safe passage of the other vessel." From time to time it is necessary to accelerate to avoid collisions. In some cases sluggish acceleration would limit the ability of the operator to avoid a collision.

Small powerboats often decelerate much faster than they accelerate, and occupants of the vessel may experience deceleration as an uncomfortable, destabilizing jerk. If a small powerboat decelerates too quickly, occupants of the vessel may be thrown forward out of their seats, resulting in a dangerous situation. On the other hand, responsive deceleration can be important in avoiding collisions or allisions.

Deceleration is a measure of negative acceleration and technically is also expressed in terms of rate of change on speed. A more relevant measure from a boat performance perspective is the distance needed to come to a stop from various speeds.

The acceleration of a boat system is a function of the mass of the system and its speed vs. power characteristics, as described above. The term "acceleration" technically means a rate of change in speed (i.e. feet/sec/sec) but is typically measured in terms of elapsed time to a certain speed or over a specified distance. In general, it refers to performance from both a standing start and for intermediate increases in speed, up to and including full speed. Even more than speed vs. power, acceleration is sensitive to boat loading.

A1.3 Maneuverability

The maneuverability of a boat is its ability to turn in response to operator input. Good maneuverability is critical to the safe operation of a boat because the importance of avoiding fixed objects such as piers, floating objects such as swimmers, buoys or logs, and other boats.

The propeller/gearcase system in a powerboat provides the yaw moment that turns a boat. The actual track of the vessel depends on the shape of the hull, and on the interaction between the hull, propulsion system, appendages and a propeller guard if installed.

Since a propeller guard system may affect the flow of water around the propeller, gearcase and other movable surfaces, the turning moment and the effort required to produce it may change. In other words, the presence of a propeller guard system can affect the torque required to turn the steering wheel to a given angle.

A1.4 Ride quality

Ride quality, or sea keeping, is an important measure of a vessel's performance. Often ride quality is expressed in terms of RMS G-force and its dominant frequencies, as measured at specific locations aboard the boat. These forces are often expressed in terms of both speed and the wave conditions present. However, there are other factors related to ride quality that are independent of sea state. For example, some boats can experience resonant pitching (porpoising) even in calm water. Also, some craft exhibit aberrant behavior during certain maneuvers and these can have implications on comfort and safety.

A boat's sea keeping also can directly affect the controllability of the boat. Such factors as excessive pitch and roll can make proper steering difficult. Sea keeping has further implications on operator fatigue and concentration.

A1.5 Fuel consumption

Fuel consumption is an important measure of boat performance as it directly impacts its cost of operation and the impact of that use on the environment. Fuel consumption is commonly measured in terms of gallons used or gallons per hour (GPH). When the speed of the vessel is known, this consumption can be converted to nautical miles per gallon (NMPG).

A1.6 Off-design performance

The above measures are applicable to most boats over a wide range of passenger and cargo loading. However, there are other considerations that can come into play when the boat is attached to another movable or stationary object. A good example of this is towing another boat or hauling a water skier. As with free-running speed or acceleration, a propeller guard could have a performance impact under these “off-design” conditions.

Some elements of off-design situations can be assessed with a bollard test. This test, when combined with free-running performance, can begin to characterize the propulsion characteristics of a boat and outboard/sterndrive combination. Trends with and without a propeller guard should be readily apparent based on these two measures.

A2 Equipment and Sensors:

Our goal in the development of a test protocol is to provide a useful measure of the performance implications of a propeller guard on a given boat/propulsion unit combination. The worth of a test protocol is its repeatability and universality, independent of by whom or where the tests are performed. An important variable in boat performance is the operator. For this reason, it is important to have a prescriptive protocol that does not require judgment calls and is not influenced significantly by the skill or strength of the operator. For example, testing maneuverability by timing a run through a buoyed slalom could be more a measure of experience and reaction time than boat performance.

A second reason to minimize the possible significance of the operator is to reduce any real or perceived sources of bias. Beyond the prescriptive adherence to procedures, the operator does need to have the right to cease a test sequence when in his or her opinion dangerous conditions are or will be encountered.

In a test protocol, various conditions and settings can be either constant or variable for the duration of a test run. For example, helm position may change during a test run, whereas the outboard or outdrive trim angle may be kept constant during a run. While the sensor for both these parameters could be similar, one is a fixed setting that can be noted at the beginning of each run and stays invariant. In the interest of economy, these parameters that are constant are not instrumented, while the varying parameters are fitted with an appropriate sensor.

The goal of this protocol is to compare performance of test craft with and without propeller guards. While environmental conditions such as water temperature, salinity, and air temperature will make an absolute difference in results, these factors will make little difference in comparing the performance of boats with and without guards. That said, it is important that the two sets of tests with and without guards be performed under similar conditions of wind and sea state.

As will be explained below, the procedures for the tests provide ready opportunities for the non-logged parameters to be recorded at the beginning of each test sequence. Some parameters such as RPM are prescribed operator settings.

A2.1 GPS tracking and navigation

To provide the desired accuracy, a Trimble Pathfinder® ProXT™ GPS receiver was used that has an integrated SBAS receiver to provide sub-meter accuracy in real time. The data can be logged using Trimble's TerraSync™ software while post-processing is done with Trimble® GPS Pathfinder Office software based on data from nearby reference station data available over the Web. The self-contained unit needs clear access to the sky and was mounted on a six-foot mast mounted on the boat’s centerline close to the longitudinal center of the water plane.

The tracking mode is used to log all test runs and through post processing numerous measures of the boats performance can be derived. However, the unit can also display measurements directly for notation during the test sequence. For example, speed can be directly displayed and can be noted during the speed vs. RPM runs. By contrast, turning radii during the maneuvering tests require extensive post processing and graphical quantification in a CAD program.

A2.2 Outboard/sterndrive Speed

Most console-controlled boats have a tachometer and it is the most convenient approach to achieving prescribed power settings based on RPM. These gauges can be calibrated if there is any doubt as to their accuracy, however, since the primary interest is performance differences with and without the propeller guard, accuracy is less important than precision and repeatability. In our test protocol we typically call for RPM increments such as 1,000, 1,500, 2,000, 2,500, 3,000, etc. to the maximum RPM.

A2.3 Pitch, Roll, Yaw and Acceleration

The motions package we used is a Microstrain Inertia-Link®, a solid-state Inertial Measurement Unit (IMU) and Vertical Gyroscope. The Inertia-Link sensor measures acceleration in 3-axes and angular rate vectors in 3-axes. The sensor communicates to the data collection system by using a wireless link. At the data collection system end, a base-station transceiver plugs into a USB port. The Inertia-Link has a user adjustable data rate (1 to 250Hz) and sensor bandwidth (1 to 100Hz). The accelerometers in the Inertia-Link can be calibrated by rotating the unit into six different positions so that its three axes orient towards and away from the center of the earth. The difference in these two measurements is 2G.

A2.4 Gearcase/Rudder Angle

A Cherry AN101101 angular position sensor is used to measure the rudder angle, which is the angular position of the outboard or the sterndrive unit. This unit is housed in a waterproof case with the rotating magnet portion of the sensor linked mechanically to the outboard/sterndrive. Within the watertight case is a Microstrain V-Link® Wireless Voltage Node and a small battery pack to power both the sensor and the wireless transmitter. The position sensor generates a voltage proportional to angular position. This sensor must be calibrated for each boat on which it is installed. An angle measuring device or an over-sized protractor can be used for this purpose.

A2.5 Steering Torque

An instrumented steering wheel was developed, which mounts on a steering console and measured the steering torque being applied by the operator. This device provides the rigidity and strength needed, while providing precise measurements of torque. The design approach was to insert a needle bearing between the helm shaft and the wheel, and then prevent their relative rotation with a strain gauge load cell positioned between two arms – one to the shaft and one to the wheel. A 2,000-pound-capacity load cell was used and the arms were 3.5" long providing a torque capacity of 583 foot-pounds. Positioned in the steering wheel hub is a Microstrain SG-Link® Wireless Strain Node which provides the 10VDC excitation for the load cell. A small battery pack is mounted on one of the torque arms.

A2.6 Outboard/sterndrive Trim

The outboard/sterndrive or lower unit trim angle can have a significant effect on performance primarily by influencing the pitch angle of the boat. While many outboard/sterndrives have power tilt adjustments and many of those have console displays, this feature in not assumed to be universally available. Therefore, ease of trim setting cannot always be assured. In addition, including the dynamic positioning of trim angle can be a subjective process if one were to attempt to optimize trim during, say, an acceleration test. Therefore, trim angle is held constant during a test sequence.

To understand the significance of trim on boat performance with and without a propeller guard, three fixed setting were used in our test matrix, one defined as "default" where the propeller shaft is parallel to the keel line of the boat, "in" where the lower unit rotated 6˚ towards the transom, and the "out" position 6˚ out from the default position. Visual or gauge-block techniques can be used to achieve repeatable trim position during the tests.

A2.7 Fuel Flow

We selected a fuel flow meter from DEA Engineering Company to provide accurate instantaneous readings of flow. Their FMTD20 Nutating Microflow Meter provides flow rates up to 20 gallons per hour with an accuracy of 0.5% of the reading and a repeatability of 0.1% of the reading. The unit provides a pulse on the passage of 0.1 cc of fuel. By using a frequency to voltage converter, the resulting signal can be fed to a Microstrain V-Link® Wireless Voltage Node. To segregate gasoline from electrical components the flow meter is packed in one watertight case, and the frequency to voltage converter, V-link, and battery pack are all housed in a second watertight case.

A2.8 Towline Tension

To measure towline tension during bollard and towing tests we used a 3,000-pound-capacity strain gauge load cell. Again, this unit is protected in a watertight housing along with a Microstrain SG-Link® Wireless Strain Node and a small battery pack.

A2.9 Data Collection

<u>Hardware</u>:

Data must be collected, labeled and time-stamped. There should be a mechanism to enable or disable each sensor from a central location to fit the particular test. For example, there is no reason to collect towline tension data during a maneuvering test. The data is coming from sensors from different manufacturers and there is no off-the-shelf, integrated data collection system that can manage all of these sensors. It was decided to develop a mechanically robust data collection system that could meet the needs of the team. Such a system should have the following physical attributes:

- Rugged. The data collection system may be exposed to more than 10 G's in vertical acceleration.
- Water proof or at least water resistant.
- Sunlight readable display.
- Minimum operator interaction to begin recording data.
- Flexible. During the protocol development process the mix and type of sensors may change, and the system must be able to support these new sensors.
- Large data storage, fast processor. The data collection system will be running powerful software that can handle all of these sensors, plus the human interface and real-time data storage. The hardware must be fast enough to handle those requirements.

A number of systems were evaluated, including dedicated data collection systems, and ruggedized laptops. The protocol development team chose a Panasonic Toughbook CF-30 laptop as the data collection system. This laptop was configured to have 1GB of RAM, and 80GB hard drive, a 13.3" (non-touchscreen) sunlight-readable display, a wireless LAN for Internet access shoreside, and a CD-ROM combination drive. The Toughbook was configured with Windows XP Professional. This laptop is water resistant, and is readily available. It is equipped with an Intel® Centrino® Duo CPU and is fast enough to handle the data rate from the sensors.

<u>Software</u>:

A software development system is required that has the following attributes:

- Can be configured graphically, or with very high-level commands. No low-level programming should be required.
- Many / most manufacturers should support the software with drivers.
- Software development system should have history in the marketplace so that other developers outside the project will be familiar with it, and so that it is likely that the software will be available in the future.
- Development system should be able to distribute standalone, executable software to other laptops so that each new data collection system does not require a full software development license and installation.

The protocol development team chose the LabVIEW Professional Development System from National Instruments. This software has the following major attributes:

- Graphical development environment
- Tight integration with a range of measurement hardware and sensors. Software development kit available for MicroStrain wireless sensors.
- Rapid user interface development for displaying live data
- Extensive signal processing, analysis and math functionality
- Source code control integration for managing the development project
- Able to distribute runtime applications to other computers
- Support for Windows Vista/XP/2000

A data collection software application was developed with LabView to run on the Toughbook CF-30. The application graphical user interface (GUI) includes switches to enable and disable sensors, a real-time chart to monitor data, and a mechanism to save and timestamp each data file. The following figure shows the GUI or control panel tab of the data collection application developed with LabView.

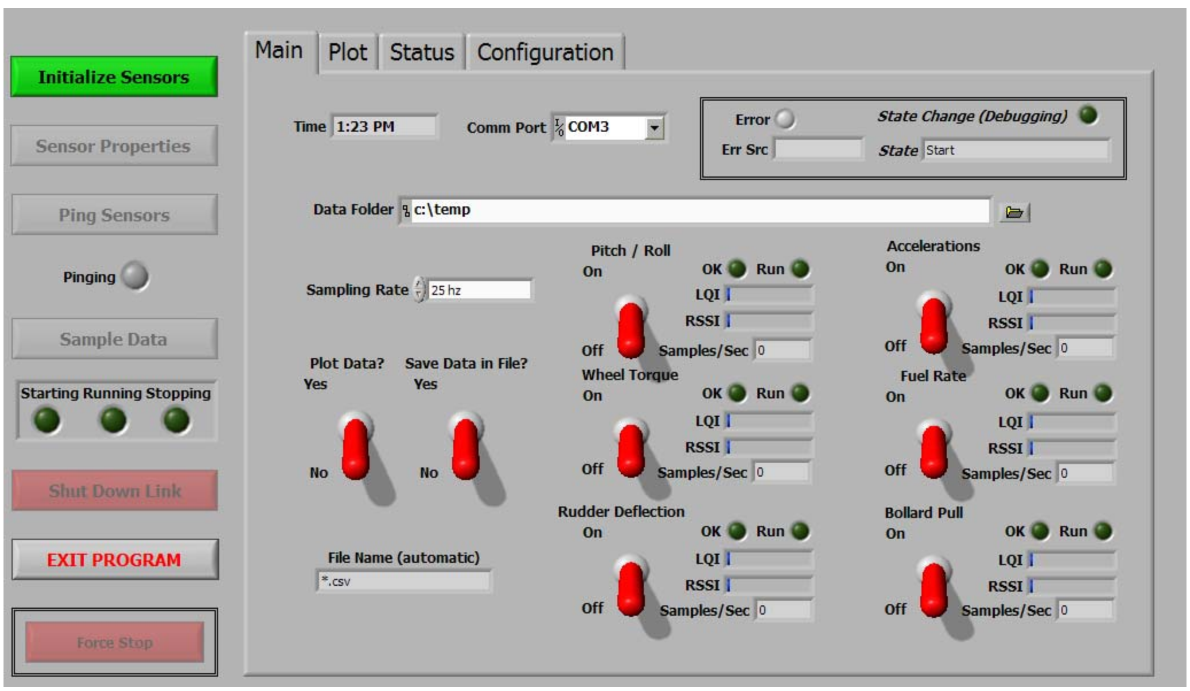

Figure 10. Sensor Data Collection Software Application.

Table of Contents

The Effectiveness of Guards in Mitigating Propeller Strikes

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March 1, 2012