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DP OPERATIONS SESSION

DP Bow Thruster Noise Remediation in ROGER REVELLE, AGOR-24

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Abstract

For Scripps Institution of Oceanography, represented by The Glosten Associates, a program was initiated to silence the bow thruster in the research vessel ROGER REVELLE, AGOR-24. The ship suffered habitability problems during long-term dynamic positioning (DP) operations. A ⅛ scale mockup of the ship's bow thruster, sea chest, guard grids and local hull surfaces was constructed for air tests. By measuring velocity distributions at the (absent) impeller location while separately drawing air through the mockup system at high velocity, it was demonstrated by calculation that the offending noise originated in unsteady cavitation of the impeller of the vertical-axis thruster. These and subsequent mock-up measurements were carried out at Offshore Model Basin, Escondido, CA. Several modifications to improve the flow were designed and evaluated in the mockup. Further, a modified impeller was designed on the basis of cavitation avoidance. The new impeller was designed-in-detail and manufactured by Bird-Johnson Company (now Rolls-Royce Naval Marine). This was installed along with several structural modifications of the thruster and sea chest, approved by the thruster manufacturer, at Southwest Marine, San Diego, during ship overhaul. Quantitative measurements of compartment levels of noise and vibration, and structural and water-borne noise were carried out to compare with pre-modification measurements. Results now indicate an absence of bow thruster cavitation noise in adjacent compartments during DP operations. Thrust performance was preserved.

Figure 1: R/V ROGER REVELLE, AGOR-24.

Introduction

R/V ROGER REVELLE, AGOR-24, is a modern oceanographic research vessel operated by Scripps Institution of Oceanography on behalf of the U. S. Navy. Built and acquired by Scripps in 1996, REVELLE displaces 3,350 tons, fully loaded, and has a length of 275 ft., beam of 52.5 ft. and full load draft of 17 ft. Powered by diesel-electric twin azimuthing propellers, she has a cruising speed of 12.5 kts., with an endurance range of 13,000 miles at 10 kts. With a crew of 22, REVELLE accommodates a scientific party of 37 persons.

The large size of her scientific party requires that some accommodations be located close to her powerful bow thruster. During long-term dynamic positioning (DP) operations, thruster noise interfered with sleep in these rooms.

The bow thruster is an Elliot White Gill model T3S-50, vertical shaft unit. The unit is rated at 10,000 kg thrust, absorbing 1062 kW at 542 RPM. It swings a 4-blade propeller (impeller) in its vertical

axis, 50 inch diameter duct bore. Thrust is azimuthally directed by a rotatable discharge deflector-louver at the keel. The thruster takes suction from a submerged sea chest compartment, Figure 2, fed though large gridded intakes that are symmetric, port and starboard. The thruster is located on centerline at frame 19.

Several of the authors had the advantage of a previous attempt to remedy the same problem in a sister ship, R/V ATLANTIS, AGOR-25, operated by Woods Hole Oceanographic Institution (WHOI). The origin of the problem was early identified as cavitation in the bow thruster propeller. This cavitation was responsible for both high and low frequency noise and vibration in the forward-located accommodations. Both waterborne and structureborne paths were deemed to play significant roles in the transmission of vibratory energy from the thruster interior to the effected spaces.

For ATLANTIS, a major effort was made to decouple the sound-energized water in the thruster sea chest from its bounding structure. To this end, the interior surfaces of the sea chest compartment were covered with a compliant, closed-cell foam-rubber decoupling material. To reduce internal transmission, the structure was extensively treated with vibration damping material. In addition, a less heroic effort was made to reduce the cavitation source strength by several means. These included enlarging the gridded intakes to reduce water velocities and pressure drops, adding grids to the thruster bell-mouth to break up suspected suction vortexes, increasing the lateral clearances between the thruster suction bell-mouth and adjacent web frames, and introducing air to the thruster intake to cushion the collapse of cavitation bubbles in the propeller.

The surface treatment has the advantage of working with constant effectiveness at any thrust level. It was recognized, however, that the treatment would be most effective at the higher frequencies and least effective at lower frequencies. In attacking the cavitation source, no structural modifications to the thruster were attempted – only removable add-ons.

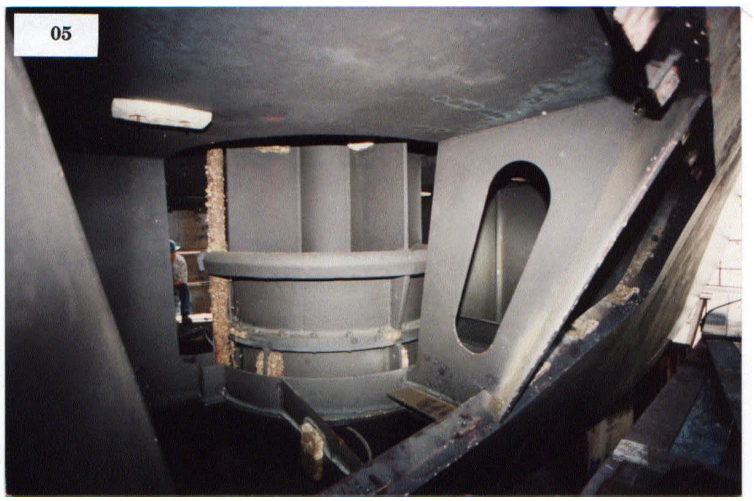


Figure 2: Thruster Sea Chest (ATLANTIS)

Upon completion and test it was found that the surface treatment and damping did work well – at the higher frequencies, Figure 3. Air injection had a smaller-than-hoped-for benefit, due to limited air supply. The bellmouth grids, intended to kill suction vortexes that were probably absent, probably made things worse by their wakes, and their removal recommended. Effects of intake and clearance enlargements were not resolvable from the noise measurements.

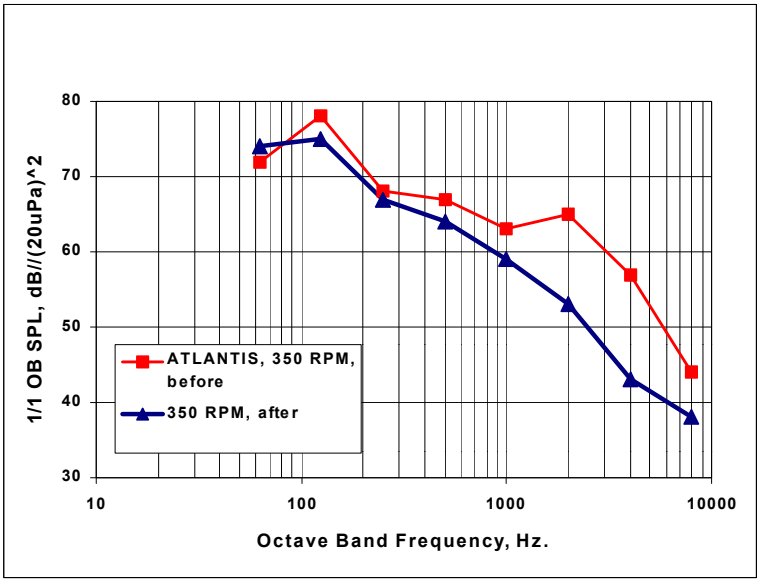


Figure 3: Room 2-22-2, Before and After SPLs, 350 RPM - ATLANTIS

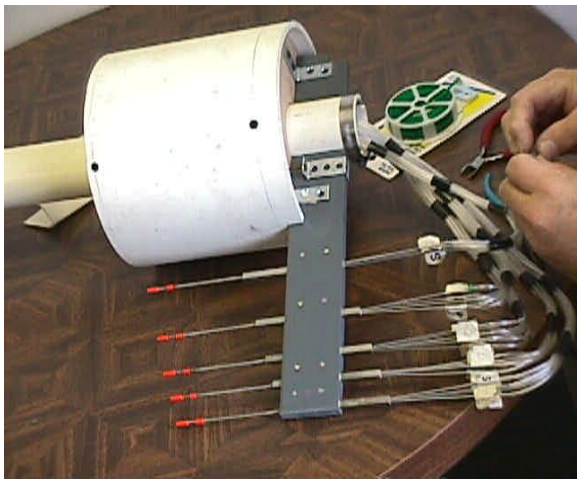
Diagnosis

A detailed mock-up model was constructed of the thruster duct, sea chest, and hull in the vicinity of fr. 19. The model was built at 48% scale because of the availability of 24" ID SonoTube to replicate the 50" thruster duct. The model was built inverted, that is, with keel up, as may be seen in Figure 4a. A tube-axial blower was fitted to take suction at the keel so as to draw air through the model thruster duct from the sea chest and through the gridded intakes in the hull. Construction was of fitted planks of ¼" plywood over beveled frames. The grid models were fabricated of PVC strip. The thruster bell mouth was replicated in Styrofoam, and plate structure in ½ plywood, Figure 4b. A rotatable rake of five, directional Pitot-static probes was installed, the probe tips located along the leading edge locus of the original thruster propeller, Figure 4c. Finally, the overhead of the sea chest compartment was replicated in transparent Plexiglass. A set of small holes in this plate allowed observers, lying underneath the mock-up, to insert slender dowels fitted with wool tufts to observe flow patterns.

The Pitot rake, was rotatable by hand to a number of angular positions. Each "hole" of the probe set was piped to an individual semiconductor pressure transducer. The output voltages of these transducers were sampled and recorded by the OMB data acquisition system on parallel channels. Averages were calculated over selected time intervals; typically 20 seconds in length. Absolute pressures were calculated for each by using no-flow zeros and through-system transducer calibrations of all channels. These pressure numbers were combined to calculate three components of absolute velocity at each position by applying calibration factors which had been measured for each of the Pitot probes.

(a)

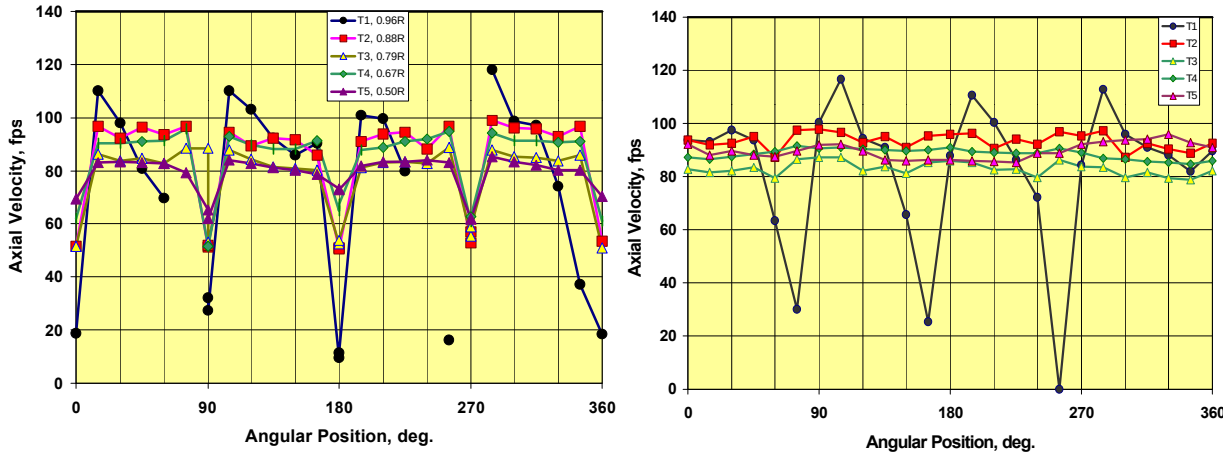
(b) “Sea Chest”



(c) Pitot Rake

Figure 4: Air Test Model

The first, baseline, velocity survey was carried out with the thruster and sea chest in the “as-built” configuration. The results showed strong wakes in the fore-and-aft and athwartships angular positions; corresponding to the four thick, radial plates, Figure 5a. Significant radial and tangential secondary flows were also evident, presumably associated with vorticity shed at the plate-bellmouth junctions.



(a) Baseline (b) Mod 1

Figure 5: Air Test Axial Velocity

The second survey, Mod 1, was carried out with all local structure removed. This was to determine just how clean the flow could be made and whether artifacts from the more distant obstructions were important, at all. The results showed very much more uniform flow except at the outermost radius, which was very close to the wall of the duct, Figure 5b. The velocity deficit was removed at 0 degrees (forward) but strong dips persisted at the other three cardinal points at this radius.

In order to quantify the value of these ultimate improvements, the ratio of estimated cavity volumes for the two cases was found. At 250 RPM, the estimated improvement at both the blade rate and twice blade rate frequencies approached 20 dB.

It was concluded that very local structural artifacts were dominating the non-uniformity of the inflow to the propeller. Redesign of these structures to interfere less with the inflow was the first priority.

Remedies

Modifications of the geometrical configuration of the thruster and its immediate environment were contemplated. Any modifications were to be do-able, at reasonable cost and time, by shipyard workers while the vessel was in drydock at the next availability.

While not appearing critical, it was decided to remove the angled plates at the mid-point between the grids (visible in Figure 2 and in Figure 4b) as an obvious source of blockage, hence wake in the thruster inflow. These angled plates were probably originally placed to keep flow out of the sea chest with forward motion of the ship. The web frame at fr. 19 had to be extended outward and fitted with landing pads for the grilles, which were redesigned to suit. All frame and grid members were thereafter more-or-less aligned with the thruster inflow through the molded surface of the hull.

As built, these same web frames extended inboard to a close proximity to the belmouth of the thruster. Considering that the sea chest was not symmetrical fore and aft across fr. 19, there was concern that fore-and-aft flow near the thruster inlet would be amplified by restriction of the passage area. As was done in ATLANTIS, it was decided to cut back the web frame in way of the thruster to increase the clearance and the area for longitudinal flow. In order to compensate for lost material, the large lightening hole in the frame was filled in.

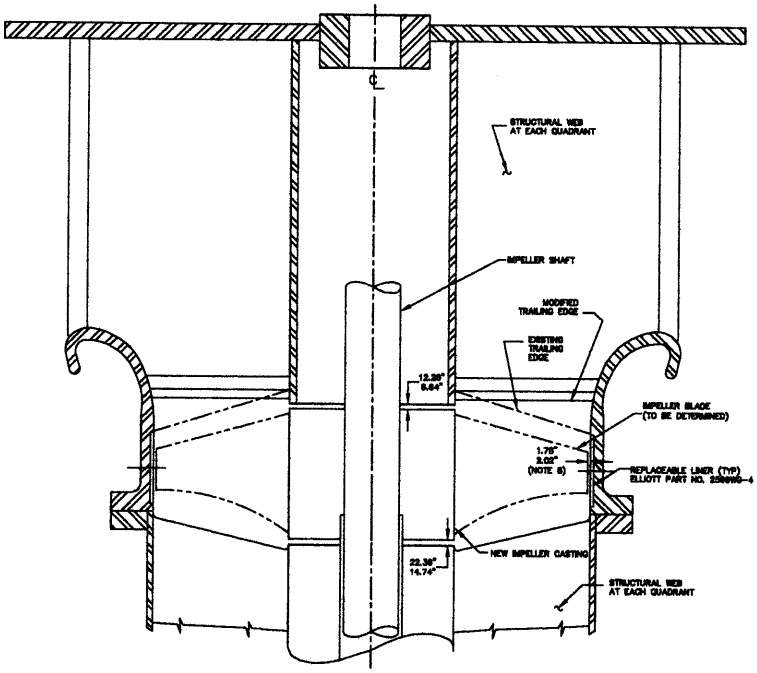
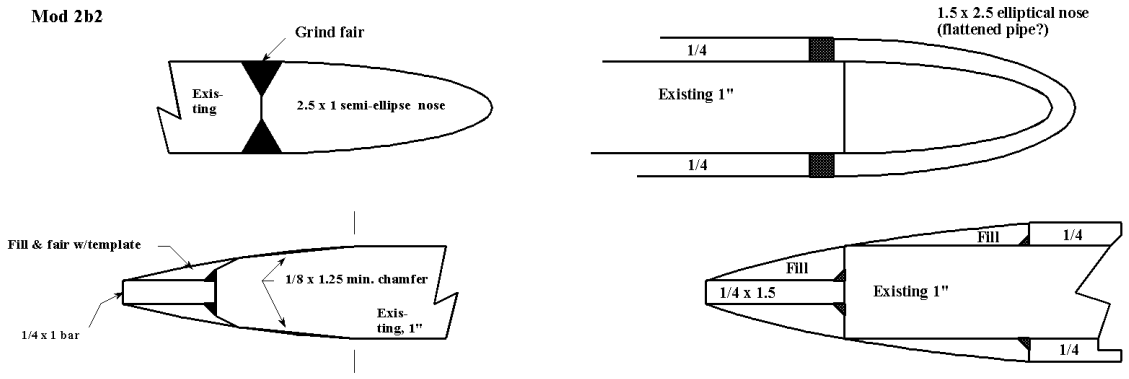


Figure 6: Thruster Modifications

The velocity surveys showed that the main culprits of inflow distortion were the four vertical plates which securely integrate the thruster barrel into the ship structure via the overhead and motor foundation. These plates are 1” thick (1.5” in ATLANTIS); their vertical, outer edges, that act as leading edges for the radially inward inflow to the thruster, were rather blunt. The velocity surveys indicated secondary flows characteristic of “necklace” vortexes near the thruster duct wall in way of these plates. Of course, flow distortions at the maximum radius of the propeller blades does the most damage to the cavitation performance. The blunt leading edges of the plates required reshaping.

The trailing edges of the plates were quite square and were clearly generating strong wakes that were carried immediately into the leading edges of the propeller blades. In order to put a fair tail on these plates it appeared that a large amount of steel would have to be removed. Instead, the trailing edges were to be cut back to a horizontal line from their highest points at the shaft tube. This greatly increased the axial clearance between the plates and propeller at the blade tips. A new, thinner trailing edge was to be established by welding to the cut edge a 1”x ¼” bar, centered on the thickness. Then, by grinding off thin wedges of steel from the thick plates and filling with epoxy, a new, fair tail could be created toward the lower, trailing edge of each. A large axial clearance was maintained at the tip radius. New nose pieces for the plates were to be machined from 1”x 4” bar stock, in a semi-elliptical shape. These “fixes” are illustrated in Figure 6 and Figure 7a.



(a) Thin (b) Thick

Figure 7: Plate Fairing

A second plate-shaping scheme was also tried that required less grinding. In this case, ¼" plate was to be added to both sides to increase the thickness to 1-1/2". The tail shape was then obtainable with only epoxy filling. A nose was to be added that could be of thin plate or tubing bent to a semi-elliptic shape, Figure 7b.

A significant length of weld would be lost in cutting back the lower edges of the radial plates, weakening and softening the connections between plates and bellmouth. The bar-stock nose pieces were to be welded to the blunt outer edges of the radial plates over their full height from bellmouth to overhead, and the welds ground fair. The new welds at the bellmouth would more than make up for the strength and stiffness lost in the cutback. This procedure was approved by Elliott Turbomachinery Ltd., the thruster manufacturer.

The steering shaft, 3" in diameter, runs vertically just behind the thruster duct, on the centerline of the ship. The barnacle-covered steering shaft is visible in Figure 2. The bellmouth rim is actually cut away to clear it. Close behind is a centerline partial bulkhead. Fairing of this shaft was thought to be important. Our first attempt avoided enclosing the steering shaft while hiding the instrumentation cable tube, which also appeared troublesome, Figure 8.

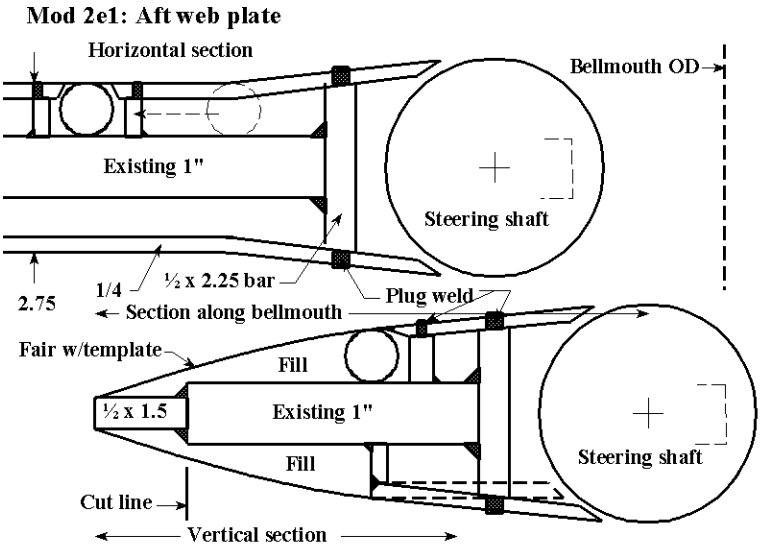


Figure 8: Steering Shaft Fairing-First Design for Air-Test

Evaluation

The modifications were easily made in the air-test mockup. One each of the thick and thin versions of the faired plates, one to port and the other to starboard, were included so that both could be evaluated in a single test.

Measurements showed no evidence of the grilles in the velocity profiles. The airfoil-shaped fairings of the heavy plates were a marked improvement, with the thin version better than the thicker version. On the other hand, the steering shaft and its fairing were a concern, as may be seen in Figure 9. A large and somewhat asymmetric wake was apparent at 180 degrees

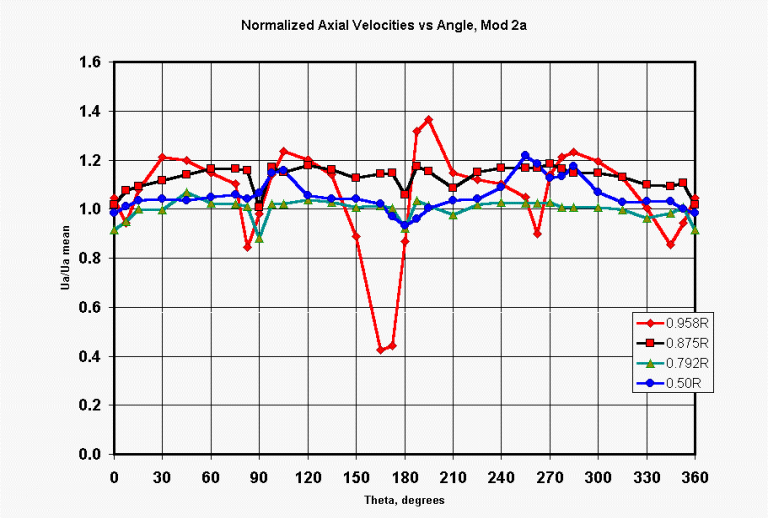


Figure 9: Air Test Normalized Axial Velocity - Mod 2

Re-design

In view of the poor wake behind the attempted fairing of the steering shaft, it was decided to enclose it entirely. This was done by adding a more-or-less triangular “compartment” which landed on the after radial plate, enclosed the steering shaft, and, widening symmetrically about the centerline, extended back to the after bulkhead of the sea chest. During installation, a small sump in the overhead was relocated behind this triangular bulkhead. Unfortunately, time did not permit this modification to be evaluated in the air-test model.

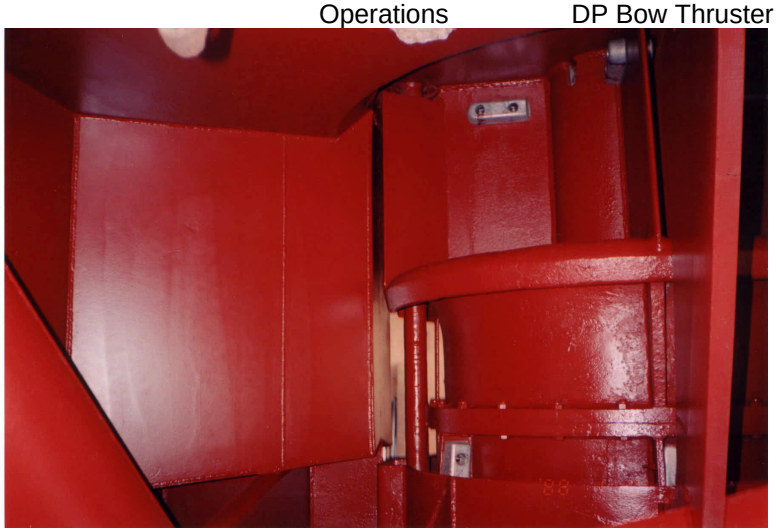


Figure 10: “Wedge-Bulkhead” Steering Shaft Enclosure

Impeller Design

In order to assure improved noise and vibration performance without regard to structural configuration-related flow improvements, it was advisable to redesign the thruster propeller (impeller) to include features that forestall cavitation.

These features are forward-skewed blades with thick nose profiles. In forward skew, the leading edge at the tip precedes that at the blade root in its normal direction of rotation. It can be shown that the tip sections lift response to a change in incidence is reduced by forward skew relative to no skew, and markedly so to the more usual back-skew. The smaller lift change is accompanied by a smaller reduction in blade back pressure, resulting in greater cavitation tolerance to incidence. Similarly, a thin, sharp leading edge is extremely intolerant of incidence changes for cavitation. A rounder, hence thicker, leading edge generates smaller pressure reductions when subjected to incidence changes, and is therefore preferable in non-uniform flow. The bluntness of leading edges is limited by “thickness”cavitation inception at the “shoulders” when operating at design incidence. If the maximum leading edge nose radius is limited by the smallness of the ambient cavitation number, ó, the local leading edge sweep angle necessary to avoid incidence cavitation can be related to the nose radius by:

$$h^2 = \frac{8}{p}\frac{r_n}{y_e}\left(\frac{s}{a^2}\right)$$

where: ç is the sweep-slope, the cotangent of the sweep angle,
r_n is the blade chordwise section’s nose radius,
y_e is the radial extent of the blade from this section to the tip,
ó is the local cavitation number, $(p-p_v)/q$, and
á is the (largest) local incidence angle of the onset flow to the section.
This is based on a low-aspect-ratio (LAR) approximation “model” of a ducted propeller swept (skewed) blade, Figure 11. In LAR, spanwise (radial) blade sections are examined and their flow properties related to the usual chordwise sections.

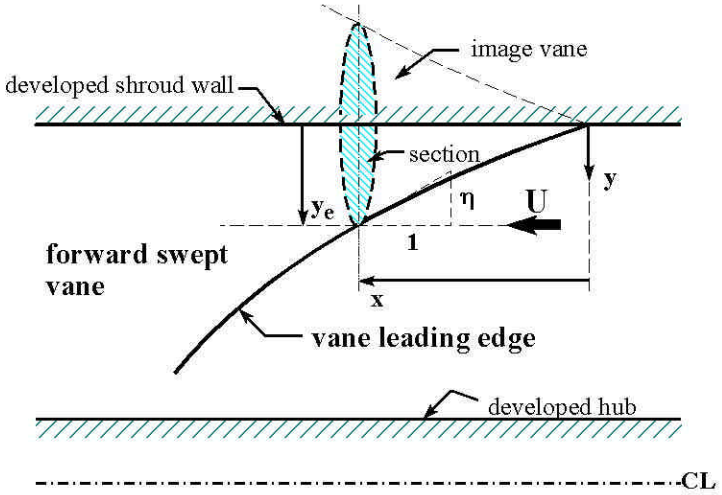


Figure 11: Forward Swept Blade (Vane) Showing Radial Section

The quantity in parenthesis is an environmental parameter, the smallness of whose value governs the inception and growth of incidence-related cavitation. Thin edges (small r_n) require smaller sweep slope, ç, that is, greater skew. Thicker edges can use less skew. The incidence angle is seen to be more important than the cavitation number. Hence non-uniform inflow is the leading cause of this type of cavitation.

The above relationship can be integrated to delineate the blade leading edge profile viewed in axial projection, in polar coordinates, (r,è):

$$\frac{dq}{dr} = \frac{1}{\sqrt{r^2 + l^2}} \left[\frac{1-r}{r_n\left(\frac{s}{a^2}\right)} \right]^{1/3}$$

where: ë is the dimensionless pitch ratio, P/ðD. Here the increase in polar angle (skew) is clear with decrease in (ó/á^2) and with decrease in nose radius, r_n ,.

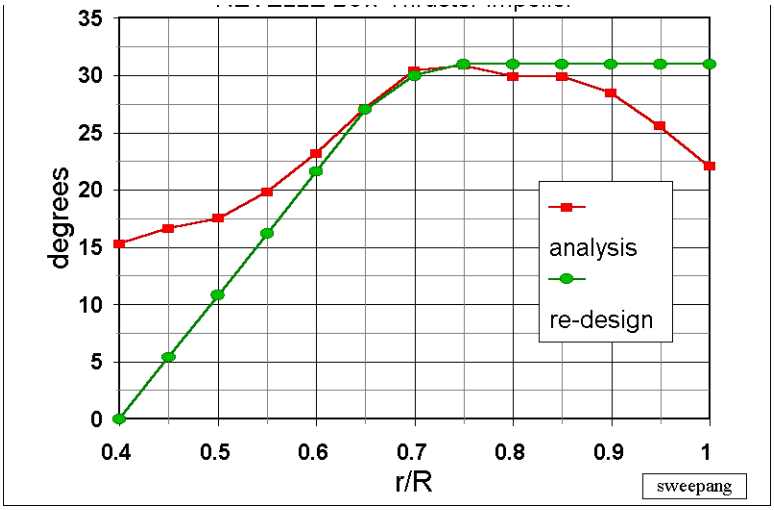


Figure 12: Leading Edge Sweep Angle vs Radius

In order to be conservative, the original, unimproved velocity survey was retained as the basis for the blade redesign. Assuming a nose radius that represented no more than 25% of local blade maximum thickness the leading edge skew profile, Figure 12, was worked out for nominally equal speed of cavitation inception for all blade sections. The skew profile to be built, Figure 13, was selected from this computed one.

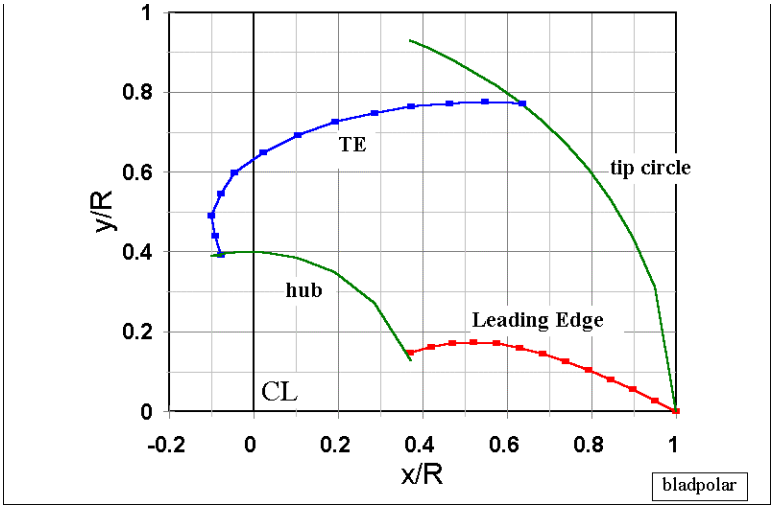


Figure 13: Axial Projection - Forward Skewed Blade

While introduction of forward skew and thick leading edges may seem radical, it was desired to minimize changes from the existing propeller design, one that had been in service for many years. In that regard, the chord length and thickness of each original blade section were maintained. It was necessary to adjust the pitch distribution, however, in order to maintain the original distribution of loading over the radial extent of the blades. This is because the forward skew tends to unload the blade at the tip. Bird-Johnson Co. applied propeller lifting surface theory modeling to determine the pitch distribution that would maintain the original load distribution with the new skew. The resulting pitch was somewhat increased at the tip, relative to that of the original un-skewed design.

A pattern was made and a mono-block propeller cast by Bird-Johnson Co. at their Pascagoula foundry facility. The propeller was machined and hand finished to Class I requirements and delivered to an Elliot-approved company for dynamic balancing. All material removal for balancing was from the hub; the blades were not disturbed. At Southwest Marine shipyard, where REVELLE was in drydock, the thruster was disassembled and the new propeller, Figure 14, installed under Elliot supervision. Modifications to the thruster structure were going on at the same time.

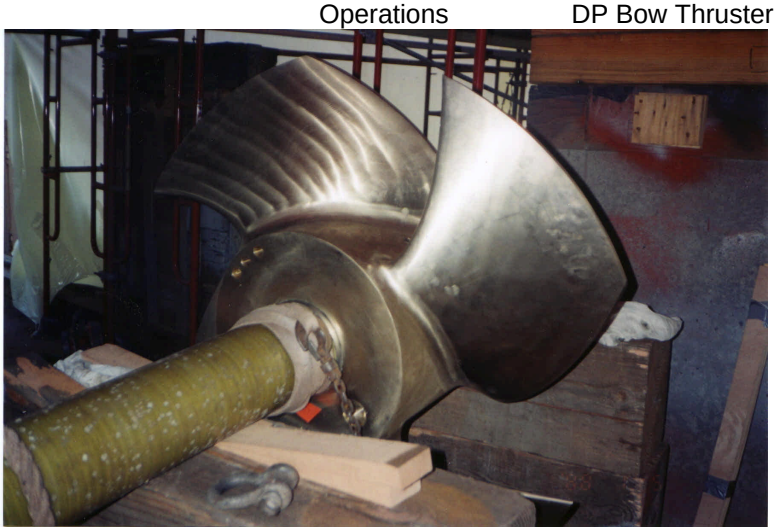


Figure 14: New Thruster Propeller

Results

The most direct indication of thruster cavitation performance is in its underwater radiated noise. In Figure 15 there are displayed the underwater sound pressure levels as a function of revolution rate, at a particular position outboard of the thruster, both before and after the above modifications. A frequency band centered on 1000 Hz. is used. It can be seen the modifications have increased the cavitation inception speed to about 250 RPM from an indeterminately low value. The resulting noise reduction in this frequency band is a valuable 15 dB, or so, in the mid RPM range. At speeds less than that for cavitation inception, there is no cavitation noise; the measured levels are due to other, or ambient sources.

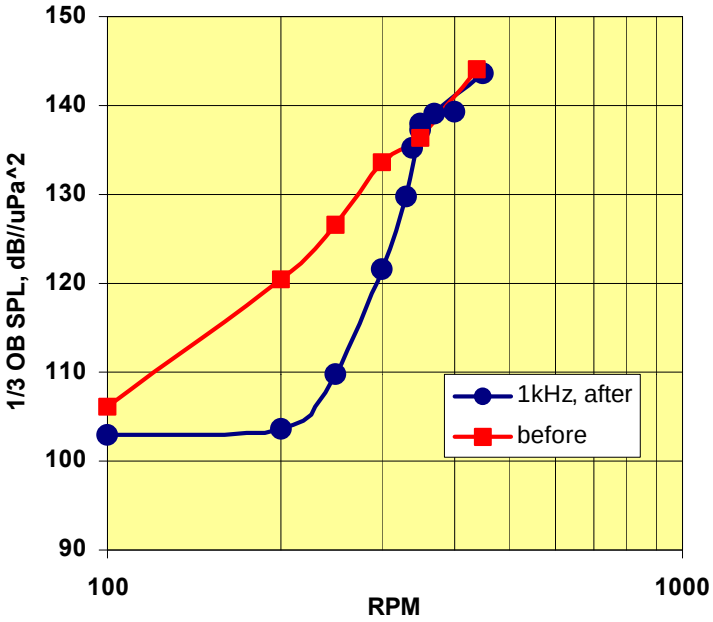


Figure 15: Underwater Noise-REVELLE Bow Thruster

The underwater radiated noise is a good measure of the "source strength" of the thruster's cavitation. The on-board noise, pertinent to habitability, is proportional to this source strength but is heavily filtered by acoustic/hydrodynamic-structural-acoustic coupling, propagation losses and

resonances. The before-and-after noise levels in room 2-22-2 are plotted vs. thruster revolution rate in Figure 16. This stateroom, housing two scientists, is immediately aft of the thruster, inboard, on the first platform. The Overall Levels are so-called "A-weighted," single number values representing the frequency-integrated acoustic energy levels sensible by the human ear. It may be seen that up to 350 RPM, the noise levels in this room are now nearly unaffected by thruster operation. That revolution rate represents approximately one-half of the rated thrust of the unit. The apparent noise reductions achieved in this operating range are, like those in the underwater noise, about 15 dB.

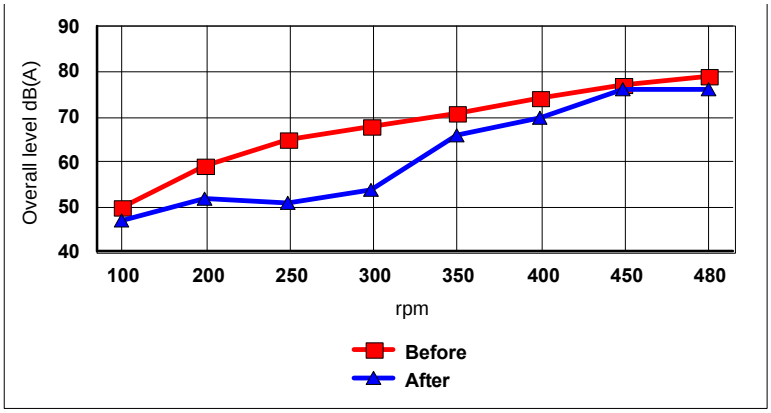


Figure 16: Room 2-22-2 Overall Noise Levels, REVELLE

According to the ship's master, the thrust generated by the modified thruster is not less than, and possibly more than before at the same revolution rates. Amperage readings on the motor suggest no increase in torque.

Conclusions & Recommendations

The purpose of the modifications to ship and thruster was to increase the speed of cavitation inception to the point where habitability noise levels would be acceptable during DP operations. This was accomplished, since in REVELLE, DP operations usually require half the rated thrust, or less. Unfortunately, we cannot determine from the test data what the individual contributions were of propeller redesign and structure reconfiguration to the observed cavitation performance improvements. Figure 17, showing the frequency spectrum of noise levels in room 2-22-2, reveals that, with the exception of the 1 kHz. band, noise levels are reduced across the board. The underwater noise measurements displayed in Figure 15, being for 1 kHz., would not suggest this favorable performance.

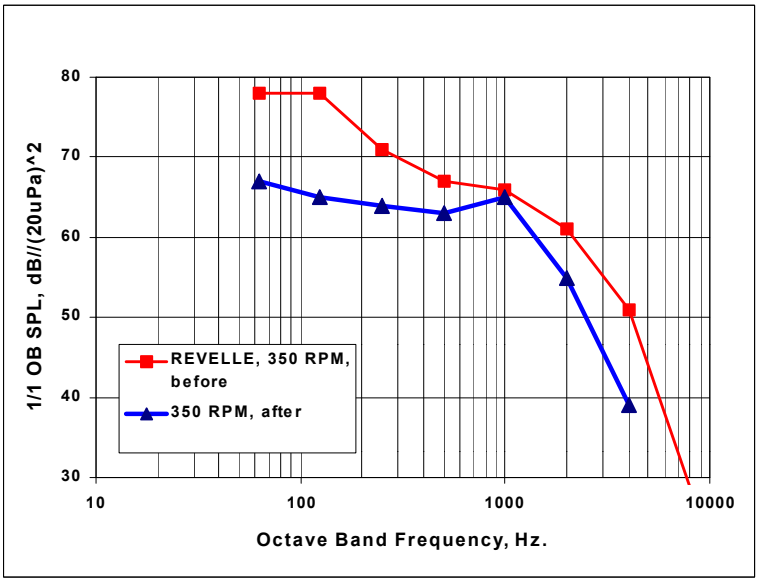


Figure 17: Room 2-22-2, 350 RPM, SPL Spectra Before & After

For vessels that require low noise levels at higher thrust levels, it is recommended that a combination of hydrodynamic source reduction measures, as in REVELLE, should be augmented by path treatments as in ATLANTIS.

Acknowledgements

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