Reducing Bubble Sweepdown Effects on Research Vessels

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Abstract - **During early stage hull form design trade studies are performed to investigate feasible and desirable attributes for the a oceanographic ship. Paramount among these attributes is excellent sonar mapping capability. This paper summarizes some of the design and analysis effort to improve sonar capability by minimizing bubble sweepdown interference while considering overall ship resistance and fuel economy. Bubble sweepdown and its detrimental effects on scientific sonar systems is a widely known phenomenon that has been experienced to some degree on nearly every research vessel. The causes and mitigation techniques are less well understood. Sonar performance is degraded when bubbles pass over or near transducers. These detrimental effects are usually worse at higher ship speeds and sea states. Gondolas, fairings and bubble fences can effectively reduce bubble sweepdown interference but generally incur significant resistance penalties. In this study, several hull form bow shapes and sonar mounts were investigated. Computational fluid dynamic (CFD) analysis was conducted to determine their effect on bubble sweepdown near the transducers. Tradeoffs between sonar performance, draft and resistance are explored. The impact on ship specification development is also reviewed.**

I. Introduction

Given the vastness of the unexplored and unmapped areas of the world's oceans, sophisticated wide-swath, high-resolution sonar mapping systems have become indispensable on modern oceanographic research and survey ships. Recent technological advances in multiband sonars are impressive in terms of increased resolution and mapping swath width. However, taking full advantage of this improved sonar performance has introduced significant challenges for oceanographic ship hull designers. A critical factor in installing these sonar systems is, simply, finding a location and configuration on the hull that supports their full performance.

On all surface ships, turbulent flow near the bow is a source of air bubble generation. Additionally, air bubbles pre-exist in the ocean surface layer and vary in size and density due to environmental conditions. Some of these bubbles may become entrained in the flow around the hull and be pulled under the hull as they flow aft. Bubble sweepdown refers to the tendency of these entrained air bubbles, originating at the free surface near the bow of the ship, to follow flow streamlines and be drawn under the hull into the area of the bottom-mounted, hydroacoustic transducers. Often the bubbles exist as clouds or sheet-like regions that sweep down and under the vessel's hull. Air bubbles that pass over or near the transducers diminish sonar effectiveness by acting as an acoustic decoupler for transmit and receive sound pulses, as well as a source of unwanted broadband noise.

Bubble sweepdown and its detrimental effects on scientific sonar systems is a widely known phenomenon that has been experienced to some degree on nearly every research vessel. For more than 30 years, institutions around the world have conducted research to understand this phenomenon. Much of this research was a result of marginal sonar performance revealed only after ship deployment. Engineers have crafted innovative solutions to mitigate the detrimental effects of bubble sweepdown. Sonar arrays have been mounted on pods, wings or gondolas and other appendages to move the transducers off the hull surface and beyond the bubble sweepdown region. Fence-like appendages have been mounted upstream of the sonar arrays to redirect the bubbles away from the arrays. In some circumstances, these retrofits have produced undesirable effects on ship performance such as increased drag and appendage cavitation (an additional noise source that can further degrade sonar performance). More recent ship design programs, including the Ocean Class AGOR, have recognized the importance of implementing bubble sweepdown mitigation early in the ship design process.

II. Bubble Sweepdown Mechanics

The mechanics of bubble sweepdown are best understood by separating it into two discrete events. The first is bubble formation either by natural wind and wave interactions or by ship induced turbulence at the air and water boundary. The second is bubble transport, the path the bubbles follow as they flow aft along the hull of a ship. Each of these events involves complex mechanisms. Wind, sea-state, ship speed and ship motions and variations in hull form all affect the size, quantity and transport path of the bubbles.

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Bubble formation occurs continuously at the ocean surface as the environmental forces associated with wind, wave and weather mix the air and water boundary. Dynamic and ocean current drag forces can be greater than buoyancy, keeping the bubbles suspended in the water column. Solid and dissolved matter on the bubble's surface can inhibit diffusion of the bubble into the surrounding water. Additionally, environmental conditions constantly replace the bubbles that do reach the surface and disperse. For these reasons, bubble populations pre-exist in densities large enough to interfere with sonar operations.

Bubbles are also generated by the motion of the ship itself, primarily in the turbulent flow near the bow at the free surface. Time correlated acoustic and photographic data clearly show bow-generated bubbles flowing aft, down and under the hull and passing over hull-mounted arrays resulting in degraded sonar performance. Some ships experience bubble sweepdown in calm water in the absence of any significant ship pitching; sufficient bubbles are generated in the steady turbulent flow of the bow wave and the flow streamlines over the ship's forebody transporting the bubbles down around the turn of the bilge and onto the bottom in way of the arrays. Ship pitching does, however, tend to increase bubble generation and increased pitch angle can detrimentally redirect the streamlines closer to the ship's centerline where the sonar arrays are usually located. Underwater video has clearly documented the dependence of bubble formation on the magnitude of ship pitching, and thus the dependence on sea state and the ship heading relative to the sea state.

Flow around a conventional bow bulb can also cause bubble formation. Underwater video has documented vortex creation as the water spills on and over the bow bulb during a bow down pitching motion. The vortex pulls the bubbles downward and the bubbles within close proximity to the hull become entrained into the flow. This type of bubble sweepdown generation has been observed at slow ship speed (less than 5 knots).

III. Bubble Sweepdown Influence On Sonar Performance

As the water flowing aft along the hull of the underway ship transports the bubbles, they can pass over or near the sonar arrays. As the sonar transmits a pulse and attempts to sense the return signal, the sound pressure wave interacts with the bubble layer which acts as an acoustic baffle between the sonar transducer and the surrounding water. Additionally, the bubbles themselves produce sound pressure waves as they flow under the ship. These combined effects result in lost return signal to the receive sonar transducers and the signal processing system. These lost returns can cause the sonar to lose track of the bottom and greatly reduce operational depth and speed as well as the swath-width of multi-beam sonars. When bubbles are seen in the multibeam and determined to be reducing the data quality, it is common practice to reduce speed. Reduction of speed reduces the pitch frequency, resulting in fewer bubbles over the transducer. The increased time and cost to continue survey, due to the slower speeds, is often debated in regards to operational productivity.

IV. Research Vessel History Of Bubble Sweepdown

Following is a short review of several ships that have had bubble sweepdown issues and the retrofit corrections that were taken.

<u>*AGOR 23 Class*</u>

The AGOR 23 Class ships are general purpose US academic fleet oceanographic research ships that were delivered between 1991 and 1997. The ships of this class have a significant bubble presence in sea states above 2.5 for ship speeds above 9 knots. The sonars were mounted on the bottom of a "cow catcher" shaped fairing that extended approximately 2 feet below the hull. This geometry worked well for the first of class, the R/V THOMPSON [1] and the follow-on ships, R/V ATLANTIS and RONALD BROWN. The R/V ROGER REVELLE, second in the class, was built without this fairing to address home port draft limitations and has experienced more bubble sweepdown problems. This is a case where a simple platform/fairing to lower the sonars below the bubble layer and direct the flow away from the transducers was adequate to mitigate bubble/performance problems. The resistance impact of this fairing is also fairly minor – 5% or less.

<u>*T-AGS 60 Class*</u>

The T-AGS 60 Class is a class of 6 general purpose US Navy oceanographic survey vessels delivered between 1994 to 2001. These ships were specifically designed with a hull shape to minimize bubble sweepdown. When the first of class was designed in the early 1990's, common belief was that bubble sweepdown was primarily associated with the bow wave, so the ship was designed with a very fine waterline entrance to minimize bow wave-making. As it turns out, however, these ships had significant bubble sweepdown issues at speeds above 8 knots in sea states as low as 2. The very fine bow shape actually appeared to increase bubble generation and the fine forward hull sections allowed them an easy pathway to the bottom mounted sonars. In an attempt to correct this, significant full scale testing and model testing were conducted. Full scale underwater video was taken of the bubbles passing over the arrays, by divers, in an attempt to characterize the nature and extent of the problem. Model experiments were then conducted at Naval Surface Warfare Center – Carderock Division (NSWCCD) in which several different flow diverting appendages were designed and tested. The most successful of these devices was the flow diverting fence, similar in construction and appearance to a bilge keel, located forward between ship stations 2 and 8, port and starboard. The leading and trailing edges of the fence were flow aligned to minimize added resistance and the potential for cavitation and flow noise, but the long straight middle portion cut across flow lines and effectively acted to keep bubble flow from turning the bilge and reaching the bottom mounted sonar arrays. This modification greatly reduced bubble sweepdown and increased the sonar performance, but came with a large resistance penalty of about 20%.

The mid-life sonar upgrade for these vessels added new generation multibeam sonars, removed the bubble fences and moved all acoustic sensors to a strut mounted gondola. In this configuration, rather than divert the bubbles, they are allowed to pass between the gondola and hull. Full scale acoustic testing and sonar trials indicate no bubble interference in the area of the sonar transducers. In addition, the overall ship's resistance penalty was reduced to about 16%, a net improvement of 4% over the bubble fence arrangement.

Extensive flow visualization model testing was performed prior to the full scale ship retrofit for both the flow fence and the gondola. In each case, model and full scale results were very consistent.

NOAA (T-AGOS monohull conversion)

The monohull T-AGOS ocean surveillance ships (T-AGOS 1 through 18) were originally designed for the single mission of towing surveillance towed array sensor system (SURTASS) arrays and did not have any hull mounted scientific sonar systems. As a result, the hull forms did not incorporate any bubble avoidance features. When these ships were retired from SURTASS missions and converted to oceanographic service with National Ocean and Administration (NOAA), a variety of scientific sonar systems were installed. In the course of designing and installing these sonar arrangements, the ships were found to have significant bubble problems. Fixed cameras were installed at the sonar locations to determine the source and propagation paths of the bubbles. It was determined after viewing the videos that the sonars could be moved forward and out of the streamlines that contain bow ingested bubbles, to mitigate the bubble problem.

NOAA FSV-40 Fishery Ships

The (NOAA) Fisheries Survey Vessel (FSV) ships, because of their acoustically demanding fisheries mission, were designed for reducing bubble sweepdown as a primary goal. Two major features were incorporated, first was a pronounced U-shaped forebody and second was a retractable centerboard where the sonar suite was installed. The pronounced U-shaped forebody sections were an innovation at the time [2]. This additional volume, forward and down low, is intended to redirect flow over the forebody; the bow flow is delayed from being drawn around the turn of the bilge and onto the bottom of the ship, thereby reducing the potential for bubble sweepdown interference. Underway video has documented that this method of redirecting the flow lines was successful in significantly reducing bubbles in the sonar region. The retractable centerboard contained the majority of the scientific systems, except for the shallow-water multibeam sonar. This allowed for the sonars to be lowered 10 feet below the keel, placing them significantly below the bubble layer. The bow modification increases resistance by approximately 1% and the centerboard increases overall resistance by 9% at the survey speed.

V. Bubble Sweepdown Analysis

During the preliminary design stage, numerous trade studies were preformed to investigate capabilities desirable in the a new oceanographic research ship. Among the most important of these attributes is excellent sonar mapping capability. Fuel economy is also of high importance. The trade studies generally look at a variety of sonar mounting arrangements including flush mount, keel fairing, cow catcher, and a gondola. A pronounced U-shaped forebody, similar to that on the NOAA FSV 40 [2], should also be investigated. Since life cycle cost is usually a key driver, a goal is to avoid hull appendage mounts that incur significant resistance penalties, the pronounced U-shaped forebody combined with a flush mount sonar can offer a desirable solution.

For the purposes of this discussion, the research vessel will be commercially crewed and will conduct general purpose oceanographic research in coastal and deep ocean areas from tropical to sub-arctic environments. Typical capabilities include physical, chemical and biological oceanography; multi-discipline environmental investigations; ocean engineering and marine acoustics; marine geology and geophysics; and bathymetry, gravimetry, and magnetometry. The following characteristics shall be the basis for this paper:

Range:	10,000 NM at sustained speed
Draft max:	17 ft
Displacement:	2200 LT
Speed:	11 knots sustained
Seakeeping:	Maximize ability to work in SS4 and above
Sonar Performance:	Full ocean depth mapping
Dynamic Positioning:	Hold station in SS5 conditions
Crew/Scientists:	40 (20/20)

VI. Sonar Mount Analysis

Various methods of preventing bubble sweepdown over the transducer surface should be evaluated based on their effectiveness, added drag, added weight and impacts to vessel operation. The bubble sweepdown can be traced with streamlines originating from the water surface near the bow and analyzed using a computation fluid dynamics (CFD) programs, such as ShipFlow, which utilize wave pattern analysis to model fluid dynamics of thin boundary layers as well as laminar and turbulent flow regions. There are generally two types of methods to address reducing bubble sweepdown: using a hull mounted appendage or incorporating ad U-Shaped forebody in the hull lines, Table 1 assesses each method's effectiveness:

1) Hull Mounted
    a. Flow Fence and Diverting Fins
    b. Flat Mount Keel Fairing
    c. Cow Catcher Fairing

d. Gondola (appendage attached with struts)

2) Hullform with U-Shaped Forebody

Table 1. Bubble Sweepdown Reduction Methods Assessment

Method	Diverting Effectiveness	Added Drag	Added Weight
Flow Fence & Diverting Fins	Very Good	High	Low
Flat Mount Keel Fairing	Fair	Low	Low
Cow Catcher Fairing	Good	Medium	Low
Gondola	Very Good	High	Medium
U-Shaped Forebody	Good	Low	Low

One of the important missions of a general purpose research vessel is traditionally deep water ocean floor mapping. Early in the design process, sonar performance analysis is generally conducted to determine which deep water multibeam could provide the best capability for the particular size ship. For this size research vessel the trade study assessed size, weight and performance capabilities between a T-shaped Mills' Cross line array [3] of a 12 kHz 1°x1° and a 1°x2° system. The Mills Cross T-Shape pattern allows for the most efficient use of area in the hull. The receive array is installed thwartships while the transceiver array is installed fore and aft along or parallel to the centerline. Since the receive array extends furthest transversely, it is more significantly affected by bubbles as they flow under the turn of the bilge. Therefore, the width of the receive array becomes the governing factor for defining the bubble sweepdown streamline flow criteria. Striving for a flush mount sonar installation if possible can offer the most desirable solution. The 12 kHz sonar transducer arrangement is flat, as such a flat of bottom into the hull form is required. The 12 kHz 1° receive array measures 8 meters wide and the 12 kHz 2° receive array measures 4 meters wide. Figure 1 shows the streamline flow pattern of a bare hull with a traditional bow at speeds of 10 and 12 knots; the 4m and 2 m lines mark the flat of bottom width criteria for the 12 kHz 1°x1° and 1°x2° receive array respectively.

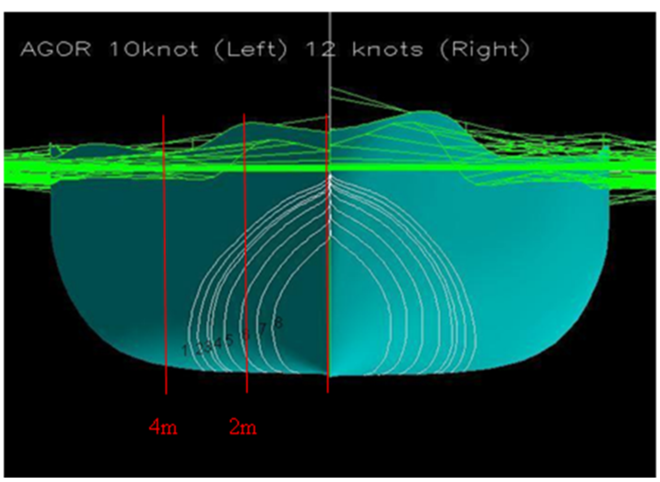

Figure 1. Streamlines for a Baseline Hull

From the analysis it can be seen by comparing the streamlines between 10 and 12 knots that the change of the streamline shape due to the ship speed is minimal and that the streamlines will flow directly into the typical area of the sonar location; hence confirming the need to study various sonar mount options.

Flow Fence and Diverting Fins

Figures 2 and 3 show typical flow fence and flow diverting fins configurations. A flow fence is a device, similar to a bilge keel appendage, mounted around the sonar transducer to divert the streamline from flowing onto the transducers surface. The flow fence and diverting fins are typically oriented on the hull surface to divert or alter the surface streamflow away from the transducer face. Flow fences and diverting fins, however, carry a significant added resistance penalty. Model testing results conclude that the increase of required delivered power of the bare hull ship can range from 20% for a flow fence installation to as much as 45% for flow diverting fins.

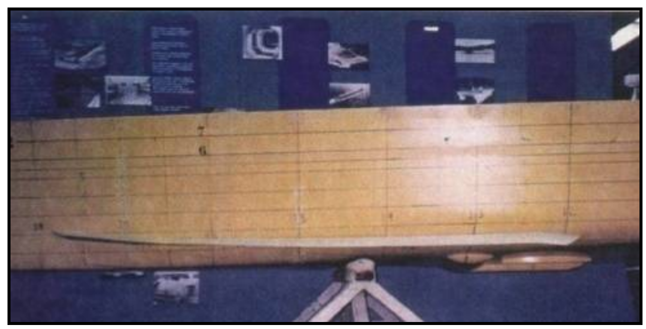

Figure 2. T-AGS 60 Model with Flow Fence

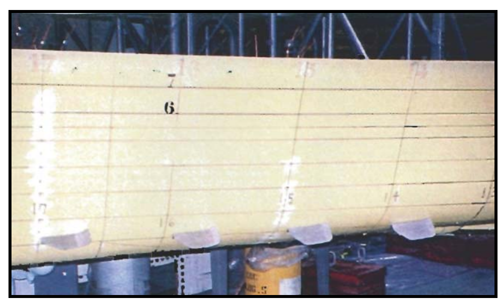

Figure 3. T-AGS 60 Model with Diverting Fins

Flat Mount Keel Fairing

The Flat Mount Keel Fairing, shown in Figures 4 and 5, is flush with the keel at the centerline and extends outboard to provide a flat surface for transducer mounting. The flush mount fairing with the smooth leading edge has low flow disturbance and low added drag. The CFD analysis shows the streamlines are partially diverted but not enough to eliminate flow over the transducer. The deepest streamlines still flow across the mount surface and therefore the transducer surface.

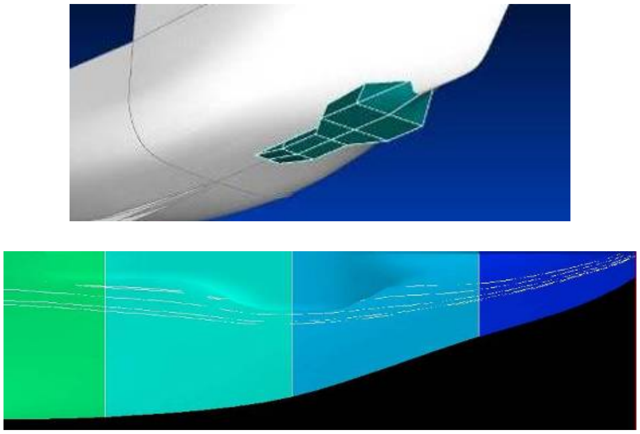

Figure 4. Streamlines for Flat Mount Keel Fairing: Rx FWD

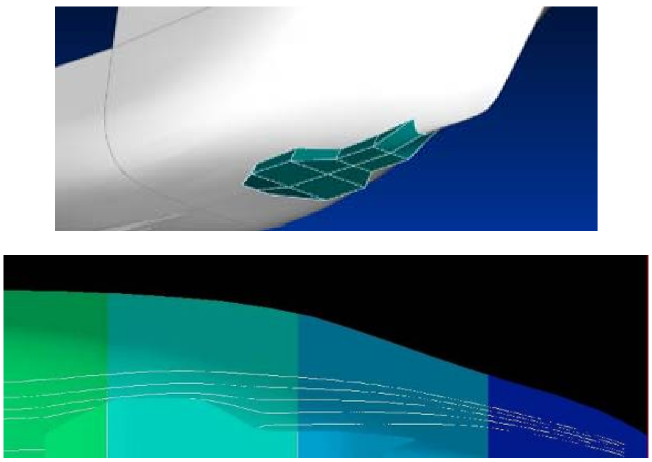

Figure 5. Streamlines for Flat Mount Keel Fairing: Rx AFT

Cow Catcher Fairing

Figures 6 and 7 show a typical Cow Catcher Fairing that is below the keel, typically at least 2 feet, depending on the sonar dimensions. To prevent the streamlines from flowing around the leading edge and over the sonars, a reverse angle leading edge is provided. Figure 8 shows that no streamlines flow over the sonar transducer surface as all streamlines are diverted around the Cow Catcher. The leading edge will have a higher added drag compared to the smooth leading edge of the Flat Mount Keel Fairing. However, according to model tests the estimated added drag for the Cow Catcher is less than 5% of the total hull drag.

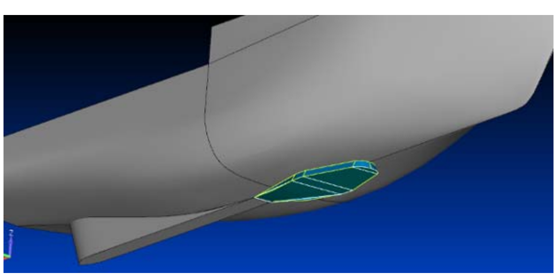

Figure 6. Cow Catcher Fairing Location and Concept

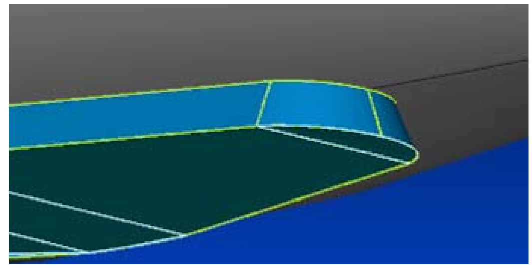

Figure 7. Cow Catcher Fairing
(modeled without the rounded leading edge for simplicity)

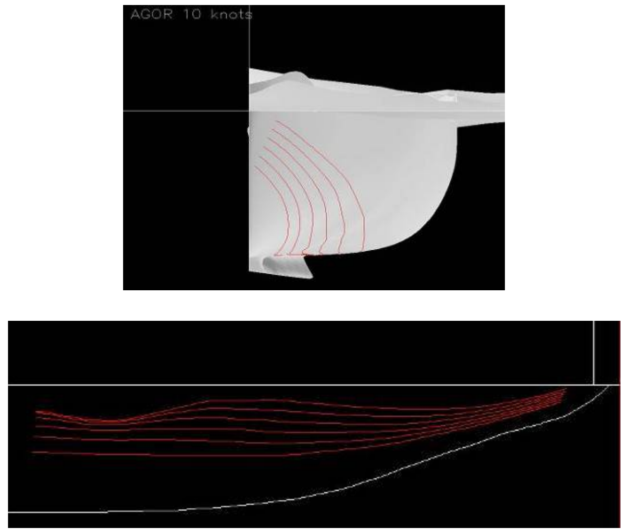

Figure 8. Streamlines for Cow Catcher Fairing

Gondola

The gondola provides an excellent capability of preventing bubble sweepdown by moving the sonar transducers below the bubble sweepdown layer. Since the gondola is only connected to the ship hull with struts, the sonar is also partially isolated from the hull noise. However, strut cavitation noise can become an issue if they are not aligned carefully. The submerged gondola depth should be adjusted based on the streamline CFD analysis or flow tank test to ensure the streamline flow passes between the keel and the top surface of the gondola. The deeper the gondola is submerged the better the chance the air bubbles will flow between the hull and the gondola. However, deeper submergence of the gondola increases the ship draft, the mount weight and the added drag.

ShipFlow CFD software is not able to model the gondola. Therefore, a suitable submerged depth of the gondola could not be determined from the CFD analysis. Extensive studies and model tests on the T-AGS 60 Class have been conducted, verifying the gondola depth on that ship.

U-Shaped Forebody

The FSV style U-shaped forebody blended into the hull form adds volume, forward and down low, redirecting flow over the forebody. The U-shaped forebody redirects the bow flow from being drawn around the turn of the bilge and onto the bottom of the ship, thereby mitigating the potential for bubble sweepdown interference. Several U-shaped forebody design iterations were completed and evaluated and compared to a traditional bow form (referred to as original). The two most successful, designated Versions A and B, are shown in Table 2 and Figure 9 along with the original hull form. Version B is a fuller variant of Version A.

Table 2. Hull Variants Characteristics

Hull Variant	Draft (ft)	Displacement (LT)	Wetted Surface (ft^2)
Original Hull	16.3	2,330	11,406
Version A Hull	16.3	2,393	11,581
Version B Hull	16.3	2,449	11,721

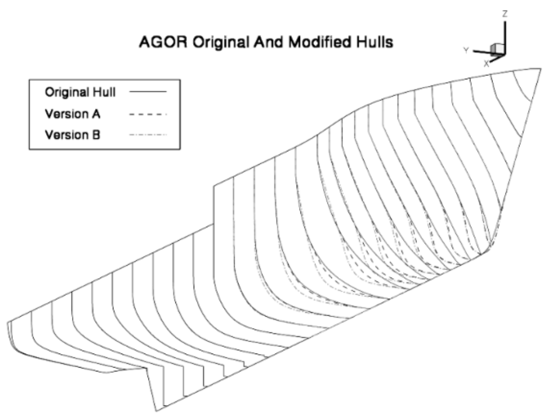

Figure 9. Isometric View of Original Hull and Variants

To assess the original hullform and to validate the modified versions, CFD analysis is preformed to evaluate representative streamline traces over all three forebody shapes. All computations were done at a constant ship draft of 16.3 feet and 10 knots ship speed. Figure 10 is a schematic showing the computed streamline traces that originate at the ship's stem at 3 feet and 5 feet below the free surface. These origin locations were chosen based on operational sea state criteria and estimated ship pitch motions. The 5 foot distance represents the maximum expected pitch conditions in sea state 4. Table 3 presents the offset locations of the streamlines as they cross ship stations 3, 5, 7, and 10. The approximate location of the sonar array is at station 7.

The effect of increasing the fullness of the U-shaped sections can be seen in Figure 10 and Tables 3 and 4. For example, the streamline that originates at the ship's stem 5 feet below the free surface crosses station 7 (the approximate location of the sonar array) at the 4.0 foot buttock on the Original hull, at the 7.7 foot buttock on the Version A Hull and at the 8.6 foot buttock on the Version B Hull. The streamline is diverted outboard by 3.7 feet on Version A and by 4.6 feet on Version B. In both cases, this represents a significant redirection of the streamline and is expected to improve sonar operations.

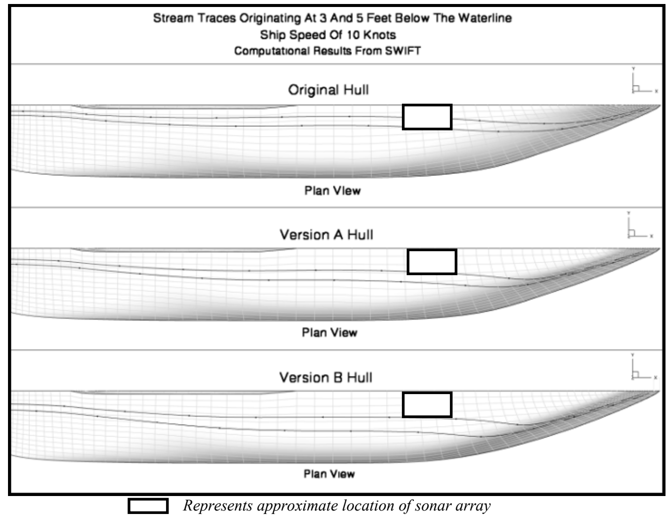

Figure 10. Streamlines Traces of the preliminary design and Variants

Table 3. 3 ft Streamline Offset Locations *

Streamline trace originates 3.0 feet below the free surface (ft)						
Ship	Original Hull		Version A Hull		Version B Hull	
Station	(Y)	(Z)	(Y)	(Z)	(Y)	(Z)
3	7.6	7.3	9.2	8.7	9.7	8.7
5	8.3	2.8	12.3	3.7	14.4	3.7
7	7.2	0.6	11.1	1.2	13.4	0.8
10	6.4	0.1	10.1	0.3	12.8	0.6

Table 4. 5 ft Streamline Offset Locations*

Streamline trace originates 5.0 feet below the free surface						
Ship	Original Hull		Version A Hull		Version B Hull	
Station	(Y)	Z)	(Y)	(Z)	(Y)	(Z)
3	5.8	5.0	8.5	6.2	9.0	5.9
5	5.2	1.3	9.1	1.4	9.9	0.6
7	4.0	0.2	7.7	0.5	8.6	0.2
10	3.5	0.0	6.9	0.1	8.3	0.2

** 10 knots ship speed*
** Streamline offset locations in feet*
** Y = Buttock location in ft outboard of ship's centerline*
** Z = Waterline location in feet above the ship's baseline*

VII. ESTIMATED SHIP RESISTANCE

Resistance calculations were analyzed for the Cow Catcher and the Gondola options as they met the bubble sweepdown criteria. The added resistance of the Cow Catcher was calculated based on a regression formula from Hoerner [4]. The added resistance of the gondola was derived based on the T-AGS 65 model tests. Cow Catcher added drag was modeled based on a low aspect fin (using actual dimensions) mounted to the ship's bottom. Friction drag was calculated using the International Tow Tank Conference (ITTC) line with the local Reynolds number and zero correlation allowance. Pressure drag was calculated using a drag coefficient for foils in turbulent flow. At 10 knots the added drag of the Cow Catcher mount is estimated to be 1.1% of the total ship bare hull resistance. The T-AGS gondola resistance coefficients were used to estimate the added drag of the preliminary design's conceptual gondola; smaller in both beam and length than the T-AGS gondola. The wetted surface area of the gondola is approximately half ($54m^2$) of the T-AGS 65 gondola wetted surface ($122m^2$). The added drag of the gondola was scaled based on the difference of the wetted surface area. At 10 knots the added drag of a gondola is 11.4% of the total ship bare hull resistance.

The impact of the U-shaped forebody design on overall ship resistance was also assessed. The flow streamlines were all computed for the hulls at constant draft (not constant displacement), an additional resistance estimate was prepared for the Version B Hull at the same displacement as the original hull. The Version A forebody adds 2.2% hull resistance relative to the original hull at a constant draft of 16.3 feet. The Version B forebody adds 4.6% hull resistance relative to the original hull at the same 16.3 foot draft. At the 16.3 foot draft, the Version B Hull is 5.1% greater in displacement than the original hull. When the Version B1 hull is compared to the original hull at equal displacements, Version B adds 0.9% hull resistance relative to the original hull. So, most of the increase in effective power is related to the added displacement; modifying the forebody for minimum bubble sweepdown is relatively benign in terms of added resistance.

VIII. Sonar Arrangement

Sonar manufacturers recommend locating the transducers in the forward 1/3 Length Between Perpendiculars (LBP) of the hull or as far forward as possible. The U-Shaped forebody allows for greater volume forward resulting in a more room to fit the typical sonar suite commonly used on general purpose research vessels. For this design the sonar suite consists of a deep and mid water multibeam sonar system, sub bottom profiler, acoustic doppler current profilers (three different frequencies), single beam echo sounders (four different frequencies) and an acoustic monitoring system (hydrophones and cameras). Figure 11 shows how difficult it is to fit the sonar suite in the forward 1/3 LBP of a traditional fine entry bow form, typically used. Figure 12 depicts how incorporating the U-Shaped forebody bow form allows for greater area in the forward 1/3 of the hull where the bubble sweepdown is less likely to interfere with the transducer.

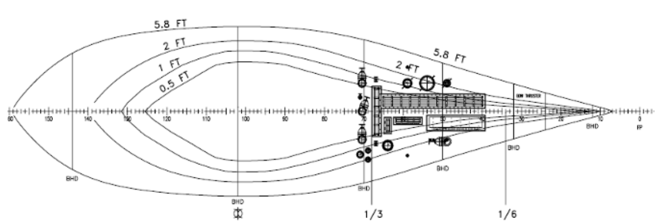

Figure 11. Sonar suite in forward 1/3 LBP of a non-U-Shaped Forebody hull

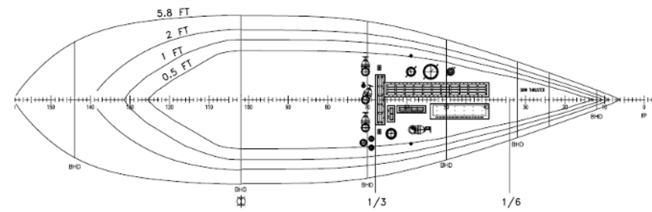

Figure 12. Sonar suite in Forward 1/3 LBP of a U-Shaped Forebody hull

IX. Conclusion

There are a variety of methods available for avoiding detrimental bubble sweepdown effects on oceanographic research ship sonars. They vary in effectiveness and impact to the ship's draft and fuel economy. Based on the sonar mount analysis the cow catcher is an effective method for diverting bubbles away from the sonar surfaces with minimal impact to ship resistance. A gondola is also a very effective method for diverting the bubbles but has a greater impact on resistance. The flat mount keel fairing has less added resistance than the cow catcher but is not as effective in diverting the bubbles from the sonar surfaces. The U-Shaped forebody designs were shown to be very promising in terms of bubble sweepdown avoidance and also had low resistance penalties. For a ship with firm draft limits and a priority for fuel economy, the U-Shaped forebody is an attractive solution. For a ship the size of the preliminary design, the U-Shaped forebody arrangement can accommodate a 4 meter receive array. A larger receive array may prove to be challenging. The selected mitigation method depends significantly on the mission requirements of the ship.

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