Improving attachments of remotely-deployed dorsal fin-mounted tags: tissue structure, hydrodynamics, in situ performance, and tagged-animal follow-up

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LONG-TERM GOALS

We recently developed small satellite-linked telemetry tags that are anchored with small attachment darts to the dorsal fins of small- and medium-sized cetaceans. These Low Impact Minimally-Percutaneous External-electronics Transmitter (LIMPET) tags have opened up the potential to monitor the movements of numerous species not previously accessible because they were too large or difficult to capture safely, but too small for tags that implant deeply within the body. One goal of this project is to improve upon our existing tagging methodology to achieve longer, less variable attachment durations by carefully examining the factors that affect attachment success. Our key goal is to develop a method for attaching tags to cetaceans that provides the data needed to answer critical conservation and management questions without an adverse effect on the tagged animal. Therefore, we will also conduct follow-up studies of whales that have been tagged with a remotely-deployed dorsal fin-mounted tag to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior. The combination of these approaches will provide an improved understanding of some of the key factors affecting tag attachment duration as well as a more complete understanding of impacts to individuals due to tagging.

OBJECTIVES

1. Design an improved barnacle-style tag shape for remote-deployment by assessing the hydrodynamic properties of tag shapes
2. Examine the tissue structure of the dorsal fin and its material properties for better informed implanted attachment design.
3. Examine the in situ performance of our current attachment devices and then design and test improved retention systems

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4. Conduct follow-up studies of tagged whales to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior

APPROACH

1. Hydrodynamics of tag shape (Key individuals: Mittal, Howle, Andrews, Schorr, Hanson): We will determine the drag on the tag through numerical modeling and analysis, primarily computational flow dynamics. High fidelity numerical simulations working in concert with physical experiments will be used to establish qualitative as well as quantitative relationships between tag configuration and the associated flow structure and surface pressure distribution, which is ultimately the key to the force/moments on the tag.

2. Dorsal fin tissue structure (Key individuals: Hanson): To evaluate the factors influencing tissue degradation (and therefore attachment duration) we will assess the anatomical factors likely to influence long-term viability. The harbor porpoise is the only species whose dorsal fin geometry and material properties have been fully described (Hanson 2001). Interspecific differences in these parameters may be an important factor in the variability in attachment duration, as might body size scaling effects. Consequently, we selected various species for examination based on differences such as size/shape of the dorsal fin (e.g., melon-headed versus killer whale), taxonomic grouping (i.e., odontocetes versus mysticetes), or dynamic behavior (*e.g*., beaked whale versus melon-headed whale).

3. In situ behavior of retention system elements (Key individuals: Andrews, Schorr, Hanson, Howle, Mittal): A key factor is the drag load imposed by the tag body but acting on the attachment elements implanted into the dorsal fin. Although we have a good idea of how the LIMPET retention system operates when first implanted, we do not fully understand the mechanics in a living fin. Therefore, we will attempt to simulate the tissue necrosis process to determine how the retention elements behave when surrounding tissues begin to lose their structural integrity. These results, along with those from the analysis of dorsal fin histology and material properties will inform modified designs.

4. Tagging effects - follow-up studies of survival, reproduction,& behavior (Key individuals: Baird, Schorr, Andrews, Hanson): More thorough assessments of the potential impacts on survival and reproduction of individuals, as well as assessment of healing of the tag attachment sites and potential behavioral changes associated with tagging, are needed to address concerns regarding sub-lethal and potentially lethal impacts of remotely-deployed tags. As part of an ongoing collaborative study, over 120 satellite and VHF tags have been remotely-deployed on 9 species of odontocetes around the main Hawaiian Islands. Re-sighting rates for the two species with the largest sample size of tag deployments, short-finned pilot whales (n = 48 individuals) and insular false killer whales (n = 27 individuals), are particularly high, as populations are small, individuals are relatively easy to approach, and there are sufficient encounters each year to have a high probability of re-sighting previously tagged whales. We will assess impacts of remotely-deployed tags on tagged animals at a variety of levels: from wound healing and potential behavioral effects of tag attachment to reproduction and survival. Wound healing assessment will be undertaken by examination of high resolution photographs of tag attachment sites by veterinarians and FLIR imaging of tagged whales before and after tag loss. Assessment of reproduction and survival of tagged whales will utilize existing photographic datasets as well as additional photos taken during this project.

WORK COMPLETED

Objective 1:
Work in computational fluids dynamics (CFD) modeling has focused on understanding the effect of tag design as well as tag orientation and location on hydrodynamics forces. Previous work has focused on drag but our hypothesis is that lift forces might also play an important role in tag detachment. A sequence of 3D, unsteady direct numerical simulations have been carried out for two different tag designs (old AM-240B and new AM-240C; Wildlife Computers model #'s) The simulations employ an immersed boundary solver that allows us to simulate flow past complex boundaries on fixed Cartesian grids (Mittal et al. 2008). The simulation, being 3D and unsteady, requires super computing resources and we employ large-scale parallel computers for these simulations. Given that the typical sequence of tag migration and eventual detachment involves an increase in the gap between the tag and the epidermal surface as well as an upward tilting of the leading edge of the tag, we have used CFD simulations to examine the effect of both these features on the hydrodynamic forces.

In preparation for water tunnel tests with physical models, a separate set of CFD simulations were run using the SolidWorks Flow Simulation package (Fig. 4). The simulations were run using incompressible flow conditions and used the turbulence model for flow speeds ranging from 1.0 to 10.0 ms^{-1} and orientations ranging from 0 to 90 degrees. Water tunnel experiments measuring lift, drag, and side force were made in the closed-circuit water tunnel at the United States Naval Academy using the Bellequant Engineering force measurement system (Weber et al. 2009, 2010; Fig. 5). The Reynolds number was changed over the range of 56,000 to 310,000 and flow orientations were varied from -20 to 90 degrees. Two configurations of the AM-S240C tag were tested, one with a smooth outer surface and one with a combination of convex and concave dimples to determine the drag-reducing effect of dimples.

Objective #2: We have made histological slides of four species of cetaceans: short-finned pilot whale, Bryde's whale, Cuvier's beaked whale, and melon-headed whale. Preliminary calculations of average percent area using image analysis software were made for the three major structural layers (*i.e*., collagen bearing layers): sub-papillary layer, vertical sheath and central core. The material properties of the major college bearing layers were also measured for these 4 fins using a uniaxial tester. Stress/strain curves were measured for these layers in various orientations

Objective #3: We are working to develop a way to simulate the tissue necrosis process and assess the performance of the retention system under steady state and high dynamic loads in tissue with reduced structural integrity. Initial work has utilized woven-mesh reinforced rubber as a substrate to simulate the dorsal fin. Key tests of the performance of the retention systems will be repeated in carcass dorsal fin tissue. In addition to studying the behavior of the tag retention system, we are also more closely examining our deployment methods. High-speed video review of ballistic flight paths revealed that as the tag and projecing arrow fly towards the dorsal fin, the arrow experiences a tag-down attitude during flight, caused by a high front-of-center weight that is exacerbated by the upward recoil of the rifle. Several modifications including shorter arrows were tested to correct for this. The flight path will determine the placement of the tag on the fin, and its orientation, which may play a role in attachment duration. Therefore we have also examined past tag deployments to determine whether there are any "better" areas or orientations on the fin.

Objective #4: In FY11 work was directed at two tasks. 1: Support for Wild Whale Research Foundation (WWRF) to obtain additional photos for tagged whale follow up and to increase the sample sizes for comparison of survival rates. 2: Sorting and matching of existing photos for species that had been satellite tagged to our long-term photo-ID catalogs. WWRF conducted a 21-day project off the island of Hawaii (Aug/Sep 2011), resulting in 25 encounters with 6 previously tagged species and over 30,000 photos. Additional photos were obtained from a variety of other contributors (whale or dolphin watching operators or other researchers) including encounters off Hawaii Island, Maui, and Oahu. We also obtained over 30,000 new photos of tagged species and deployed additional satellite tags through 4 CRC field projects supported by other sources. Of the 24 additional satellite tags deployed in FY11, 20 were on resident populations. Of these 20, 2 were on individuals that had been tagged prior to Nov. 2009, thus these additional deployments increase the sample size of tagged individuals from known resident populations that may be re-sighted for analyses of survival and reproduction from 78 individuals to 96 individuals.

All photographs obtained through Aug. 2011 of 4 of the 6 tagged species with photo-ID catalogs (false killer whales, 13,664 photos; pygmy killer whales, 18,405 photos; Cuvier's beaked whales, 2,348 photos; Blainville's beaked whales, 2,753 photos) have been matched to our catalogs. For short-finned pilot whales, all photos through 2009 and most photos from 2010 have been matched and added to our catalog (over 80,000 photos since the start of this NOPP project). Given the strong social bonds for false killer whales and short-finned pilot whales, it is only possible to re-sight previously tagged individuals if their social group is re-sighted. During FY11 analyses of photo-ID data were undertaken to identify social groups or clustering for both Hawaiian insular false killer whales and short-finned pilot whales off the island of Hawaii.

RESULTS

Objective 1: Figure 1 shows the computed vortex structures for the new tag (AM-240C) with zero gap and zero inclination. The flow over the tag and in the wake of the tag is highly three-dimensional and consists of a number of distinct vortex structures. The wake also exhibits vortex shedding. These features are typical for all the tag configurations studied. Figure 2 shows the effect of gap on the drag (Fx) and lift (Fy) forces on the tag. The drag force on the tag is relatively independent of the gap whereas in contrast, the lift force depends significantly on the gap. The lift force is highest for zero gap and decreases monotonically to a low value as the gap is increases. The highest value of lift for the zero gap is comparable to the value of drag. This implies that in its initial stages of attachment when the tag is snug with the epidermal surface, both lift and drag forces are important whereas with increasing gap (and zero inclination), drag becomes the dominant force on the tag. Figure 3 shows the effect of inclination on the hydrodynamics forces experienced by the tag. For the case with zero gap, a positive inclination of 5 degrees increases both the lift and drag. However, while the increase in drag is small (~ 15%), the increase in lift is very large (~ 50%). This leads to a situation where the lift is roughly twice the value of drag. A similar behavior is observed for a case with a finite gap (gap = ¼ the tag height); drag forces show marginal increase whereas lift forces increase by over 100% with a small inclination. Based on all of the above simulations, it is clear that the most unfavorable situation for the tag is when the gap is small and the inclination is large.

The Solidworks CFD results showed recirculation on the downstream side of the tag. This recirculation was found to result in unsteady vortex shedding (Fig. 6) for some flow speeds and orientations. The CFD-generated predictions of drag (Fig. 7) displayed typical quadratic dependence on flow speed. These CFD results were used to select the force transducers for our water tunnel study. Water tunnel experiments were run in 2 different measurement configurations. First we analyzed drag and side force, while in the 2nd measurement configuration we analyzed lift force. The drag coefficient (Fig. 8) was found to have high dependence on Reynolds number whereas the lift coefficient (Fig. 9) was found to have little dependence on Reynolds number. We found that neither the smooth nor the dimpled tag was a clear winner over the range of flow speeds and orientations we tested. There was, however, a reduction in peak lift coefficient at certain flow orientations for the dimpled tag so this tag design was found to be slightly preferable.

Objective #2: For a given structural layer, the collagen content of the 4 cetacean species examined varied substantially between species. In all species the vertical sheath had the highest collagen content of the three layers and the central core the least. Preliminary review of the material property data collected to date with the uniaxial tester appeared to reflect collagen content when tested in the primary axis of the fibers. A full assessment will be required to prior to concluding this association.

Objective #3: Median transmission duration was assessed for all SPOT5 deployments on pilot whales (n = 35). All variations of tag locations and orientations were compared and tested for significance. Attachments in the mid-fin (both top to bottom and anterior to posterior; Table 1) had longer median transmission durations, though none of the results were statistically significant.

Objective #4: For short-finned pilot whales off the island of Hawaii 41 dart tags have been deployed on 38 individuals between Apr. 2006 and Dec. 2010. Of the 41 deployments, tagged individuals have been re-sighted post-tag loss for 30 deployments (range 11-1689 days post-tag loss, median = 538 days). However, for the remaining 11 deployments with no resighting, there have been no sightings of the tagged whale's social group. Thus using photos analyzed to date there have been post-tag loss re-sightings of all 30 of the short-finned pilot whales tagged off the island of Hawaii where there has been a potential for re-sighting. For Hawaiian insular false killer whales, 7 social clusters have been identified (Baird et al. in prep). Of the 7, 1 cluster (Cluster 1) is seen regularly, 2 clusters are seen once or twice a year (Cluster 2 and 3), and the remaining 4 clusters are seen infrequently. Of the 27 individual Hawaiian insular false killer whales that have been satellite tagged, 16 were from Cluster 1, and all 16 individuals from this cluster have been re-sighted after tag loss[1]. Of the 15 tag deployments on individuals from Cluster 1 prior to Oct. 2010, re-sighting periods (tagging date thru most recent sighting) have ranged from 295 to 1,470 days (median = 828 d). Seven of the remaining 11 tagged false killer whales are from Cluster 3, but encounter rates with whales from this cluster are very low and 3 out of 7 Cluster 3 deployments were within the last 12 months, making it too early to assess re-sighting data for Cluster 3. Overall our high within-Cluster 1 re-sighting rates suggest that tagging has little or no impact on survival for Hawaiian insular false killer whales.

IMPACT/APPLICATIONS

National Security

Understanding the potential for impacts of naval activities on protected species of marine mammals, as well as estimating the number of individuals potentially impacted, and mitigating such impacts, all requires information on movements and habitat use. The development of better tag technologies and deployment techniques will make a significant contribution to the ability of researchers to track movements, monitor behavior, and determine distribution of species of interest. The improvements that we made to our location-only satellite tag and attachment system with previous ONR funding have already resulted in attachment durations well beyond our expectations and are currently being shared with other researchers so that they also can benefit from these advances.

Economic Development

[1] Two of these 16 individuals have been tagged twice. One has been re-sighted after tag loss for both taggings. The second was re-sighted after tag loss after the first tagging, but not yet after the second.

All improvements in methodology and technology will be shared with the marine mammal research community and companies that produce biotelemetry equipment, and this may lead to new economic opportunities for these entities. Our previous developments were made in close collaboration with a small business partner and have resulted the production of commercially available products that have been purchased by other researchers, and we anticipate a similar outcome from these current R&D efforts.

Quality of Life

The ability to track cetaceans that have never before been tracked will provide much-needed knowledge for improved management of their populations and the ecosytems in which they live.

TRANSITIONS

National Security

This project has resulted in improvements to our methods for tagging cetaceans and have been recently used to track animals in projects that are critical to understanding the impact of naval activities on protected species of marine mammals. For example, our methods have been used in the Southern California Behavioral Response Study (*e.g.* Southall et al. 2011) and for monitoring of beaked whales on the Southern California Offshore Range (*e.g.* Schorr et al. 2011).

Quality of Life

Improved tagging methods have also been applied to track cetaceans to provide critical data needed to protect endangered species and mitigate threats in the process of coastal resource management (*e.g.* Andrews et al. 2011; Baird et al. 2011; Falcone et al. 2011; Hanson et al. 2011).

RELATED PROJECTS

The National Marine Fisheries Service Pacific Islands Fisheries Science Center is supporting research on false killer whale movements in Hawaiian waters (Baird et al. 2010), and the Naval Postgraduate School (with funding from N45) is supporting tagging studies of a variety of species. Tag and deployment developments from this work are being incorporated into these ongoing studies. See:
www.cascadiaresearch.org/hawaii/beakedwhales.htm
www.cascadiaresearch.org/hawaii/falsekillerwhale.htm
www.cascadiaresearch.org/SCORE/SCOREMain.htm

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Tables and Figures

Table 1. Median (range, n) transmission duration (days) by location on the dorsal fin for all SPOT5 deployments on short-finned pilot whales (n = 35).

	Anterior -> Posterior		
	Leading	**Mid**	**Trailing**
Top	29.8 (29-31, 2)	49.6 (23-229, 6)	13.8 (1)
Mid	36.1 (17-73, 4)	52.0 (8-110,7)	39.2 (15-58,4)
Base		37.2 (10-66, 5)	25.4 (3-71, 6)

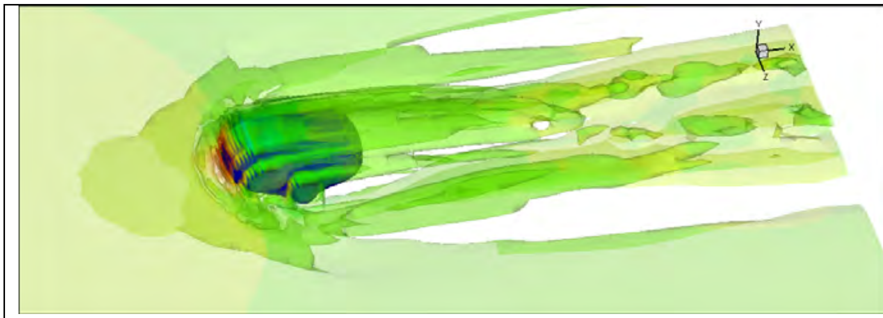
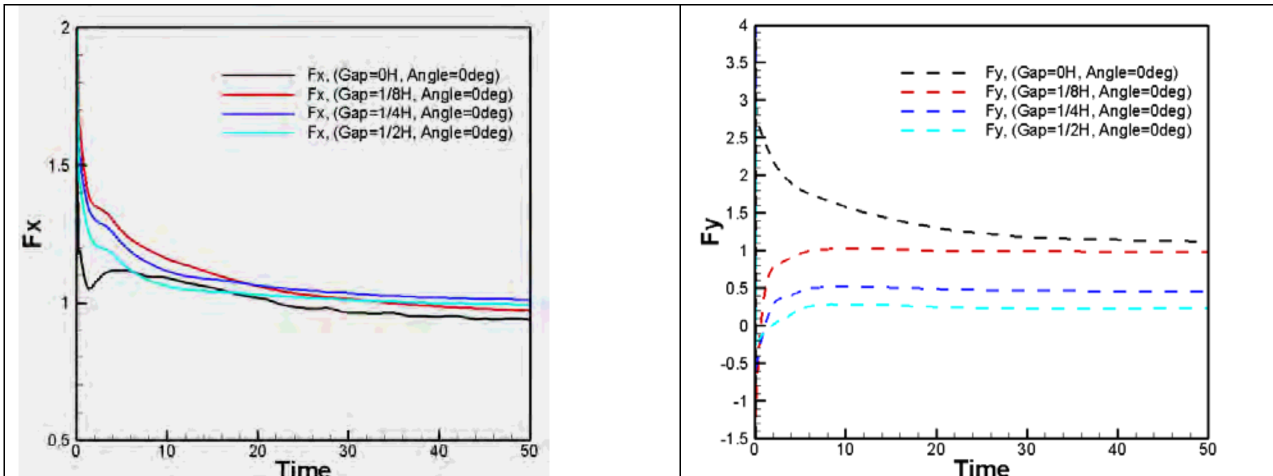
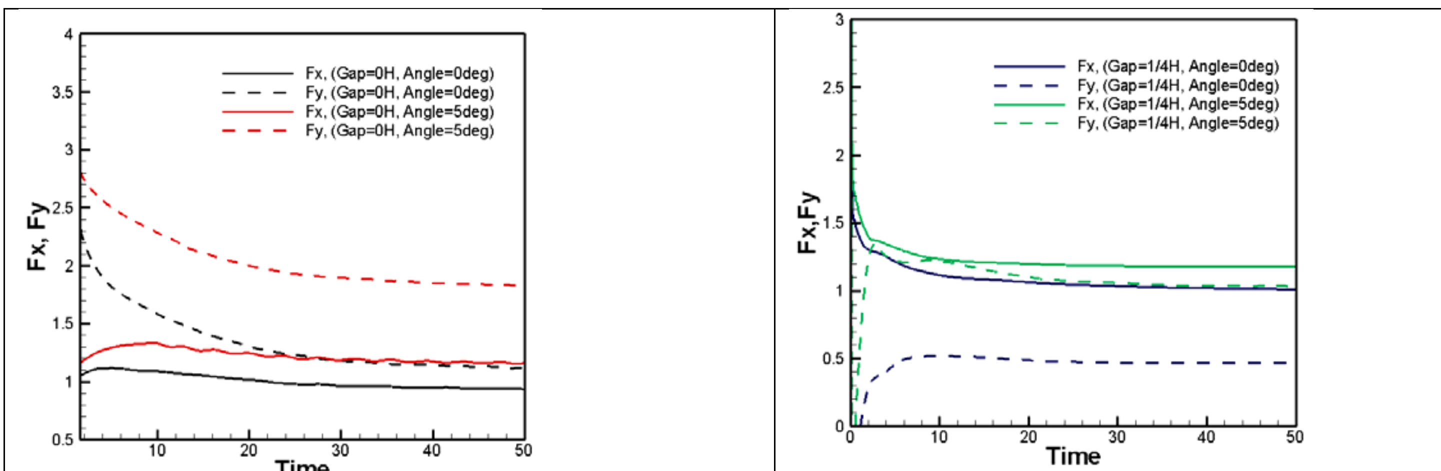


Fig. 1. Vortex structures computed for the new tag (AM-240C) with zero gap and zero inclination.



Drag | Lift

Fig. 2. CFD results for effect of gap on the drag and lift forces on tag AM-240C.



Zero gap | Finite gap

Fig. 3. CFD results for effect of inclination on the lift and drag forces on the tag

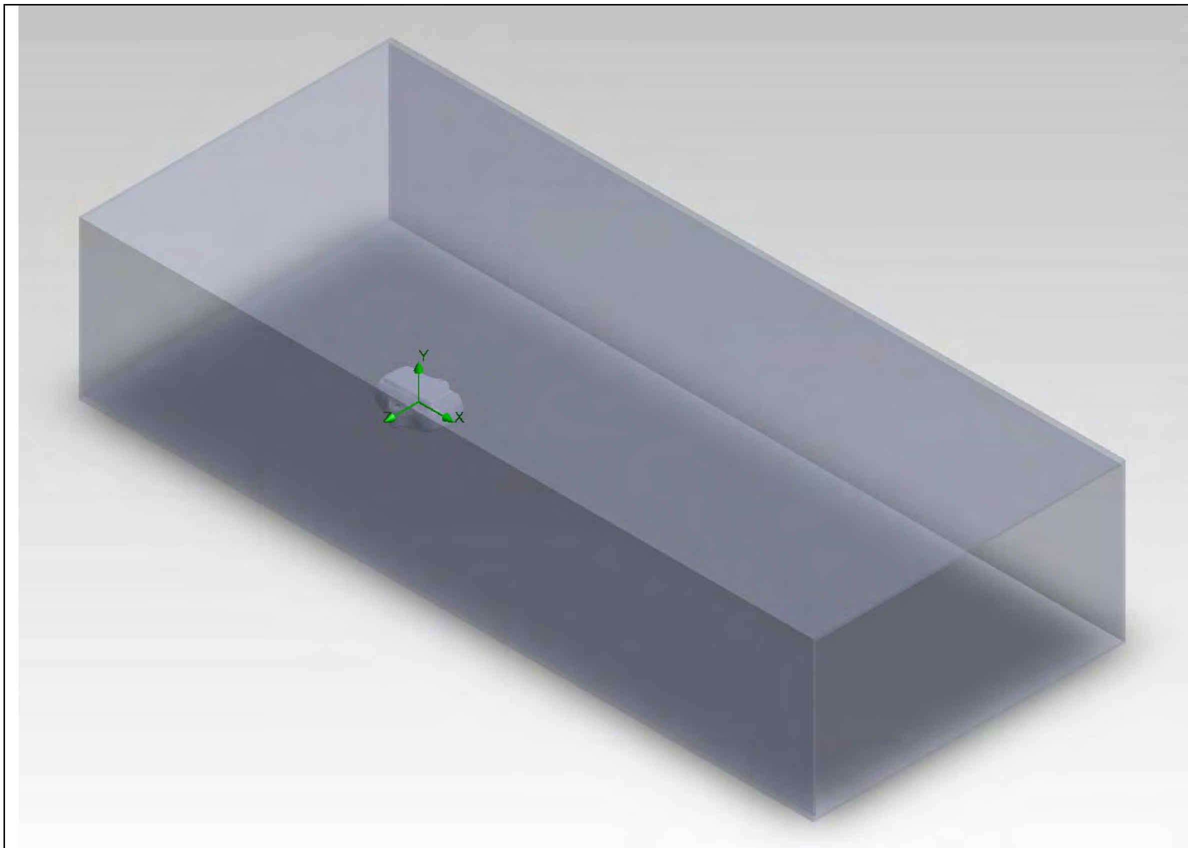


Fig. 4. AM-S240C tag showing computational domain for SolidWorks CFD studies.

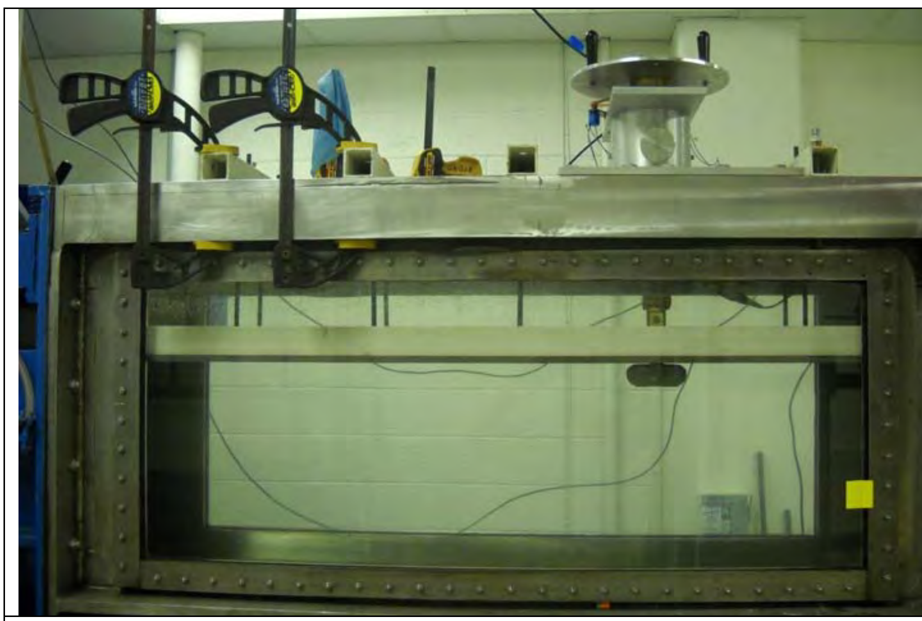


Fig. 5. AM-S240C tag mounted in the USNA water tunnel test section.

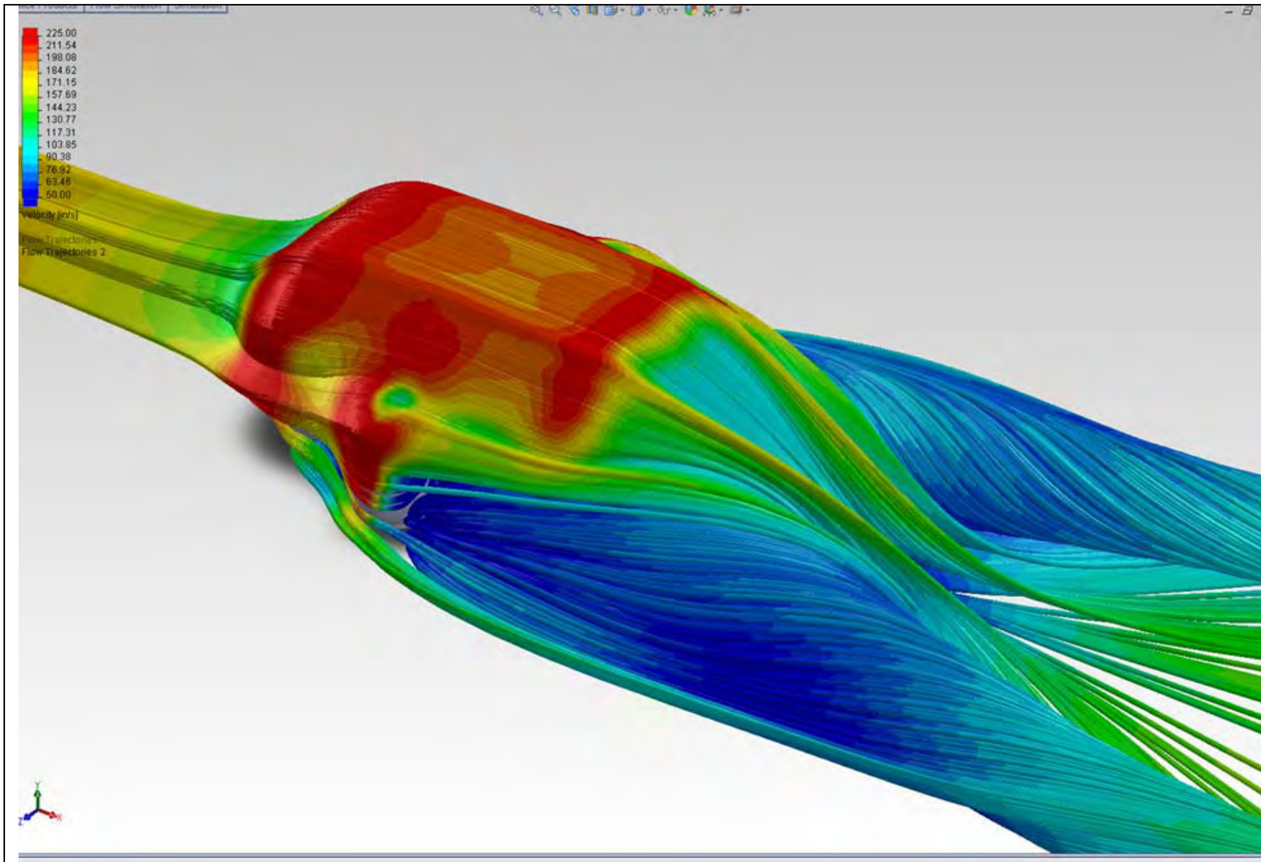


Fig. 6. Particle path lines for flow past the AM-S240C tag. In this SolidWorks CFD simulation, water flows from upper left to lower right. Notice the counter-rotating vortex pairs on the downstream end of the tag indicating lifting flow.

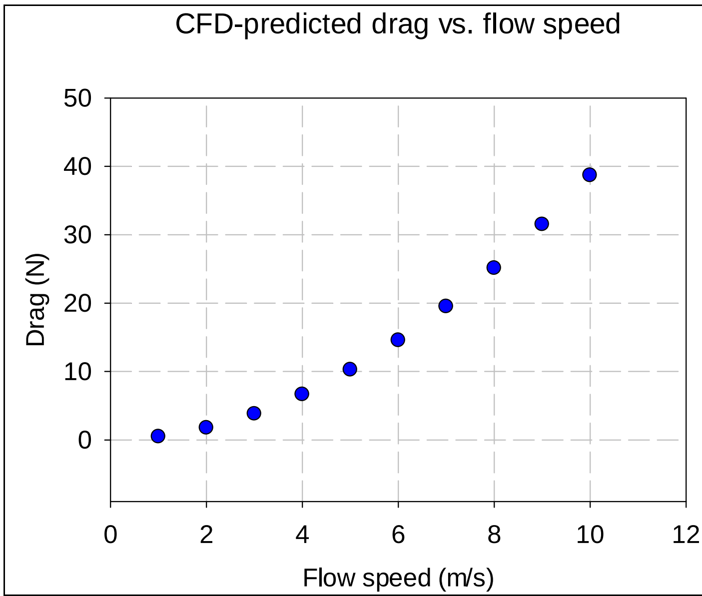


Fig. 7. SolidWorks CFD predictions of drag (Newtons) vs. flow speed (m/s).

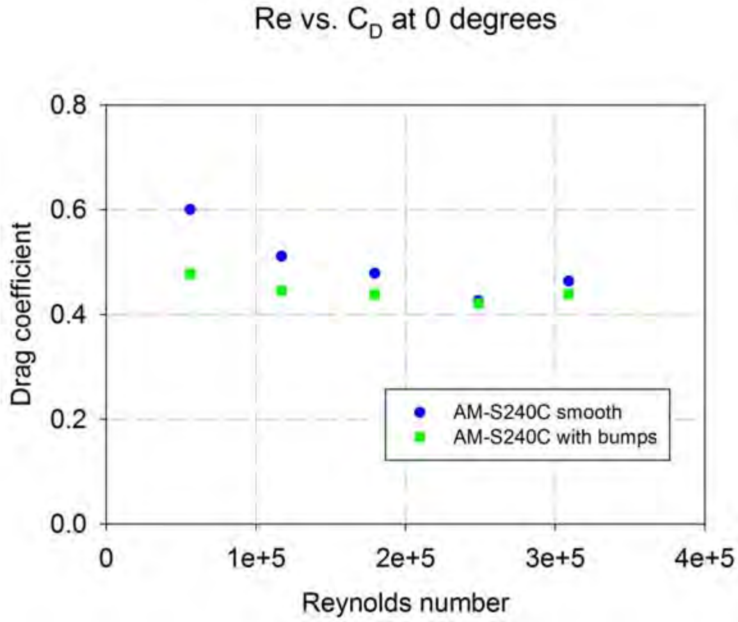


Fig. 8. Water tunnel results with tag AM-240C. Drag coefficient as a function of Reynolds number at the 0° orientation.

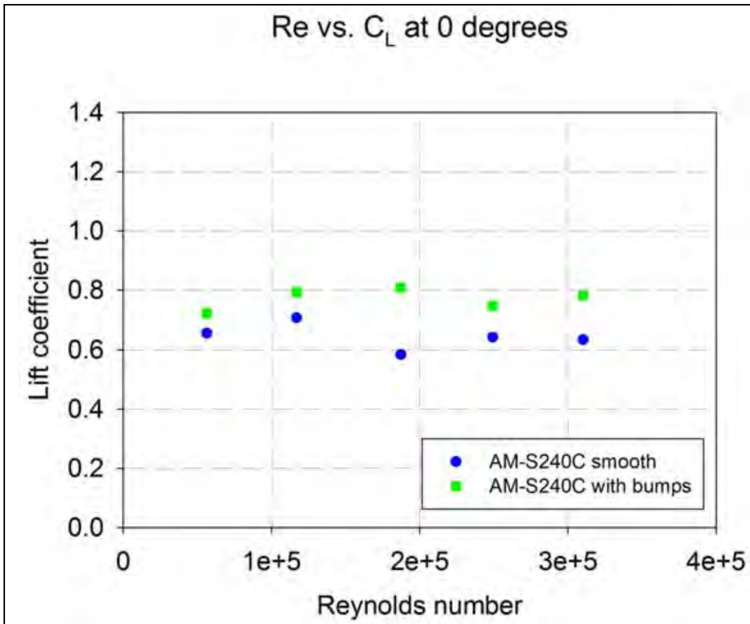


Fig. 9. Water tunnel results with tag AM-240C. Lift coefficient as a function of Reynolds number at the 0° flow orientation.