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Developing a Predictive Capability for Bioluminescence Signatures

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LONG-TERM GOALS

Bioluminescence represents an operational threat to naval nighttime operations because the flow field associated with their motion stimulates naturally occurring plankton. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that are also known to form red tides. Dinoflagellate bioluminescence is stimulated by flow stress of sufficient magnitude to cause cell deformation, such as in the boundary layers of swimming animals, in separated flow of the wakes of animals, fixed objects, and ships, and in breaking surface waves, leading to spectacular displays of bioluminescence during periods of high dinoflagellate abundance. The oceans can be considered a luminescent minefield where bioluminescence is stimulated by flow disturbance. The bioluminescent signatures of some swimming fish are distinct enough to differentiate species; nocturnally foraging predators may use bioluminescent wakes to locate their prey.

The bioluminescence signature of a moving object depends on the bioluminescence potential of the organisms (related to their species abundance), the volume of the flow regions associated of sufficient shear stress, and its detectability from a surface observer based on radiative transfer of the light through the water and surface interface, as well as surface ambient light conditions. We are interested in predicting bioluminescence signatures, specifically in developing the capability to model flow stimulated bioluminescence and applying the model to a computational fluid dynamics model of the flow field of a moving object, and exploring mitigation strategies that reduce the bioluminescence signature to reduce the threat of detection of moving underwater vehicles.

OBJECTIVES

An extremely challenging goal is to accurately predict the intensity and spatial footprint of bioluminescence signatures of naval relevance. Advances in computational fluid dynamics (CFD) led by PI Hyman make it possible to model the flow around a moving object, and now a new bioluminescence stimulation (BIOSTIM) model developed by PI's Deane and Stokes (Deane and Stokes 2005) provides an initial capability to estimate bioluminescence levels as a function of flow properties, specifically fluid shear stress, which we have previously shown to be the flow property most closely correlated with flow-stimulated bioluminescence in primarily laminar flows (Latz et al. 1994; Latz et al. 2004; Latz and Rohr 1999; Maldonado and Latz 2007).

The overall scientific objectives of this project are to: (1) perform calibration experiments to determine the relationship between bioluminescence stimulation and fluid shear stress; (2) update the BIOSTIM model based on the calibration experiments results to include a high shear stress stimulation component; (3) evaluate computational approaches using Reynolds-averaged Navier-Stokes (RaNS) and Direct Numerical Simulation (DNS) solvers, to determine which is more suitable for bioluminescence predictions; (4) validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are characterized using CFD models, so that model predictions of bioluminescence intensity can be compared to experimental results; and (5) couple the BIOSTIM and CFD models to provide a unique flow visualization tool, which can be used to predict bioluminescence signatures for flow fields of naval interest.

APPROACH

The current probabilistic model for bioluminescence stimulation (BIOSTIM) contains three components to allow for: (1) direct stimulation by the local fluid shear stress field, (2) rate-of-change of fluid shear stress, and (3) a memory term to allow for cell desensitization resulting from prolonged exposure to stimulation. The model is based on the fundamental assumption that over any small time interval there is a small but finite chance that a cell will flash, which depends on these three factors. This study considers the case of intense but brief stimulation lasting for no more than a few seconds. In this case we do not have to account for the effects of cell desensitization (von Dassow et al. 2005) and cell memory, greatly simplifying the experiments and analysis required to model the effects of turbulence.

The overall objective of this study has been to obtain bioluminescence stimulation data under conditions of high shear stress to feed into the BIOSTIM model, which then is incorporated into CFD models to predict bioluminescence signatures created by bodies traveling in or on the ocean. The most generally applicable simulation techniques are algorithms that solve the unsteady Reynolds-averaged Navier-Stokes u(RaNS) equations and compute the ensemble-averaged velocities, as well as turbulent energy and energy dissipation fields throughout a given flow, allowing an estimation of local (averaged) turbulent shear stress. The uRaNS algorithm used was CFDSHIP-IOWA, a well-documented algorithm (Carrica et al. 2006) previously used by PI Hyman and verified with full-scale tests with many types of naval ships. However, such algorithms cannot resolve the very small scales that are responsible for bioluminescent stimulation. The action of such small-scale turbulence is approximately characterized by the averaged energy dissipation rate – a modeled quantity. In contrast, the BIOSTIM model, as currently written, is most appropriate for use in a Direct Numerical Simulation (DNS) solver. DNS solutions capture all relevant length and temporal scales in the flow including bioluminescence stimulatory scales (these are in the Kolmogorov or inertial range, depending on

Reynolds number). To accomplish this, however, the solvers require extremely fine grids – grids that become too large when flow simulation of model-scale vehicles is attempted and far too large to be considered for full-scale naval vehicles. Therefore the new bioluminescence stimulation model developed in Task 2 will accept the ensemble-averaged flow data produced during a practical flow simulation as a means of determining stimulation probability.

The final task was to validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are modeled using computational fluid dynamics (CFD), so that model predictions of bioluminescence intensity can be compared to experimental results. It is critical to validate the updated BIOSTIM model to determine how predicted results compare to experimental measurements with independent flow fields. The BIOSTIM model is coupled to the CFD model of a body mounted in a flow field to predict levels of stimulated bioluminescence. A new vertical test tank with a 122 cm square cross section was used for the validation tests. Test bodies are attached to a non-stretchable line, which ran on an overhead pulley, and connected to a stepper motor under computer control for acceleration, speed, and distance. Speeds up to 4 m/s in air are possible with this setup. Bioluminescence was measured with a low-light digital camera system to quantify stimulation in the boundary layer and wake regions. The experimental results are then compared to the coupled BIOSTIM-CFD model predictions.

WORK COMPLETED

Computational work. During the past year, work continued on improving the CFD simulation of flow, shear stress and related bioluminescent stimulation in the wake of a sphere and expanding the work to other bodies of interest. Computations in FY 10 and FY 11 were encouraging, but the stimulation probability computed using those solutions showed a much smaller geometry than the images from tow tank measurements. Very high resolution, high order-of-accuracy computations using a Cartesian grid code with immersed-boundary (Yang and Stern, 2010) revealed that grids with spacing on the order of a Kolmogorov length scale are required to obtain accurate turbulent flow structure in the separated wake behind a sphere. Once that was accomplished, flow simulations like those seen in figure 1 could establish a good baseline for modeling purposes. Concurrent work in FY 11 and FY12 that attempted to obtain DNS solution around a high aspect ratio spheroid was not successful – too little turbulence was generated by the CFD sphereoid model to stimulate bioluminescent organisms. In addition, some ambiguity existed in the laboratory images for that geometry. The ambiguity was created by the requirement that the test object had to be supported by a wire ahead of and behind the body. Bioluminescent stimulation by the wire obscured the low stimulation associated with the body. The experience led us to restriction our work to spheres. Other bodies that create a very turbulent wake would also have been applicable.

At this point, it may be useful to revisit the goals and approaches of the effort, colored by experience. The goal was and continues to be the development of a model of bioluminescence stimulation that can be used with engineering level flow solvers. As noted above, these flow solvers cannot, and will not for many years, be capable of resolving very small scale flow structures, i.e., turbulent eddies, which control the shear field around bodies of interest, on the scale that is leads to stimulation. Instead, they can capture ensemble-averaged flow, effectively integrating over the entire spectrum of turbulent structures that are present in the flow. The reason is that as the body of interest becomes larger, the range of size of turbulent structures becomes larger. A sphere of with diameter of 0.01 m moving at 1 m/s ($Re = 10^4$) will exhibit a turbulent wake with structures ranging in size between 100 microns to 0.1-0.2 m. A sphere of size 1 m moving at 10 m/s ($Re=10^7$, i.e., flows of naval interest) will exhibit a

wake with structures of size 1 micron to 1 m, or three orders of magnitude greater range than the smaller sphere and requiring a grid much larger that currently possible. Even if the solver only needs to resolve the shear field around an organism (L >300 microns), the grid is still prohibitively large and in practice, only the largest turbulent scales will be resolved if they are resolved at all. The most common engineering level solvers focus on computing an ensemble-averaged (either steady or unsteady) flow field with either coherent structures not resolved (steady) or resolved (unsteady). In neither case are uncoherent turbulent structures resolved. There are other approaches, such as DES or LES, which begin to address both the unsteady coherent structures and the largest (in the case of DES) or larger (in the case of LES) turbulent structures. For the sake of brevity in the present discussion, we will ignore those approaches and focus on uRaNS algorithms. These algorithms solve a form of the Navier-Stokes equations in which turbulence at all scales is averaged out. The effect of turbulence is modeled via a selection of turbulence models, usually chosen to best achieve the goals of the simulation. At present, it is reasonable to assume that some two-equation model such as the widely used k-epsilon/k-omega model will be applied in simulations of flows with the intent of determining bioluminescent stimulation. Such a model will provide a 3-D field of turbulence kinetic energy (k), energy dissipation rate (epsilon) and an effective viscosity. Using these, a 3-D stress field can be computed but it has a relatively weak relationship to the local stress field that a bioluminescent organism "feels". There is an important point hiding in this discussion. An ensemble-averaged flow model (and shear field) should never be expected to correctly produce an instantaneous bioluminescent signature and attempts to do so will fail. Instead, they may be capable of predicting an **averaged** signature, the average being over several (large scale) turbulent structure turn-over times.

As a result of these considerations, our approach was to first compute the high resolution shear field (i.e., with resolution comparable to the size of a bioluminescent organism) around a small body such as a 32 mm diameter sphere (Re=30000). For this body, the smallest turbulent structures are on the order of 100 microns that can be resolved with a reasonable grid (150 million points) and still be comparable in size to a bioluminescent organism. This shear field was used directly by the BIOSTIM model to estimate stimulation probability. This was followed by a computation using an uRaNS flow solver with much coarser resolution and a two-equation turbulence model. In other words, obtain a flow solution very analogous to a ship or underwater mammal flow solution.

Knowing that a coarse grid solution could not capture the shear field **local** to a bioluminescent organism, it was hypothesized that a "correction" factor could be constructed that would enable the ensemble-averaged shear field to be used to estimate the organism-scale shear field. However, in hindsight, it is clear that the correction factor is likely to be sensitive to the range of scales over which it must "correct". In other words, it is likely to be Reynolds Number dependent. In our work, we focused on a small sphere with only about two orders of magnitude range between organism size and large structure size. In real applications, the range will be nearer 4 orders of magnitude. It is possible that the correction factor obtained in our work will be inadequate for these bodies.

The procedure of bioluminescence image simulation of a particular flow (such as a small sphere) is as follows. First a high resolution flow field is computed. Using this field, the associated shear field can be constructed via differentiation. The shear field is then used in the BIOSTIM model to estimate probability of stimulation at each location in the 3-D domain. If the concentration of organisms in the flow of interest is known, then the number of cells stimulated per unit time at all points in the flow can be computed. Since a camera image is what will be used for comparison, the number of stimulated cells in each volume must be integrated along the direction normal to the camera plane – this produces a 2-D array of values (cells/sec). Each cell produces a given number of photons when stimulated and,

using these results together with knowledge of the false color mapping used by a camera, a synthetic image can be produced that should be roughly comparable to that produced by a camera. The comparison is approximate because there is an issue with time scales. The camera has a shutter speed, the organisms have a flash duration, and the computation has a time step. They are all different and the effects of each must be considered. The computational time step is chosen to be less than the turnover time of the smallest resolved turbulent structure and is on the order of 10^{-5} s. We are implicitly assuming that an organism will flash when stimulated at, or above the threshold used by the BIOSTIM model for any length of time. Flash durations of bioluminescent organisms are on the order of 100 ms, or 10^4 times the computational time step and, when immersed in a flow of 1 m/s, means that the organism will travel 0.1 m over the course of a flash – the flash becomes a streak. This, in turn, implies that, once stimulated, an organism will be emitting light for a comparatively long time, after it has passed through the region of flow that stimulated it. Finally there is the camera shutter speed. The images acquired in the measurement phase of the work were obtained using a camera with shutter speed of 50 ms. So a flashing organism will likely be emitting light during the entire time that the camera is recording an image and will be traveling across the field of view while flashing. Since we are not following the trajectory of an organism, all the synthetic images will be an underestimate of a single camera image.

RESULTS

1. Computational work. Earlier in the project the flow field at very high resolution was computed around a sphere. This was motivated by the first year experimental effort devoted to obtaining bioluminescent images of a small (32 mm) diameter sphere. Results from a sequence of increasingly better resolution computations are shown in Figure 1 for the velocity field and for the corresponding stimulation field. While a grid convergence study has not been performed (clearly the grid was not converged in the earlier solutions), the fact that shear stress above the stimulation threshold does not extend to the end of the high resolution grid suggests that this grid is at or close to convergence. In addition, the stimulation field geometry is more similar to that seen in the tow tank images. The stimulation region extends nearly 2.5 diameters downstream and exhibits a roughly cylindrical shape. The solution strongly suggests that unsteady vortex shedding should lead to a stimulation field a little larger than the sphere diameter, a prediction not seen in the tow tank images. In addition, the maximum stimulation probability is a small distance downstream of the body, also in contrast to the images.

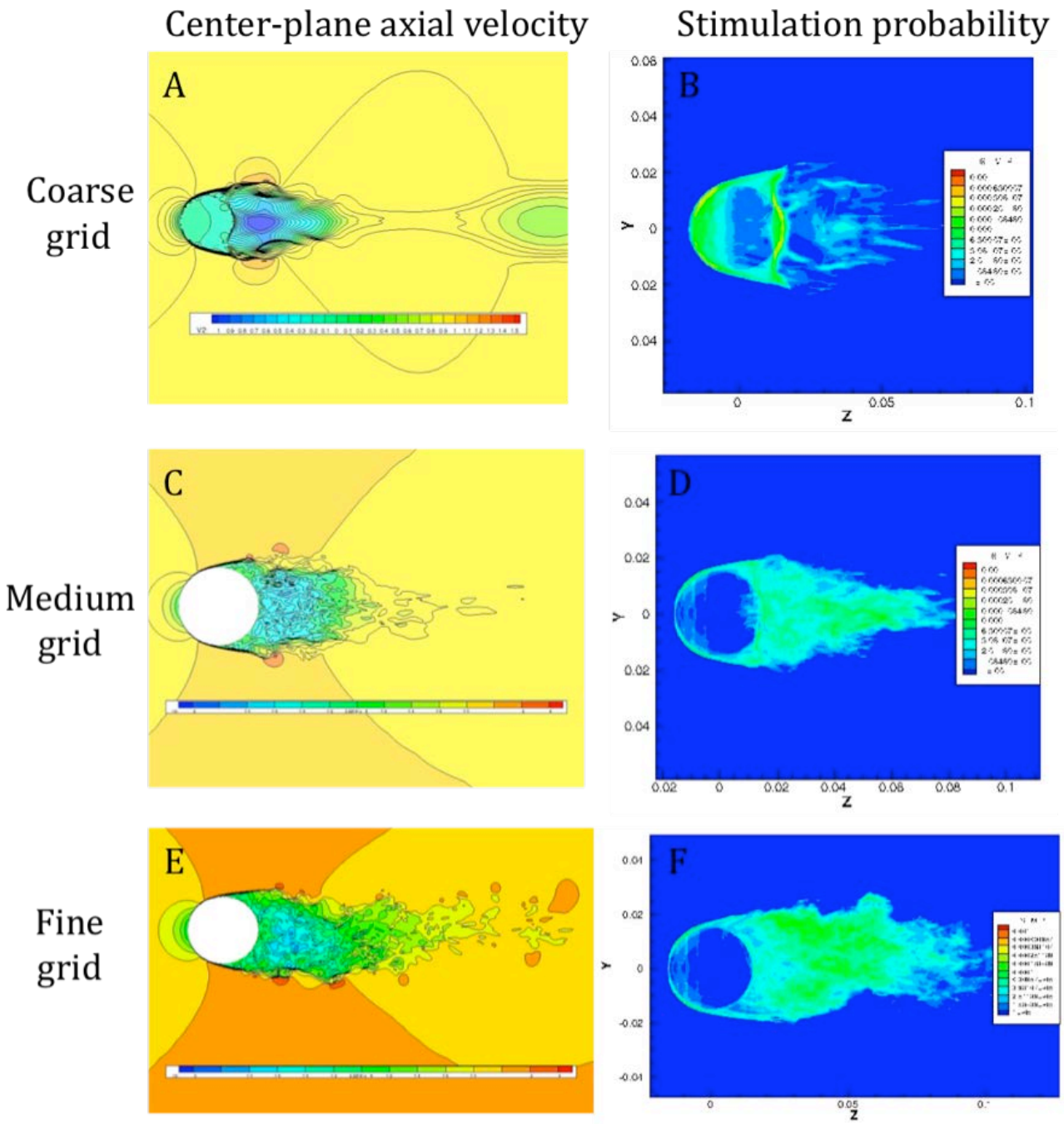

Figure 1. Contour plots for a 32 mm diameter sphere, moving to the left at a speed of 1 m/s (Re=30000), of computed center-plane instantaneous axial velocity field (left column) based on direct numerical solutions, and the probability of bioluminescence stimulation (right column) around a sphere, based on integrating the computational flow dynamics model with the bioluminescence stimulation model. (A-B) Results for the original coarse resolution grid. (C-D) Results for a medium resolution 351 x 351 x 601 grid. (C-D) Results for a fine resolution 351 x 351 x 801 grid. The stimulation region extends nearly 2.5 diameters downstream and exhibits a roughly cylindrical shape. The solution strongly suggests that unsteady vortex shedding should lead to a stimulation field a little larger than the sphere diameter, and that maximum stimulation probability peaks at a small distance downstream of the body.

Beginning with the fine grid solution, the shear stress field can be computed using local velocity gradients and viscosity. The result is shown in Figure 2 along the sphere centerline. It can be readily seen that the grid resolution becomes coarse enough beyond 4 diameters that the solution is damped out. However, most of our interest is in the near field and in this region, the resolution is quite adequate

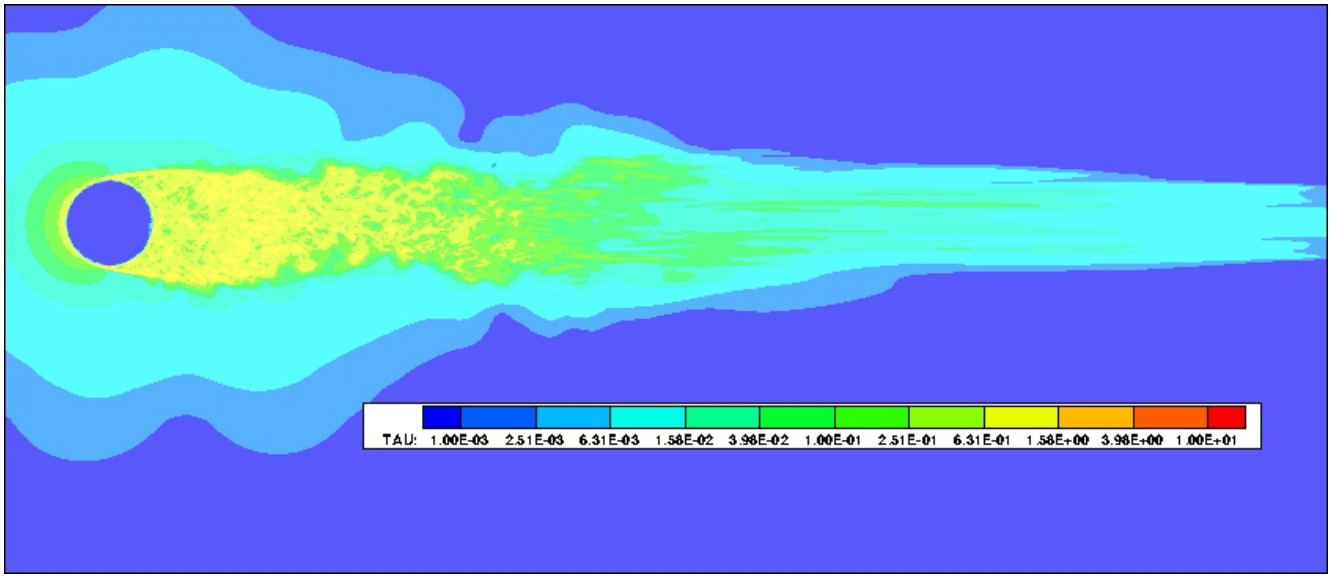

Figure 2. Contour plot of the centerplane stress field computed using the DNS solution around a sphere at Re=30000.

The stress field can be used with the BIOSTIM model to compute a 3-D stimulation probability field. That field in turn, can be integrated along the line-of-sight of a viewer, producing the effective 2-D stimulation field shown in Figure 3.

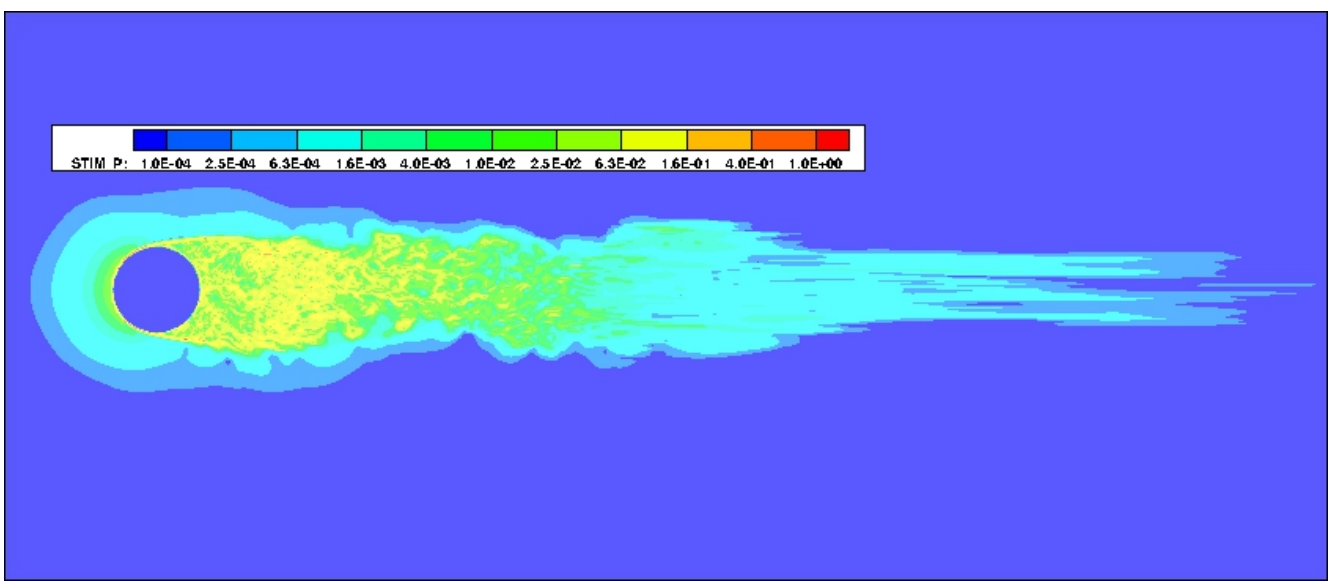

Figure 3. Contour plot of the 2-D stimilation probability computed using the stress field in Figure 3 and the BIOSTIM model around a sphere at Re=30000 and integrated along a ray into the image.

Using this result, attention can now be focused on the solution that would be computed using a uRaNS algorithm. Figure 4 shows the centerline stress field from such a solution. It can be immediately noted that the stress field obtained from the uRaNS solution is larger by a factor of five than the stress field obtained from the (near) DNS solution. We will assume that this is effectively the correction factor and proceed accordingly. It should also be noted that the uRaNS solution was indeed unsteady – the wake meandered up and down with time. Figure 4 shows only one time step of that unsteady simulation.

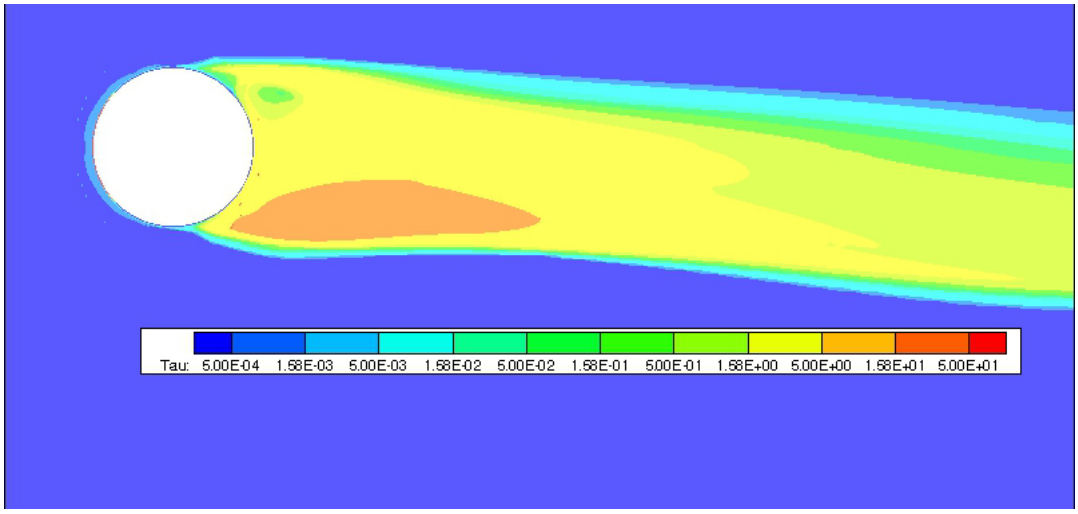

Figure 4. Contour plot of the centerplane stress field computed using the uRaNS solution around a sphere at Re=30000.

If the **uncorrected** uRaNS stress field is used to compute a stimulation probablity field, the result shown in Figure 5 will be produced. Note that the image in figure 5 is a 2-D field, with values stimulation probablility integrated along the viewers line-of-sight.

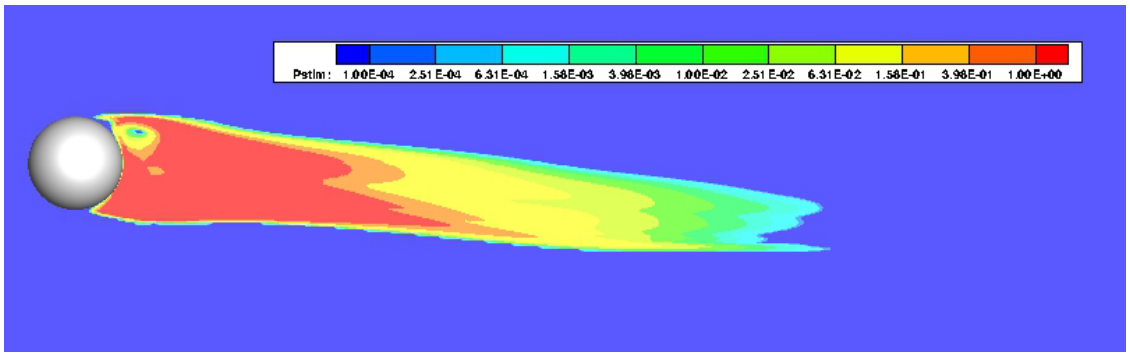

Figure 5. Contour plot of the 2-D stimulation probability computed using the uRaNS solution-derived stress field and the BIOSTIM model around a sphere at Re=30000.

If instead the **corrected** uRaNS stress field is used in the same way, results like those in Figure 6 will be obtained. Up until this point, the proceedure has been independent of bioluminescent organism concentration or characteristics but in order to compare these results with measurements, that information must be included.

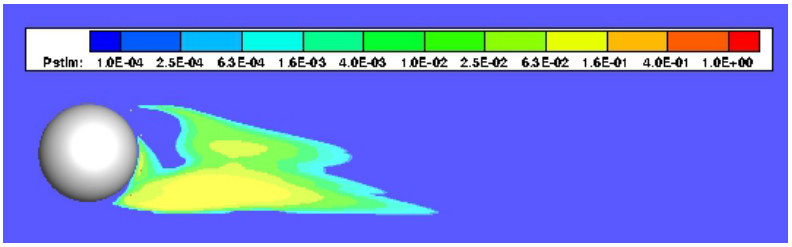

Figure 6. Contour plot of the modified 2-D stimulation probability computed using the uRaNS solution-derived stress field and the BIOSTIM model around a sphere at Re=30000.

Measurements made at Scripps Institution of Oceanography during the first year of this project include false color images made of the bioluminescence stimulation behind the sphere used in all the above computations. The images were a composite of 5 or more independent images taked with a shutter speed of 1/20 second in a tank with a 32 cell/ml concentration of *Lingulodinium polyedrum*, a bioluminescent dinoflagellate species commonly used in laboratory work. These images can be cautiously compared to the calculations if the cell concentrations are accounted for. The results are shown in Figure 7 A and B showing the predicted number of flashing cells (A) and the 5-frame averaged number of flashing cells (B). The results are in fair agreement; the model is predicting a stimulation rate that is less than a factor of 2 different from the measured stimulation rate and with very similar spatial distribution.

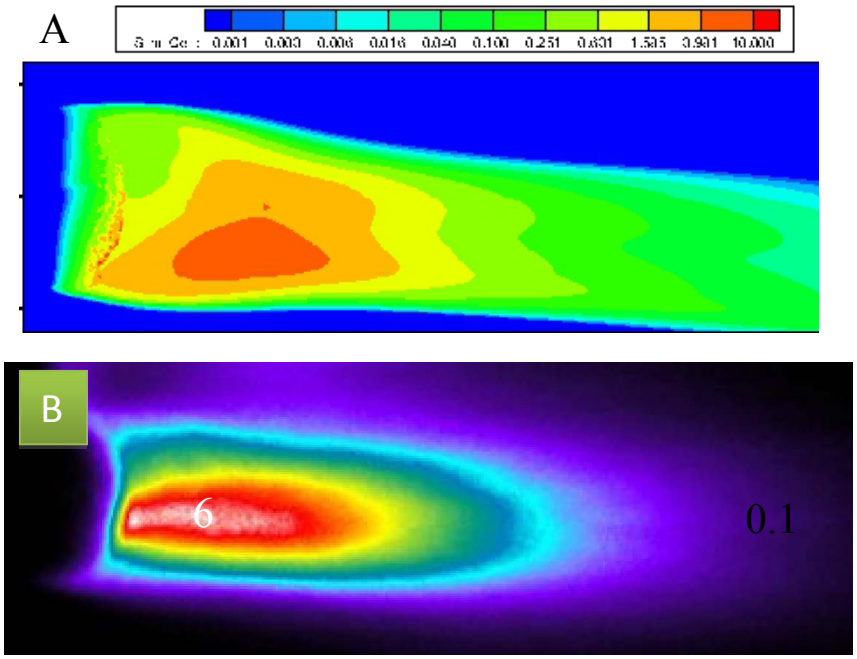

Figure 7. Contour plots of the A, cell stimulation rate computed using the uRaNS solution-derived stress field and the BIOSTIM model around a sphere at Re=30000, and B, false color image taken with a sphere at Re=30000 taken a SIO in a tank with 32 cell/ml concentration of* Lingulodinium polyedrum**.

In making the comparison in Figure 7, it is argued that a comparison between an image derived from an ensemble-averaged flow calculation with an image derived from multiple, averaged images is valid. The same comparison with a uRaNS-derived synthetic image and a single,essentially instantaneous laboratory image would not be as valid. In addition, it is noted that, as argued earlier, we should expect the symthetic image to be an underestimate of a comparable laboratory image and we observe that it is.

It is noted that the correction factor used to obtain these results is approximately the same as the ratio of body characteristic length (32 mm) and the size of energy-containing turbulent structures (obtained from the uRaNS solution – 7 mm). Though not a rigorous extrapolation due to the very different range of scales, if that idea is used to construct a correction factor and used with a larger body (a harbor porpoise with pectoral fins removed), the results in Figure 8 are obtained for stimulation probability along the centerline. The figure suggests that an intense bioluminescent near-wake could be expected for a 1 m long animal moving at 5 m/s (10 knots). In addition, very intense stimulation in the animal's boundary layer should be observable, particularly in the streamwise vorticies that are formed between the mid-section and fluke.

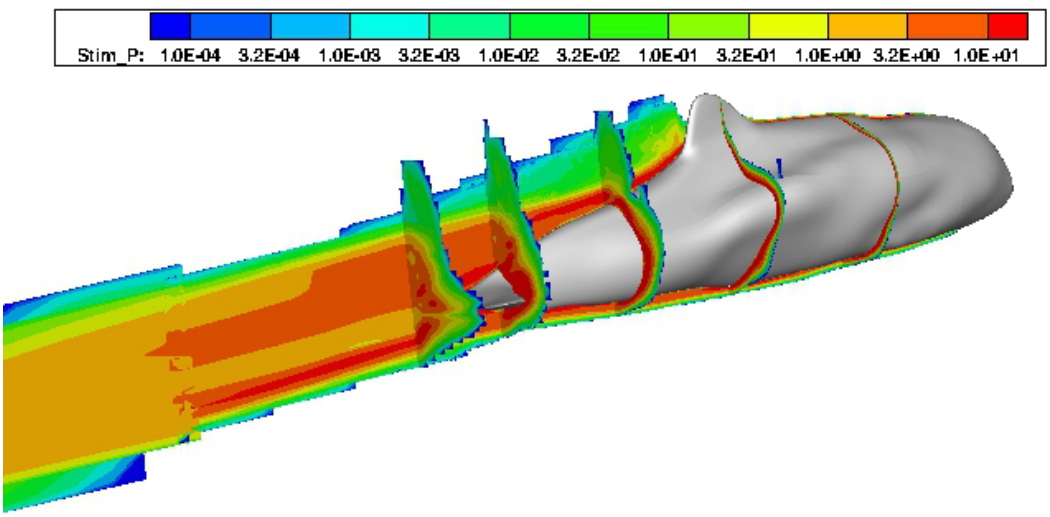

Figure 7. Contour plots of the stimulation probability computed using the (modified) uRaNS solution-derived stress field and the BIOSTIM model of a harbor porpoise at Re=4.5 million.

IMPACT/APPLICATIONS

Project results will enhance DoD capability for predicting levels of bioluminescence associated with surface and underwater vehicles of naval interest. The BIOSTIM model can be used in applications involving swimmer delivery vehicles and other submersible platforms, as well as torpedoes and other high-speed objects. The breakthrough in providing this capability is the development and application of the BIOSTIM model, developed by Deane and Stokes, that forms a theoretical basis for studying the relationship between flow stimulation and the bioluminescence response. The BIOSTIM model, when coupled to computational hydrodynamics models that provides values of shear stress for a given flow field, allows for predictions bioluminescence intensity for a given level of bioluminescence potential, either measured directly or obtained from the NAVOCEANO METOC database once a transfer function between the flow agitator and flow field is known.

A coupled BIOSTIM-CFD model introduces a new predictive capability for estimated bioluminescence signatures. A validated model can then be verified with full-scale experiments with surface ships and underwater vehicles of naval interest. In situations where field tests are not possible, once a transfer function between the flow agitator and flow field is known, it can be used with the NAVOCEANO METOC database of bioluminescence potential measurements to predict bioluminescence signatures in essentially any oceanic region. The Non-acoustical Optical Vulnerability Assessment Software (NOVAS) being developed by NRL (Matulewski and McBride 2005) has a placeholder in which the coupled BIOSTIM-CFD model can be incorporated into the nighttime visibility assessment component.

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