VISUALIZATION OF SUBMARINE TOWED ARRAY DEFORMATION

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Acoustic information obtained from submarine towed line arrays is an important component in the determination of the undersea battlespace tactical picture. Currently, acoustic towed arrays are limited in their continuous utility by the influence of array aperture deformation and hydrodynamic flow excitation that occurs when a submarine maneuvers and the array shape distorts. Array quasi-static and dynamic deformation behavior results from: 1) hydrodynamic drag and lift induced mechanical stresses on the array, 2) distortion of the array beam patterns caused by deformation of the linear aperture, 3) elevated noise levels on parts of the array due to Strouhal induced vortex shedding, and 4) interaction of the deformed acoustic beam pattern with the boundary limits of the media, i.e. the bottom and surface. An understanding of all of these components, which are truly 3-dimensional, can be facilitated by display in an immersive 3-D environment such as a *CAVE*™ or a Passive Stereo Wall. Such environments support the rapid, cost effective exploration of complex datasets to streamline the process through which high-fidelity modeling and simulation information is transformed into engineering insight. A true 3-dimensional view of the physical and acoustic forces affecting the array could visually define and locate key features to be investigated for optimizing towed array performance during submarine maneuver allowing for reduced loss of signal time on this tactically significant sensor.

This paper explores a methodology for modeling towed array behavior, both physically and acoustically, and displaying that information in a 3-D immersive environment. Kinematic and acoustic models to predict array behavior where developed by the Naval Undersea Warfare Center. Examination of an infinite iso-sound-velocity medium was chosen for clarity of display.

1 Introduction

The objective of this work is to design, develop, and assess 3-D visualization as an aid for understanding the deformation of towed array beam pattern signal strength as it relates to submarine maneuvering and target detection. Towed line arrays are an important tool used by submarines for long-range target detection. A towed array is string of passive hydrophones towed at some distance behind the submarine. By separating the hydrophones from the submarine, the array is no longer limited by platform noise, thereby increasing detection range. Because the towed array can be made as long as necessary, it can detect sounds of extremely long wavelengths, i.e. low frequencies. Since low frequency sounds travels much farther through the ocean than high frequency, this allows for very long detection ranges. Figure 1 depicts a typical towed array system.

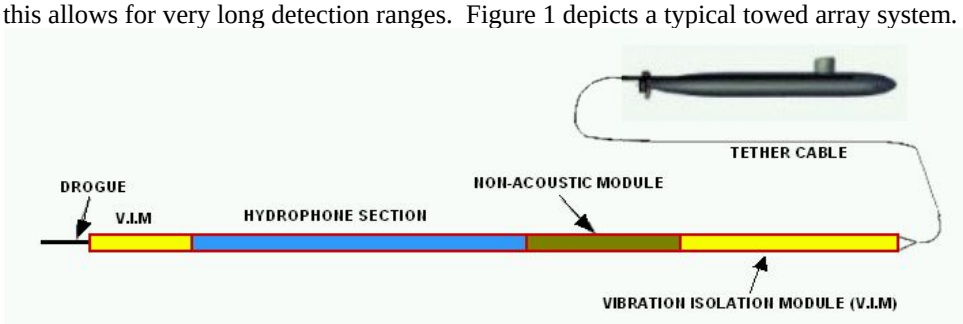

Figure 1. Typical Towed Array System.

The Submarine Force is making significant improvements in acoustic sensors and processing. Operational beamformers for towed arrays currently assume the array geometry to be straight and horizontally aft of the tow ship. In reality, there is always some deformation from this geometry. The major limitation in current systems is that beam forming cannot be carried out when the ship is maneuvering, which can result in downtimes as great as 50 percent [3]. Legacy submarine combat systems utilize a stiff stick model to estimate towed array position and heading. Currently heading and depth sensors measure these deformations with varying degrees of success. The newer tactical systems are equipped with sensors to accurately determine towed array position and heading. This information is more accurate than either the chain link or stiff stick models and should be used, when available, to optimize "target localization"[1] when obtaining Target Motion Analysis (TMA) solutions.

A significant problem for acousticians is the visualization of the three-dimensional beam patterns outputted from advanced beamformers that are incorporating the towed array position and heading information. Towed array behavior is counterintuitive and constantly changing resulting in complex time varying 3-D volumetric beam patterns of variable signal strength and side lobe size. By developing an effective means to observe these constantly changing signal detection relationships the acoustician can better understand when and when not to use towed array information for target detection.

The outputs of a towed array 3-D beamformer are beam patterns called conical angles. A conical angle represents the angle at which energy from a target was received at the horizontal array towed by the submarine. The information the conical angle provides is truly 3-D providing a "cone" that contains a contact somewhere on its surface (see figure 2). Traditionally conical angles been processed as a single 2-D depth slice of the ideal 3-D conical angle [1]. The reason for this traditional representation is simple; the computational power did not exist to visualize the full three-dimensional "ideal" cone or realistic cones generated by high-resolution acoustic beamformers stimulated by accurate towed array position and heading information. This technical breakthrough is now achievable thanks to affordable and highly capable personal computer systems that have powerful graphics display systems.

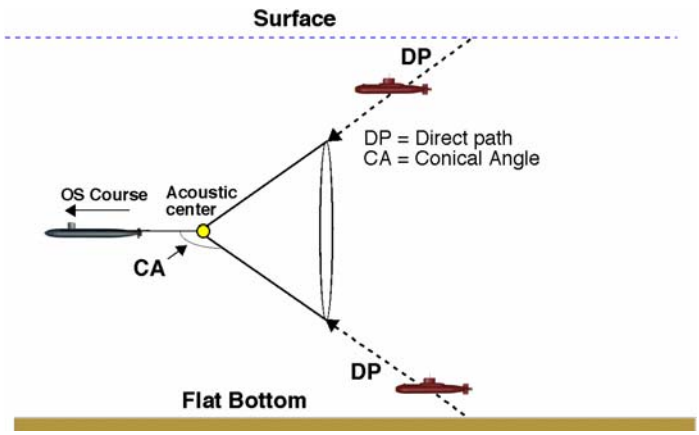

Figure 2. Ideal Conical Angle Measurement.

[1] The term "target localization" connotes minimizing the region in which a potential target is located.

The ongoing work at the Naval Undersea Warfare Center has produced such prototype 3-D towed array visualization. Through the collaborative efforts of experts in towed array kinematics and acoustics in concert with experienced 3-D visualization experts, a tool to expand the capabilities of towed array systems has been created. This paper focuses on the core components that comprise this towed array visualization system which are: 1) a towed array cable dynamics model, 2) a towed array beamformer and 3) a visualization application that displays the volumetric conical information in a 3-D immersive environment that the user can manipulate to obtain an integrated visual comprehension of the constantly changing nature of the towed array conical beam patterns.

2 Towed Array Cable Dynamics Model

The towed array undergoes physical deformation in response to both submarine maneuvers and subsurface currents. The towed array cable dynamics model calculates the behavior of the acoustic sensors traveling through the fluid medium. A finite element model driven by the six degree-of-freedom motion of the tow point was used to calculate the time-varying geometry of both the tether cable and towed array. The data presented in this paper corresponds to a submarine performing a 90° turn to starboard in a static medium.

The current implementation of the cable dynamics model accounts for the submerged weight and inertia of the tether cable and array, the normal and tangential drag acting on the cable, and the elastic and mechanical damping properties of the system. The tether cable and the array segments are modeled as a series of elements and a Newmark-Beta time integration scheme is employed. Dynamic equilibrium is maintained through the use of stable residual feedback and a modified gauss reduction scheme was employed to efficiently solve time stiffness matrices.

The cable dynamics model characterizes the deformation of both the tether cable and the array. An example of towed array typical deformation in turns is depicted in figure 3. Additionally, this model is also able to calculate the tension forces along the length of the cable and describe the relative motion of the fluid over the individual array hydrophones. Achieving a better understanding of the tension forces associated with specific submarine maneuvers is critical from a towed array reliability perspective and information related to the motion of fluid around each hydrophone provides an indication of sensor self-noise. It is important to note that no effort was taken in this study to address the impact of elevated sensor self-noise levels during submarine maneuvers on beamformer effectiveness.

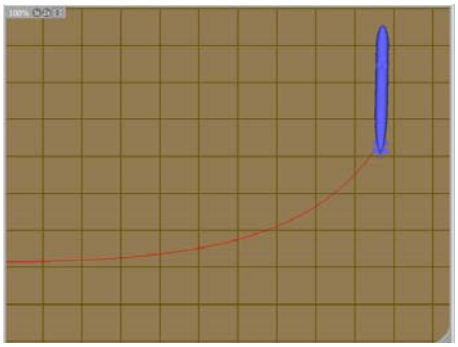

Figure 3. Towed Array Deformation In Turn.

3 Towed Array Beamformer

Passive array beamforming is a spatial filtering process designed to achieve maximum sensitivity to waves arriving from a specified direction (the look direction) while minimizing sensitivity to waves arriving from other directions. In a traditional towed array, this is accomplished using a conventional delay-and-sum beamformer, where the array element outputs are time-delayed in a manner such that the phased arrival matches that of an incident wave in the look direction. The beamformer output power spectrum for an array of *M* sensors at locations $\{(x_m, y_m, z_m)\}_{m=1}^{M}$ is given by

$$V(\omega,\theta^{inc};\theta^{S}) = \sum_{m=1}^{M} w_m d_m(\theta^{inc}) \exp\left[i(k_x^{inc} - k_x^{S})x_m + i(k_y^{inc} - k_y^{S})y_m + i(k_z^{inc} - k_z^{S})z_m\right]$$

where θ represents a two-dimensional angle, (k_x, k_y, k_z) is the wave-number representation of a wave propagating in the direction of the angle, $d_m(\theta)$ is the directivity associated with an individual sensor, and w_m are the beamformer shading weights. In the above expression, superscripts are used to distinguish components tied to the incident/arrival wave direction (*inc*) from those for the steered direction (*S*). The two dimensional angles are translated to the wave-number representation via

$$\begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix} = \left(\frac{\omega}{c}\right) \begin{bmatrix} \cos(\theta_1)\cos(\theta_2) \\ \sin(\theta_1)\cos(\theta_2) \\ \sin(\theta_2) \end{bmatrix}$$

where $\theta = (\theta_1, \theta_2)$ is the two-dimensional angle represented in spherical coordinates, ω is the frequency of interest and *c* is the local sound speed.

For a towed array application, we assume the element directivity is negligible, and thus set $d_m(\theta) \equiv 1$. When the array is straight and the elements are evenly spaced with separation along the *x*-axis, the beamformer output power spectrum reduces to

$$V(\omega,\theta^{inc};\theta^{S}) = \sum_{m=1}^{M} w_m \exp\left[i(\cos(\theta^{inc}) - \cos(\theta^{S}))m\Delta\right]$$

where θ is now the angle off the x-axis. This expression provides the simple conical beams as shown in figure 2. For the array that bends under maneuvering, the simple symmetric solution is replaced by the full 3-dimensional beamformer. The beams are computed for a single steering angle and visualized as power levels emanating from the acoustic center of the array. The power levels are geometrically oriented according to the incident/arrival angle relative to this acoustic center. Thus, for the beginning and end of the maneuver (when the array is straight), the beam visualization appears to be a narrow-rimmed cone. When the array shape deforms significantly, the lack of symmetry causes a

number of lobes to appear in directions other than the steered direction (sidelobes) as shown in figure 4. The shape of both the mainlobe and sidelobes is not symmetrical in this case due to the asymmetry in the full three-dimensional beamforming expression. For a practical array, a number of different steering angles are beamformed simultaneously and the energy obtained in each is plotted on a display versus steered direction. For visualization purposes, we only simulate the effect on a single steering direction. Tracking problems arise when the distortion of these lobes causes reduced energy from the desired target (in the mainlobe) concurrent with increased energy from non-desired directions (in the sidelobes). Thus, the distortion of the lobe structure is an important component of understanding the towed array beamforming problem within a maneuver. Actual towed arrays use slight deviations from this basic framework; however, the basic impact of the array shape and noise field is well-represented by the conventional delay-and-sum beamformer formulation.

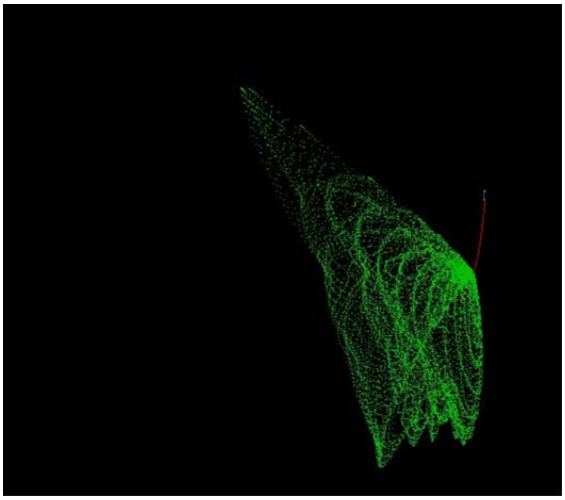

Figure 4. Towed Array Deformation In Turn.

4 Towed Array Visualization

The towed array visualization application was developed to enable the interactive, high-fidelity simulation of towed array operation at greater than real-time speeds. Advanced visualization techniques are often utilized to support the playback and integration of pre-computed data. The goal of this effort was to integrate the highly-coupled, multi-disciplinary simulation elements that are integral to understanding of towed array behavior into a highly interactive, visual environment. The development of such a capability ultimately enables the timely, information-based assessment of alternative operational and engineering solutions by diverse stakeholder groups though a common understanding of system-level behavior and the collaborative, heuristic assessment of critical solution components.

The application was prototyped in C++ and utilizes the OpenGL Performer API [2] to manage the interaction between the simulation and visualization elements. Performer[2]

[2] Silicon Graphics Performer is a software environment for developing high-performance, real-time graphics applications. It is compatible with all Silicon Graphics (SGI) graphics platforms.

provides a programming interface for creating real-time three-dimensional graphics applications. Figure 5 depicts the relationship between the current simulation elements. The flight simulator calculates the movement of both the submarine and tow point for the array, the towed array dynamic simulation calculates the geometry of the towed array given the movement of its tow point, and the beamformer calculates the beam patterns of the towed array given both the geometry of the array and the current direction of interest.

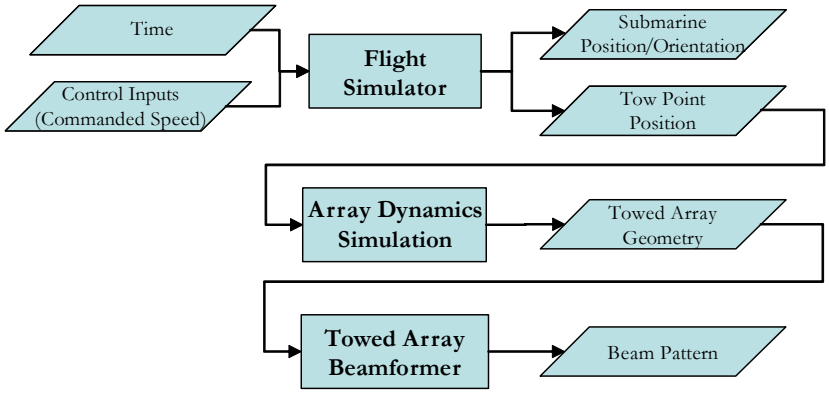

Figure 5. Relationship between Towed Array Simulation Elements.

The simulation elements were integrated using OpenGL Performer[3] to enable the simultaneous, asynchronous execution of multiple simulation instances. This implementation enables the integration of codes that are too computationally expensive to run within the refresh rate of the monitor and the acceleration of simulation runtimes in multiprocessor and high performance computing environments. Additionally, the same code with little modification renders scenes on machines running Windows or SGI IRIX in mono, passive stereo or active stereo modes.

The current prototype application supports the visualization of submarine motion, towed array cable dynamics and towed array beamforming.

4.1 Submarine Motion

The submarine path is a fixed racetrack with a constant forward speed. It does not slow as a real vessel would in turns and accelerate in the straight legs. A more sophisticated model could easily be incorporated in future versions.

4.2 Towed Array Cable Dynamics

The previously described high fidelity model was too computationally expensive to run as an interactive graphics application on the typical desktop computer. Therefore, a simplified cable dynamics model was implemented based on [1]with an extension for one free end and one end with a specified acceleration.

A finite element model was derived from the equations of motion of a cable with negligible bending and torsional stiffness. Hydrodynamic loads were modeled using Morison's equation and a simple added mass relationship: no Reynolds number or

[3] Term is equivalent to Performer used in footnote 3. New Silicon Graphics nomenclature for the latest versions of its high-performance, real-time graphics applications. Latest version is compatible with MS-Windows, Linux, and IRIX operating systems.

frequency dependencies were explicitly included. A system of linear ordinary differential equations (ODEs) was solved numerically for each time step displayed.

The towed array was split into two sections, each with its own set of material properties. The first section was the tow cable (1000 feet in length); the last was the sonar array (2700 feet in length). These sections were further split into finite elements each 100 feet long. This coarse discretization was adequate to provide a visual representation sufficiently accurate for visualization yet run quickly enough to be termed "interactive". However, a downward adjustment by a factor of 100 of the array spring constant was required, otherwise the system of ODEs was too stiff to solve in a timely fashion

4.3 Towed Array Beamforming

The beams formed by the array were calculated off-line for the array geometry determined using the high fidelity array dynamics model. These results were displayed centered about the position of middle element of the array as calculated by the low fidelity model.

5 Summary/Conclusions

In the absence of significant deformation, a towed array beam pattern is characterized by a single conical beam with very low side lobes. Traditional approaches for processing towed array information have largely focused on processing of information from multiple beams that do not explicitly consider the impact of noise sources that reside outside a given conical angle of interest. This paper demonstrates that effective beamforming is possible even with significant towed array deformation but that these beams are often characterized by very high side lobe levels. New methods to support the beamforming of towed array sensors during submarine maneuvers and the integration of multiple, asymmetric beams with high side lobe levels must be developed to produce a tactically significant outcomes.

Noise levels produced in the beamformed array output must be considered in order to correctly quantify the array signal-to-noise ratio. Dynamic models of the vortex shedding induced by array curvature have been incorporated for future assessments of array maneuvering performance.

6 References

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