



Dynamic Analysis of a SWATH Vessel

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ABSTRACT

The Autonomous Surface Vessel is a program that will create a platform for science capable of carrying a myriad of instruments repeatedly into remote sites. The completed system is expected to allow a scientist oversight from his or her desktop using tele-presence or artificial intelligence concepts combined with infrastructure of the internet. Key aspects to accomplishing these goals are a robust vessel design with predictable and well understood performance parameters. This paper discusses the dynamic analysis of and design modifications to the selected vessel, an Autonomous Small Water plane Area Twin Hull (SWATH) boat named WASP. This work was accomplished during the summer of 2005 at the Monterey Bay Aquarium Research Institute using their underwater robotics lab and associated test tank. After several testing iterations a number of modifications were implemented and retested. The tank testing and successful outcomes have enabled the next phase of the project; a preliminary / demo autonomous operation in the Elkhorn slough in preparation for further testing that will include full wave tank simulations and complete dynamic analysis.

INTRODUCTION

The vision of the Autonomous Surface Vessel program is to develop an instrumented boat capable of robust, automatic sampling of oceanographic data at specific locations and depths in estuary and coastal waters. The objective of the initial project was to develop a prototype of such a system including software, physical hardware and electronic components. The physical structure includes pontoons, vertical

struts, and a main platform supporting the onboard electronics and payload. The onboard electronics control the movement and functionality of the vessel and the payload of scientific instruments are attached to a cable reel for taking readings at depth. Also, the user interface developed for the wireless communication and control of the vessel is Internet based allowing the user to control the vessel anywhere in the world.

The final design of the ASV was a Small Water-plane Area Twin Hull (SWATH) design. Similar to a catamaran or standard pontoon boat, a SWATH vessel has two pontoons set wide to increase stability, but unlike the standard pontoon boat, the SWATH's pontoons are completely submerged below the surface, and are connected to the main deck by thin vertical struts. This design increased the stability of the vessel by decoupling the boat from the oscillation due to the waves. This is especially important when the instruments are deployed to prevent unnecessary stress and fatigue on the cable. Having the pontoons spread out helps to keep the center of buoyancy and the center of gravity more closely aligned, reducing the tendency of the vessel to flip over.

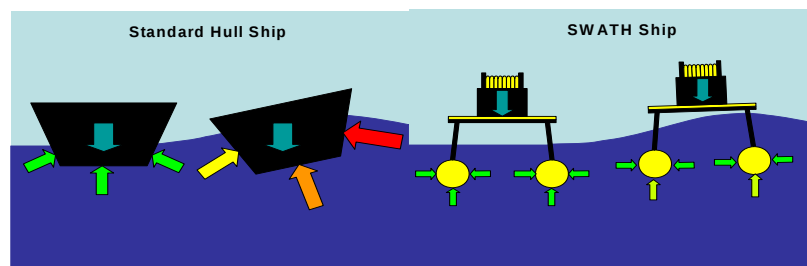


Figure 1. Standard hull response to waves vs. SWATH response to waves

MATERIALS AND METHODS

The focus of the work done at MBARI during the 2005 summer was on the dynamic response. As this was the first time that the vessel would see water, it was clear that there would be much work to do. Numerous modifications were made, and many testing iteration were done.

FABRICATION

The focus of the fabrication changes was on improving the vertical struts. The biggest problem was that the vessel lacked stability in both the pitch and roll directions, but there were several other issues like stiffness and weight placement. In order to

combat these, several modifications including strut wedges, passive buoyancy packs, and strut stabilizers were added.

To increase stability in the roll direction, wedges were added to widen the stance. They were machined from UHMD for its strength and corrosion resistance. Two angles of 10° and 15° were created in addition to the 5° cant built into the strut. This allowed for testing at different strut angles to find the optimal stability without sacrificing too much vertical travel in the narrow water plane section. Final testing showed that the 15° wedges (for a total of 20° per strut) provided the optimal setup.

During the first test it was shown that the vessel was acting in an “ultra” SWATH mode with too little response to vertical displacement. This made it nearly impossible to balance the vessel and very unstable. To improve the stability it was necessary to increase the ratio of volume displaced to change in height. The passive buoyancy packs were made of medium-density polyurethane foam and covered a fiberglass shell to provide increased impact resistance and prevent water absorption. The packs were designed in two parts, an inside and an outside, which were strapped together with a high tensile strength plastic. The packs had smooth fairings to improve hydrodynamics by minimizing the drag. The base flows up from the pontoon to the narrow mid section which angles out at the top to provide a larger reserve foam area for high sea states and emergency conditions. Figure 2 shows some the changes implemented during the project.



Figure 2. Shown to the left is the state at the beginning and to the right shows the top grating was removed to lower the CG, and 15° wedges and the passive buoyancy packs were added.

Several of the minor problems had simple solutions. In order to improve the rigidity of the vessel stainless steel cross bracings were stretched between the middle of the strut and the opposite end of the deck. To lower the location of the center of gravity, the top grating was removed and new batteries were selected that will be able to fit inside the pontoon instead of on top of the deck. To increase the ease of mounting the end caps threaded inserts were installed, they were then filled with foam to improve flotation, and the thruster mounts were moved farther aft to decrease the local turbulence.

INSTRUMENTATION

In order to accurately analyze the response of the system proper instrumentation would be needed. The instrumentation selected to record both the ASV's response and the wave characteristics (such as the length, amplitude, frequency, speed, crest, trough, ect...) included a Crossbow Attitude and Heading Reference System (AHRS) and three fast capacitive Wave Staff IIs developed by Ocean Sensor Systems.

The AHRS unit is based on solid-state MEMS sensing technology and it combines the functions of a both a Vertical and Directional Gyro to provide the angle and rate of change of the Roll, Pitch, and Yaw. Also included in the package is a three axis linear accelerometer and magnetic field measurements to electronically stabilize the AHRS. This will give a complete response of the vessel relative to an inertial plane. The AHRS unit can be seen below in Figure 3.



Figure 3. The Crossbow AHRS unit and the OSS Wave Staff II.

The fast capacitive wave staff, which is also shown in Figure 3 above, was designed to provide a high-resolution measurement of liquid surface height. By instrumenting a wave staff on the boat itself the vertical response (also know as heave) in relation to the wave can be found. In addition, by mounting two wave staffs to the deck (one in front and one behind the vessel) the wave characteristics can be recorded.

SOFTWARE

While each instrument had its own data acquisition software, it was necessary to implement some type of time synchronization. To do this, all four instruments were run via a serial port to USB hub into Lab View. This allowed for the creation of a custom data acquisition system integrating all instrument with a single controller and recording file. The final GUI (Graphic User Interface) showed all the important data live, including the angles and rates for the roll, pitch, and yaw, the linear acceleration, wave staff values, and internal temp of the AHRS to monitor overheating. The GUI controls included the sampling rate, which could run at up to 10Hz, the path for the data file, which was stored in an excel spreadsheet, and two buttons, one to begin writing to the file and one to stop all the instruments. A screenshot of the GUI is shown in Figure 4 below.

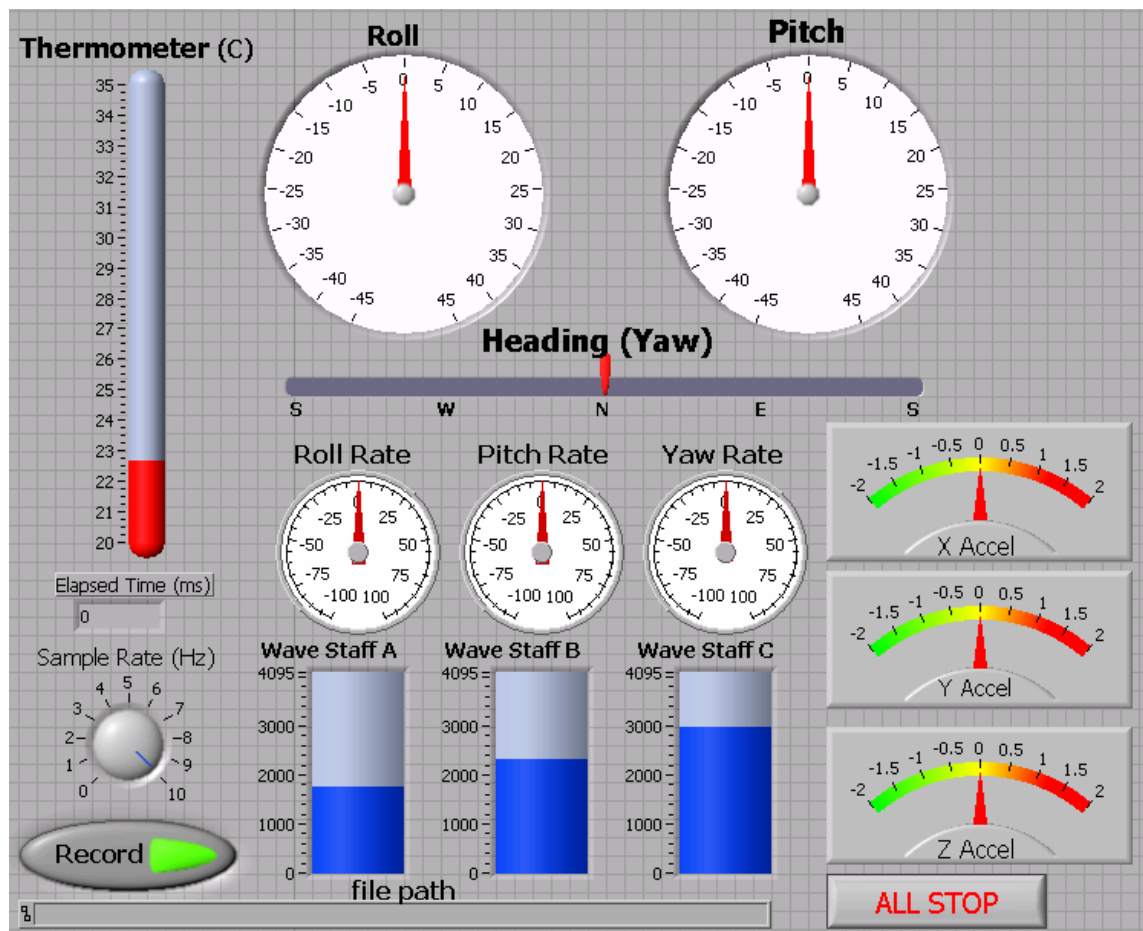


Figure 4. A screenshot of the LabView GUI created to interface the instruments. (See Appendix B for the block diagram)

TESTING

While the original testing plan turned out to be too extensive, the modified testing plan gave excellent results and proved to be a valid proof of concept. Due to time restrictions the wave generator was not completed. In order to compensate, a disturbance response testing was implemented. Since for this testing no wave characteristics would need to be monitored, all three of the wave staffs were mounted on the ASV, one in front and one in each rear corner. This was in addition to the AHRS unit, which was centrally mounted on the deck of the ASV. The testing involved displacing one side of the ASV, holding to stabilize, and then releasing. Both the instrumentation setup and testing procedure can be seen in Figure 5 below. The testing was done by sequentially displacing the right, front, and then back edges of the deck, each at three different loading heights (16", 12" and 8" of freeboard). Each test setup was repeated ten times for a total of 90 test runs.

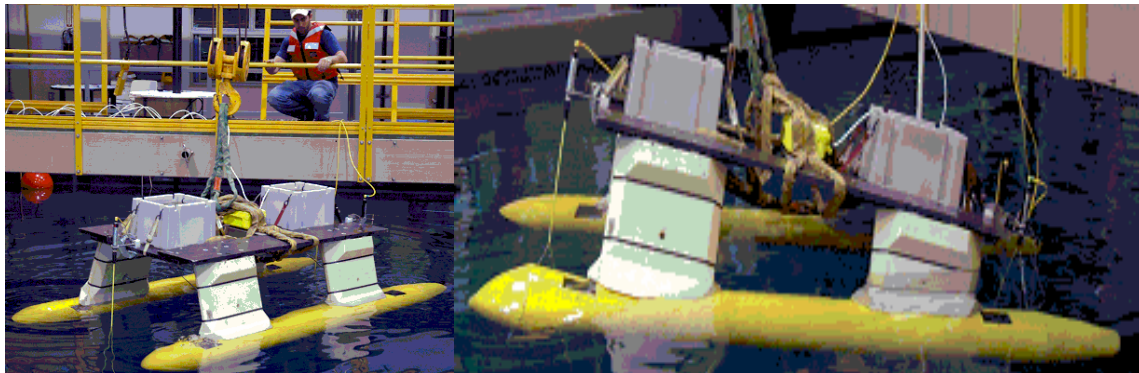


Figure 5. Instrumentation setup and testing procedure, the gray bins and holes in the pontoons allowed for the balanced addition of weight to achieve each of the loading setups.

RESULTS (for complete results see the appendix)

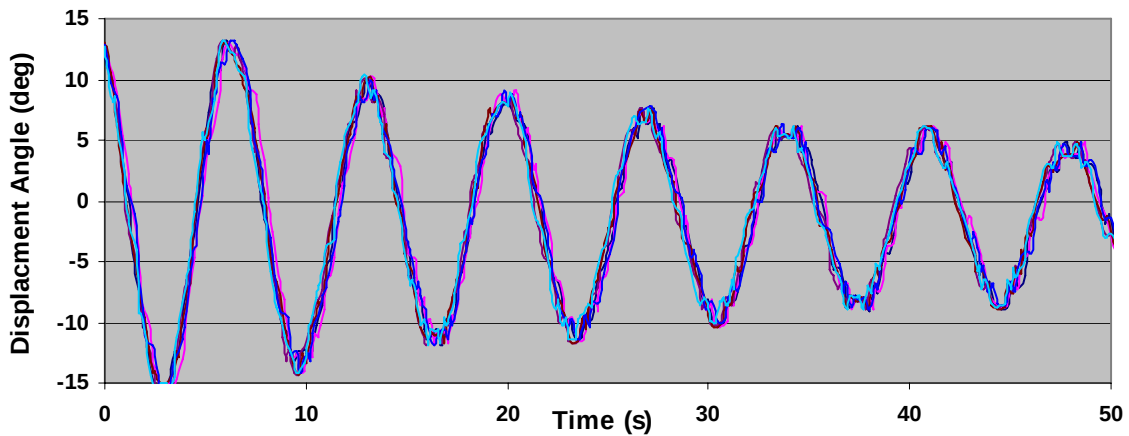


Figure 6. This graph shows the side-to-side response of the ASV with 8" of freeboard. The slow decrease in the response implies a low damping and stiffness that correlates well with the theory, and the very small deviation show the data is valid.

	Freeboard	cycles	Displacement		time	period
	in	n	B 1	B (n+1)	Δt (s)	P
Roll	16	6	7	3.5	37.90	6.32
	12	5	10.5	4.5	36.33	7.27
	8	6	13	4.5	41.60	6.93
Pitch (Back)	16	2	1.5	0.5	12.61	6.31
	12	4	3.5	0.75	27.66	6.91
	8	4	3.25	0.75	25.74	6.44
Pitch (Front)	16	2	1.5	0.5	12.26	6.13
	12	5	2.5	1	34.46	6.89
	8	6	2.75	1	38.48	6.41

Table 1. This data read from response graph will yield the logarithmic decrement, which is the first step in the dynamic analysis.

logarithmic decrement	damping ratio	damped frequency	natural frequency	stiffness	damping	critical damping constant
δ (delta)	ζ (zeta)	ω_d	ω_n	k (lbs/ft)	c (lbs-sec/ft)	c_c
0.116	0.00919	0.99459	0.99464	24.58	0.454	49.42
0.169	0.01348	0.86474	0.86482	19.74	0.616	45.66
0.177	0.01407	0.90619	0.90627	22.96	0.713	50.66
0.549	0.04367	0.99638	0.99733	24.71	2.164	49.56
0.385	0.03063	0.90876	0.90919	21.82	1.470	48.00
0.367	0.02916	0.97641	0.97682	26.67	1.592	54.61
0.549	0.04367	1.02482	1.02580	26.14	2.226	50.97
0.183	0.01458	0.91166	0.91176	21.94	0.702	48.14
0.169	0.01342	0.97960	0.97969	26.83	0.735	54.77

Table 2. This is dynamic response data is calculated from the data in Table 1. Several trends shown here correlate well with the theory, including the ideal loading range and overall response.

DISCUSSION

The model selected for this system is a linear second order, which follows the formula:

$$mx''+cx'+kx = f(t) \quad (\text{eq. 1})$$

where m is the mass of the system, c is the damping, which is a factor of the horizontal surface area and slows vertical motion, and k is the stiffness which is a factor of the change in displacement versus the change in height (this was increased by adding the foam packs). For a typical system high values would imply a large resistance to input forces, however with aquatic vessels the higher damping and more specifically high stiffness correspond to greater wave tracking. So for the SWATH case the both values should be low compared to the mass, which they are. Thus it can be predicted that the vessel will have low response to waves for the targeted sea state.

By testing at different heights we can determine the optimal loading and operating range. For each of the test settings the middle data set (which corresponds to 12" freeboard) gives the lowest stiffness. This is because it is using the thinner section of the struts, whereas the lower setting ended up using the reserve flotation, and the higher setting brings the pontoons out of the water in extreme cases. We can now set the vessel up to operate in the range when the instruments are deployed.

Stability is a very important issue, and while we could see that it was stable from the test, it is also necessary to prove it mathematically. In order to determine if a system is stable the Stability property is used

$$s = \frac{-c \pm (c^2 - 4mk)^{1/2}}{2m} = s_1, s_2 \quad (\text{eq. 2})$$

The system is defined as stable if both roots have negative and real parts, which occurs when m , c , and k have the same sign. In this case all three are positive proving for this range the system is stable.

CONCLUSIONS/RECOMMENDATIONS

In conclusion the project was successful. The vessel is much more stable and has an improved response to disturbances. However, the analysis is not complete and more

testing needs to be done. Specifically the wave response that was in the original project goals should be completed. This will find the Amplitude Response Output (ARO), which will be crucial in the final closed loop control design. This can hopefully be done with a scaled sea state to match facilities at MBARI. Some of the other testing that should be done is a current response, which could be used to calculate the response for 2-D navigation. There are several different trends, such as the relation of damping and stiffness to roll or pitch angle, in the data that should also be explored more completely in future tests.

In addition to the testing there are other design and fabrication goals including active ballast, a gas-electric hybrid power system with hull-mounted battery bank, a more efficient propeller, and a tunnel or bow thruster. The work performed to date has been critical in the development of the ASV concept, which is expected to lead to an operational system deployed in the Kasitsna Bay Laboratory in Alaska and other national estuaries.

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