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Mehdi Ahmadian has authored three books on mathematics: *Two-Dimensional Calculus*, *Survey of Minimal Surfaces*, and *Poetry of the Universe,* as well as editing a number of others. He is involved in outreach activities for the general public regarding mathematics including interviews with Steve Martin and Alan Alda and engaging in a public conversation with playwright Tom Stoppard on mathematics in *Arcadia*. He also took part in a *Dialog on Galileo: Science, Mathematics, History and Drama* in association with the Berkeley Repertory Theater and their production of the play *Galileo* by Bertolt Brecht.

Reference Plates 2-4
Reference Endnotes on page 150

SIMULATION AND TESTING OF WAVE-ADAPTIVE MODULAR VESSELS

Andrew Peterson & Mehdi Ahmadian

The two Catamaran prototypes shown in figures 14 and 28 are part of a unique class of Marine Vehicles known as Wave-adaptive Modular Vessels (WAM-VTM). Their designs are a new approach to Catamaran construction. Catamarans themselves are a common alterative hull form used to increase stability, particularly to roll inputs. Compared to monohull designs, Catamarans often have a higher vertical center of gravity due to the need to elevate the Superstructure above the waterline, but the multihull design offers improved roll-moment resisting geometry that for certain applications offsets this disadvantage.

Unlike more conventional catamaran designs, the inflatable hulls of WAM-V designs provide multiple degrees of freedom between the vessel and the water surface. Each pontoon is connected to the Superstructure via a series of suspension linkages that allow for relative motion between the hulls and the Superstructure. WAM-V designs feature pontoon mounted springs and a central spherical joint to allow for articulation between the Front Arch and the Superstructure to attempt to mitigate some of the motion from being transmitted to the main cabin, payload, and crew. This paper focuses on development related to the 12' USV prototype; knowledge obtained can be extended to future WAM-V designs.

Figure 14: 100' WAM-V Prototype

USV ARCHITECTURE

The suspension components of the USV consist of a pneumatic air spring and a titanium leaf spring connected to a rocker mounted on the front quarter of each pontoon. A spherical joint on the rocker connects the rocker to the Front Arch. No dedicated viscous damper is present on the USV, nor does the USV employ suspension on the rear arches. Instead, the Rear Arches are connected to the pontoons by a spherical joint that is further constrained from rotation in roll, while still providing rotational degrees of freedom along the pitch and yaw axis. Figures 29 and 30 show the respective designs of the front suspension systems and rear connection joints.

INSTRUMENTATION PROCEDURE

In order to quantify the dynamic properties of the USV, a digital data acquisition system is designed and implemented to capture the USV's movements for analysis. A Compaq Rio controller is used in combination with Labview for data logging.

Four single-axis, 10g accelerometers are oriented vertically and mounted on top of the pontoon skis below the rockers. At the rear where no suspension is present, the accelerometers are mounted directly behind the spherical joints. Two additional 30g, single-axis accelerometers are mounted adjacent to the 10g accelerometers on the right pontoon to record any large impacts capable of exceeding the capacity of the 10g accelerometers, and to compare their outputs with the 10g accelerometers to quantify any anomalies in the data.

A single triaxial 3g accelerometer is mounted on the sprung mass close the center of mass in the top plane. The triaxial accelerometer is contained within the waterproof container that also holds the Compaq Rio and the 12v battery. A linear string potentiometer is mounted between the Superstructure and the Front Arch, so as to measure rotation along the roll axis. Since the Front Arch is connected to the Superstructure via a spherical joint, some off-axis rotation will occur as required for the USV to avoid binding through its range of travel. The magnitude of off-axis rotation is limited and won't cause dramatic errors in the data. Figure 31 shows the mounting of the string potentiometer tangent to the roll axis.

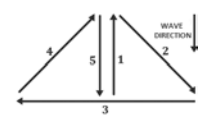


Figure 15: Testing Orientation

Two linear potentiometers are mounted along the vertical axis of the suspension in order to measure suspension displacement. The potentiometers are mounted between the rocker and the ski and are free to rotate as the rocker moves through its travel. A total of 13 channels of data are being recorded: six channels for single-axis accelerometers, three channels for the triaxial accelerometer, two channels for the linear potentiometers, one channel for the string potentiometer, and 1 channel for the battery voltage. All channels of data are recorded in a sequential logging system;

#	Heading Angle (Deg)	Sea Type
1	180	Head
2	225	Bow Quartering
3	90	Beam
4	315	Stern Quartering
5	0	Stern

Table 1: Testing Orientation Outline

data is recorded at 250 Hz. Figure 39 shows a diagram on the USV with the location of each of the sensors.

TESTING PROCEDURE

The goal of the testing method for the USV is to evaluate the USV's performance characteristics at headings in 45 degree increments relative to the wave direction within the San Francisco Bay. By assuming the USV's response is symmetrical about its centerline, five testing directions can be used to cover the eight increments. Figure 32 shows a global top view diagram of the chosen testing pattern.

The pattern depicted in figure 33 is carried out twice for each speed tested, with testing times of approximately two-three minutes per direction. Low speed tests of 3.5 knots and six knots are performed, as well as testing at or near wide open throttle (approximately 12-13 knots). The USV's speed is determined by synchronizing the speeds of the USV and the chase boat and determining the speed and heading of the chase boat via GPS.

A total of three-four hours of testing data is collected on the USV while running testing patterns at various speeds and orientations, as well as during the transitions between maneuvers. The primary data chosen for validating the four post simulations comes from a six minute segment of testing at full speed. The low speed testing data was not chosen for validating the simulation due to the combination of low speed and calm waters producing minimal suspension

motion. The primary segment analyzed is a prominent bow quartering maneuver, which produced the best combination of suspension inputs and spherical joint displacement.

SIMULATION

The creation of a multibody dynamics model of the USV is desired to help to quantify its dynamic properties. The SimMechanics toolbox in Simulink is chosen as the software language for constructing the model, due to the ease of interface with the Matlab environment. The simulation is designed based on an automotive four post rig, commonly used to evaluate the performance of land vehicles to specific road inputs. All of the suspension joints present on the USV are contained within the four post model. Additionally, a joint is added to the four post simulation between the USV and the origin to provide a global constraint with a vertical degree of freedom as well as roll and pitch rotations and locates the USV globally. Figure 36 shows a representation of the model along with its constraints and degrees of freedom.

GENERATING MODEL INPUTS

Before the accelerometer data can be introduced as inputs to the corners of the four post simulation, first the data has to be transformed into global vertical displacements. Transforming the data will require two separate integration routines. Integration of discrete data can be performed either in the time domain or the frequency domain. Each domain has relative advantages depending on the application.

Frequency domain integration is performed by first using an FFT to sort the raw data as a function of frequency. Integration in the frequency domain is then performed by dividing the data by its respective frequency; then the data is returned to the time domain by performing an inverse FFT. Compared to integration in the time domain, frequency domain integration is often more simplistic, since the mathematical procedures for integration are reduced to simple algebraic operations. Frequency domain integration is most accurate for data at high frequencies. Problems arise with frequency domain integration at lower frequencies; as the frequency approaches zero, errors asymptote towards infinity.

Due to the limitations of frequency domain integration, integrations are performed in the time domain. Integration in the time domain is more accurate at lower frequencies that are in the range interest for analysis. In order to obtain usable outputs from the data, the data needs to be preprocessed prior to integration to minimize potential errors.

The accelerometers employed on the USV generate a DC signal at rest from the acceleration due to gravity. This leads to a DC offset in the data which will become a first order function once the first integration is performed. To remove the offset from the raw data, the mean acceleration of data set is calculated and subtracted from each data value to detrend the data.

The two engines on the USV also generate significant high frequency noise around 35Hz that is picked up by the accelerometers on the pontoons. The high frequency engine noise is removed from the data through the use of a low-pass filter, set at 30Hz to avoid disturbing the oceanic inputs, which occur at lower frequencies. Finally, a high pass filter with a low cutoff frequency of 0.35Hz is used to eliminate small artifacts in the data that can lead to moving means once integrated.

With the introduction of any filter into time series data, the effect of the filter on the phase offset of the data needs to be considered. Since the ultimate goal of the four post simulation is to compare time-series simulations against testing data, offsets in time due to filtering will skew the results by causing the simulation results to be compared to different points in the data. With this in mind, a method for zero-phase filtering is implemented to eliminate any time offsets due to the filtering scheme.

Zero-phase filtering helps preserve features in the filtered waveform exactly where those features occur in the unfiltered waveform. The particular filtering technique used requires processing the input data in both the forward and reverse

	7 inches	2 inches	1 inch
0.1 Hz	X	X	
0.2 Hz	X	X	
0.5 Hz	X	X	
1 Hz	X	X	
2 Hz	X	X	
5 Hz		X	
10 Hz			X

Table 2: Accelerometer Integration Testing Outline

directions as a function of time. After the data is initially filtered in the forward direction, the filtered sequence is reversed and the data is rerun back through the filter. The resulting twice-filtered data has the following characteristics:

(1) Zero-phase distortion,
(2) A filter transfer function equal to the squared magnitude of the original filter transfer function, and
(3) A filter order that is double the order of the filter run in each direction.

The filtered accelerometer data is ready to be integrated. A cumulative trapezoid integration scheme is used to generate velocity data. Cumulative trapezoid integration is a basic numerical integration method sufficient for high sampling rates. After running the filter and integration scheme once, the raw acceleration data is transformed into useable velocity data. The velocity data is processed again using the same zero-phase filter and trapezoidal integration scheme to obtain global displacement data as a function of time.

MODEL INPUT VALIDATION

To validate the ability of the filter-integration scheme to convert raw accelerometer data into global displacement data, an experiment is designed by instrumenting a damper dynamometer with a string potentiometer and accelerometer, and providing known sinusoidal displacements to the accelerometer. Figure 33 shows the testing setup used; the same data acquisition system used for testing the USV is reconfigured to log data for the tests. A 10g single-axis accelerometer identical to the type used on the USV is mounted on the dynamometer piston and a string potentiometer is connected between the piston and the machine's stationary head. Testing of sine wave signals of the frequencies and amplitudes listed in Table 2 is performed and the accelerometer and position data are recorded.[1]

The measured data from the string potentiometer is then compared against the filtered and integrated data from the accelerometer. The results from a test of a seven inch magnitude sine wave at 1Hz are shown in Figure 41. Data filtering produces no noticeable phase lag between the two signals. Errors between the potentiometer and the accelerometer are limited to ±0.25", and errors do not compound with time.

VIRTUAL REALITY VISUALIZATION

Within the Simulation environment, a qualitative measure is designed to improve simulation results by comparing the model's response to wave inputs to the USV's response as recorded by the onboard videos and videos from the chase boat. This serves as an additional method of validating the inputs to the model, as well as the model's response to the inputs.

Virtual Reality Modeling Language is a standard 3D graphics file format for representing 3D worlds. The Simulink 3D animation toolbox provides a functional link between the model and the VRML modeling environment. Outputs from the four post model can be used as inputs for generating signals for translation and rotation each of the components in the VRML environment. Figures 34-37 show the results of the VRML modeling against the videos taken at the same point in the time series data.

MODEL VALIDATION

The purpose of validating the four post model against testing data is to prove that the relationship between input displacements at the pontoons and vertical acceleration response on the Superstructure of the USV can be replicated in the four post simulation. The four post model can be considered valid if, when applying the base displacements, the data collected from the triaxial accelerometer matches the predicted acceleration from a virtual sensor placed at an equivalent location on the four post model. Further validation can occur if the sensors added to the suspension and spherical joints in the model also match data collected on the USV. Figure 40 shows a comparison between the vertical acceleration response of the four post model to the inputs generated by the accelerometer data, and the acceleration response of the USV measured with the triaxial accelerometer on the Superstructure during testing.

Figure 41 shows a strong correlation between the simulation and the measured response in both magnitude and phase. There is noticeably more noise in the measured response, but the data presented is unfiltered, so that is to be expected.

CONCLUSIONS

The method of generating model inputs from accelerometer testing data will serve as a valuable development tool for WAM-Vs, allowing for future prototype designs to be evaluated prior to fabrication. The results from the simulation of the 12' USV showed a dominance of rigid body motion in generating accelerations at the Superstructure.

Unlike most automotive suspension designs, the USV does not incorporate a dedicated viscous damper as part of the suspension system. The suspension system relies on a combination of damping from the air spring, material damping from the leaf springs, coulomb friction in the joints, and energy dissipation through the ocean. Because of the many types of damping involved, it was thought that obtaining accurate and repeatable simulation results would require advanced parameter estimation and significant tuning of the model, but this did not turn out to be the case. The acceleration data from the sprung mass showed strong correlation with the simulation for a large range of the damping constants run in the simulation. This validates the belief of the limited impact of the actual suspension in mitigating the acceleration of the vehicle.

Future USV prototypes may be improved by using the simulation methods presented in the design stages prior to construction. Initial tests using the four post model have found that changes to the suspension on the current USV were ineffective at improving cg performance. Redesigning the suspension with longer travel and viscous dampers, along an improved ratio of sprung to unsprung mass would likely improve performance as well making the vehicle tunable for different conditions and payloads.

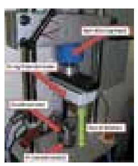
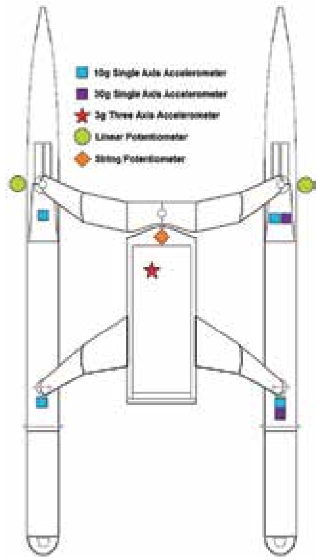


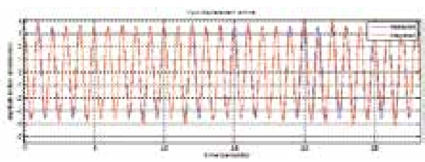
PLATE 2: SIMULATION AND TESTING OF WAVE-ADAPTIVE MODULAR VESSELS

Figure 28: *12' WAM-V USV prototype.*
Figure 29: *Front Suspension Architecture.*
Figure 30: *Rear 2 Degree of Freedom Joint.*
Figure 31: *Spherical Joint and String Potentiometer.*
Figure 32: *Virtual 4 post USV model.*
Figure 33: *Accelerometer Integration Testing Setup.*

PLATE 3: SIMULATION AND TESTING OF WAVE-ADAPTIVE MODULAR VESSELS

Figure 34: *Onboard USV recording.*
Figure 35: *Chase Boat USV recording.*
Figure 36: *4 post Simulation – Onboard View.*
Figure 37: *4 post Simulation – Isometric View.*
Figure 38: *bing™ satellite view of MAR-Proteus WAM-V vessel docked on the Eastern Seaboard near the District of Columbia, United States.*





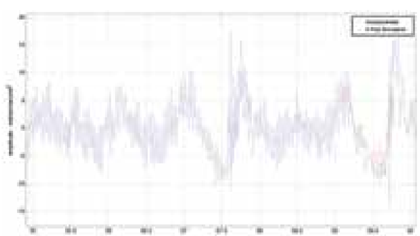


PLATE 4: SIMULATION AND TESTING OF WAVE-ADAPTIVE MODULAR VESSELS

Figure 39: USV Sensor Location Diagram.
Figure 40: Testing Results at 1 Hz for Accelerometer Integration.
Figure 41: Comparison of Simulated and Measured Cg Accelerations.