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Controller and Platform Design for a Three Degree of Freedom Ship Motion Simulator

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Abstract— **With the use of tow-tank experiments, data may be generated for ships of various classes using comprehensive instrumentation. This data gives the ability to determine the response of ships to various sea-state conditions far in advance of their construction and launch. However, this data does not indicate the effects of those sea-states to the individuals aboard that ship. In order to determine these effects a full-sized sea-state simulator was designed and built. Construction is completed and a series of tests were conducted to determine the response of the simulator. These responses allow for the comparison to actual tow-tank data to determine if the simulator is capable of performing the desired research.**

I. INTRODUCTION

THE purpose of the ONR project, award number N00178-09-D-3017-0008, was to analyze and optimize the sequence in which remote multi-mission vehicle (RMMV) launch processes took place by leveling the effort required for each task in order to meet the manning requirements for the mission. In addition, the research was to expand the current knowledge of the effects of motion-induced interruptions (MIIs) and motion- induced fatigue (MIF) on working in a moving environment. Biomechanical as well as time study data was to be collected on the sea-state simulator and analyzed to determine the influence of both sea-state and sea-state related perturbation on work performance.

In order to properly test MIIs and MIFs a three degree of freedom (DOF) platform was designed and constructed. The motion simulator discussed in this document spans nearly 96 square feet of useable area. A range of sea-state conditions was created by mounting a substantially rigid platform on three hydraulic lifts with spherical bearings at their attachment points. In this way, the principal motions of roll, pitch, and heave could be generated according to a range of predetermined and/or random ship motions. The other three DOF (sway, surge, and yaw) represent second-order movements. Therefore, they were not considered for the purpose of this research. The control system, written in LabVIEW, processes lifts motions derived from the desired platform positions, velocities, and accelerations in three degrees of freedom. With available space and equipment restrictions the simulator was capable of performing sea-state conditions 1, 2, and 3 for ships of Artemis class.

II. LITERATURE REVIEW

A common definition for a control system is an arrangement of physical components connected or related in such a manner as to command, direct or regulate itself or another system (DiStefano, Joseph, et al. 1990 [1]). A control system is able to identify or define the inputs and outputs. If these are given, it is then possible to identify or characterize the nature of the system's components. The main objective of a control system is to obtain a desired response for a given system. This objective can be achieved with the implementation of either an open-loop system or closed loop system.

A closed-loop control system, which is the system of interest in this research, uses a measurement of the output and compares it with the desired output. Simply stated the system is dependent on the output. These systems are commonly called feedback control systems. Feedback is defined as the property of a closed loop system which permits the output to be compared with the input to the system so that the appropriate control action may be formed as some function of the output and input (DiStefano, Joseph, et al. 1990 [1]). A system that is considered to be closed-loop has five important features that feedback imparts to it:

1.) Increased accuracy
2.) Reduced sensitivity of the ratio of output to input to variations in the system characteristics
3.) Reduced effects of nonlinearities and distortion
4.) Increased bandwidth
5.) Tendency toward oscillation or instability.

The stability of a system is determined by the system's response to inputs or disturbances. A stable system will remain at rest unless excited by an external source and will return to rest after all excitations are no longer present. A common definition is that a system is considered stable if its impulse response approaches zero as time approaches infinity. Alternatively, if the definition is based upon the response of the system to inputs whose magnitude is less than some finite value for all time. The new definition would state that a system was stable if and only if every bounded input produced a bounded output.

Consideration must be made on the degree of stability of the system, which is the concept of relative stability. Normally,

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relative stability is expressed in terms of some allowable variation of a particular system parameter for which the system will remain stable (DiStefano, Joseph, et al. 1990 [1]). In order for a system to be considered stable the real parts of the roots of the characteristic equation must have negative real parts, which will ensure that the impulse response will decay exponentially with time. If the system does not meet this condition, but has some roots with real parts equal to zero and none with positive real parts the system is considered to be marginally stable. Nevertheless, certain inputs will produce unbounded outputs, which mean a marginally stable system is actually unstable. Various methods are available in determining the stability of a system. They include the Routh stability criterion, the Hurwitz stability criterion, and the continued fraction stability criterion. The transfer function of a linear system is defined as the ratio of the Laplace transform of the output variable to the Laplace transform of the input variable, with all initial conditions assumed to be zero (Dorf and Bishop, 2005 [2]). The transfer function of a system delineates the relationship characterizing the dynamics of the system under consideration. Only systems that are linear or stationary may be defined by transfer functions. If a system is determined to be non-stationary, which may be defined as a time-varying system, it has one or more time-varying parameters. Therefore, the Laplace transformation cannot be used.

A proportional, integral, and derivative controller, is most commonly referred to as a PID controller. First, the P element is proportional to the error at the instant *t*, also known as the present error. Secondly, the I element is proportional to the integral of the error up to the instant *t*, which can be interpreted as the accumulation of the past error. Finally, the D element is proportional to the derivative of the error at the instant *t*, which is normally interpreted as the prediction of the future error. Simply stated, the PID controller takes the present, the past, and the future of the error into consideration.

III. HYDRAULIC SYSTEM

Power to operate the platform came from pressurized hydraulic fluid. Proportional valves allowed hydraulic fluid to be pumped into the lift cylinders to raise the platform. The same valves allowed hydraulic fluid to flow back out of the cylinders into a tank as gravity forced the platform down. The proportional valves operated with an input signal ranging from -10 V DC to +10 VDC. At -10 V the valves were fully open in the drain direction and the lifts lowered. At +10 V the valves were fully open in the raise direction and the lifts elevated.

The system was designed to operate at up to 1500 psi. The weakest link in the system was the largest hydraulic feed or pressurized hose, which was rated at 1800 psi. The system was set to operate at 900 psi, as this pressure was adequate to operate the platform and provided a large safety margin. The operating pressure was set on the hydraulic pump, which was a variable displacement constant pressure pump. The flow of the pump varied to maintain the set pressure.

The hydraulic pump was driven by a 40 HP 440 V 3 phase AC motor. The motor soft start control, located on a pedestal next to the power unit, started the motor without drawing excessive current and provided for emergency shut off of the motor. For all emergency situations not directly related to the pressurized hydraulic fluid, hydraulic pump, or drive motor, the emergency stop button on the computer desk could be used, the wiring diagram for this e-stop is shown in Figure 1. This emergency stop button was used to shut off power to the proportional valves. If the emergency stop for the motor was pressed, the 24 V DC power supply signal was stopped and each proportional valve locked into position.

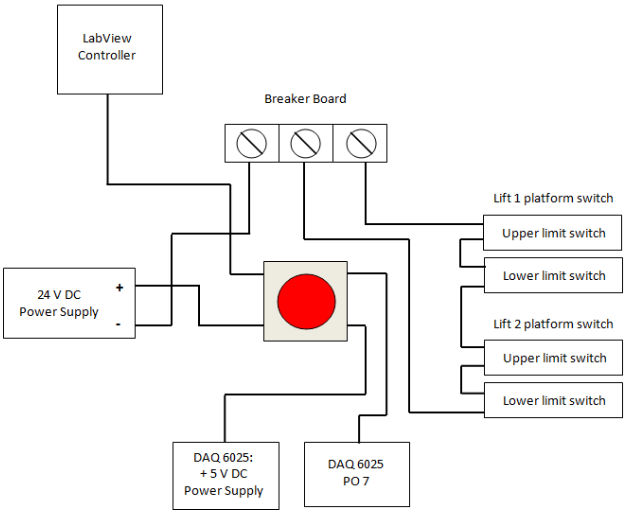


Fig. 1. Emergency Stop

Pressurized hydraulic fluid flowed in a common manifold to each proportional valve. A gauge on the manifold registered the pressure of the fluid. The proportional valves controlled the flow to and from the lifts individually. Flow from the lifts passed through the respective proportional valve and into the low pressure side of the common manifold, and from there back to the hydraulic tank. Manual drain valves were included to have a means of lowering the platform in an emergency. When opened the hydraulic fluid flowed from an individual lift, through the corresponding manual drain valve, into the common low pressure manifold and then to the tank.

IV. ELECTRICAL SYSTEM

The electrical system can be divided into three sections. These sections include:

1.) The feedback section which provided feedback of lift position to the PD controller and VI.

2.) The valve signal section which sent a signal to the proportional valves.

3.) The valve power and over-tilt safety system which provided power to the valves and shuts off power to the valves in emergency situations.

The displacements of the three hydraulic lifts were measured with string potentiometers mounted on the lifts.

These potentiometers were powered by an independent 5 V DC power supply. With the use of terminal strips, connections were made to a laboratory break-out board.

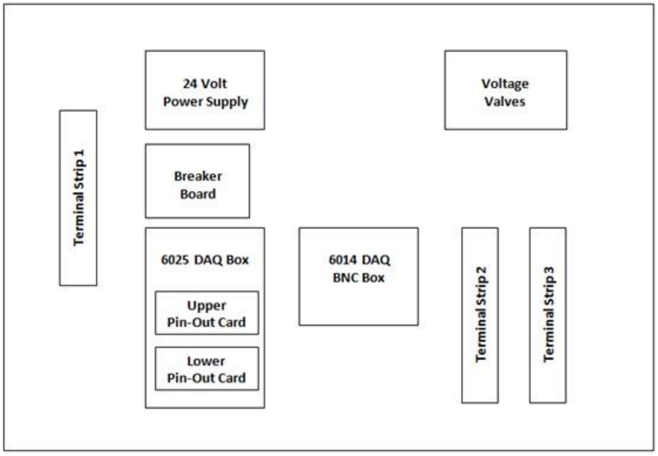


Fig. 2. Electrical Component Layout

These terminals allowed for connections between Data Acquisition (DAQ) cards and signals being sent from the proportional valves, valve meters, and potentiometers.

The feedback signals from the potentiometers were read by the DAQ cards, fed into the LabVIEW program, and the output from the program sent back out through the DAQ cards to the proportional valves. The signals from the string potentiometers ran through the LabVIEW PD controller as well as a 6014 DAQ card. The DAQ cards send the desired position signal to the LabVIEW controller, which then sent the control signals to the proportional valves.

The signal for the valves was generated solely by the LabVIEW controller. The signal from the valves varied from –10 V DC to + 10 V DC. The positioning signals for valves 1 and 2 came from a 6014 DAQ card and the signal for valve three cames from a 6025 DAQ card. Figure 2, illustrates how the input and feedback signals were connected to the DAQ cards.

Additionally, the valves were powered by a 24 V DC power supply. An emergency stop button, previously shown in Figure 1, was wired into the control system. The e-stop was powered by a + 5 V DC power supply. The e-stop then connected the DAQ 6025 card. This allowed a signal to pass to the controller when the platform had been stopped. This signal then stopped the LabVIEW program from running.

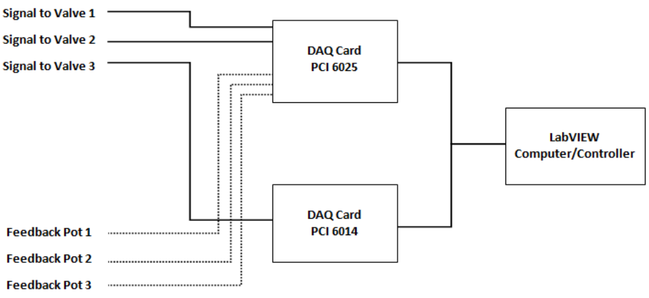


Fig. 3. DAQ Cards Wiring Diagram

V. CHARACTERIZATION OF THE SYSTEM

In order to properly characterize the platform system, values for m, b, and k had to be determined (Dorf, Richard C. and Robert H. Bishop. Modern Control Systems [2]). The m value was determined by approximating the weight of the system and converting it to mass. First, the steel plate thickness and dimensions were calculated. Once this was completed the weight value of 1/8 inch thick steel plate per square foot was researched. The values found ranged anywhere from 7.65 to 8.50 lbs/ft2. Therefore, the weight was approximated to be 8 lbs/ft2.

Next, the weight of the I-beams was calculated. The depth, flange width, and flange thickness of the I-beams were measured. These values were then compared to standard I-beam weight charts to determine the weight of each I-beam per foot. Additionally, the weight of the RMV mock-up, the weight of the material being lifted by each lift, and the painting material on the deck had to be approximated. The weight was approximated to be between 500-600 lbs. With all these factors taken into consideration the weight was approximated to be 2,000 lbs or 907 kg.

With m approximated the next step was to determine the value for k. First, the amount of pressure to move the platform 1% of volume change was determined. A height of 40 inches was determined to be the starting position at half the total lift. So, a 1% change of volume changed meant a position change of 0.4 inches. The value was determined to be 2,000 lbs/in2. The area of the pistons was then found to be 1.5 inches. With this it was calculated the k value was approximately 7500 N/m. With m and k calculated, a determination on the natural frequency and the value of b could be made. The natural frequency was calculated to be approximately 2.88 Hz while the value of b was 5216 kg/s.

VI. LABVIEW VIRTUAL INSTRUMENT DESIGN

program used two separate virtual instruments (VIs) for operation. The first VI, named Motion File Generator, was created to generate a single input file when the platform was in operation. The theory behind this method was to reduce the possibility of an incorrect file being loaded. With this VI, the operator is able to browse input files he/she desires to run. Once selected, the operator enabled the file, which verified that the file did not exceed the parameters defined for height. These limits were set at a 70 inch maximum and a 5 inch minimum. If the file met these parameters the file could then be run. Once the file was run, the VI then wrote a motion comma-separated value (csv) file to the main platform VI controller. However, if the file failed the check, the output file was not written.

The first section of coding on the main VI created the 3D image of the lifts and platform. First, the base was created and dimensions were set. Next, each lift was individually created with its own set of dimensions and their positions set in the 3D image. Finally, the platform dimensions were set. When the controller was initially started this was the very first section of coding that was run, which built the 3D image on the front panel, which is shown in Figure 4 on the next page. Once the platform began to run, this 3D image had to be updated. The coding for this was located within a while loop that continuously updated the image. First, the values from each lift were fed into the loop and computed from lift position to heave, pitch, and roll. Calculations were then performed to take the average distance between the lifts and the center point.

To determine the roll, the position of lifts 2 and 3 were divided by their distance from one another, which was 96 inches. The value was then converted from radians to degrees. Heave was calculated by determining the center point between lifts 2 and 3 and adding them to the position value of lift 1. Once these values were summed they were then divided by two, which gave the average position of each lift. The calculation for determining pitch used the center point between lifts 2 and 3 subtracted by the value of lift 1. This pitch value was then divided by 108 inches, which was the length of the platform. Finally, this value was converted from radians to degrees by using the same constant that roll was converted from. The total magnitude for the pitch and roll were then found and normalized.

These values were then checked to determine if the value was considered to be not a number (NAN). If they were determined to be NAN they were then set to 0. Since these calculations were fed into the function that would rotate the 3D image, heave was set to a constant of 0, also known as z = 0. The value for heave was translated to the 3D image, separate from the rotate function. The values for pitch and roll were set at a constant of 0, while z was set to equal heave. These translations and rotations were cleared every frame, to update the 3D image. Also located in the while loop was the coding for the lift position indicators. Each lift, also known as a mast, had a separate code, which updated every frame.

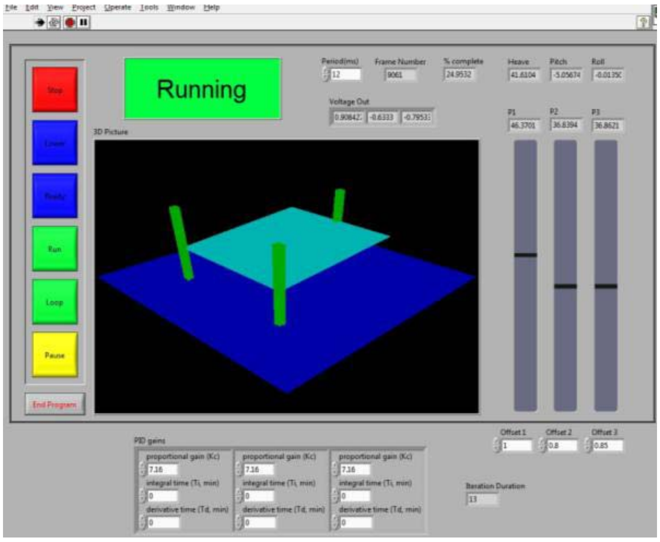
The final while loop located on the back panel, controlled the actual movements of the platform. This while loop was set to a period of 12 ms and the motion csv file was fed into this loop. The total length of the motion csv file was calculated. Then a calculation of frame number and percent complete was calculated. As previously mentioned, the operator could choose from six different operating states. These states were displayed on the front panel and updated through the back panel.

Located within the while loop was a DAQ assistant that read the analog inputs. This input was then fed from each potentiometer. The potentiometers were calibrated by determining the voltage at ½ inch increments. The string potentiometers were linear; therefore, the voltage feedback signal to the LabVIEW controller resulted in a straight line. These values were then plotted and a linear trend line added to determine the equation for each potentiometer. Initial testing of the new controller showed that the potentiometers read a start value ranging from 0.8 to 1 inch. Therefore, an offset function was added so each potentiometer could be adjusted to a height of 0 inches.

This varying potentiometer value was then fed into the state select function. Additionally, the value of the maximum number of frames in the motion file, the current frame the program is on, and the file itself were fed into the state select function. Each state function performed a separate action:

1.) Stop state: runs the current position continuously
2.) Lower state: lowers the platform by a step function
3.) Ready state: either lifts or lowers the platform to the 40 inch mark through a step function
4.) Run state: runs the motion csv file
5.) Loop state: runs the motion csv file continuously
6.) Pause: continuously runs the same position value

The output of the selected state was then fed into the PID controller, where the gain values were determined and set. The values were then fed into each lift where the output of each lift was written into a feedback csv file. Figure 4, illustrates the front panel.



Period(ms) 12
Frame Number 9061
% complete 24.9532
Heave 41.6104
Pitch -5.05674
Roll -0.0135(
Voltage Out 0.90842; -0.6333; -0.7953;
P1 46.3701
P2 36.8394
P3 36.8621
proportional gain (Kc) 7.16
integral time (Ti, min) 0
derivative time (Td, min) 0
proportional gain (Kc) 7.16
integral time (Ti, min) 0
derivative time (Td, min) 0
proportional gain (Kc) 7.16
integral time (Ti, min) 0
derivative time (Td, min) 0
Offset 1 1
Offset 2 0.8
Offset 3 0.85
Iteration Duration 13

Fig. 4. LabVIEW Front Panel

VII. DETERMINATION OF KP AND KD VALUES

Submission To determine the proportional gain (Kp) and derivative gain (KD) values, simulations of an ideal second order system were run using MATLAB Simulink. The transfer function used in this simulation was:

$$T(s) = \frac{(K_P + K_D s)w_n^2}{(s^2 + 2\zeta w_n s + w_n^2) + (K_P + K_D s)w_n^2}$$

To determine the proper transfer function of the system values for KP and KD were initially set at 10 and 0.75 respectively. These values had no significant meaning except that these values were assumed to be appropriate through MATLAB simulation. A simple MATLAB program was to determine this transfer function. The program used set values of 2.88 Hz for wn and 1 for ζ. Additionally, the aforementioned KP and KD values were used. With these values the program gave a transfer function of:

$$\frac{245.7s + 3276}{s^2 + 281.9s + 3604}$$

In addition, a step response of the transfer function was plotted. The step response showed that the transfer function would have only a marginal overshoot of 0.435% with a rise time of 7.9 ms and settling time of 13.6 ms. With this a determination was made that these initial values were acceptable and progress could continue on the design of a Simulink simulation.

The Simulink program consisted of a signal generator, an error input, the PD controller, a saturation limit, and the plant itself. The PD tuner values were initial set to KP = 10 and KD = 0.75. The controller was set to an ideal system and the time domain as continuous. The integral time (I) element, which would be present in a PID controller, is not designed in our system The I term responds to accumulated errors from the past and can cause the present value to overshoot the set point value. With the parameters set the PD controller could then be tuned. The simulation returned a KP value of 56.24 and a KD value of 0. According to the simulation, the rise time would be 0.156 ms with a settling time of 0.277 ms. The percent overshoot would be 0. With the platform weighing approximately a ton, a determination was made that the system would be unable to reach this rise and settling time safely. Therefore, the KP value was scaled approximately 1/8th for initial testing. If this value was not scaled, the possibility of the system going unstable was high according to the control theory criterion that states a large proportional gain value can lead to system instability.

VIII. CONCLUSION

With the use of simulation, control theory, and visualization the characteristics of the system have been defined. The maximum frequencies that the platform can operate safely at have been defined as 0.64 Hz for roll, 0.32 Hz for pitch, and 0.16 Hz for heave. Based on the characteristics of our maximum sea-state, sea-state 3, the average frequency for roll was 0.137 Hz, 0.194 Hz for pitch, and 0.091 Hz for heave for any input file. Therefore, we can successful operate in the ideal ranges of sea-states 0, 1, 2, and 3. Control theory has given us the ability to determine our optimal proportional and derivative values, which were scaled once the weight of platform was taken into consideration.

Greater speed and accelerations are possible within the nominal capabilities of the lifts and platform if higher capacity valves and hydraulic supply was provided. Additionally, sea-states beyond that of sea-state 3 would be possible with this system. Modifications to the lab and lifts would need to be made in order to reach the proper height of these sea-states. If the need for the other 3 DOF becomes apparent the platform could be retrofitted with an additional platform performing yaw, sway, and surge. Modifications could also provide the ability for the platform to test other scenarios besides that of sea-states. Scenarios such as vehicles in rough terrain and individuals working in unstable environments are just a few of the possibilities.

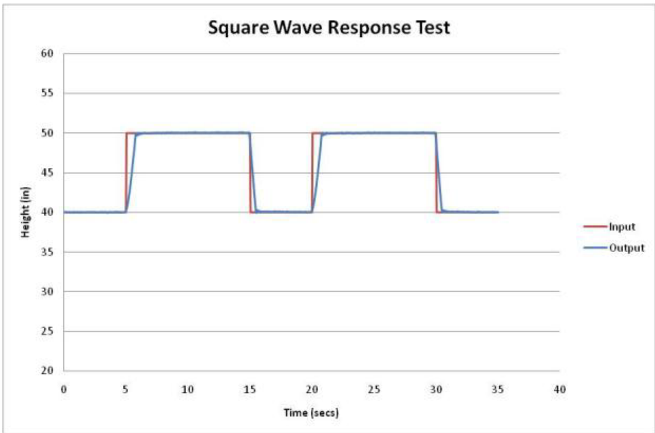


Fig. 5. Sine Wave Test

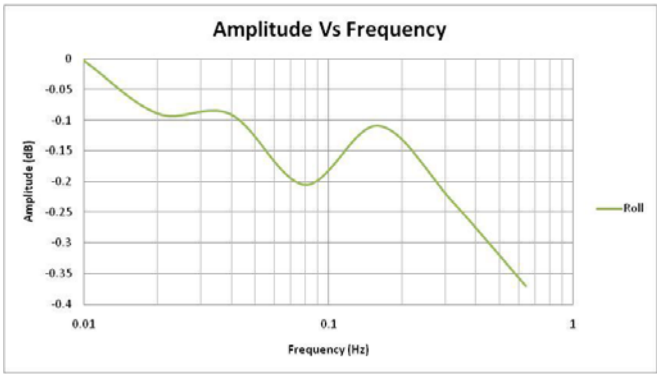


Fig. 6. Roll Bode Plot

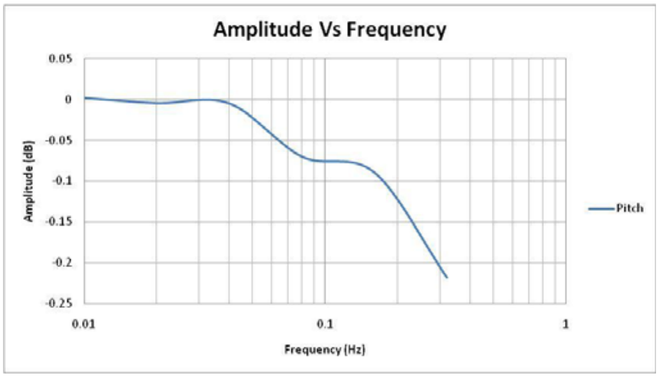


Fig. 7. Pitch Bode Plot

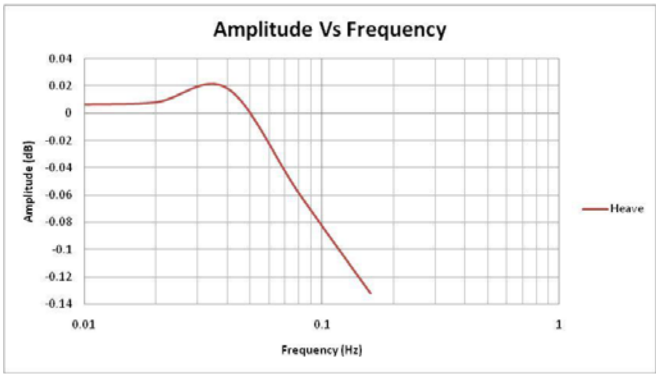


Fig. 8. Heave Bode Plot

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