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Laboratory Memorandum

LM-2004-17

Large Amplitude Motion Program

A. Chinn

August 2004



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LAMP:

LARGE AMPLITUDE MOTION PROGRAM

LM-2004-17

Amanda Chinn

August 2004

Summary

Large Amplitude Motion Program is a computer program that calculates forces and tensions placed on an ocean structure by sea conditions. Through simulation of the ship/object in a storm these values are generated. This program is currently being tested for validity. Hoping the results could be used for many ship related activities such as research and development.

Running a number of different cases and comparing the computed values with experimental values completed tests. Experimental values provided by Hermanski. Values were very similar but the slight difference was due to the restriction placed on the ship by the program. The program gave ideal results for it was able to maintain a steady speed and course direction.

A downfall in this program is time consumption. When it came to running complicated cases (irregular waves in a 20-minute storm), it would take approximately 5 days to conduct one run due to the computer program being 750 times slower than real time causes this.

Once results were formed they were used in uncertainty analysis for validation and verification. They were also used to conduct convergence grid studies. With the completion of 180 runs it was proven that this program has potential for future shipbuilding and Ocean/Naval studies.

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1.0 Introduction

LAMP is an acronym for Large Amplitude Motion Program. It is a program designed to calculate certain attributes of a ship caused by different waves. It is run through Dos commands and obtains its information from input files supplied by the user. The time-domain motions and loads calculated by the program supply numerical solutions to seakeeping-related problems. Both linear and non-linear responses can be analyzed by specifying a certain LAMP mode to conduct the run.

This program, created by SAIC, Science Applications International Corporation, is being tested by the Institute of Ocean Technology to see if it is sufficient for future shipbuilding and research. Tests are conducted by running multiple cases under different conditions and determining if the results are logical. Simulation runs were conducted in regular waves with varying wave frequencies and in irregular waves with varying periods. Both waveforms were tested under varying speeds. Results are compared with experimental values that were provided by Hermanski. A slight variation in value is due to restrictions imposed by the software. This proves there are flaws in the program that affect values. However, there are other flaws that affect the process of running as well.

Limitations were imposed by time and machinery. To run a program in its non-linear mode it could take anywhere from a few hours to a few days. Using the non-linear mode option should provide the most defined results but is extremely time consuming to run. If the number of steps does not result in well-established responses then the number of steps must be increased, increasing the time it takes to run. To simulate a 20 minutes full-scale storm, 12, 000 step could be required. The machinery is very sensitive. A

laptop battery does not last very long therefore it must be monitored at all times. If the computer is to shut down the program shuts off and cannot be resumed. Therefore making the user start running the program over again.

2.0 Discussion – Testing and Evaluating of LAMP

2.1 How does it work??

LAMP is a relatively easy program to operate. It requires a hardware key connected to the computer and input files in order to run (refer to appendix A). By running the program through Dos entails the user to know the command prompts for which they need to obtain the information. All commands and options are fully defined in the eleven-volume User's Guide. Some examples are:

-LAMPRUN – begins running the program to obtain numerical solutions.

-LMCLOT – a post-processing option used to create graphs and tables that are used for evaluations and conclusions.

-ANIM – creates animation of the ship motion on the wave for a visual evaluation of the result.

Information is put into this program through the use of input files. The user or pre-processor generates them. These files hold all the information the program needs to form its results. Comments are useful in the file so that the user can identify what each value represents. They are easily added by typing an exclamation mark (!) in front of the comment. There are 33 data sets in an input file, so it is important to keep organized.

When blank spaces are left in the input file the program will insert default values. A detailed description on how to fill out an input file can be found in the User Guide. With 33 data sets, a lot of information is needed to obtain valid and thorough results.

The benefit of sorting the information into data sets is for easy detection of errors. The system is able to echo out the error and in which data set it is located, allowing for easy debugging. Some important data sets contain information on where to save data (output files), type of results (linear or non-linear), and the number of grid panels needed in x, y, and z direction. Time interval step is the real time it takes to go from one calculation point to the next. At each point measurements are taken. Computational time can be up to 750 times slower than real time, which is why the program is time consuming to run. Wave information such as direction, frequency, amplitude, and phase are needed to determine sea type (heading or following) and intensity of the storm.

LMCLOT uses the results from LAMP RUN to present attributes such as body acceleration, body motion, and wave elevation. These are all outputted in forms of graphs and tables, which are used to compare the results of different LAMP runs. By doing this it is evident that LAMP mode 4 gives the most precise results. Therefore it is used more frequently for the testing results. LAMP 4 is the large-amplitude 3-D full body nonlinear method, LAMP 2 is the approximate large-amplitude 3-D mode applying nonlinear hydrostatic and linear hydrodynamic method, and LAMP 1 is the fully linearized 3-D method.

LAMP uses linearized free-surface condition to calculate velocity potential on the surface of the incident wave. These linear calculations are coming from the mean value of the waves being formed. Non-linear calculations are from the actual wave pattern its

self. Hydrodynamic and hydrostatic pressures are used to calculate forces and results of body motions.

This program not only is able to create graphs and tables but also motion pictures of the results. These movies are viewed through the animation option and are connected to the LMPLOT option for it needs certain files to play. Animation and sea files must be saved from LMPLOT and the user or pre-processor must create an animation file. This animation simulates the ship on the waves. It is useful when determining if a run was logically sufficient. Evaluating the proper direction of the wave compared to the ship does this.

2.2 Tricks of the trade

This program is capable of running for long periods of time with only the one command. By doing this a number of different cases can be set up to run over night or weekend. This way not much time is lost during the workday. To do this just type:
lamprun filename #1 [space] filename #2 [space] filename #3 [space] etc. The program will begin the command and run file #1 then when that is finished it will start running file #2 right away. When using this it is important to be aware of the files ran and that will be running.

Results generated by this program can be easily lost. It is important to insure that the computer is fully plugged in and that typing errors are avoided. If the computer is to shut down the run cannot be resumed. The user must restart the run from the beginning, which is time consuming especially if it is a LAMP 4. If one intends to LMPLOT a run but accidentally types LAMPRUN the old information is lost and the run must complete again. Also results will not generate if the filename is typed incorrectly. The file will be

skipped and the rest will continue to be completed. The file directory too must be correct. The program will not search the computer for the file, it will return an error message saying file not found. It is important to remember with this program that computers are not smart they only do as they are told.

Even if things are done correctly, responses may not be satisfactory. If this occurs the user must increase the number of steps and re-run the program. It is of good practice to use a large number of steps and then decrease the number of steps after. To determine the proper number of steps, one must pick different points along the graph and calculate standard deviation, amplitude, and response amplitude operator, RAO or significant value. The user tries to decrease the second point value as much as possible (shorter run time) while maintaining the same values calculated. The second point number is then equal to the number of steps needed to achieve steady responses for calculations.

When comparing the RAO's from well-defined responses it is better to use percent difference than unit difference. If something varies by a few percent it is not as significant as if it varies by a few units. For example, if a comparison is showing a difference of 4% it is extremely small but if it shows 4 meters then that is a large difference. In these runs, many of the differences calculated can be contributed to restriction placement on the vesicle. In real life situations speed and heading are not constant. People have a tendency to swerve off course and to speed up and slow down. In this program we were able to reduce this by holding the ship at a constant speed and direction giving us ideal results.

2.3 How to tell if motion is correct??

Based on an animation of a following sea case the wave was appearing to be a head sea. After checking the input file a couple of times to see if all the information was input right it was noticed that the velocity of the ship was greater than the velocity of the wave. This gave the relative velocity of the wave with respect to the ship the opposite sense of direction in which it was assigned. By determining the relative velocity of the ship and waves, the response was proven to be correct although it appeared to be wrong.

To calculate this relative velocity of the wave the user must use a number of different formulae (refer to appendix B). First the frequency (f) must be calculated by dividing the angular frequency (ω) by two times pi (Π). The period of the wave can be computed since it is the reciprocal of the frequency. Finally the velocity is equal to wavelength divided by period.

2.4 How to compare information??

The important information gathered from this program was body acceleration, body motion, and wave elevation. These specific attributes are collected into a single Excel document and the information is used to compute standard deviation and amplitude for heave acceleration, pitch degree, and wave elevation and RAO for heave acceleration and pitch degree (refer to appendix C). Results change for different frequencies and amplitudes. Also from this Excel document a graph of the way the ship and wave behaves is formed. Heave acceleration represent the motion of the ship center in vertical direction, pitch degree represents the motion of the ship's bow in an up and down motion,

and elevation represents the motion of the waves. All points for calculations were determined from the curve representing pitch on the graph.

When these graphs are formed for all responses, the RAO's can be calculated and compared. If all the heave acceleration and pitch degree's RAOs are similar then it was a good run. If they vary then check for mistakes in input file or adjust number of steps ran.

2.5 Uncertainties

Uncertainty analysis made it possible to quantify accuracy of LAMP calculation. Verification of numerical calculations was used to find the true value in which the results approached. Validation compensated for small numerical values omitted during experiment. Water viscosity and the coefficient of friction were not considered for their values were extremely small. By running LAMP under three different grid sizes we can conduct convergence studies. Using a course, medium, and fine grid, these convergence tests are conducted. Two grids would only indicate sensitivity. Some time it is possible to need more than three grids to obtain reasonable values. As in our case we ran a multiple number of simulations, changing one variable in each run and keeping others constant. By changing the NXFS, NYFS, and Time step values the best three grids were chosen for calculation. Appendix D shows some results of uncertainty analysis used to form conclusions.

2.6 LAMP Options

2.6.1 LAMPRUN

This is the main option in LAMP. In order to obtain the results for a ship this step must be used first and allowed to run completely (refer to log file in appendix E). For the different LAMP modes and number of steps required, this option takes different amounts of time to conduct. LAMP 1 and 2 are faster in the process than LAMP 4, therefore LAMP 1 and/or LAMP 2 simulations are conducted initially. When run is complete, the other options use results obtained to present data. LAMPRUN generates all the output files these options need. As the program is running the file, geometric, and pressure data output files are all generated from information inputted through the input file. When the other options are called upon, these output files supply the information needed to display the graphs and tables requested. During LAMP runs the other options available cannot be used. Under the Dos system used to activate the program no multitasking can be performed. The user must wait until the run is complete before they can perform tests and calculations with results. If a set of files is sat up to run over night or a weekend then it is just like running one long file. The Dos system does not allow the user to plot the information of the files until they are all complete.

2.6.2 LMPLLOT

This option allows the user to obtain results that are usable for future analysis. From the use of output files it is able to generate graphs and tables that show how the ship is reacting to the different frequencies and amplitudes of the waves. When LMPLLOT is in use a table of options is presented to the user. Each option is fully explained in the user guide. The option time history (#27) is the saving option. After being selected another table of options is available. Here the user will select the

information important to their project, which is then saved on to the computer. By doing this it allows the user to transfer information into excel documents for presentations and comparisons. Some options found here are body acceleration (#3), body motion (unsteady) (#4), and incident wave elevation with respect to fixed origin (#26). Another choice that could be made under time history is the animation option (#24). This must be selected if one plans on using the animation command. This option will generate the animation and sea files needed to produce that animation picture of the ship on the wave.

2.6.3 ANIM

This is the animation option where a motion picture is created from the animation and sea files. It allows the user to view the ships reactions to the waves created. It runs through all the steps quickly to produce the motion. Options are available that can start/stop (space bar), rewind (type b), speed up (type f) and slow down (type s) the clip. The motion picture can be ran in real time by synchronizing it to the clock on the computer by typing ctrl t. Arrow keys will move the ship and grid so that different views can be observed. This is great for presentation and visual analysis. By determining from calculations, it is possible to create a movie in one's head. This allows the user to know if the clip generated seems logical or not.

3.0 Results

3.1 Regular Waves

Results are calculated for regular waves from graphs like that in appendix F. After determining point 1 (PT1) and point 2 (PT2) from the consistency of the graph, standard deviation, amplitude, and RAO can be calculated in Excel. Comparing RAO's from runs with different LAMP modes, frequencies and amplitudes forms conclusions.

Parameters for variations were chosen based on two test matrices, US and DND. After comparing with experimental values a slight difference was noted. This was due to restrictions placed on the ship by the program that are uncontrollable in real situations.

Results were formed after running 172 regular wave cases. The longest run took 8 hours when a run under LAMP mode 4 need 1000 steps to obtain well defined responses. The following is an example of a graph of the resultant pitch angle (Figure 1) and heave acceleration's (Figure 2) RAOs and corresponding table (pitch angle Table 1 and heave acceleration Table 2).

Figure 1 – Pitch Degree Graph (DND matrix, head sea, 8.2 knots)

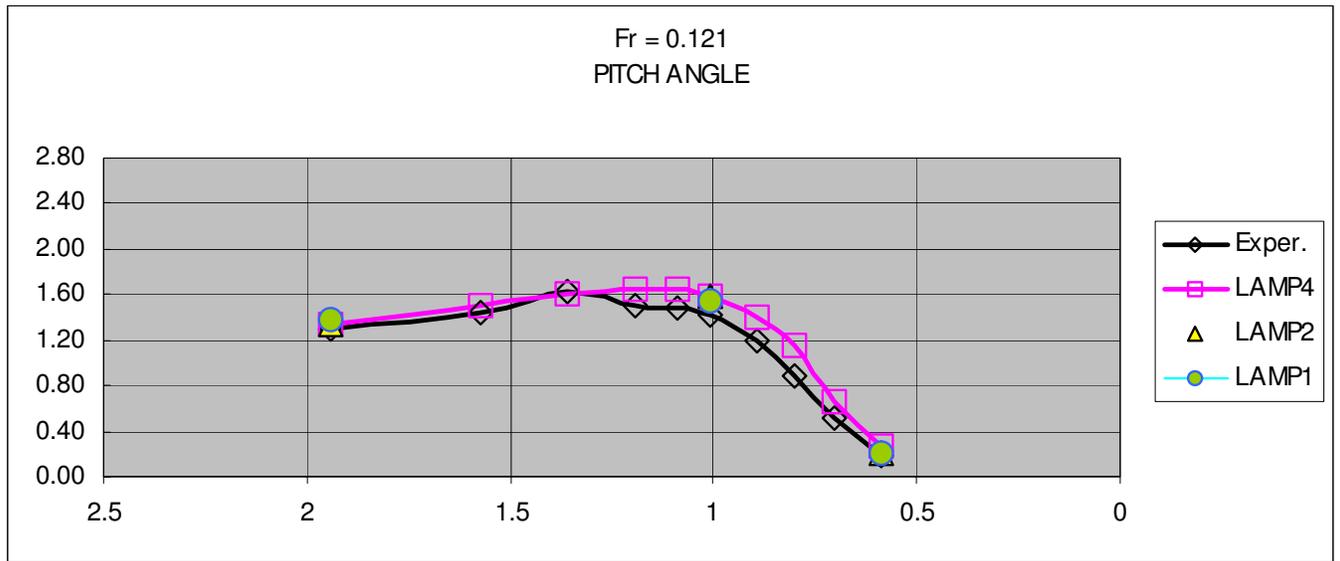


Table 1 – Pitch Degree Chart (DND matrix, head sea, 8.2 knots)

	Run #	L_w/L_s	FREQ.	FREQ. E	PITCH ANGLE			
					Measured	Calculated		
					[deg/m]	[deg/m]	[deg/m]	[deg/m]
					Exper.	LAMP4	LAMP2	LAMP1
cpf_	129,130,131	0.59	0.916	1.276	0.1893	0.27507	0.21146	0.20152
cpf_	144	0.7	0.841	1.145	0.5066	0.6621		
cpf_	143	0.8	0.787	1.052	0.8899	1.15719		
cpf_	142	0.89	0.746	0.985	1.2005	1.39166		
cpf_	132,133,134	1.01	0.700	0.911	1.4274	1.57506	1.58384	1.54926
cpf_	141	1.09	0.674	0.869	1.4809	1.65		
cpf_	140	1.19	0.645	0.824	1.5073	1.63719		
cpf_	139	1.36	0.603	0.760	1.6181	1.60634		
cpf_	138	1.57	0.561	0.697	1.4369	1.51216		
cpf_	135,136,137	1.94	0.505	0.615	1.2869	1.34528	1.34143	1.38375

Figure 2 – Heave Acceleration Graph (DND matrix, head sea, 8.2 knots)

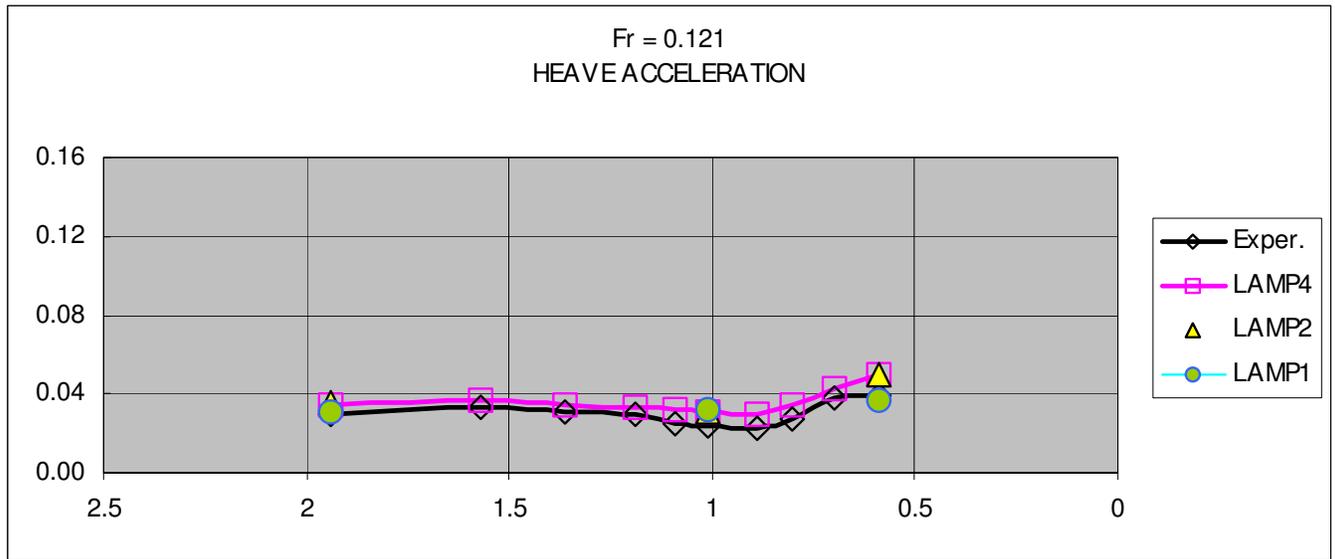


Table 2 – Heave Acceleration Chart (DND matrix, head sea, 8.2 knots)

					HEAVE ACCELERATION			
					Measured	Calculated		
					[g/m]	[g/m]	[g/m]	[g/m]
Run #	L_w/L_s	FREQ.	FREQ. E	Exper.	LAMP4	LAMP2	LAMP1	
cpf_ 129,130,131	0.59	0.916	1.276	0.0396	0.05009	0.05021	0.03719	
cpf_ 144	0.7	0.841	1.145	0.0378	0.04253			
cpf_ 143	0.8	0.787	1.052	0.0274	0.03434			
cpf_ 142	0.89	0.746	0.985	0.0226	0.03013			
cpf_ 132,133,134	1.01	0.700	0.911	0.0237	0.03061	0.03127	0.0325	
cpf_ 141	1.09	0.674	0.869	0.0249	0.03175			
cpf_ 140	1.19	0.645	0.824	0.0297	0.03261			
cpf_ 139	1.36	0.603	0.760	0.0312	0.03452			
cpf_ 138	1.57	0.561	0.697	0.0338	0.03681			
cpf_ 135,136,137	1.94	0.505	0.615	0.0299	0.03422	0.03581	0.03059	

3.2 Irregular Waves

Irregular wave's results form the graph shown in appendix F. The points for determining standard deviation are difficult to determine due to random character of responses. Therefore they are chosen by estimation. The first couple of hundred steps are omitted to allow for stabling of waveform. Standard deviation and significant value are calculated from these points in excel.

Due to the time consumption to obtain precise results, only 8 cases were completed. The variables in each case were significant wave height, period, and speed. The longest run took about 6 days for it contained 12, 000 steps. These runs were extremely complex with 400 different wave patterns to each storm. The following is an example of a table formed from the resultant pitch angle and heave acceleration's (Table 3) significant values.

Table 3 – Irregular Wave Chart

Froude Number	Velocity	Height (H 1/3)	Period (Tp)	Measured Values		Significant Value	
				Heave Acceleration	Pitch Angle	Heave Acceleration	Pitch Angle
	(knots)	(m)	(s)	(m/s ²)	(degrees)	(m/s ²)	(degrees)
0	0	3.26	9.7	0.010	0.864	0.012	0.89
0.147	10	3.26	9.7	0.025	1.031	0.031	1.146
0.221	15	3.26	9.7	0.035	1.103	0.048	1.296
0.294	20	3.26	9.7	0.049	1.134	0.067	1.32
0.368	25	3.26	9.7	0.063	1.140	0.083	1.201
0.147	10	5.03	12.69	0.038	1.659	0.0454	1.834
0.294	20	5.03	12.69	0.071	1.875	0.0965	2.127
0.147	10	11.22	13.5	0.088	3.798	0.101	3.763

4.0 Conclusion

This program has potential to be a valuable asset to the company. With the values of the 180 runs completed matching the experimental values it is proven that the program will give proper results. The ideal aspect will be quantified by the uncertainty analysis using verification and validation for numerical and modeling values respectively.

LAMP is an easy program to learn to use. The user guide is very explanatory and helpful. By following the instructions for the animation option, visual results are helpful in understanding the sea-like situation. Results are easy to use since they are in the form of tables and graphs.

References:

Mansour, A.E. and R.C. Ertekin, eds. *Ship and Offshore Structures Congress*. Oxford, UK, 2003.

About the Large Amplitude Motions Program (LAMP) System. 19 July 2004. Science Applications International Corporation. 19 July 2004.
<http://www.ship.saic.com/overview_lamp.html>

Appendices

Appendix A – Input file

Regular Waves

```
!01 DESCR - Descriptive Title (max 80 char)
CPF test, Lw/lb=0.5
!02 FPROG - Source file for programmer's input (blank for defaults)
cpf.prg
!03 FAPLT - Source file for autopilot input (blank for defaults)

!04 FGEOM - Source file for geometry definition
cpf_n.lmp
!05 FOUT - Destination file for primary output
cpf_14.out
!06 Output frequency for pressure, geometry, etc.
!
      POUT          GOUT          SOUT          BOUT
0    450    500      2        500    500      1      0      0      0      0
0
!07 FPOUT = File for pressure data output if POUT>0
cpf_14.pout
!08 FGOUT = File for geometry output if GOUT>0
cpf_14.gout
!09 FSOUT = File for balance check output if SOUT>0

!10 FBOUT = File for elastic beam output if BOUT>0

!11 AUXOUT(20) - Flags for auxiliary output files
      0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
!12 IVEC - Use Non-vectorized (0) or vectorized (1) kernel
      0
!13 LMPTYP (1/2/4)  MOTYPE (forced/impulsive/free)  MIXED
(Rankine/mixed)
      4      2      -1
!13 (cont) IFSMIX NXFS NYFS  IMSMIX NXMS NZMS - mixed-source surface
points
      5      51      31      1      21      11
!13 (cont) XMIX YMIX ZMIX - mixed-source surface extent
      374.000      218.000      37.0000
!14 TINIT NSTEP DTH IRST - Initial Time, Number of Steps, Time Step,
Restart
      0.00000      500      0.140000      0
!15 USHIP UCURNT DCURNT WDEPTH - Steady speed, current vel/dir,
water depth
      5.14400      0.00000      0.00000      0.00000
!16 PMGG(1:6) Initial location and orientation of Cg in oxyz
      0.00000      0.00000      1.35000
      0.00000      0.00000      0.00000
!17 VMGSHP(1:6) Initial Velocity and Rotation rate in ship fixed system
```

```

5.14400      0.00000      0.00000
0.00000      0.00000      0.00000
!18 AMPM(1:6) Amplitude for forced sinusoidal motion (if MOTYPE=0)
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
!19 OMEGM(1:6) Frequency for forced sinusoidal motion (if MOTYPE=0)
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
!20 SWITCH(1:6) Sets which modes of motion will be considered
0      0      1
0      1      0
!21 ISEA  NWAVES  NWSC
1      1      2
!21 (cont)  FREQW  PHASEW  AMPW0  HEADW
0.59500      0.00000      1.7430      180.000
!21 (cont)  WSCSTP(i)  WSCFAC(i) - wave scaling step/factor
1      0.00000
50     1.00000
!22 GRAVIN  RHOIN  LENIN  ANGIN - Scale Factors for Input
9.81000      1025.00      124.500      57.2900
!23 GRAVOUT  RHOOUT  LENOUT  ANGOUT - Scale Factors for Output
9.81000      1025.00      124.500      57.2900
!24 GSHIFT(3),  GORIG(3),  GROT(3) - Input geometry transformation
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
!25 SMA = Ship mass,  SMI(1,1), (2,1), (3,1), (1,2)...(3,3) Mom. of Inertia
1.00000
36.4600      0.00000      0.00000
0.00000      1413.68      0.00000
0.00000      0.00000      1413.68
!26 RGRAV = center of gravity in input system
0.00000      0.00000      1.35000
!27 SYMGEO= 1 for Symmetry in calc.,  SYMINP =1 for symmetry in input
1      1
!28 NCOMP0 ...
2
!28 (cont)  KCTYPE0  NEWWLO  KSPWLO  SPWLO  NEWST0  KSPST0  SPST0,1->NCOMP0
0      7      1      0.00000      31      7      0.150000E-01
1      0      0      0.00000      0      0      0.00000
!29 IVM,  IHM,  ITM,  NBCA,  NBMX ...
1      0      0      5      6
!29 (cont)  XMC(123,1->NBCA)
108.940      0.00000      0.00000
93.3800      0.00000      0.00000
77.8100      0.00000      0.00000
62.2500      0.00000      0.00000
39.2200      0.00000      0.00000
!29 (cont)  XMS(3,I)  AMS(I)  AIS(3,I)  AMI(3,I)  DWS(I)  AWS(I)  EWS(I)  (I=1->NBMX)
116.2 0      0.00000      2.03000      184090.
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000
99.1380      0.00000      1.49000      519716.
0.00000      0.00000      0.00000
0.00000      0.00000      0.00000

```

0.00000	0.00000	0.00000	
84.9960	0.00000	1.63000	688472.
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
69.6320	0.00000	1.13000	821230.
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
50.9940	0.00000	1.03000	0.1184162E+07
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
23.1240	0.00000	1.63000	0.1373664E+07
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	

!29 (cont) STRDMP(2,4) structural damping, fraction of critical in 1st
2 modes

! for vertical, horizontal, torsional, and tension vibration

0.100000	0.200000	
0.100000	0.200000	
0.100000	0.200000	
0.100000	0.200000	

!30 KINVIS (kinematic viscosity) IHROLL (roll damping option)
1.19E-06 1

!31 IHLIFT (hull lift option)
1

!32 NFIN - Number of wing-like lifting appendages (e.g. rudder, fins)
2

!32 (cont) center, span vec., chord vec.span length, chord length, and
angle

4.50000	0.00000	-4.00000
0.00000	0.00000	1.00000
-1.00000	0.00000	0.00000
5.30000	3.40000	0.00000
100.600	0.00000	-5.85000
0.00000	0.00000	1.00000
-1.00000	0.00000	0.00000
1.75000	4.57700	0.00000

!33 NBK - Number of plate-like lifting appendages (e.g. bilge keels)
2

!33 (cont) center, span vec., chord vec.span length, chord length

58.3500	6.50000	-3.50000
0.00000	0.707000	-0.707000
1.00000	0.00000	0.00000
0.800000	66.0000	
58.3500	-6.50000	-3.50000
0.00000	-0.707000	-0.707000
1.00000	0.00000	0.00000
0.800000	66.0000	

TABLE 3.2 PROPERTIES OF HARMONIC WAVES IN DEEP WATER

Elevations of Lines of Equal Pressure (at a depth z)	$\zeta_z = \zeta_0 e^{-kz} \cos k(x - V_w t)$
Surface Profile (i.e. elevation of line of equal pressure at $z = 0$) (first approximation)	$\zeta = \zeta_0 = \zeta_0 \cos k(x - V_w t)$ $= \zeta_0 \cos(kx - \omega_w t)$
Horizontal Water velocity	$u = k \zeta_0 V_w e^{-kz} \cos k(x - V_w t)$
Vertical Water Velocity	$w = k \zeta_0 V_w e^{-kz} \sin k(x - V_w t)$
Wave Velocity or Celerity	$V_w = \frac{L_w}{T_w} = \frac{g}{\omega_w} = \left(\frac{gL_w}{2\pi}\right)^{1/2}$
Wavelength	$L_w = \frac{2\pi V_w^2}{g} = \frac{2\pi g}{\omega_w^2} = \frac{g T_w^2}{2\pi}$
Wave Number	$k = \frac{2\pi}{L_w} = \frac{\omega_w^2}{g} = \frac{g}{V_w^2} = \frac{4\pi^2}{g T_w^2}$
Wave Period	$T_w = \left(\frac{2\pi L_w}{g}\right)^{1/2}$
Pressure	$p = \rho g(z - \zeta)$ or $p = \rho g z - \zeta_0 \rho g e^{-kz} \cos(kx - \omega_w t)$ where $\rho g z$ is hydrostatic pressure
Maximum Wave Slope (first approximation)	$\alpha_{M1} = k \zeta_0 = \frac{2\pi \zeta_0}{L_w} = \frac{\pi h_w}{L_w}$
Energy per unit wave Surface	$E = \frac{1}{2} \rho \zeta_0^2$

Froude Scaling Laws

Scale Factor:	λ
Model Scale:	MS
Full Scale:	FS
Length:	$L_{FS} = \lambda L_{MS}$
Area:	$A_{FS} = \lambda^2 A_{MS}$
Volume:	$V_{FS} = \lambda^3 V_{MS}$
Mass:	$m_{FS} = \lambda^3 m_{MS}$
Density:	$\rho_{FS} = \rho_{MS}$
Acceleration:	$a_{FS} = a_{MS}$
Force:	$F_{FS} = \lambda^3 F_{MS}$
Moment:	$M_{FS} = \lambda^4 M_{MS}$
Pressure:	$P_{FS} = \lambda P_{MS}$
Power:	$P_{FS} = \lambda^{3.5} P_{MS}$
Velocity:	$v_{FS} = \lambda^{0.5} v_{MS}$
Time:	$T_{FS} = \lambda^{0.5} T_{MS}$
Frequency:	$\omega_{FS} = \lambda^{-0.5} \omega_{MS}$
Mass Moment of Inertia:	$I_{FS} = \lambda^5 I_{MS}$
Area Moment of Inertia:	$I_{FS} = \lambda^4 I_{MS}$
Polar Moment of Inertia:	$J_{FS} = \lambda^4 J_{MS}$
Section Modulus:	$S_{FS} = \lambda^3 S_{MS}$
Young's Modulus:	$E_{FS} = \lambda E_{MS}$
Shear Modulus:	$G_{FS} = \lambda G_{MS}$
Axial Rigidity:	$(EA)_{FS} = \lambda^3 (EA)_{MS}$
Bending Rigidity:	$(EI)_{FS} = \lambda^5 (EI)_{MS}$
Shear Rigidity:	$(GA)_{FS} = \lambda^3 (GA)_{MS}$
Torsional Rigidity:	$(GJ)_{FS} = \lambda^5 (GJ)_{MS}$

Appendix C – Comparison Calculations

Excel Commands – Regular Waves

Standard Deviation = STDEV(pt 1 : pt 2)

Amplitude = SQRT(2)*STDEV

RAO (heave) = Heave Amplitude/Elevation Amplitude

RAO (pitch) = Pitch Amplitude/Elevation Amplitude

Irregular Waves

Standard Deviation = STDEV(pt 1: pt 2)

Amplitude = 4*STDEV

Appendix D – Uncertainty Calculations

GRID CONVERGENCE STUDY												
		X domain			Y domain			Time step			Experiment	Experimental Uncertainty
		Grid 3	Grid 2	Grid 1	Grid 3	Grid 2	Grid 1	Grid 3	Grid 2	Grid 1		
Heave Accel.	[m/sec ²]	0.997	0.967	0.959	0.883	0.948	0.959	0.965	0.981	0.994	0.71	0.02
	ε		-3.1%	-0.9%		6.9%	1.1%		1.6%	1.3%		
Pitch Angle	[deg]	3.059	2.876	2.839	3.957	2.929	2.839	2.877	2.828	2.818	2.56	0.05
	ε		-6.4%	-1.3%		-35.1%	-3.2%		-1.8%	-0.3%		
VERIFICATION												
		GRID REFINEMENT	CONVERGENCE RATIO	ORDER OF ACCURACY	RE ERROR ESTIMATE	CORRECTION FACTOR		UNCERTAINTY	UNCERTAINTY % S _i	GRID CONVERGENCE INDEX		
		r	R	p	δ* _{RE}	C		U _G	U _G	CGI		
		copy	zmieniac	zmieniac	zmieniac	copy			zmieniac			
Heave Accel. X	[deg]	1.56	0.292	2.759	0.0036	1.683	C>>1	0.0086	0.90%	0.0109		
Heave Accel. Y	[deg]	1.58	0.156	4.062	0.0019	3.613	C>>1	0.0118	1.23%	0.0057		
Heave Accel. t	[deg]	1.25	0.802	0.987	0.0517	0.438	C<<1	0.0517	5.40%	0.1552		
								0.07	7.5%	0.17		
Pitch Angle X	[m/sec ²]	1.56	0.204	3.560	0.0096	2.704	C>>1	0.0422	1.49%	0.0287		
Pitch Angle Y	[m/sec ²]	1.58	0.088	5.315	0.0088	6.920	C>>1	0.0397	1.40%	0.0263		
Pitch Angle t	[m/sec ²]	1.25	0.193	7.365	0.0023	7.419	C>>1	0.0112	0.39%	0.0069		
								0.09	3.3%	0.06		
VALIDATION												
		D	U _D	S	U _{SN} / %D	E / % (D)	U _v / %D					
Heave Accel.	[m/sec ²]	0.71	0.02	0.96	0.07	0.25	0.07	E >> U_v				
			2%		7.5%	34.5%	10.4%					
Pitch Angle	[deg]	2.56	0.05	2.83	0.09	0.27	0.11	E >> U_v				
			2%		3.6%	10.5%	4.2%					

Appendix E – Log file

Regular Waves (condensed)

LAMP - Large Amplitude Motions Program : Standard Output

VERSION : LAMP VERSION 2.9.9e / March 2002

PROCESSOR : PC/Windows

RUN DATE : 05/07/2004 :: 18:15:09.555

INPUT_FILE_ECHO

!***** INPUT FILE ECHO (reformatted) *****

!***** PROGRAMMERS FILE ECHO (reformatted) *****

!***** AUTOPILOT FILE ECHO (default) *****

!***** END OF INPUT ECHO *****

Computed Hydrostatic Values:

Wetted Surface Area S = 1983.6
Submerged Volume V = 4500.7
Longitudinal Center of Buoyancy ... LCB = 59.842
Transverse Center of Buoyancy TCB = 0.0000
Vertical Center of Buoyancy VCB = -1.8977
Waterplane Area Awp = 1439.5
Longitudinal Center of Flotation .. LCF = 54.142
Longitudinal Metacentric Height ... BML = 301.50
Transverse Center of Flotation TCF = 0.0000
Transverse Metacentric Height BMT = 4.5770
Vertical Center of Gravity (input) . VCG = 1.3500
Longitudinal Metacentric Height ... GML = 298.25
Transverse Metacentric Height GMT = 1.3293
Waterline Length LWL = 124.92
Waterline Maximum Beam BWL = 14.869
Maximum Draft T = 4.9856
Overall Length LOA = 136.67
Maximum Beam B = 16.400

Adjusting ship mass and mass center to match hydrostatics:

Input value of SMA = 1.00000

Corrected value of SMA = 0.461325E+07

Input value of RGRAV0 = 0.00000 0.00000 1.35000

Corrected value of RGRAV0 = 59.8422 0.00000 1.35000

NOTE: RGRAV0 values include initial geometry transformation, if any

Checking mass distribution for longitudinal sectional loads calculations:

Sum of mass distribution = 8.9400
Ship mass (input or hydrostatics) ... = 0.46132E+07
Discrepancy in point mass total = -100.00% of displacement
Long. center (point masses) = 26.385
Long. center (input or hydrostatics) = 59.842
Discrepancy in point mass center ... = -24.48% of Loa
Long. radius of gyration (point masses) = 48.681
Long. radius of gyration (from SMI) . = 37.599
Discrepancy in radius of gyration .. = 8.11% of Loa

WRN186 - Longitudinal mass center for specified weight stations

does not match longitudinal center of buoyancy
 Adjusting mass distribution to match ship mass and center...
 Scaling point masses by 0.32380E+06 + 0.90701E+06 * x
 Ship mass (corrected point masses) .. = 0.46132E+07
 Discrepancy in point mass total = 0.00% of displacement
 Long. center (corrected point masses) = 59.842
 Discrepancy in point mass center ... = 0.00% of Loa
 Long. radius of gyration (corr. masses) = 58.074
 Discrepancy in radius of gyration .. = 14.98% of Loa
 Adjusting mass station lengths (DWS) to match overall length...
 Corrected mass distribution:
 !29 (cont) XMS(123,I), AMS(I), AIS(123,I),AMI(123,I), DWS(I), AWS(I), EWS(I), (I=1->NBMX)

0.00000	0.796289	0.00000	0.243911E-03
0.169510E-07	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.306611E-01	0.00000	0.00000	
0.00000	0.682699	0.00000	0.266828E-03
0.224551E-07	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.559293	0.00000	0.184979E-03
0.267852E-07	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.409590	0.00000	0.168609E-03
0.386225E-07	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.00000	0.185735	0.00000	0.266828E-03
0.448033E-07	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.466667	0.00000	0.00000	
0.933333	0.00000	0.00000	0.120109E-02
0.600426E-08	0.00000	0.00000	
0.00000	0.00000	0.00000	
0.600434	0.00000	0.00000	

Start of LAMP time stepping

time step : pmgg(1)...

1	59.8422	0.000	1.350	0.000	0.000	0.000
2	60.5624	0.000	1.350	0.000	-0.5487E-04	0.000
3	61.2826	0.000	1.350	0.000	-0.1374E-03	0.000
4	62.0027	0.000	1.349	0.000	-0.7027E-03	0.000
5	62.7229	0.000	1.348	0.000	-0.2552E-02	0.000
6	63.4430	0.000	1.346	0.000	-0.5898E-02	0.000
7	64.1632	0.000	1.344	0.000	-0.1170E-01	0.000
8	64.8834	0.000	1.341	0.000	-0.1962E-01	0.000
9	65.6035	0.000	1.337	0.000	-0.3020E-01	0.000
10	66.3237	0.000	1.332	0.000	-0.4340E-01	0.000
11	67.0438	0.000	1.327	0.000	-0.5913E-01	0.000
12	67.7640	0.000	1.321	0.000	-0.7754E-01	0.000
13	68.4841	0.000	1.313	0.000	-0.9846E-01	0.000
14	69.2043	0.000	1.306	0.000	-0.1219	0.000
15	69.9245	0.000	1.297	0.000	-0.1478	0.000

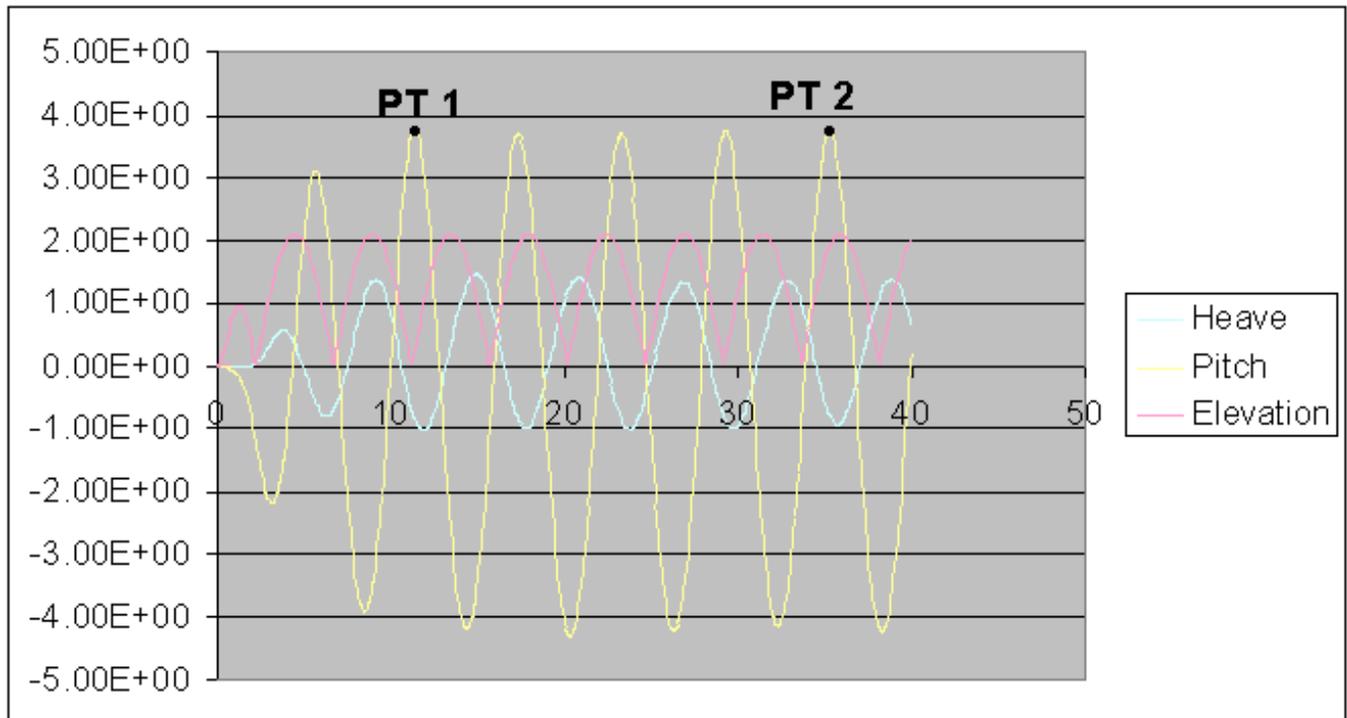
486	409.122	0.000	1.785	0.000	-3.092	0.000
487	409.842	0.000	1.884	0.000	-3.108	0.000
488	410.562	0.000	1.979	0.000	-3.091	0.000
489	411.282	0.000	2.068	0.000	-3.044	0.000
490	412.002	0.000	2.151	0.000	-2.966	0.000
491	412.723	0.000	2.227	0.000	-2.859	0.000
492	413.443	0.000	2.295	0.000	-2.725	0.000
493	414.163	0.000	2.354	0.000	-2.564	0.000
494	414.883	0.000	2.404	0.000	-2.379	0.000
495	415.603	0.000	2.443	0.000	-2.171	0.000
496	416.323	0.000	2.472	0.000	-1.941	0.000
497	417.044	0.000	2.489	0.000	-1.691	0.000
498	417.764	0.000	2.493	0.000	-1.422	0.000
499	418.484	0.000	2.485	0.000	-1.137	0.000
500	419.204	0.000	2.465	0.000	-0.8365	0.000

Total : clock=04:15:22.72

.. Execution Terminating .. End of Program LAMP ..

Appendix F – Wave Graphs

Regular wave



Irregular wave

