Computation of Vessel Motion Statistics in Combined Wave Spectra: Enhanced Motion Analysis of T-ACS, Lighter and Containership Combinations

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0 Executive Summary

The speed at which cargo can be lowered onto a lighter by a ship-mounted crane is limited by the relative motion between the vessels and by the ability of the lighter and cargo to withstand the impact loads that arise when the cargo impacts the lighter deck. A previous study performed complementary hydrodynamic and structural analyses on three lighters: a Joint Modular Lighter System [JMLS] module, a Landing Ship-Vehicle [LSV], and a Landing Craft-Utility [LCU-2000]. The hydrodynamic analysis provided the relative velocity between the Auxiliary Crane Ship [T-ACS] crane boom tip and the lighter decks in an environment characterized by 5 ft. irregular seas. Subsequently, a broader investigation of effects of sea and swell was made, analyzing vessel and lighter responses to wind-driven waves as well as swell in different combinations of headings from all directions, while considering the effects of an additional ship. A 3D tool was developed to display the relative and absolute motion for each of the three vessels covering all degrees of freedom for displacement, velocity and acceleration. This tool represented a great advance by providing a convenient method for finding and displaying vessel motions.

In the present work, calculations are carried out at additional wave headings, making data available at 15° increments for the entire heading range (0° - 360°). In addition, the capability to handle seas and swells having arbitrary significant height and modal period is added.

The report is supplemented by two EXCEL spreadsheets, which are used to display the results in the form of three-dimensional surface plots of the motions against sea and swell directions.

1 Introduction

The speed at which cargo can be lowered onto a lighter by a ship-mounted crane is limited by the relative motion between the vessels and by the ability of the lighter and cargo to withstand the impact loads that arise when the cargo impacts the lighter deck. A previous study (Reference 1) performed complementary hydrodynamic and structural analyses on three lighters: a Joint Modular Lighter System [JMLS] module, a Landing Ship-Vehicle [LSV], and a Landing Craft-Utility [LCU-2000]. The hydrodynamic analysis provided the relative velocity between the Auxiliary Crane Ship [T-ACS] crane boom tip and the lighter decks in an environment characterized by 5 ft. irregular seas. However, this analysis was quite limited in scope. Only a single wave heading was examined, and T-ACS/lighter combinations were analyzed in the absence of an alongside containership.

To correct this deficiency, a broader investigation of effects of sea and swell was made (Reference 2), analyzing vessel and lighter responses to wind-driven waves as well as swell in different combinations of headings from all directions, while considering the effects of an added containership. A 3D tool was developed to display the relative and absolute motion for each of the three vessels covering all degrees of freedom for displacement, velocity and acceleration. This tool was a great advance in providing a convenient method for finding and displaying vessel motions.

The tool provided vessel responses at 9 wave headings at a single significant waveheight/modal period combination for the sea and swell spectra. In the present investigation, calculations are carried out at 14 additional wave headings, making data available at 15° increments for the entire heading range (0° - 360°). In addition, the capability to handle seas and swells having arbitrary and independent significant height and modal period is added.

This and the preceding analyses are focused solely on the wave-induced motions and so do not account for the effects of the mooring system or wind and current on the vessel motions. These latter effects contribute to mean and very low-frequency lateral motions but have little influence on the wave-frequency motions that are of interest here, particularly in the vertical modes, in the sea states that are relevant for cargo transfer operations.

2 Theory

Ocean waves are generally modeled as a Gaussian random process. For such a process, statistics of the maxima (wave peaks) are functions only of the moments m_n and the bandwidth ε of the wave spectrum $S(\omega)$,

$$m_n = \int_0^\infty \omega^n S(\omega) d\omega \, ; \quad \varepsilon = \sqrt{1 - \frac{m_2^{\,2}}{m_0 m_4}} \tag{1}$$

In a linear system, the same relationships hold for the statistics of the output, which in the present case consists of the motion, velocity, and acceleration components of the ship.

Of particular interest is the largest value of the output (motion, velocity or acceleration) that is expected in a given sea state with a specified level of confidence. The value X that will be exceeded with probability p is given by

$$X = \sqrt{2 m_0 \ln\left[\frac{\sqrt{1-\varepsilon^2}}{p(x)}\right]} = \sqrt{2 m_0 \ln\left[\frac{m_2}{p(x)\sqrt{m_0 m_4}}\right]} \tag{2}$$

where m_0 and ε are determined from the spectrum of the Gaussian random process x using Equations (1).

Since each wave component is assumed to be an independent zero-mean random process, the total spectrum is equal to the sum of the components. Using (1) and (2) it follows that the result of superimposing several spectra is just

$$X = \sqrt{2\sum m_{0i} \ln\left[\frac{\sum m_{2i}}{p(x)\sqrt{\sum m_{0i}\sum m_{4i}}}\right]} \tag{3}$$

In the narrow-band limit, ε→0 and the above expression reduces to

$$X = \sqrt{-2\ln[p(x)]\sum m_{0i}} = \sqrt{\sum X_i^{\,2}} \tag{4}$$

as one might intuitively expect. However, in general the spectrum that results from the summation of multiple components cannot be regarded as narrow-banded, so that the more general relationship (3) must be used. Thus one must compute the area under the response spectra, and the second and fourth moments of the response spectra, in order to obtain the statistics of the total response. Note that for velocity and acceleration components, these must be the moments of the corresponding velocity or acceleration spectra, obtained from the motion spectra by multiplication by ω^2 and ω^4, respectively. So to compute acceleration spectra, the fourth, sixth, and eighth moments of the motion spectrum are required (see Reference 3).

In the present study, the wave-induced forces and moments acting on the three vessels (Figure 1) were computed in the frequency domain using the 3-D panel code AQWA [4]. Due to a limitation on the number of panels that the software is capable of handling, separate computations were carried out for the lighter + T-ACS and T-ACS + containership combinations. Thus direct hydrodynamic interactions between the lighter and the containership are neglected; however, these interactions are not expected to be significant since these two ships are separated by the T-ACS (See Figure 1). All other hydrodynamic interactions are fully accounted for.

The hydrodynamic forces are used to compute the Response Amplitude Operators (RAOs) of the motions and relative motions of the three vessels in the frequency domain. The spectra of the motions and relative motions are calculated from the RAOs and the wave spectra:

$$S_x(\omega,\chi) = |H(\omega,\chi)|^2 S(\omega,\chi) \tag{5}$$

where $S_x(\omega,\chi)$ represents the spectrum of a motion at frequency ω for wave direction χ, $H(\omega,\chi)$ is the RAO of the motion, and $S(\omega,\chi)$ is the wave spectrum in direction χ. The moments of the motion spectra (Equation 1) are then found by numerical integration.

3 Configuration

The vessel configuration for this study consisted of a T-ACS 4-class ship, with an LCU2000 lighter located on the port side opposite Crane #1, and a containership on the starboard side. A schematic sketch of the vessel locations is shown on Figure 1. The water depth was taken to be 50 ft. The vessels were all assumed to be in their full-load conditions. Principal particulars of the vessels and their locations are summarized in Table 1. No mooring lines or fenders were modeled in this study; their effects on the vertical motions, which are of primary interest here, are expected to be negligibly small in the sea states that are relevant for cargo transfer operations.

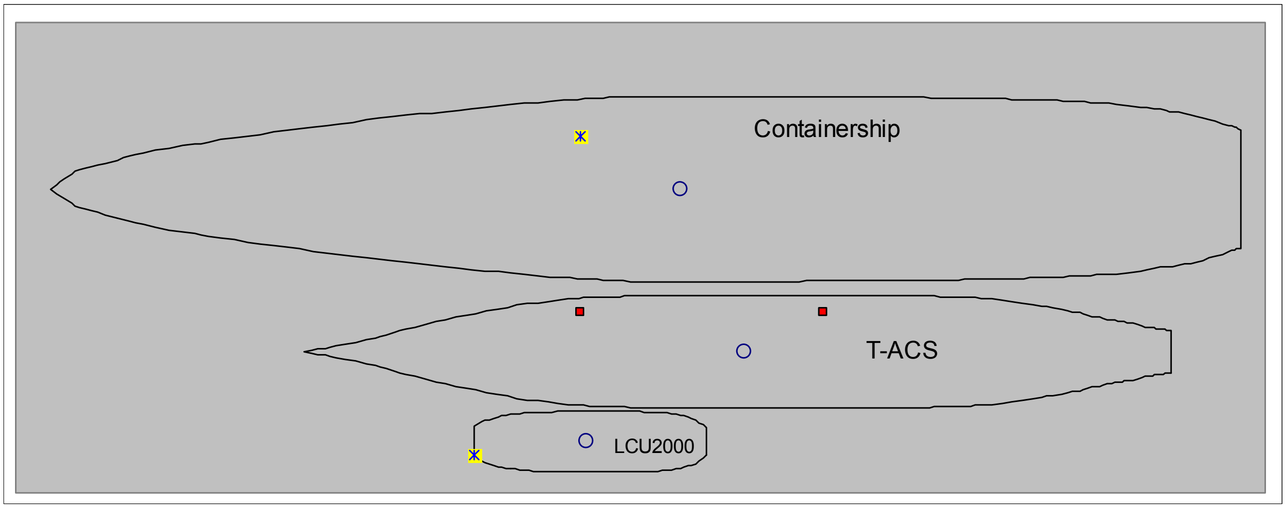

FIGURE 1 Schematic sketch of vessel locations. Circles: CG; Filled squares: Crane pedestals; Squares with *: Points for relative motions study.

TABLE 1 Vessel particulars and locations†

	T-ACS	Containership	LCU2000
Length (LWL), ft	581.8	813.2	158.1
Beam, ft	78.0	129.2	42.0
Draft, ft	31.6	36	8.0
Displacement, LT	25,308	61,440	1,158
KG, ft	28.15	63.9	6.6
CG location, ft†:			
longitudinal	300.35	256.95	193.04
transverse	0	113.54	62.66
vertical	-3.43	27.90	-1.44

†locations are relative to the FP of the T-ACS at the waterline

Two sets of locations were specified by NSWC (representing "worst-case" locations) for the relative motions study:

1. T-ACS - Containership:
   T-ACS: Tip of crane #1 boom, with boom horizontal and at 90° to the ship's centerline.
   Containership: Point on the main deck which is initially directly below the crane boom.
2. T-ACS - LCU2000:
   LCU2000: Furthest forward, outboard point on the deck that can be reached by the T-ACS crane.
   T-ACS: Tip of crane boom, located initially directly above the point specified for the LCU2000.

Coordinates of these points, relative to the reference points (centers of gravity) of the respective vessels, are summarized in Table 2.

TABLE 2 Coordinates* of points for relative motions study

Point	x, ft	y, ft	z, ft
#1, T-ACS	-111.452	150.458	56.495
#1, Containership	-68.057	36.916	13.586
#2, T-ACS	-183.679	-71.804	56.495
#2, LCU2000	-76.367	-9.147	5.489

*Coordinates are relative to the CG of each vessel; x, y and z are positive aft, to starboard, and up, respectively.

4 Visualization Tool Upgrade

The visualization tool now consists of two Excel spreadsheets, one for the absolute motions and one for relative motions. In the spreadsheets, the maximum (95% confidence) motions, velocities, and accelerations of the vessels are computed in waves consisting of combinations of a Bretschneider (wind-driven) spectrum (Reference 5) and a non-coincident swell spectrum. The swell spectrum is based on the Ochi 3-parameter formulation (Reference 5), with the shape parameter determined to satisfy the McCreight/Dalzell swell spectrum criterion: “the half-power bandwidth is 25% of the center frequency” (Reference 5). The appropriate value for the “shape parameter” λ that yields the required bandwidth is 5.5. Typical sea and swell spectra are shown on Figure 2.

The maximum values are calculated at the 576 combinations of the 24 available headings for each spectrum. The results are displayed in the form of a three-dimensional surface plot, showing the maximum motion, velocity, or acceleration as a function of the sea and swell headings. The sign convention for wave headings is shown on Figure 3; note that the sign has been reversed relative to that in the previous work (references 1 and 2) at the direction of NSWC.

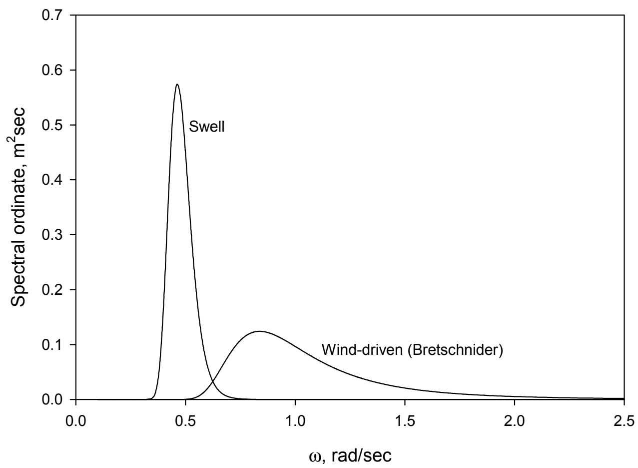

FIGURE 2 Typical sea and swell spectra (in the figure each has a significant height of 5 ft)

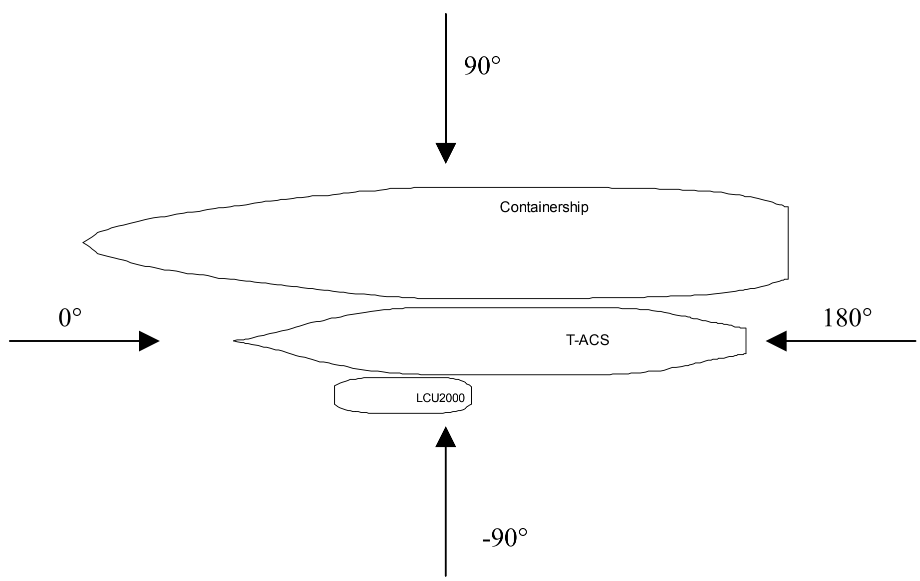

FIGURE 3 Wave heading convention. Arrows indicate direction of wave motion.

The user selects the desired vessel or vessel combination and motion direction, and chooses displacement, velocity or acceleration. He then sets the wave conditions using sliding controls to select the significant waveheights and modal periods of both the sea and swell spectra. Results are immediately displayed on the surface plot, which the user can rotate to obtain the best perspective for each condition. The worksheet labeled "KeyResults" contains a table of the maximum and minimum values of the quantity shown on the plot, along with the corresponding sea and swell directions. More detailed guidance on the use of the spreadsheets is provided in Appendix A.

The sliding controls can be used to set the wave parameters within the following ranges:

Parameter	Permissible Range
Sea Significant Height, ft	0 - 10
Sea Modal Period, sec	0 - 20
Swell Significant waveheight, ft	0 - 10
Swell Modal Period, sec	5 - 30

Thus the total significant waveheight is limited to 14 ft (a low Sea State 6). Above this value, nonlinear effects (which are not accounted for in the calculations) may become important; it is doubtful that cargo transfer operations would be considered under these conditions anyway.

A second chart containing a traditional contour plot has also been added to the Relative Motions spreadsheet ("ContourChart"). This corresponds to the surface plot viewed from directly above (but without the distortions that result from the 3-D perspective view). Note that the user can adjust the contour spacing by double-clicking on the legend, which brings up the "Format Legend" menu box. The contour spacing is controlled by the "Major Unit" entry under the "Scale" tab. The color scale on the surface plots can be adjusted in the same way. It is recommended that the "Auto" box be selected initially since the same major unit will obviously not be applicable to all cases.

Examples of the 3-D plots with corresponding maxima/minima are shown on Figures 4, 5 and 6 below. Figure 4 shows the relative vertical velocity between the T-ACS and the LCU2000, in the following wave conditions:

Sea significant waveheight, ft	3.5
Sea modal period, sec	8.0
Swell significant waveheight, ft	2.0
Swell modal period, sec	15.3

The plot displays the combined significant waveheight, which in this case is 4.03 ft corresponding to Sea State 3. The Key Results table from the spreadsheet (Figure 5) shows that the resulting maximum relative vertical velocity ranges from 0.425 to 5.723 ft/sec. In this case the sea heading has a much more pronounced effect on the relative velocity than does the swell heading (grid lines corresponding to constant sea heading are nearly horizontal). The situation is quite different for the relative vertical motion of the T-ACS and containership, as can be seen on Figure 6. In general, larger ships have longer natural periods and so are more sensitive to the longer-period waves in the swell spectrum. However, in the limit of very long waves, all relative motions are expected to approach zero since all vessels will "track" the waves in this limit.

As an example of a potential use of the tool, the maximum expected relative vertical motion between the T-ACS and the LCU2000 was computed as a function of the sea and swell modal periods (each at a fixed value of the other's modal period); results are shown on Figure 7. The figure shows that the maximum vertical relative velocity decreases with increasing swell period (left panel), approaching the value obtained if no swell were present at periods greater than about 20 seconds (indicating that very long-period waves have no effect on the relative motions, as predicted above). For the wind-driven waves, the figure (right panel) shows a peak at about 8 seconds, which is near the peak of the heave and pitch RAOs of the LCU2000.

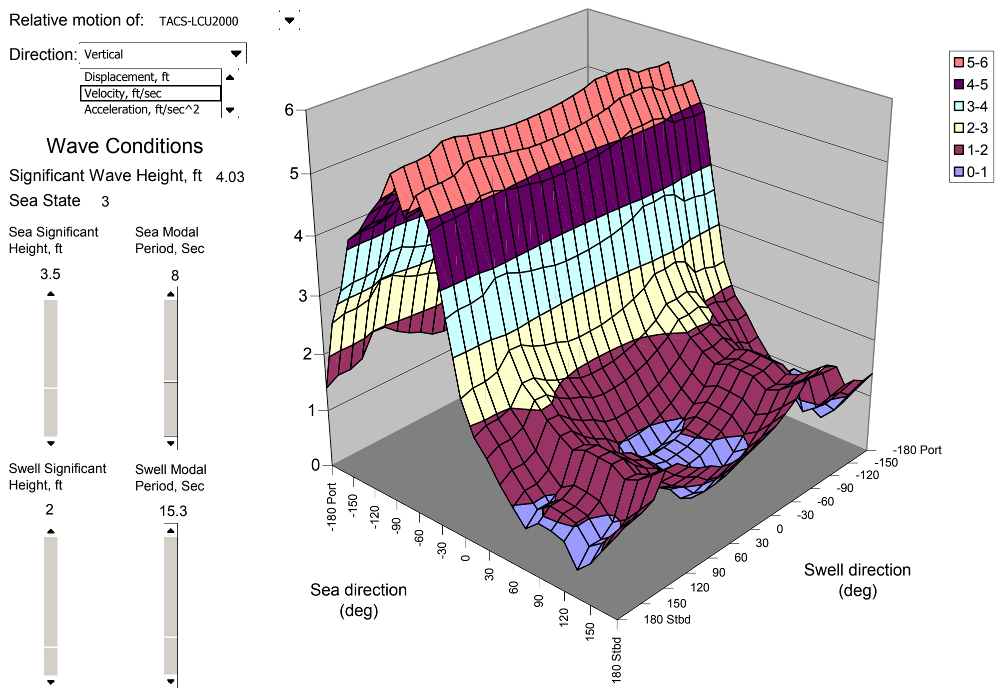

FIGURE 4 Example relative motion plot: Relative vertical velocity of T-ACS/LCU2000

SUMMARY OF KEY RESULTS

Vessels: TACS-LCU2000
Direction: Vertical
d/v/a: Velocity

MAXIMUM VALUE:	5.723	ft/sec
Sea Direction	-75	deg
Swell Direction	-105	deg

MINIMUM VALUE:	0.425	ft/sec
Sea Direction	135	deg
Swell Direction	-165	deg

FIGURE 5 “KeyResults” sheet for the example shown on Figure 4

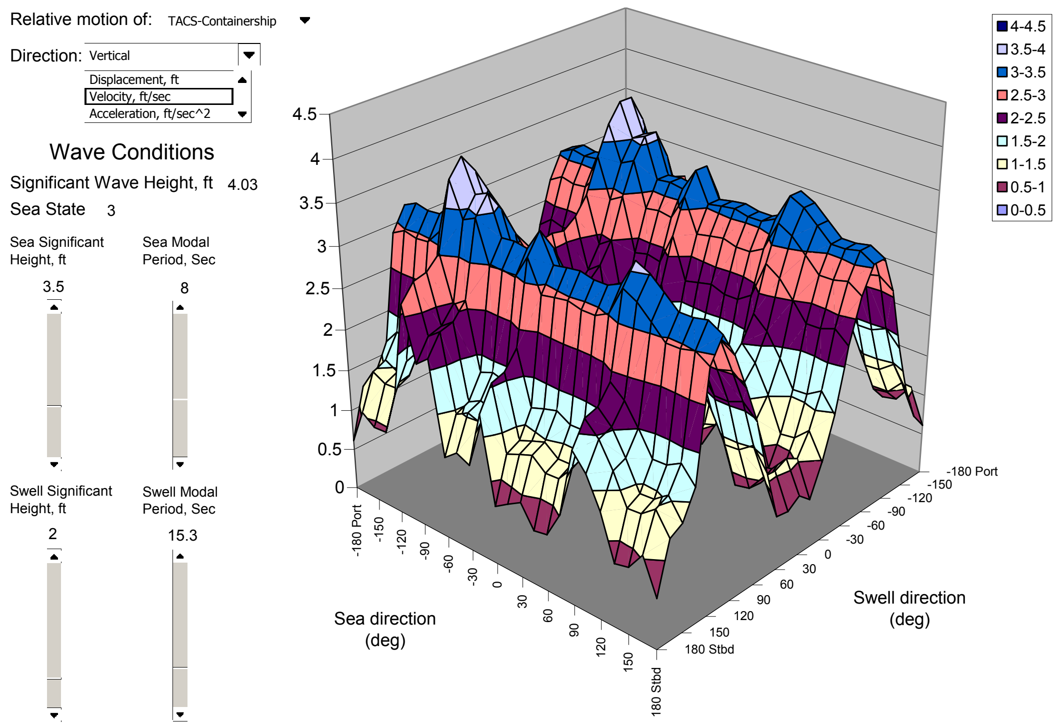

FIGURE 6 Relative vertical motions of T-ACS/Containership, same wave conditions as for Figure 4

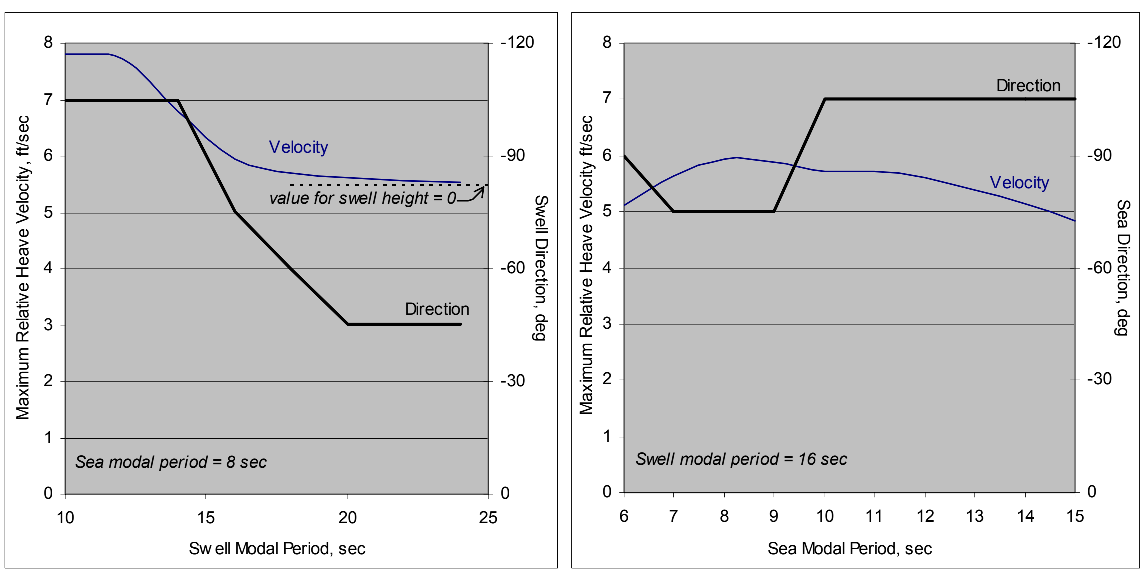

FIGURE 7 Behavior of maximum relative vertical velocity (T-ACS/LCU2000) with modal period of sea and swell.
Significant waveheight of each component = 3.5 ft

Another potential use of the tool is to find the optimum heading in a given wave environment. For example, the following data were recorded by National Data Buoy Center Station #46029 off the coast of Washington in the Pacific Ocean on June 1, 2002:

	Significant Waveheight, ft	Modal Period, sec	Direction*
Sea	4.3	4.8	NW
Swell	8.2	12.5	W

*Direction *from* which waves are travelling

In this example the sea and swell directions differ by 45°, which can be expressed as

Sea direction = Swell direction + 45°.

Figure 8 shows this expression plotted on the contour chart for the T-ACS/lighter relative vertical velocity; the contour spacing has been set at 0.5 ft/sec. For the given relationship between sea and swell, the figure indicates minimum motion (1.0 - 1.5 ft/sec) for swells incident from 10° to 30° and seas from 55° to 75°. Referring to the wave heading convention shown on Figure 3, it can be seen that the ships should be oriented toward the southwest at a heading of -100° to -120°, as shown on Figure 9, for the sea and swell to attain these values.

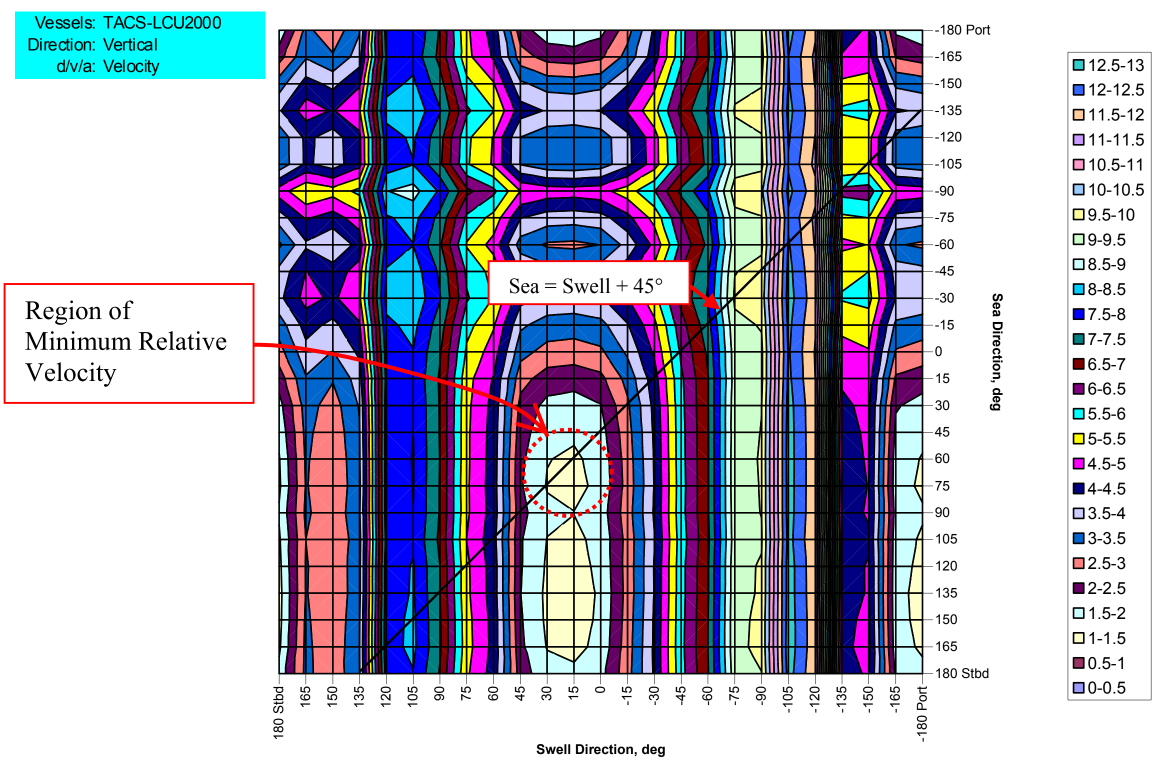

FIGURE 8 Contour plot of relative vertical velocity for "optimum heading" example

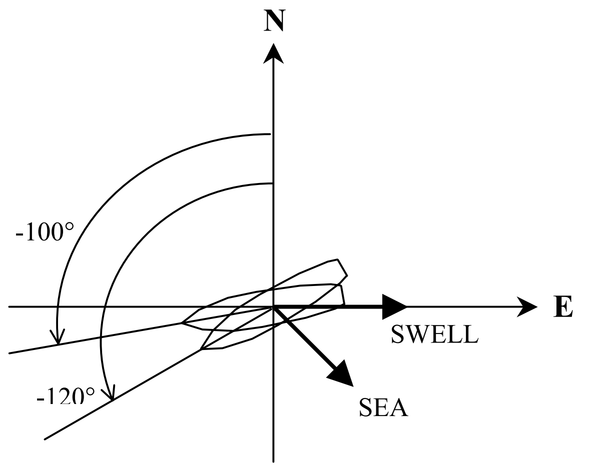

FIGURE 9 Headings for "optimum heading" example

5 Summary

The versatility of the visualization tool has been considerably enhanced by inclusion of additional headings and provision for arbitrary user-selected wave conditions. In fact the tool can be used for quantitative calculations such as determination of the heading for minimum motions as illustrated by the example in the previous section.

With some straightforward modifications the tool could be reconfigured to output the maximum expected absolute or relative motions for given (input) sea and swell directions. In addition, the data now exists to produce a similar tool (with the original, more limited range of headings) for the following vessel combinations:

- LCU2000, T-ACS, Containership, with the LCU2000 located opposite Crane #2;
- LCU2000 and T-ACS without the containership (LCU2000 in either longitudinal location);
- LSV in either longitudinal location with the T-ACS and with or without the containership; and
- NL Causeway in either longitudinal location with the T-ACS and with or without the containership

Of course, with data from additional AQWA runs, a tool could be created to examine virtually any combination of vessels.

6 References

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2. "Computation of Vessel Motion Statistics in Combined Wave Spectra: Lighter/T-ACS/Containership Motion Analysis Report", Computer Sciences Corporation Advanced Marine Center, November 2001.

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4. “User’s Manual for Atkins Quantitative Wave Analysis (AQWA) Suite”, Century Dynamics Ltd., http://www.century-dynamics.co.uk/software/aqwa.htm.

5. McCreight, K.K., “A Note on Selection of Wave Spectra for Design Evaluation”, CDNSWC Research and Development Report CRDKNSWC-HD-974-02, January 1998.

APPENDIX A

Notes On Spreadsheets "3DplotsAbs.xls" and "3DplotsRel.xls"

The spreadsheets "3DplotsAbs.xls" and "3DplotsRel.xls" are furnished to provide 3-D interactive graphical displays of the results of the "motions in combined sea spectra" studies. "Abs" and "Rel" denote absolute and relative motions, respectively. The spreadsheets have been set up so that the user needs to work with only the chart sheet in each workbook. Controls on the sheet are used to select the vessel(s), motions, and to choose displacement, velocity or acceleration. The chart sheets are shown on Figures A1 and A2, which identify the various controls.

The list and drop-down boxes are self-explanatory. The scroll bars (sliding controls) are used to set significant waveheight and modal period within the limits given in the main text. Clicking on the arrows at the top or bottom of the control increases or decreases the setting by 0.1 unit (feet or seconds); clicking on the bar in the gray area changes the height setting by 1 ft and the period setting by 2 sec. There may be a slight delay (one or two seconds, possibly longer for Absolute Motions) in updating the chart after clicking on the controls, depending on the speed and memory characteristics of the computer.

The orientation of the charts can be changed by clicking once on one of the corners of the chart; the corners become highlighted with black squares and the word "Corners" should appear when the cursor is placed over one of these squares. The corners can then be "grabbed" by moving the cursor over one of the squares and holding down the left mouse button. Moving the mouse then drags the corner, rotating the chart in the corresponding direction.

As explained in the main text, maximum and minimum values of the quantity displayed are tabulated on the "KeyResults" sheet, which also lists the corresponding sea and swell directions. The relative motions spreadsheet also includes a 2-D contour plot, which is useful for some applications (see the example above). The absolute and relative motion spreadsheets have 14 and 9 other worksheets, respectively, which are hidden in the distribution versions.

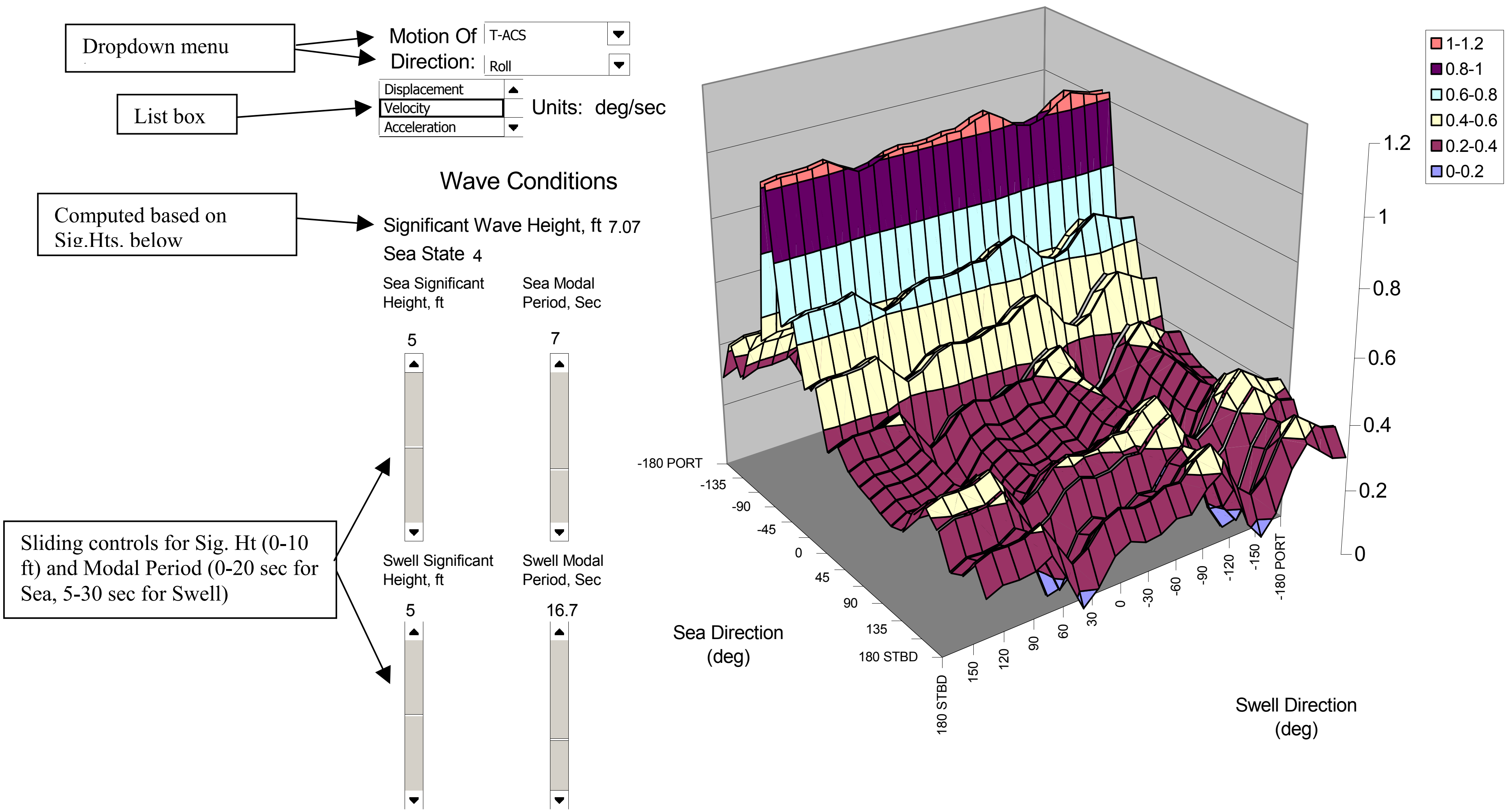

FIGURE A1 Absolute motion chart from 3DplotsAbs.xls

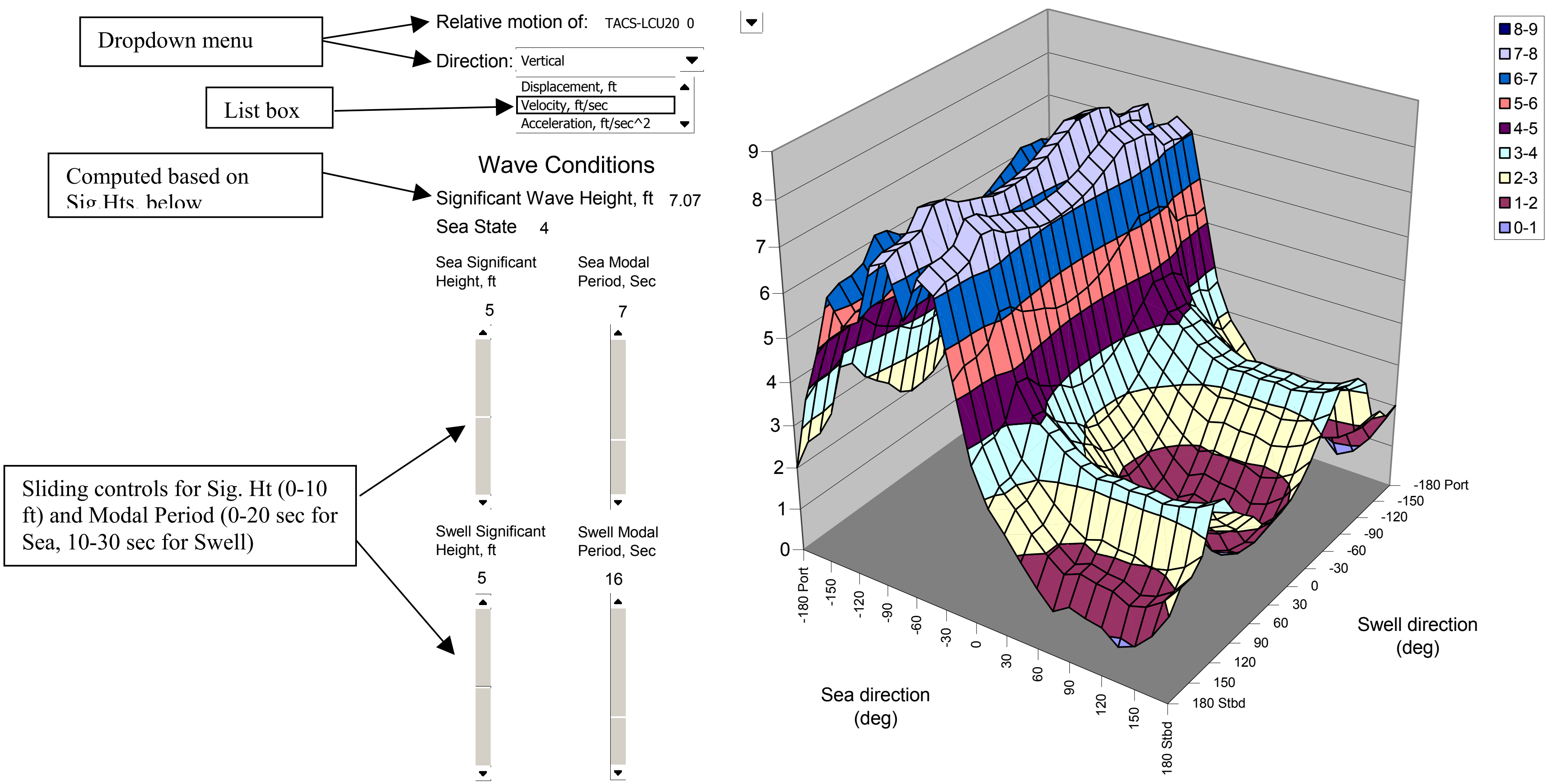

FIGURE A2 Relative motion chart from 3DplotsRel.xls