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Technical Memorandum

A Generalized Approach and Interim Criteria for Computing $A_{1/n}$ Accelerations Using Full-Scale High-Speed Craft Trials Data

by

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NAVSEA
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14. ABSTRACT

This report presents a generalized approach and interim criteria for computing the average of the 1/n^{th} highest accelerations when analyzing accelerometer data recorded during trials of manned and unmanned small boats and craft. The computational approach has evolved over a number of years as a set of best-practices for achieving repeatability when computations are performed by different data analysts.

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Administrative Information

The work described in this report was performed by the Combatant Craft Division (Code 23) of the Ship Systems Integration and Design Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The objectives of the overall task were to develop data analysis guidelines, to seek alternative analysis techniques, and to develop comparative analysis tools for design evaluation. This effort was sponsored by the Office of Naval Research, Sea Warfare Applications Division (Code 333), Arlington, VA, and funded under document numbers N0001408WX20581 and N001408WX20619.

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Summary

This report presents a generalized approach and interim criteria for computing the average of the $1/n^{th}$ highest accelerations when analyzing accelerometer data recorded during trials of manned and unmanned small boats and craft. The computational approach and the interim criteria are based on analysis practices that have evolved over a number of years at the Combatant Craft Division of Naval Surface Warfare Center, Carderock Division as a set of best-practices for achieving repeatability when computations are performed by different data analysts. The historical background of the computational approach is summarized, the fundamental physics of craft wave encounters and wave slam events are discussed, and interim criteria for the generalized computational approach is presented. Typical data recorded during full scale trials of a high-speed planing craft is presented to illustrate results of the generalized computational approach.

Introduction

Background

The Combatant Craft Division (CCD) of Naval Sea Systems Command (NAVSEA), Naval Surface Warfare Center Carderock Division conducts at-sea performance trials of manned and unmanned new-technology prototype and new acquisition craft for numerous government agencies and private industry. During these trials accelerometers are typically installed to capture the dynamic motions of the craft in waves. These motions are of interest because they are applied in craft design and comparative craft evaluations to address multiple factors associated with seaworthiness, including hull design loads, stability, component ruggedness, and crew or passenger comfort and safety.

Historical Perspective

Twenty years ago high-speed craft motions data was collected using servo and piezo-resistive accelerometers and analog magnetic tape recorders with relatively low frequency bandwidths (dc to a few hundred Hz). Signal conditioning was relatively straightforward and there were no concerns about aliasing frequencies in the data. Post-trial data analysis was time intensive and limited by memory cost and computer availability

Modern digital data acquisition and measurement systems are self-contained, relatively inexpensive, and available from a number of vendors. Most equipment has a minimum of 16-bit A/D conversion with signal resolution of 65,536 parts (98dB signal/noise), and accelerometer resolution of up to 0.003 g is possible for a ± 100 g range. Analog sensors are still used, but they have become smaller, lighter, and more robust. They are also less expensive and have higher frequency bandwidths. Personal computers are now relatively inexpensive with large memory capability at very high processing speeds, and commercially available software can be programmed to perform a variety of analysis techniques.

Data Acquisition Guidelines

Successful data acquisition begins with requirements definition. Key requirements must be defined, including the trials objectives, key parameters of the investigation, anticipated parametric variation, the required data resolution, and the post-trial data analysis methodologies to be applied. Historically the acceleration response of the craft has been a key parameter for most design applications and seakeeping evaluations.

Accelerometers are typically installed at three locations near the bow, the stern, and at the craft's longitudinal center of gravity (LCG) to measure rigid body motions. Primary installations are oriented in the vertical direction to capture heave and pitch responses, with additional accelerometers oriented longitudinally (fore-aft) and transverse (athwartship) depending upon the requirements of the investigation. For most applications the primary interest is for data within the dc to 100 Hz frequency band. Standard practice is therefore to provide an analog pre-filter at 100 Hz with data sampled at 512 samples per second.

Peak Acceleration Data

One aspect of data analysis methodology that has been adopted for high-speed planing craft involves the assessment of peak vertical acceleration values encountered during individual wave slam events [1], [2], [3]. Peak acceleration amplitudes recorded during a test sequence are tabulated, and averages are calculated using a peak-to-trough methodology adopted from ocean wave measurement techniques [4]. In addition to the overall RMS acceleration, three statistics have been reported in numerous test and evaluation reports for both model-scale and full-scale tests to quantify the acceleration response of the craft. These are referred to as the average of the one-third, one-tenth, and one- hundredth highest accelerations. Although the algorithm for calculating these statistics is not consistently defined or implemented, it is conceptually simple to understand. Peak accelerations are extracted from the acceleration time history by a peak-to-trough algorithm with a subjectively defined threshold, above which data are considered to be important for design or comparative study. The statistics are calculated by ordering extracted peak accelerations from highest to lowest, selecting the highest one-third, one-tenth, or one-hundredth peak values, and calculating the average. For example, the average of the one-tenth highest accelerations (typically used in craft design) can be represented by equation (1),

$$A_{\frac{1}{10}} = \frac{1}{\frac{1}{10}N} \sum_{i=1}^{\frac{1}{10}N} A_i \qquad \text{Equation (1)}$$

where A_i are the individual acceleration peaks (extracted from an acceleration time history) sorted in such a way that the largest amplitude acceleration has $i=1$ and the lowest acceleration is $i=N/10$. The average of the one-third and one-hundredth highest acceleration values can be determined similarly.

Three different methods have been evaluated at Combatant Craft Division to calculate these statistics. All three methods employ a peak-to-trough analysis, as described by Zselecsky and McKee [2], to identify acceleration time history maxima and minima, but each method employs different threshold criteria for identifying and extracting peaks from a record.

The first method applies a user-defined vertical threshold value. It recognizes as a peak any maximum (whether above or below the zero level), that exceeds the preceding and following minima by the value of the vertical threshold (or buffer value). The number of peaks identified depends on the threshold value chosen, and thus returns subjective and often non-intuitive results.

A second method is referred to as the vertical difference or zero crossing method. It identifies peak accelerations based on maxima (peaks) that exceed the user-selected threshold above the zero value, and minima (troughs) that exceed the user-selected threshold below the zero value. Like the vertical threshold method described above, the results of this analysis method often yield non-intuitive outcomes.

In an effort to reduce the subjectivity of acceleration time-history analysis, a third method was developed which relies on a horizontal duration (in seconds) criteria typically related to the wave encounter period. Evaluation of many sets of time-history acceleration data resulted in the observation that craft encounters with waves (wave impacts) exhibit a relatively constant periodicity for a given craft speed. If, instead of relying on an amplitude threshold as the peak discriminator, a time duration discriminator were used, the calculation of impact accelerations became more predictable and intuitive.

Figure 1 illustrates the average of the 1/3rd, 1/10th, and 1/100th highest peak acceleration values calculated using the horizontal duration method. In this example the method was applied to the acceleration time history shown in Figure 2. The curves illustrate that an infinite number of answers exist for each of the average acceleration parameters depending upon the choice of the horizontal threshold value. A final value requires the analyst to choose a subjective threshold value.

While the three calculation methods are simple and straight forward, their application is problematic due to the subjectivity of individual analyst choices. Different analysts will choose one of the three peak-to-trough methods while selecting from an infinite range of threshold criteria, and invariably will produce different estimates of average 1/3rd, 1/10th, and 1/100th peak accelerations. The purpose of this report is to present rationale and criteria for a generalized approach that obviates the subjectivity when analyzing either full scale or model scale acceleration data to achieve similar results among multiple analysts.

The vertical acceleration record shown in Figure 2 is presented as a typical example throughout this report. It was recorded at the longitudinal center of gravity (LCG) during trials of a 36-foot craft traveling at an average speed of 28 knots in a significant wave height of 4.4 feet. The average wave period was 3.7 seconds. A 240-second time period was selected to illustrate examples in this report.

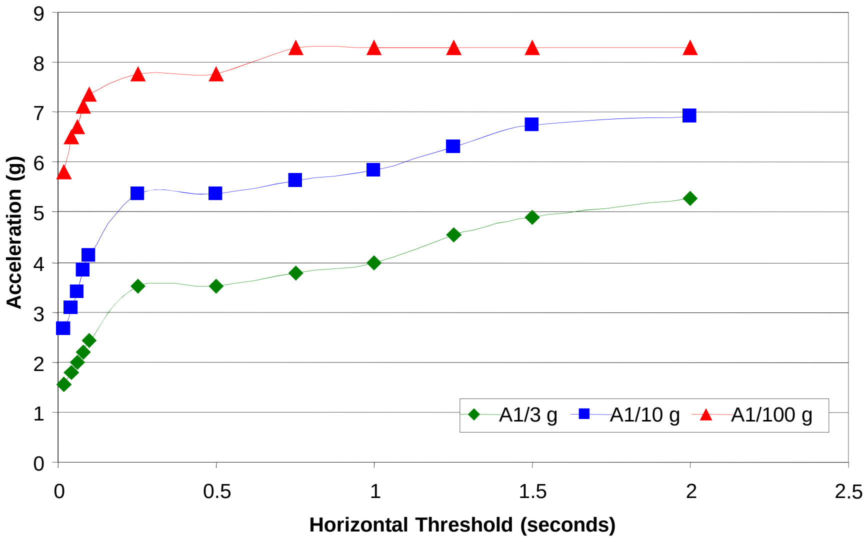

Figure 1. Horizontal Threshold Method Peak Acceleration Values

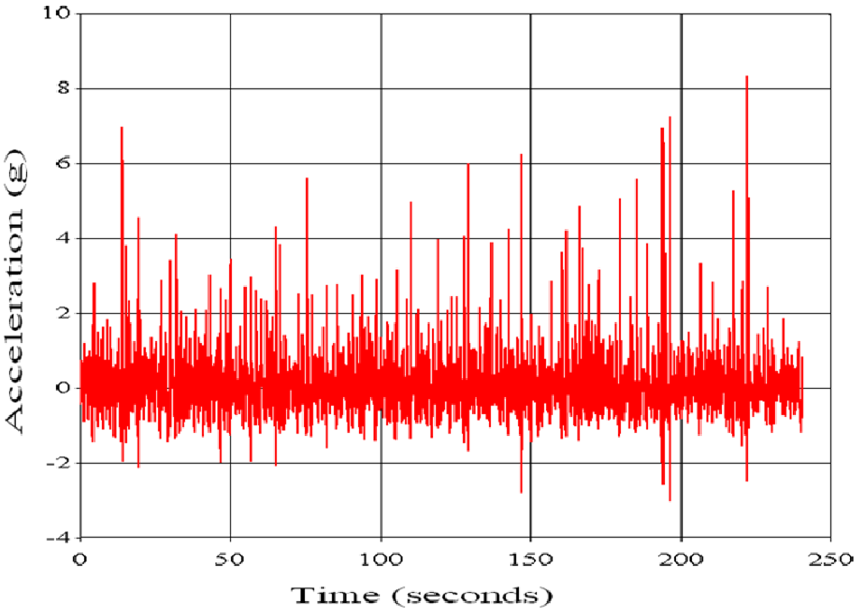

Figure 2. Vertical Acceleration at the LCG of a 36-Foot Craft

Craft Wave Encounters

Effect of Craft Speed

Figure 3 shows four different wave encounters for four different craft moving at different speeds in different sea states. The speed-length ratio $V_k/L^{1/2}$ is a convenient parameter used in numerous historical documents because of its relationship to ocean wave celerity, and the well known planing craft speed regimes related to values of 2, 4, and 6.

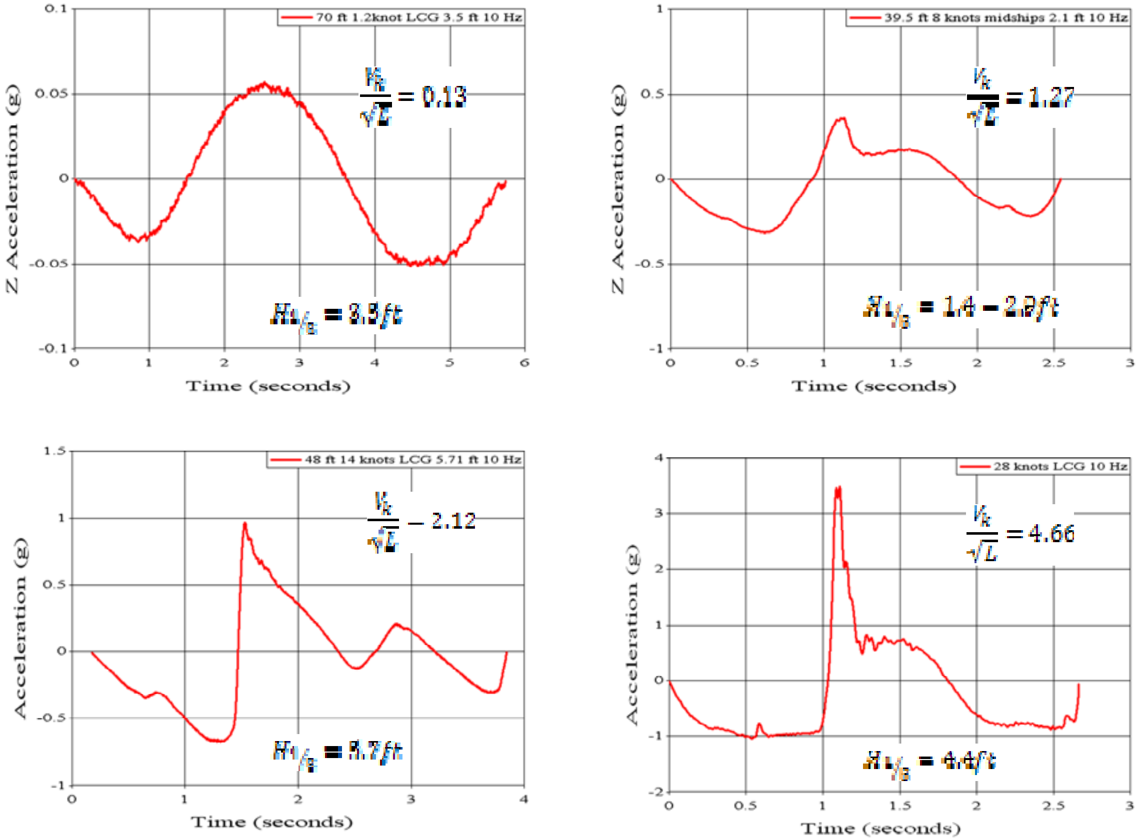

Figure 3. Slow-Speed and High-Speed Wave Encounters

A speed ratio of two and below represents the pre-hump condition where buoyancy forces dominate. A ratio greater than 4 is the post-hump regime where the craft is beginning to plane, and both dynamic and buoyant forces participate. For a ratio of 6, hydrodynamic forces dominate over buoyancy [1].

In the upper left curve in Figure 3 the very low value of 0.13 is approximately equivalent to “underway but not making way.” The smooth curve is characteristic of the craft bobbing up and down due to gravity and buoyant forces with each passing wave. The figure illustrates that the peak acceleration due to a wave encounter may be the maximum value of a smooth sinusoidal shape, or it may be the maximum value of a response shape characterized by a much more rapid almost linear increase from a low amplitude to the peak value. In each plot the time scales and amplitude scales vary as a function of sea state and craft speed.

As speed increases, the upward and downward forces due to buoyancy and gravity are still observed in the time histories, but the shapes of the responses become less smooth. Dynamic effects of higher speed wave impacts are observed as acceleration spikes followed by smooth transitions to the next impact spike. The shape, amplitude, and duration of the spike can depend upon numerous parameters, including significant wave height, impact angles (due to craft trim, deadrise, and buttock, for example), wave slope, and craft speed [4]. As speed increases into the planing regime the acceleration spikes are more pronounced and wave slams are observed (and felt by riders) as violent impacts between the craft and the incident wave. The wave slam for the 4.66 speed ratio shown on the lower right curve in Figure 3 is from the 240 second acceleration record shown in Figure 2. The large acceleration spike due to a wave slam is clearly visible, and after the impact the forces due to up and down wave interactions are observed in a smooth phase were hydrodynamic lift forces, thrust, drag, and gravity are participating.

Using Savitsky's empirical equation that computes the average of many peak accelerations as a function of craft design dimensions, craft speed, and the significant wave height, the following approximate relationship illustrates how craft speed and significant wave height can be used to scale from speed and height for test condition “a” to test condition “b”.

$$\frac{A_{cgb}}{A_{cga}} \approx \text{constant}\left(\frac{H_{1/3b}}{H_{1/3a}}\right)\left[\frac{V_b^2}{V_a^2}\right] \qquad \text{Equation (2)}$$

Where: A_{cg} is the average peak vertical acceleration at the CG

$H_{1/3}$ is the average of the 1/3rd highest wave heights

V is the craft speed

Equation (2) indicates that the ratio of the acceleration responses is approximately in proportion to the ratios of the craft potential and kinetic energies associated with conditions *a* and *b*.

Sequence of Events

Figure 4 illustrates the sequence of events in a typical wave slam event for speed-length ratios in the planing regime. The top curve is one of the individual unfiltered acceleration time histories extracted from the vertical acceleration time history shown in Figure 2 for a wave slam

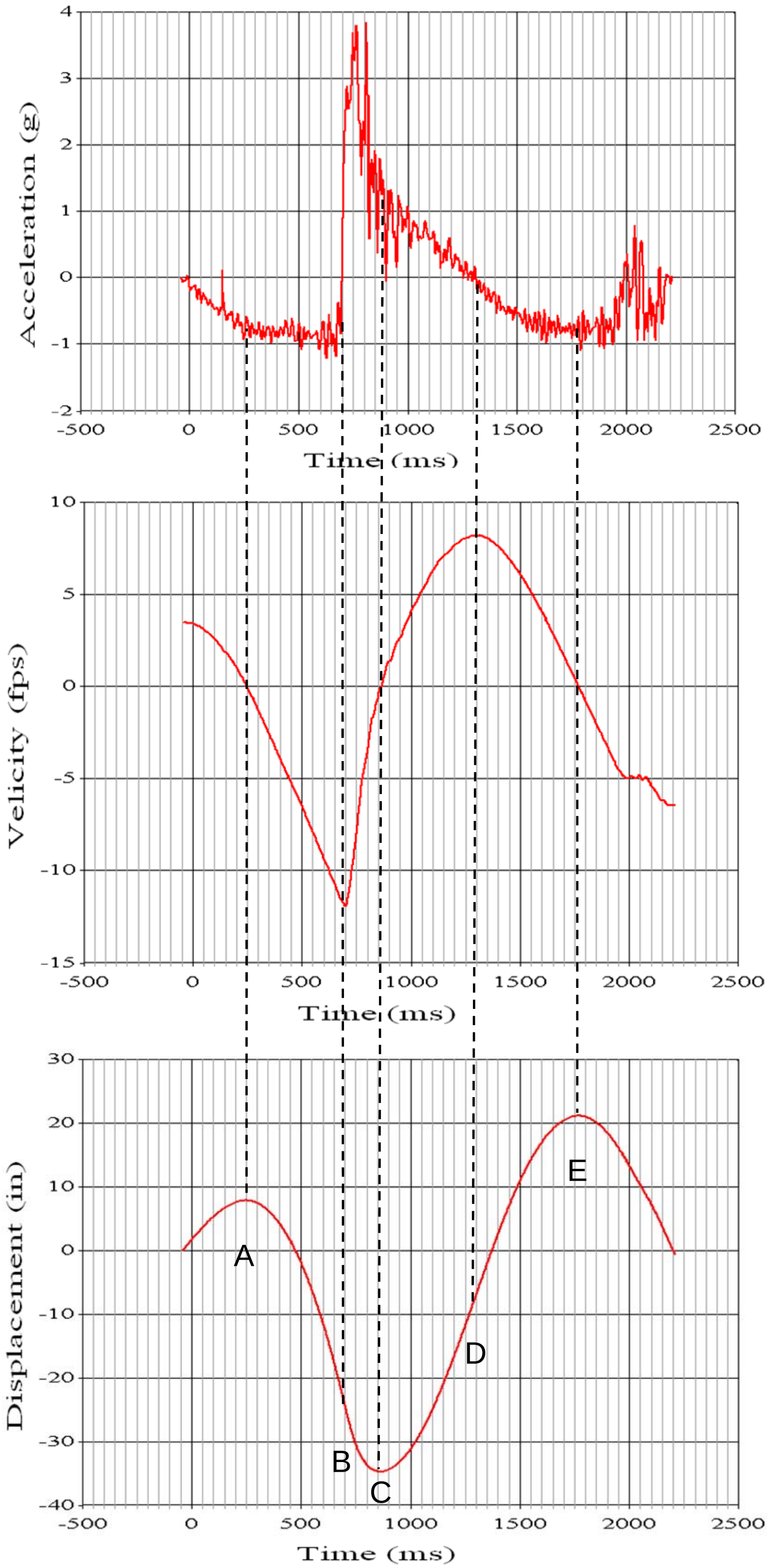

Figure 4. Wave Encounter Sequence of Events

event roughly 66 seconds from time zero. The middle curve is the velocity time history obtained by integrating the acceleration curve, and the bottom curve is the integral of the velocity to show the absolute vertical displacement of the craft. These curves characterize the vertical rigid body motion of the craft which includes contributions from both heave and pitch responses.

At time A the minus 0.9 g vertical acceleration indicates a condition very close to a gravity free fall phase. The relatively constant minus 0.9 g from time A to time B and the linear decrease in velocity suggests that the craft is rotating downward with the stern in the water. The drop in height from time A to B is then a combination of heave and pitch motions.

At time B the craft impacts the incident wave, the velocity reaches a minima and changes rapidly to an increasing value, and the force of the impact is seen as an almost instantaneous jump to a maximum acceleration (the beginning of the acceleration spike). In this example the peak acceleration is achieved on the order of 0.1 seconds after initial wave impact.

From time B to time C the craft continues to move down in the water, the velocity approaches zero, and the acceleration decreases rapidly toward a value of approximately 1.0 g. The decreasing acceleration is characteristic of an impact event whose initial large peak force is decreasing to an ambient value.

At time C the downward motion of the craft reaches a maxima, and the instantaneous velocity is zero, but forces due to buoyancy, hydrodynamic lift, and components of thrust and drag combine to produce a net positive force upward. The impact event is complete at time C and the craft motion is now dominated by wave interaction forces.

From time C to D the combined forces of buoyancy and hydrodynamic effects continue to push the craft upward, but the net force (and the acceleration) approaches zero. The hull is still in the water, but gravity is rapidly overcoming upward lift forces.

At time D gravity becomes equal to the other forces, the instantaneous acceleration is zero, and a velocity maxima is achieved.

Between time D and E the hull below the LCG rises vertically with the velocity approaching another maxima. Gravity once again dominates the other dynamic forces and at time E another peak vertical displacement is achieved, the instantaneous velocity is zero, and another wave impact sequence of events begins.

The duration of the wave slam event from time B to C is roughly 0.16 seconds. From time C to D (approximately 0.45 seconds) buoyancy and hydrodynamic lift forces dominate gravity to yield an upward force (acceleration). From time D until the next wave encounter gravity dominates the other forces as the hull moves above its static and planing draft line.

Wave Encounter Period

Appendix A presents the table of wind and sea scales that define fully risen sea state conditions with parameters that include significant wave height ($H_{1/3}$), average wave period (T_W), and average wave length (L_W). The listed significant wave heights are the average of the 1/3rd highest observed during a specified period of time. The relationship between tabulated values of significant wave height in feet and the average wave period in seconds is shown in Figure 5.

Equation (3) predicts this trend within ± 2.5 percent and a 0.996 correlation coefficient for significant wave heights of 0.5 to 6.3 feet.

$$T_W = -(0.0133H_{1/3})^4 + (0.1967H_{1/3})^3 - (1.0553H_{1/3})^2 + \left(2.8982H_{1/3}\right) + 0.4269$$

Equation (3)

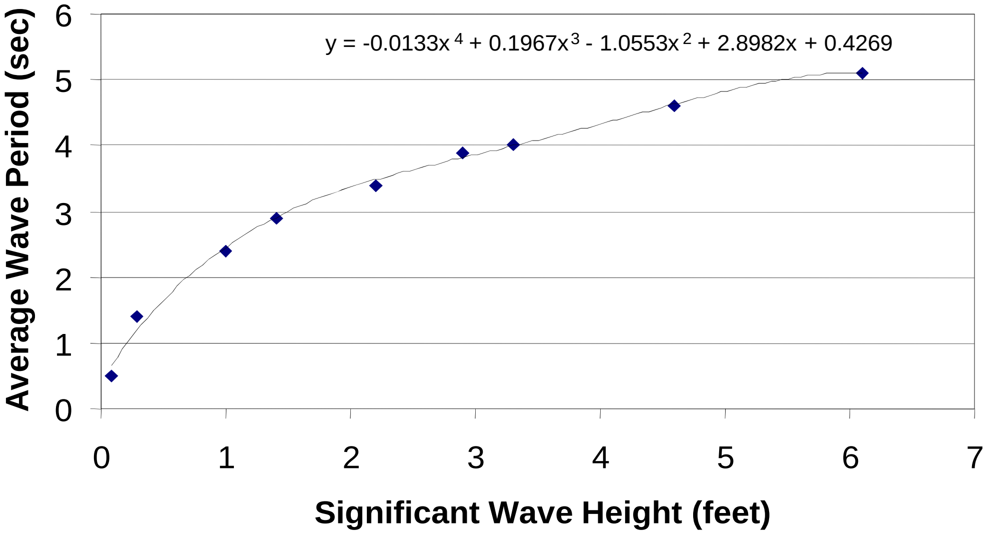

Figure 5. Average Wave Period Versus Significant Wave Height

If it is assumed that a craft is moving in head seas at a constant speed V_k in knots, it can be shown that the average wave encounter period (T) in seconds for water depths greater than 0.5 L_W is :

$$T = \frac{5.12T_W^2}{1.686V_k + 5.12T_W}$$

Equation (4)

When equation (3) is substituted into equation (4) it can be shown that the wave encounter period (T) is great than 0.5 seconds for speeds up to 50 knots and significant wave heights greater than 1.0 foot. The wave encounter frequency shown in Figure 6 is the reciprocal of equation (4). The curves for 10 to 50 knot speeds indicate that the wave encounter frequency will be less than 2 waves per second for significant wave heights greater than 1.6 feet.

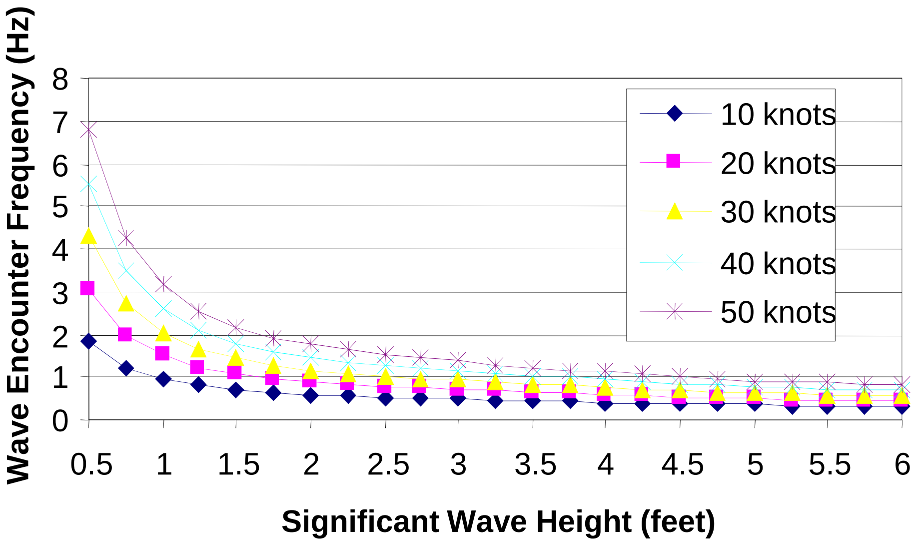

Figure 6. Wave Encounter Frequency Versus Speed

This is important because it means that the rigid body response of a craft moving at planing speeds in sea states greater than 1.6 feet will manifest itself as repeated acceleration pulses whose cyclic frequency is on the order of 2 Hertz or less. Any frequency content in the acceleration record greater than 2 Hertz is therefore coming from a source other than longitudinal (surge) rigid body encounters with waves. As shown in Figure 7 and Figure 8, the most prevalent source for other frequency content in small boats and craft recorded at bow, LCG, and stern accelerometer locations is from local oscillations of contiguous structure in the vicinity of the gage. Local flexure of deck plating or panels induced by wave slams or machinery vibrations, or even rotational motions of equipment installations are examples of likely high frequency responses observed riding on top of craft rigid body motions. Figure 8 presents the Fourier spectrum of the acceleration record shown in Figure 2 that highlights the presence of high frequency motions above the wave encounter frequency.

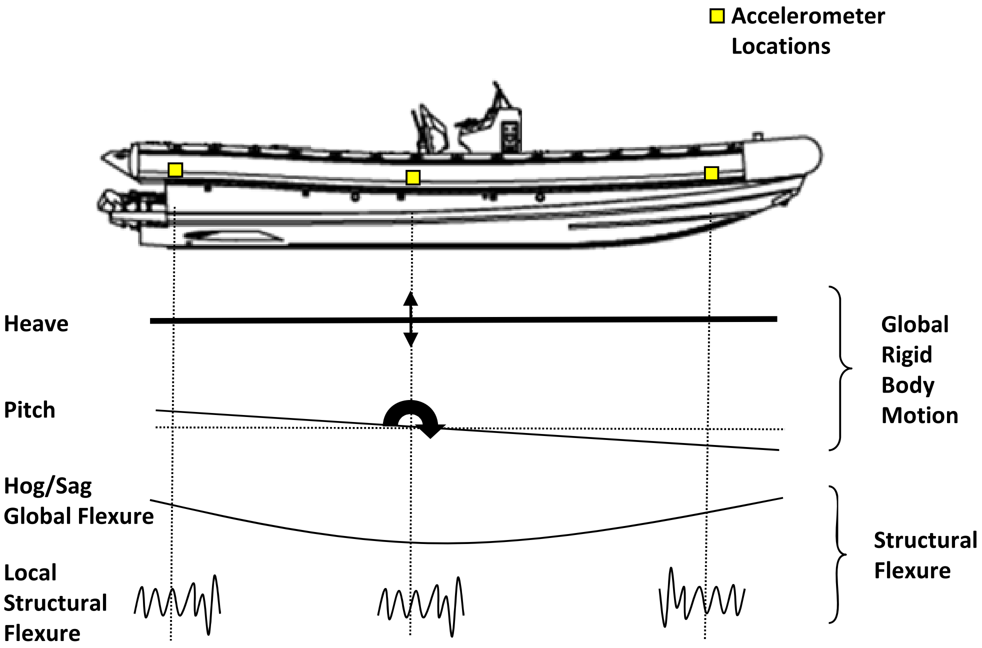

Figure 7. Local and Global Craft Motions

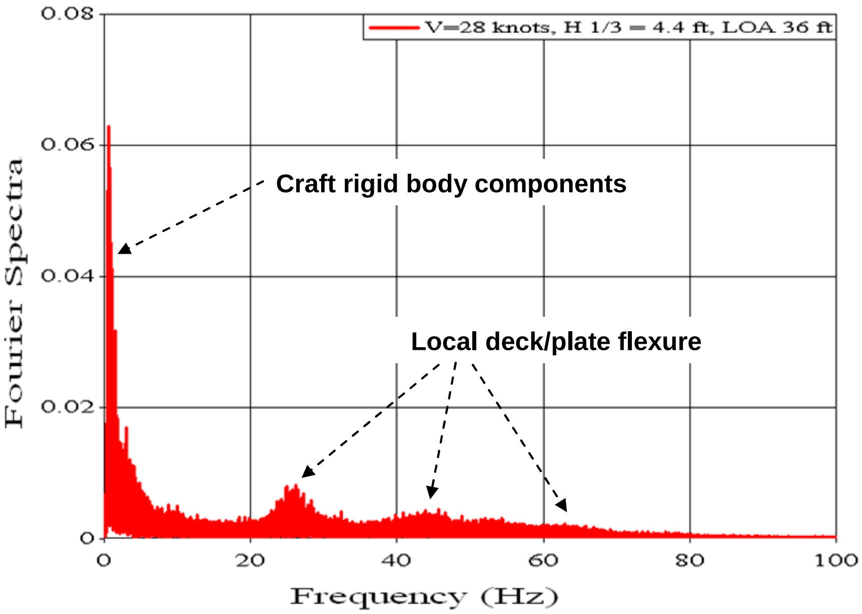

Figure 8. Fourier Spectrum of Typical Vertical Acceleration Record

Rigid Body Motion

Figure 9 shows a 4-second segment extracted from the typical acceleration record of Figure 2. The red curve is the original unfiltered record. It contains high frequency oscillations on the order of 25 to 26 Hz, most likely due to deck vibrations close to the gage. These oscillations add significant amplitude to the acceleration response at the time of the wave slam peak acceleration response. Gage placement should focus on stiffened locations to minimize structural flexure.

For many applications of interest, including structural design, seakeeping comparisons, or impact events on crew or equipment, the rigid body acceleration is the parameter most often related to global loading conditions. It is therefore necessary to take extra steps to estimate the rigid body response by removing the local high frequency responses.

Data Filtering

There are two simple approaches to removing high frequency responses: low-pass signal filtering and curve fitting. The black curve in Figure 9 illustrates an estimate of the rigid body acceleration by use of a 10 Hz low-pass filter. The peak acceleration for the filtered wave slam event is 3.5 g. The same unfiltered wave slam has a peak of 5.29 g.

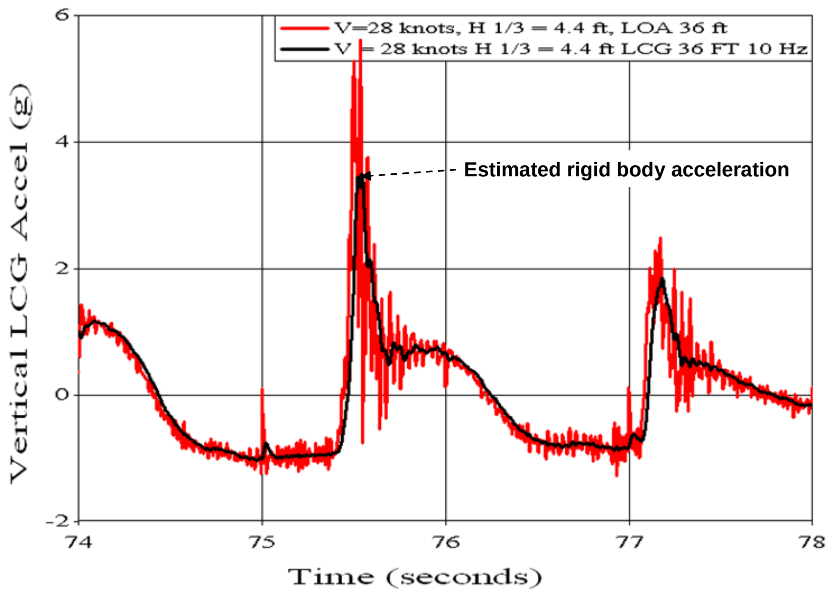

Figure 9. Unfiltered and Filtered Acceleration Responses

Low-pass signal filtering after inspection of frequency spectra has evolved as the process of choice, and inspection of many records for different small craft at different speeds has shown that a 10 Hz low-pass filter removes sufficient high frequency oscillation without excessive removal of peak rigid body response content. Figure 10 presents three Fourier spectra for vertical accelerations at the LCG recorded on three different craft at varying speeds. In each case they confirm that the largest spectral amplitudes correspond to frequencies below 10 Hz. This is an indication that the rigid body wave encounters are below the 2 Hz threshold, and that flexural responses will not dominate recorded peak accelerations after applying a 10 Hz low-pass filter.

Care must be exercised during the frequency analysis for craft with larger length-to-beam ratios to ensure that flexure of the hull girder (hog/sag) is understood. The nominal 10 Hz value may have to be adjusted if global flexural responses are part of the data.

The filter used for this effort was a Bessel two-pole filter with a characteristic 12 dB per octave attenuation (6 dB per octave per pole). The higher the filter order, the steeper the attenuation characteristic, and the more likely that unwanted frequencies will be attenuated. At the same time, as filter order increases, so does phase (or time) delay, although this delay has no effect on the statistical analysis. See Appendix B for additional information. Different filter types have different characteristics for amplitude and phase response. While there are many kinds of filters (Butterworth, Bessel, and Kaiser Window, for example), those designed for amplitude accuracy provide results that are within a few percent of one another.

Wave Slam Pulse Shapes

A wave slam is a violent impact between the hull and an incident wave. Figure 11 presents eight wave slams from Figure 2 with expanded time scales to show just the impact period and the plateau. Each was normalized by dividing by the peak value so that the maximum is 1g. The left plot shows five impact events whose original peak values were from 3.1g to 3.8g. Three more slams whose original peaks were 1.9 g, 4.5g, and 5.3g are compared in the plot on the right. The fourth red curve on the right is the average of the five curves on the left. In general the impact pulse shapes (from B to C in Figure 4) rise from zero to a maximum in 50 to 80 ms, and have a total duration on the order of 200 ms or less.

The good correlation illustrates the repeatability of the different wave slam events and suggests that, while the energies associated with each incident wave may be random, the response of the craft to individual slams may be repeatable with amplitudes being a function of initial conditions just prior to each slam event.

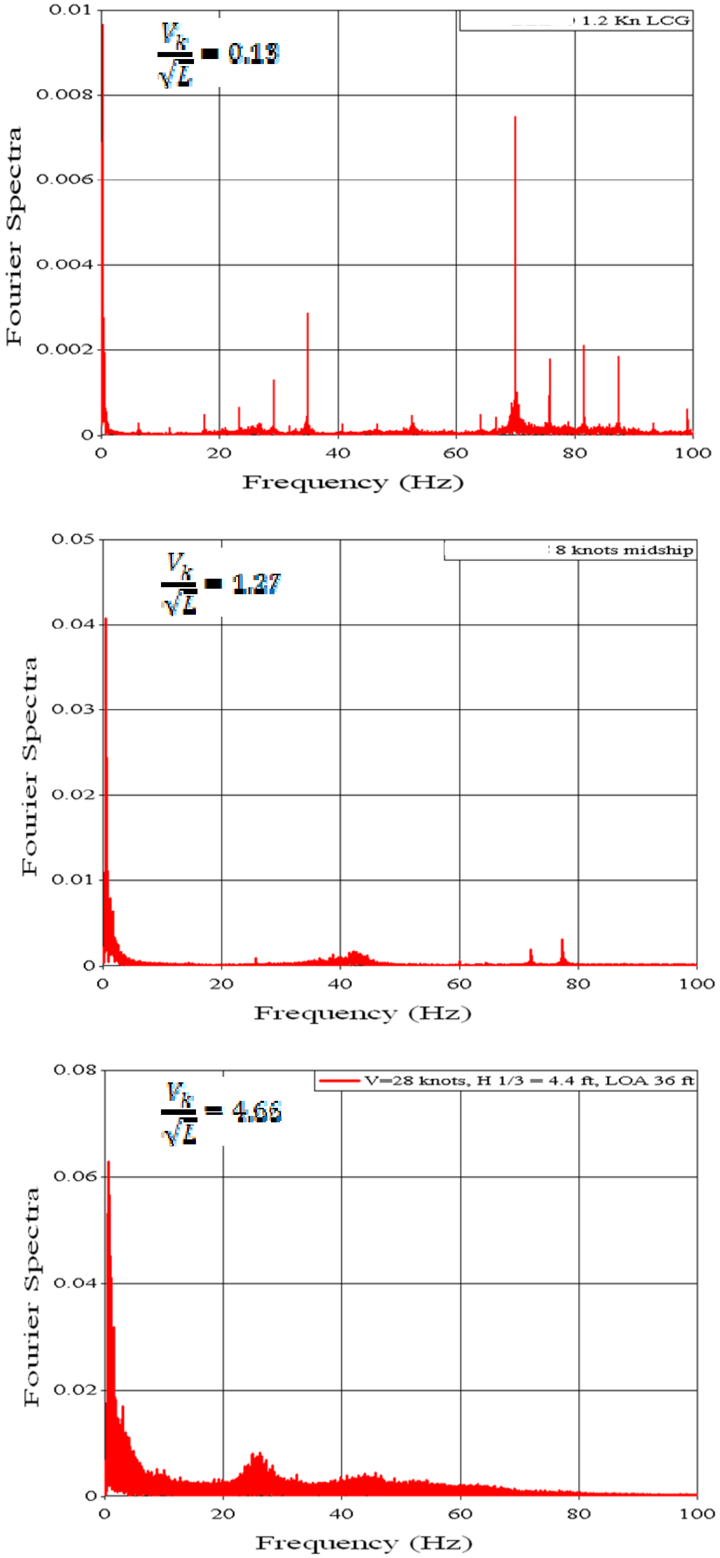

Figure 10. Frequency Spectra for Varying Conditions

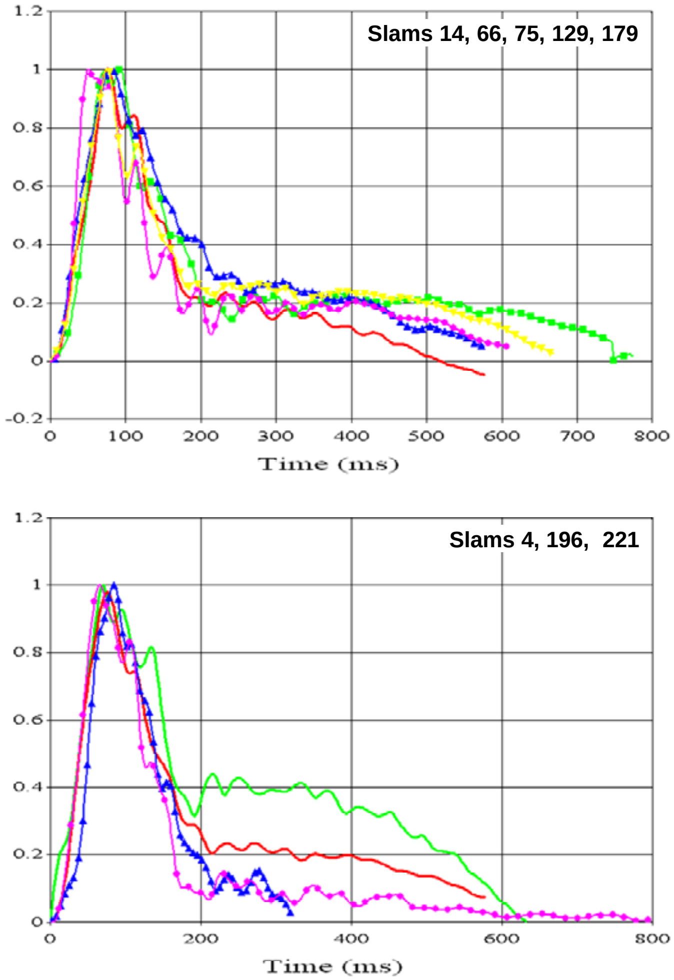

Figure 11. Normalized Pulse Shapes for Wave Slams

RMS Acceleration

The root mean square (RMS) is a measure of the average fluctuation about the mean for a time varying signal. RMS is often referred to as the effective value. For time varying signals with an average value of zero (acceleration data should be processed in such a way that the average value is zero), the RMS value is equivalent to the standard deviation, and is calculated as presented in reference [6] using the relationship

$$RMS = \sqrt{\frac{\sum_{i=1}^{m} Ai^{2}}{m}} \qquad \text{Equation (5)}$$

where A_i are the data points and m is the total number of discrete points within the data record.

The RMS value of the acceleration time history shown in Figure 2 is 0.62 g. This amplitude is much less than the thirty wave slams with peak accelerations in the 2.0 to 5.3 g range, but it is characteristic of the response amplitudes, both positive and negative, just before and just after wave slams. This is illustrated in Figure 12 and Figure 13.

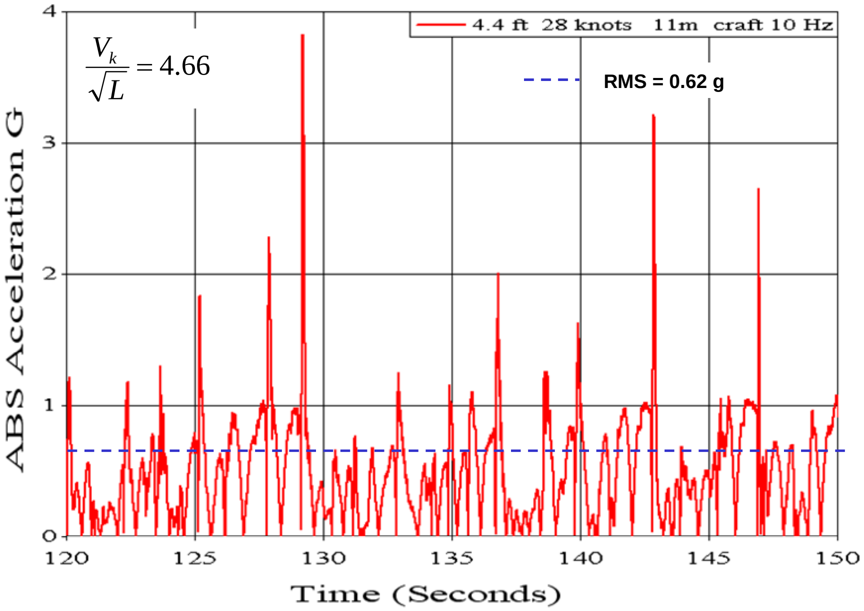

Figure 12. Absolute Values in a 30-second Acceleration Record

Figure 12 shows a 30-second segment of the Figure 2 acceleration record where all the negative values have been made positive. Individual wave slam events are seen as acceleration spikes. The hydrodynamic phases of response just after the slam events, as well as those phases dominated by gravity just before slam events typically have absolute magnitudes that vary from zero to 1.5 g, with many of these lower amplitude response phases in the 0.4 g to 0.9 g range. This is illustrated further in the 5-second segment shown in Figure 13. The wave interaction shapes have many positive and negative plateaus that dominate the statistical computation of the RMS value.

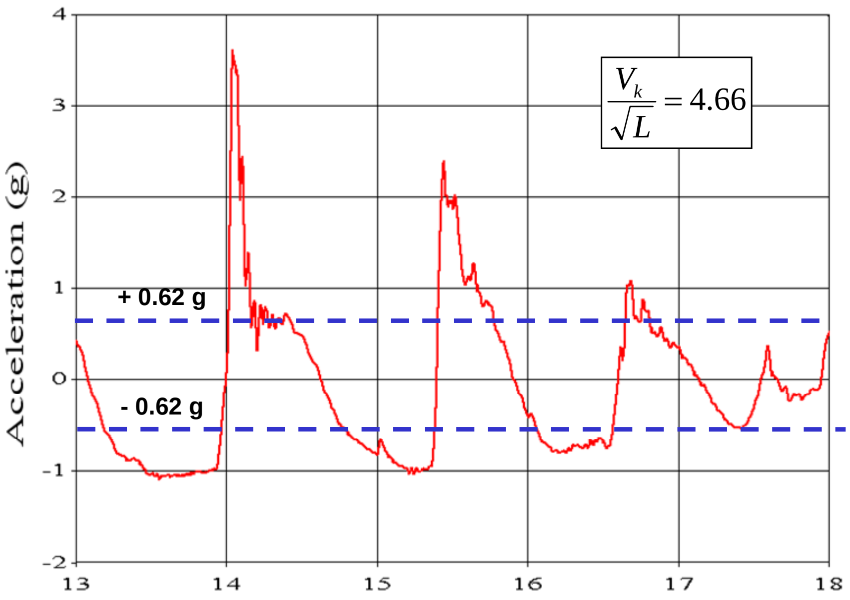

Figure 13. RMS Acceleration Correlation with Low-amplitude Responses

Figure 12 and Figure 13 demonstrate that for high-speed craft operating in the planing regime, the RMS value correlates well with the lower amplitude values associated with buoyancy, hydrodynamic lift and drag, and gravity forces, and therefore serves as a rational baseline for counting higher peak accelerations caused by wave impacts. Wave slam events for planing craft typically dominate the loading regime of interest; therefore, determination of peak acceleration values for high-speed craft should focus on amplitudes greater than the RMS baseline value.

Generalized Computational Approach

The following four-step generalized approach is recommended for calculating the average of the 1/nth highest peak accelerations for a given acceleration time history recorded in any orientation axis.

Frequency Analysis

The first step in the data analysis process is the computation of a frequency spectrum in the 0.1 to 100 Hz range and plotting of the results as illustrated in Figure 10. If the largest spectral amplitudes are less than 2 Hz then the data can be low-pass filtered to remove flexural components. If the largest spectral amplitudes exist in the 2 to 15 Hz range, other techniques such as multivariate data reduction (using three or more acceleration gages) may be necessary to extract rigid body peak acceleration estimates.

10 Hz Low-Pass Data Filter

As a starting point for data analysis, application of a 10 Hz low-pass filter to the acceleration record to estimate rigid body acceleration motions is recommended. Experience has demonstrated that in some specific cases a filter frequency of 8 Hz or sometimes 12 to 15 Hz may be sufficient to extract rigid body estimates. The nominal 10 Hz value is recommended to establish a generalized value greater than the 2 Hz threshold, which still allows rigid body rotational components that may exist in the 2 to 4 Hz range.

RMS Calculation

The RMS value for the 10 Hz filtered acceleration record should then be calculated. Its value establishes a rational baseline for analyzing and counting higher acceleration peaks induced by wave impacts.

Calculation of the $A_{1/n}$ Values

A peak-to-trough algorithm with the following interim criteria to select peak amplitudes from the acceleration time history is then applied. The vertical threshold should be equal to the RMS acceleration for the time history, and the horizontal threshold should be equal to one-half the data sampling rate (i.e., 0.5 seconds).

Use of the one-half second horizontal threshold provides a lower bound wave encounter period that ensures all rigid body peaks will be counted. It was demonstrated previously that average wave encounter periods will be greater than 0.5 seconds for speeds up to 50 knots and significant wave heights greater than 1.6 feet.

The peak acceleration values are then tabulated from highest to lowest amplitudes and a histogram is constructed. Finally, the average of the highest $1/n^{th}$ peak values using equation (1) is calculated.

Documentation

It is recommended that any document used to report computed average of the $1/n^{th}$ highest accelerations should also include the following information: craft displacement, length, beam, draft, deadrise, and LCG; craft heading (e.g. head or following seas), average speed, and speed versus time if available; environmental conditions including significant wave height, average wave period, and average wave length; instrumentation characteristics such as bandwidth, sampling rate, and anti-alias filter rate; and acceleration data, including typical 30-second time history with maximum peak acceleration, tabulated or plotted peak acceleration values (greater than the RMS value, presented largest to smallest), number of peaks, peak acceleration histogram plot (each bin = 1 RMS), tabulated acceleration values, including A_{PEAK}, $A_{1/100}$, $A_{1/10}$, and RMS.

Example Calculations

After the typical acceleration record shown in Figure 2 was subjected to a 10 Hz low-pass filter, one-hundred fifty-one peak accelerations were counted greater than the 0.62 g RMS value. Figure 14 shows a 30-second segment illustrating the wave slam peaks counted (triangles) and the peaks ignored (circles) by the computational procedure. Thirty of the peaks were greater than 2.0 g, and the largest peak was 5.3 g. Figure 15 shows all one-hundred fifty-one peak acceleration values sorted and plotted from largest to smallest. The distribution of all peak values is shown in the Figure 16 histogram.

Figure 17 compares filtered and unfiltered peak acceleration levels for seven of the high-amplitude wave slams observed in the Figure 2 record. The slam number is the approximate time (in seconds) when the slam occurred in the acceleration record. Computed averages of the one-third, one-tenth, and one- hundredth highest accelerations for filtered and unfiltered data are also presented to illustrate their magnitudes relative to the seven high-amplitude wave slam peak accelerations. As N becomes large, the average of the 1/nth highest accelerations approaches the maximum value in the data set.

Figure 18 compares the computed average of the 1/10th highest accelerations for the filtered and unfiltered acceleration record. The average of the 1/10th highest acceleration equal to approximately 3.2 g (shown as the circled data point) is the value all analysts would compute using the one-half second horizontal threshold and RMS vertical threshold values.

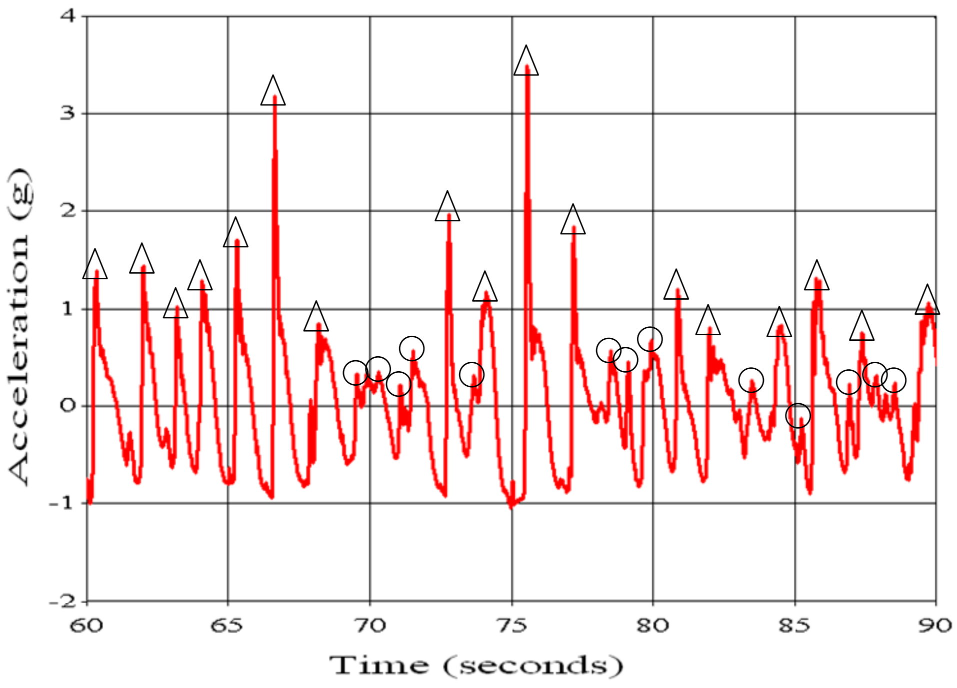

Figure 14. Peaks Counted Using Standard Criteria

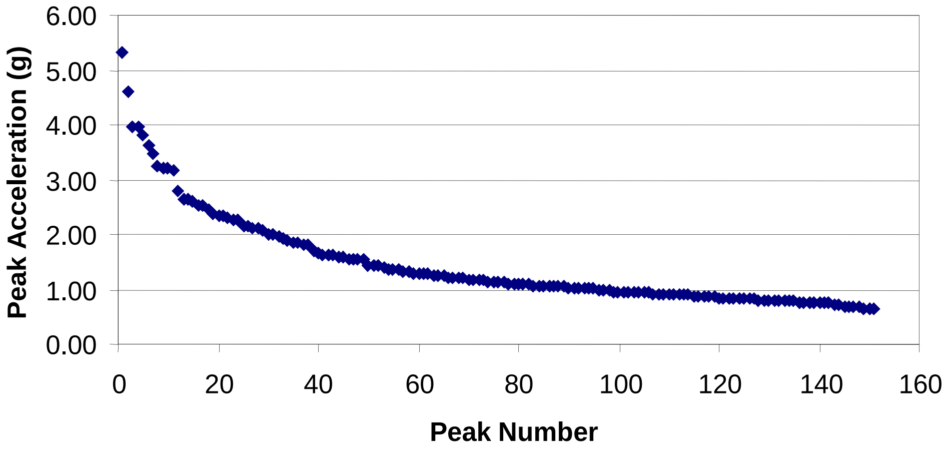

Figure 15. Sorted Peak Accelerations Greater than RMS Value

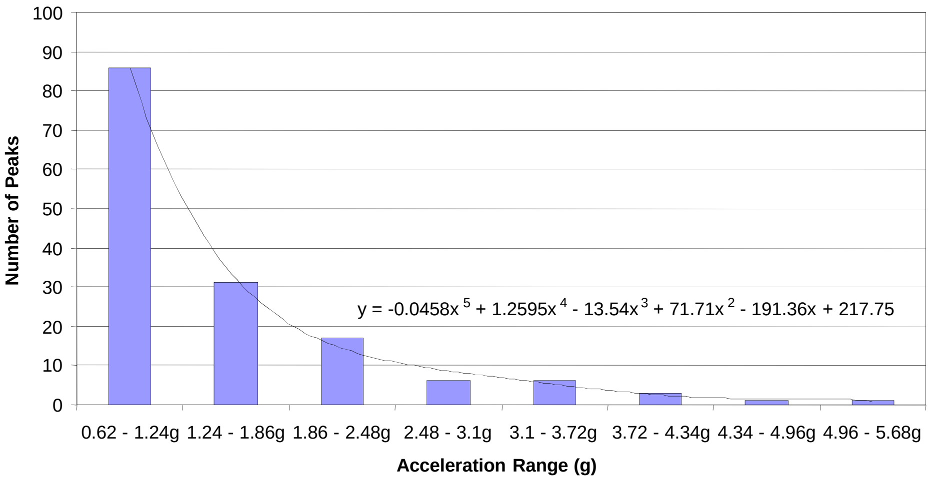

Figure 16. Planing Craft Peak Acceleration Histogram

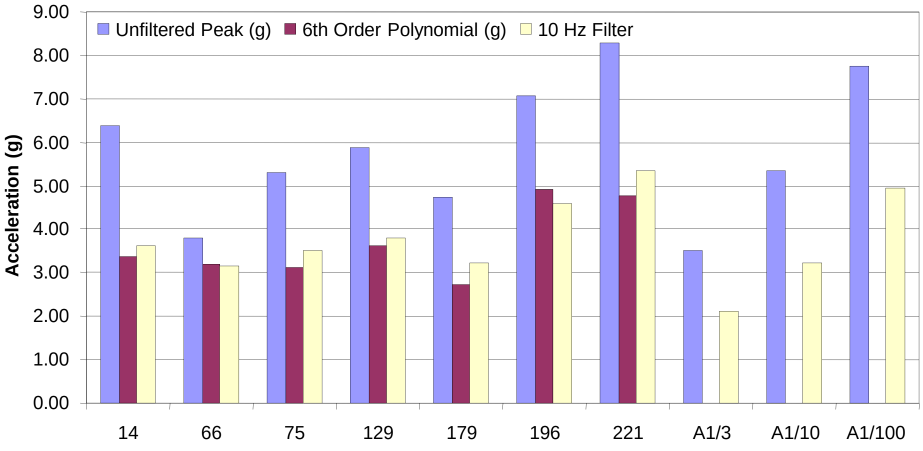

Figure 17. Peak and Average Highest Acceleration Values

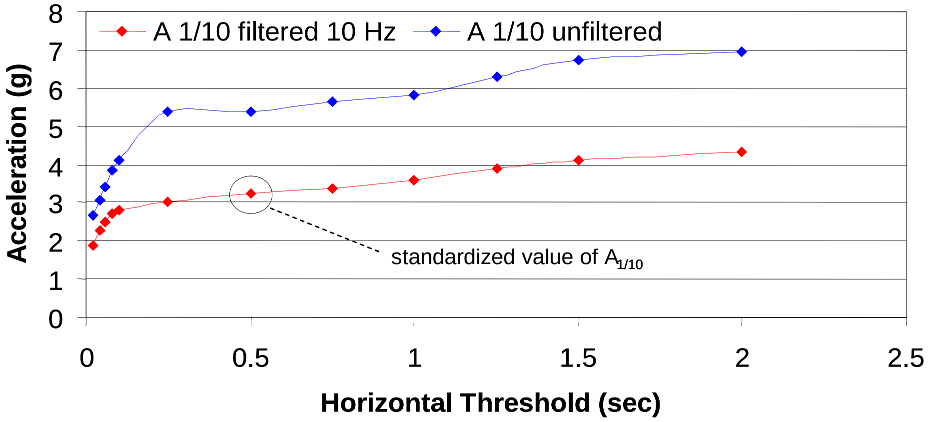

Figure 18. Computed Average of 1/10th Highest Acceleration Value

Conclusions

As craft speed increases into the planing regime, individual wave encounters can result in violent impacts between the hull and the wave. The wave slams are typically short duration events, on the order of two-tenths of a second or less, whose initial rigid body peak acceleration rapidly decreases to ambient values.

The rigid body response of a craft moving at planing speeds in sea states greater than 1.6 feet will manifest itself as repeated acceleration pulses whose cyclic frequency is on the order of 2 Hz or less. Any frequency content in the acceleration record greater than 2 Hz is therefore coming from a source other than longitudinal (surge) rigid body encounters with waves.

In addition to rigid body motions of a craft, recorded acceleration data invariably includes small amplitude, high frequency, structural oscillations in the vicinity of the gage induced by wave slams. Gage placement should focus on stiffened locations to minimize recording structural flexure. The recommended 10 Hz low-pass filter attenuates local oscillations to better estimate rigid body acceleration.

For craft operating in the planing regime, the RMS value correlates well with the lower amplitude values associated with positive and negative hydrodynamic forces (i.e., ambient wave interaction and gravity). The recommended vertical threshold equal to the RMS value for an acceleration record establishes a rational baseline for counting higher rigid body peak accelerations caused by wave impacts.

Craft operating at planing speeds up to 50 knots in head seas greater than 1.6 feet will encounter waves on the order of every 0.5 seconds or more. The recommended 0.5 second horizontal threshold establishes the lower bound for counting peak acceleration values.

A four-step process is recommended for a generalized computational approach for computing the average of the $1/n^{th}$ highest acceleration when analyzing accelerometer data recorded during trials of manned or unmanned small boats and craft. Use of three interim criteria, including low-pass filtering at 10 Hz, a peak-to-trough vertical threshold equal to the acceleration record RMS value, and a peak-to-trough horizontal threshold equal to 0.5 seconds significantly reduces subjectivity in the calculation. The methodology is based on analysis practices that have evolved at the Combatant Craft Division of Naval Surface Warfare Center, Carderock Division as a set of best-practices for achieving repeatability when calculations are performed for different data sets and by different researchers for varying projects.

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Symbols, Abbreviations, and Acronyms

A	peak vertical acceleration (g)
A_{cg}	average vertical acceleration (g) at the CG
A/D	analog-to-digital
dB	decibel
ft	feet
g	acceleration due to gravity (32.2 ft/s^2)
$H_{1/3}$	average of the 1/3rd highest wave heights, significant wave height (ft)
Hz	Hertz (cycles per second)
L	craft length (ft)
L_W	average length of ocean wave (ft)
LCG	longitudinal center of gravity
ms	millisecond
N	number of peak values in a data record
RMS	root mean square
s	second
T	average wave encounter period (s)
T_W	average wave period (s)
V	average craft speed (ft/s)
V_k	average craft speed (knots)

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Appendix A - Wind and Sea Scales for Fully Risen Seas

	FULLY RISEN SEAS[2]										WIND			
	WAVE HEIGHT (feet)							WIND[3]						
SEA STATE[1]	AVERAGE	SIGNIFICANT (avg. of 1/3 highest)	AVG. OF 1/10 HIGHEST	SIGNIFICANT RANGE OF PERIODS (seconds)	T_{max} (period of max.energy of spectrum, sec.)	$\tilde{T}$ (average period, sec.)	$\tilde{L}$ (avg. wave length, ft.)	WIND SPEED (knots)	MINIMUM FETCH (nmi)	MINIMUM DURATION (hrs)	BEAUFORT No.[4]	WIND DESCRIPTION	WIND SPEED (knots)	APPEARANCE OF THE SEA[5]
0	0	0	0	~	~	~	~	~	~	~	0	CALM	<1	Sea like a mirror.
	0.05	0.08	0.10	up to 1.2 sec.	0.7	0.5	0.83	2	5	0.3	1	LIGHT AIRS	1-3	Ripples with the appearance of scales are formed, but without foam crests.
1	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7	5	8	0.7	2	LIGHT BREEZE	4-6	Small wavelets, still short but more pronounced; crests have glassy appearance and do not break.
	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	8.5	9.8	1.7	3	GENTLE BREEZE	7-10	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.
2	0.88	1.4	1.8	1.0-6.0	4.0	2.9	27	10	10	2.4				
	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	12	18	3.8	4	MODERATE BREEZE	11-16	Small waves, becoming longer; fairly frequent white horses.
	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	13.5	24	4.8				
3	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	14	28	5.2				
	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	16	40	6.6				
4	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	18	55	8.3	5	FRESH BREEZE	17-21	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray.)
	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	19	65	9.2				
5	5.0	8.0	10	3.0-11.1	8.1	5.7	111	20	75	10				
	6.4	10	13	3.4-12.2	8.9	6.3	134	22	100	12	6	STRONG BREEZE	22-27	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)
	7.9	12	16	3.7-13.5	9.7	6.8	160	24	130	14				
6	8.2	13	17	3.8-13.6	9.9	7.0	164	24.5	140	15				
	9.6	15	20	4.0-14.5	10.5	7.4	188	26	180	17				
	11	18	23	4.5-15.5	11.3	7.9	212	28	230	20	7	MODERATE GALE	28-33	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. Spindrift begins.
7	14	22	28	4.7-16.7	12.1	8.6	250	30	280	23				
	14	23	29	4.8-17.0	12.4	8.7	258	30.5	290	24				
	16	26	33	5.0-17.5	12.9	9.1	285	32	340	27				
	19	30	38	5.5-18.5	13.6	9.7	322	34	420	30	8	FRESH GALE	34-40	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.
	21	35	44	5.8-19.7	14.5	10.3	363	36	500	34				
	23	37	46.7	6.0-20.5	14.9	10.5	376	37	530	37				
	25	40	50	6.2-20.8	15.4	10.7	392	38	600	38				
8	28	45	58	6.5-21.7	16.1	11.4	444	40	710	42				
	31	50	64	7.0-23.0	17.0	12.0	492	42	830	47	9	STRONG GALE	41-47	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Spray may affect visibility.
	36	58	73	7.0-24.2	17.7	12.5	534	44	960	52				
9	40	64	81	7.0-25.0	18.6	13.1	590	46	1110	57				
	44	71	90	7.5-26.0	19.4	13.8	650	48	1250	63	10	WHOLE[6] GALE	48-55	Very high waves with long overhanging crests. The resulting foam in great patches is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shock like. Visibility is affected.
	49	78	99	7.5-27.0	20.2	14.3	700	50	1420	69				
	52	83	106	8.0-28.2	20.8	14.7	736	51.5	1560	73				
	54	87	110	8.0-28.5	21.0	14.8	750	52	1610	75				
	59	95	121	8.0-29.5	21.8	15.4	810	54	1800	81				
	64	103	130	8.5-31.0	22.6	16.3	910	56	2100	88	11	STORM[6]	56-63	Exceptionally high waves. (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.
	73	116	148	10.0-32.0	24	17.0	985	59.5	2500	101				
	>80[7]	>128[7]	>164[7]	10-(35)[7]	(26)[7]	(18)[7]	~	>64	~	~	12	HURRICANE[6]	64-71	The air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.

From a table compiled by Wilbur Marks, David Taylor Model Basin

[1] Sea states refer only to wind waves. Swells from distant or old storms are often superimposed on the wind wave pattern.

[2] Practical Methods of Observing and Forecasting Ocean Waves, Pierson, Neuman, James, H.O.Pub. 603, 1955.

[3] Wind required to create a fully risen sea. To attain a fully risen sea for a certain wind speed, the wind must blow at that speed over a minimum distance (fetch) for a minimum time (duration).

[4] The Beaufort Number is a wind force scale. While wind and seas are causally related, Beaufort Number and sea state are not the same. For example, it is common to have force 7 winds, but because of limited fetch or duration, a sea state of only 2.

[5] Manual of Seamanship, Vol. II, Admiralty, H.M. Stationary Office, 1952.

[6] For whole gale, storm, and hurricane winds (50 knots or more) the required durations and fetches are rarely attained. Seas are therefore not fully arisen.

[7] For such high winds the seas are confused. The wave crests are blown off, and the water and air mix.

Appendix B - Data Filtering

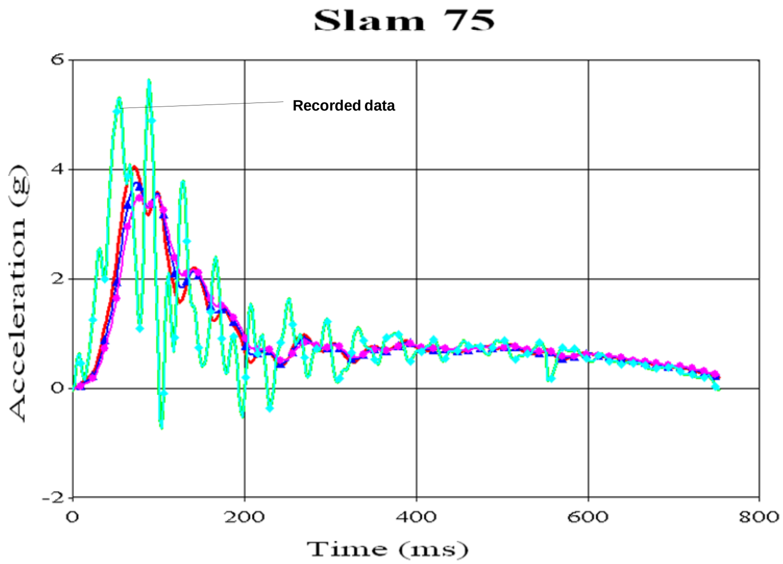

Figure B1. Filtering Effects on Slam Event 75

When used in a systematic analysis process, data filtering is useful for extracting needed information from an original data record. When applied indiscriminately the methods often result in lost valuable information, leading to incorrect conclusions.

The high frequency content of the typical acceleration record presented in this report contains local flexural oscillations in the vicinity of the sensor with dominant frequency on the order of 25 to 26 Hz. The low frequency components associated with the rigid body motion of the craft are below 2 Hz with an average impact frequency of 0.5975 Hz (corresponding to an impact period of 1.67 seconds) as determined by frequency analysis.

Figure B1 presents the original unfiltered slam 75 event and compares the effects of 10 Hz, 12 Hz, and 15 Hz low-pass filters. The comparison plot shows that in late time (400 to 600 ms) the 10, 12, and 15 Hz filters effectively remove the 25 Hz oscillation. During the 100 to 400 ms period the 12 Hz and 15 Hz filtered records exhibit 25 Hz components that are most likely affecting the peak in the filtered plot. For this slam event, each 5 Hz of additional filter below 15 Hz reduces the peak acceleration approximately 0.3 g, and shifts the peak to the right on the order of 0.2 to 0.4 milliseconds. The applied filter for this effort was a Bessel two-pole filter with a characteristic 12 dB per octave attenuation (6 dB per octave per pole). The higher the filter order, the steeper the attenuation characteristic, and the more likely that unwanted frequencies will be attenuated. At the same time, as filter order increases, so does phase (or time) delay, although this delay has no effect on the statistical analysis.


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