High-Speed Craft Motions: a Case Study

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Craft motions data was acquired on the MKV Special Operations Craft (SOC) during testing off the coast of Port Royal, South Carolina in April 1996. Acceleration measurements were conducted to define the craft's operational performance relative to hull and equipment integrity and human factors. Data was acquired using self-contained environmental data recorders located at various positions on the craft during operations in 3-foot seas. Examples of acceleration data are presented in terms of its frequency and response statistics, which include the maximum, average, and root mean square (RMS) values.

INTRODUCTION

Craft motions testing was conducted on the MKV Special Operations Craft (SOC), an 82-foot high-speed monohull, in the Atlantic Ocean off the coast of Port Royal, South Carolina in April 1996. Testing was conducted in seas which averaged approximately 3 feet significant (average of the 1/3 highest) wave heights. The objective of the measurements was to determine acceleration levels at various craft locations to qualify their effects on hull, equipment, and personnel. These measurements are conducted to determine the safe performance limits when operating in a seaway. Vertical, transverse, and longitudinal acceleration levels were recorded at each instrument location.

This paper presents a discussion of the acceleration measurements and the data analysis, and suggests considerations for additional work.

Figure 1. MKV Special Operations Craft

The MKV SOC, shown in figure 1 is a high-speed combatant whose primary mission is the medium range insertion and extraction of special operations forces. A sleek aluminum vessel 82 feet long, it has a top speed of approximately 50 knots and a range of 500 nautical miles. Operated by five crew members, it is designed to carry 16 fully-equipped Navy SEALs in addition to its payload of CRRCs and other equipment. It has been designed to be mission-ready anywhere in the world within 48 hours, transported by an Air Force C-5 aircraft.

TEST MEASUREMENTS

Background

Craft motions, or the way in which a vessel behaves in a seaway, can be characterized through the measurement of acceleration levels at various locations to qualify their effect on craft structure, installed equipment, and passengers. The measurement, analysis, and interpretation of acceleration data as applied to high speed planing craft is very complex. Factors which affect accelerations include the hull form, speed in a seaway, sea state, craft direction to the prevailing sea, craft displacement, and operator proficiency among others. Because of this complexity, the results generally cannot be interpreted in an absolute sense. However, valid comparisons may often be made between craft operated under similar conditions. In order to minimize the effects of uncontrolled variables on the data, as many of these factors as possible are held constant (or at least measured and documented) during the test.

Test Method

Generally, craft motions testing is conducted relative to eight directions to the sea at a number of craft displacement conditions and at speeds representing typical operating conditions. A wavebuoy is used to collect sea condition information, and the direction of the prevailing sea is determined. When a dedicated wavebuoy is unavailable for testing, wave heights may be estimated through direct observation or determined from secondary sources such as the weather stations maintained by the National Oceanographic and Atmospheric Administration (NOAA). Once all test equipment has been initialized and confirmed operational, the test craft is directed to proceed in a direction into the prevailing sea at a constant predetermined speed.

Accelerations data is collected over a period sufficient to record at least two hundred impact events for each direction to the sea. This allows for an adequate statistical sample. For head and bow seas, two hundred events can be collected in approximately five to ten minutes, depending on the wave period and craft speed. For beam, quartering, and following seas, impact frequencies are generally much lower and consequently, longer data acquisition periods are required. If memory constraints limit acquisition time, data must be downloaded periodically during testing. Once sufficient data has been collected at the first heading to the sea, the test craft is stopped and data is uploaded from the recording system to a portable computer for later analysis. Prior to subsequent runs, recording control parameters are downloaded from the computer to the data recorders. Data is collected for all sea directions in a similar manner.

Because acceleration levels are generally symmetric about the craft's longitudinal axis, the data collection effort can be reduced by testing in only five of the eight directions to the sea (i.e., head, port bow, port beam, port quarter, and following). Acceleration levels at the starboard bow, starboard beam, and starboard quarter aspects are assumed to be the same as for the port directions.

Collecting acceleration data at different locations along the length of the craft allows assessment of acceleration levels by interpolation for any location on the craft. This allows naval architects a comparison of real-world measurement results with design predictions. Acceleration measurements were recorded at four locations on the test craft as shown in figure 2; 1) on the ammunition rack at the forward weapon mount, 2) on the forward middle shelf on the starboard side of the CIC, 3) at the coxswain's seat foundation, and 4) on the port midship gun mount located on the aft deck.

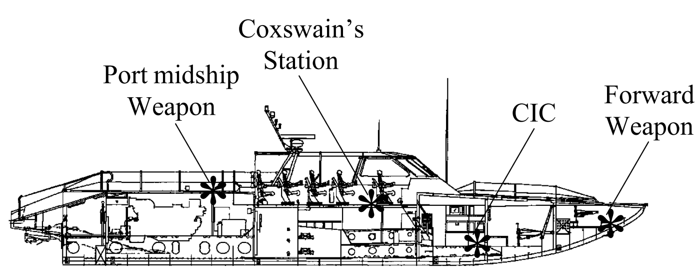

Figure 2. Acceleration Measurement Locations

Acceleration Measurement Equipment

Figure 3. IST EDR-3 Environmental Data Recorder

Normally, acceleration measurements are made using discrete accelerometers, signal conditioning, and recording devices (magnetic tape recorders or digital data acquisition systems) connected by cabling. For measurements on the MKV, accelerations in the vertical, transverse, and longitudinal directions were acquired using Instrumented Sensor Technology (IST) EDR-3 environmental data recorders, as illustrated in figure 3.

The EDR-3 is a microprocessor-based data acquisition system that contains a triaxial piezoresistive accelerometer, signal conditioning, and solid-state memory. Recording parameters are defined by the user and downloaded from a portable computer to the EDR-3 prior to accelerations measurements.

After data acquisition has been completed, the recorded acceleration events are uploaded from the EDR-3 to the computer for processing and analysis. Each recorded acceleration event is processed to include the time and date of occurrence. Acceleration data can be processed to provide the maximum, minimum, peak, and RMS acceleration levels, crest factor, and duration of the peak acceleration. Additionally, power spectral density (PSD) calculations can be performed, and velocity and displacement conditions determined.

The amount of data which can be recorded is limited by the user defined sampling frequency and the amount of memory available in the EDR-3. For measurements on the MKV, a sampling rate of 512 samples per second was selected as a minimum for the recorder's 200 Hz anti-alias filter. Approximately eight minutes of data could be recorded before the 1 MB internal memory was filled. User defined recording parameters dictated that any acceleration event that exceeded 0.5 g for a minimum of 50 milliseconds would be captured and stored to memory.

Analog signals from the internal accelerometers are converted into a series of discretely quantized time samples through the process of digital sampling. The number of quantization levels available in the EDR-3's analog-to-digital converter is 1024 levels (10 bits) equally spaced over the positive and negative g range. The effective resolution is based on the quantization level and the full scale range of the internal accelerometers. A recorder with 20g internal accelerometers, for example, will have a resolution of 0.04g (20g/512).

Wave Height Measurement Equipment

Figure 4. Datawell Waverider Bouy

Wave heights were measured using a Datawell Waverider buoy. The wavebuoy was launched and wave height data was monitored from a support craft. Sea states can be determined from the wave height statistics based on published wind and sea scales for fully risen seas.

The Datawell Waverider illustrated in figure 4 is a stainless steel spherical buoy approximately 0.7 meter in diameter and capable of following movements of the water surface resulting in the measurement of the buoy's vertical acceleration. Wave height and periodicity are detected by an inertial accelerometer suspended in a viscous fluid and mounted in the lower half of the buoy. The signal generated by the accelerometer is double-integrated to obtain displacement and is transmitted along with frequency information by telemetry to the remote receiver. The signal is then recorded on magnetic tape and paper strip chart for later analysis. A Fast Fourier Transform (FFT) analysis is conducted to determine the magnitude and frequency of the wave data which is then compared with published sea scale tables to determine sea state. Wave heights up to 20 meters (peak) can be measured using this instrument.

U. S. Weather Observation Stations

In the absence of a dedicated wavebuoy, information provided by the National Data Buoy Center (NDBC) can be used to establish weather and sea conditions. A division of the National Oceanographic and Atmospheric Administration (NOAA), the NDBC maintains wavebuoy and Coastal Marine Automated Network (CMAN) stations within the United States. These weather observation platforms provide meteorological and oceanographic data to forecasters, researchers and other users in the United States and around the world. An hourly weather report is available through the National Weather Service which includes information on temperature, wind speed and direction, barometric pressure, sea surface temperature, wave height, and wave period, depending on the particular station's capabilities. Wave height information is derived from accelerometers onboard the buoys which measure heave acceleration (or vertical displacement) of the buoy hull for a 20-minute period each hour. An FFT analysis is applied to the data by the onboard processor to transform the data from the time domain to the frequency domain from which non-directional wave measurements are derived. Significant wave height (average of the 1/3 highest) and average wave period are determined from this data. Wave direction was assumed based on the average wind direction for data acquired during the test period.

TEST RESULTS

Wave Height Measurements

Wave data collected from the Datawell buoy, which was launched in the general vicinity of craft motions testing, indicated average significant wave heights during the test period of 3.0 feet. Sea direction was determined based on direct observation. As a comparison, wave data was also collected from the NOAA CMAN station nearest the test site, which was located at Savannah Light. Average significant wave heights reported from this CMAN station during the test period were 3.1 feet.

AccelerationResults

During these measurements, accelerations resulting from wave impact were recorded in one-second data windows each time the user-defined trigger level was exceeded. The digital acceleration data was processed using IST's Dynamax software. This software was used to analyze the mean, peak, and RMS values of the acceleration waveform. Power Spectral Density (PSD) analysis was conducted to allow an interpretation of the frequency content of the acceleration signal. To help qualify the human factors effects with respect to vibration tolerance, an Acceleration Spectral Density (ASD) analysis was performed which allows a comparison of the data with International Standard ISO 2631. A definition of the calculated quantities follows:

<u>Acceleration Event</u>. Each one-second data window as defined in the recording control parameters constitutes an acceleration event. Acceleration data is written to memory each time the trigger level and trigger duration threshold values as defined in the recording control parameters is exceeded.

<u>Number of Events</u>. The aggregate number of one-second data windows as defined in the recording control parameters is the number of events. For this test, an overwrite limit of 400 events was specified.

<u>Peak</u>. The absolute value of the greatest positive or negative sample point in an event is defined as the peak value.

<u>Mean</u>. The mean value is the average of all the sample points in an event.

<u>RMS</u>. The root mean square is a measure of the average fluctuation about the mean for a time varying signal and is often referred to as the effective value. It is calculated by taking the square root of the mean square, where the mean square is the sum of the squares of the sample points divided by the number of samples in the event.

<u>Average of the 1/3 Highest</u>. This is a statistical measure of the significant amplitudes of the acceleration events. The value is determined by sorting the events by their peak acceleration value and averaging the greatest 1/3 peak values of those events.

<u>Average of the 1/10 Highest</u>. This is a statistical measure of the extreme amplitudes of the acceleration events. The value is determined by sorting the events by their peak acceleration value and averaging the greatest 1/10 peak values of those events.

PSD. The power spectral density is used to determine the energy distribution of an acceleration waveform as a function of frequency. It is also valuable for identifying the dominant frequencies present in vibrational data.

ASD. The acceleration spectral density is used to calculate the 1/3 octave frequency response of the RMS acceleration waveform compared with the ISO 2631 whole body vibration criteria. This technique can be useful for qualifying vibration phenomena.

Over measurement periods of approximately 10 minutes each, nearly 400 one-second data events were recorded at each heading to the prevailing sea. Because accelerations resulting from wave impact were less severe in a following sea, only 50 one-second events were recorded in that heading. Intuition suggests that for high-speed planing hulls like the MKV the most severe ride (and consequently the highest accelerations) would occur in a head sea orientation (that is, with the craft headed directly into the sea) with the softest ride in a following sea. In fact, the results of this testing (and other testing conducted over the past 30 years) support intuition. Highest accelerations result from operation in head seas, followed by bow seas (waves at 45 degrees to the bow), beam seas (waves perpendicular to the beam), quartering seas (waves at 45 degrees to the stern), and finally following seas (waves at the stern).

Vertical acceleration levels are considerably greater than longitudinal or transverse accelerations for a given measurement location. Consequently, these have the greatest impact on craft structure, installed equipment, and personnel safety and comfort. Although an emphasis is placed on vertical acceleration levels, longitudinal and transverse acceleration levels cannot be ignored and must be considered for specific design applicability. Figure 5 is a time-domain representation of the five highest one-second acceleration events in the longitudinal (X), transverse (Y), and vertical (Z) directions for measurements collected in a head sea as measured at the coxswain's station.

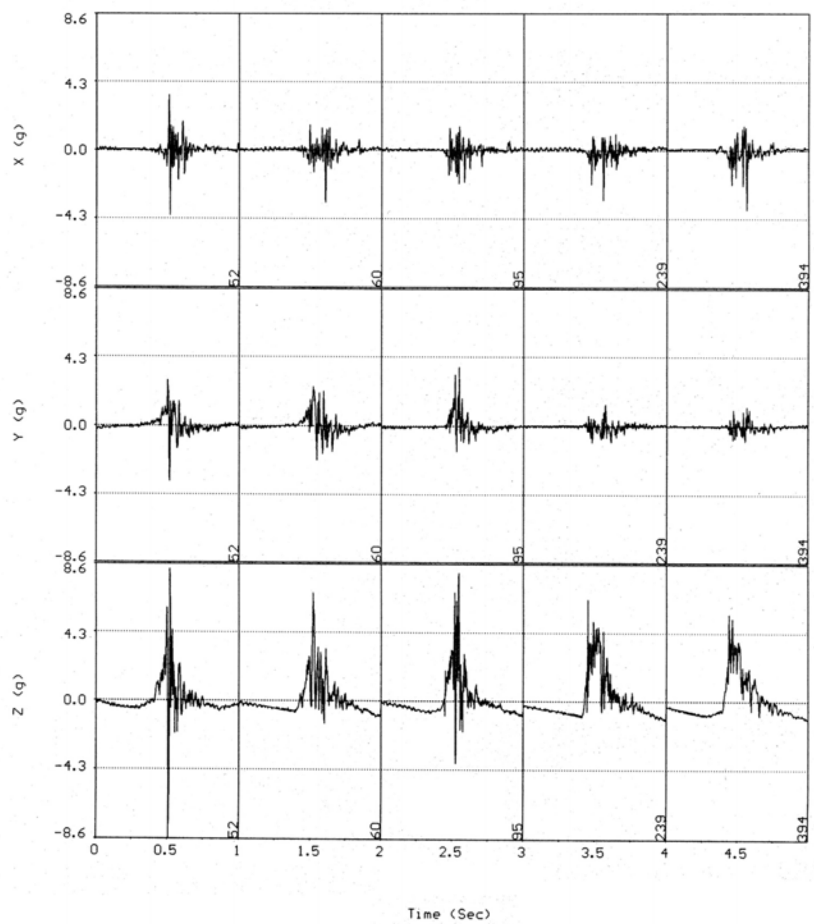

Figure 5. Five Highest Acceleration Events for Head Sea

Table 1 presents the peak, average 1/10 highest, average 1/3 highest, mean, and RMS vertical acceleration levels measured at the coswain's station. The average 1/10 and 1/3 highest vertical accelerations have been typically used by designers to validate model predictions, although the RMS accelerations are also used. The RMS accelerations are used as well to validate adequacy for installed equipment and for decisions concerning personnel safety and comfort.

Table 1. Vertical Acceleration Statistics for Measurements Acquired at Coxswain's Station

	Craft Heading Relative to Sea Direction				
	Head (g)	**Bow (g)**	**Beam (g)**	**Quartering (g)**	**Following (g)**
Peak	8.62	3.94	6.02	1.67	1.51
Average 1/10 H	4.30	2.48	2.39	1.56	1.26
Average 1/3 H	2.90	1.89	1.65	1.12	0.96
Mean	1.67	1.24	1.07	0.71	0.64
RMS	0.44	0.38	0.32	0.24	0.23

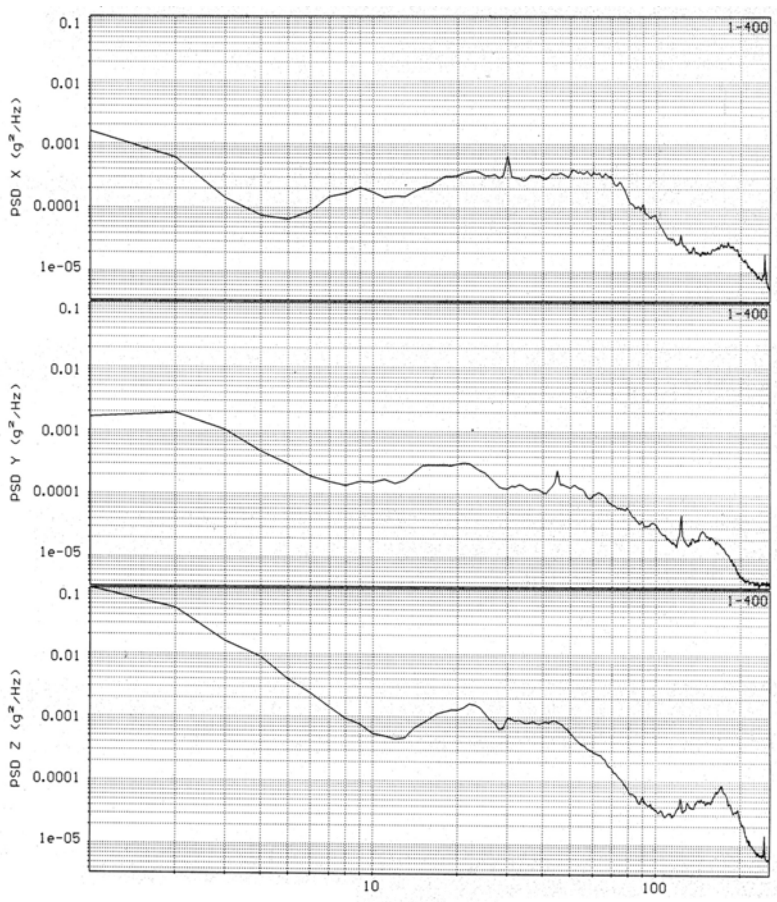

Figure 6. Power Spectral Density for Data Collected at the Coxswain's Station in a Head Sea

Power spectral density analysis of the acceleration data allows insight into the frequency content of the acceleration signal. Figure 6 illustrates the relative amplitude versus frequency relationship for data collected at the coxswain's station in a head sea. It is apparent that at lower frequencies in particular, where the most damaging effects of wave impact are experienced, vertical (Z) accelerations are considerably greater than either longitudinal (X) or transverse (Y). At about 1 Hz (wave impact frequency) vertical acceleration levels are on the order of 100 times greater than either longitudinal or transverse. It is also interesting to note that at 10 Hz, acceleration response, especially in the vertical direction has decreased to less than 1 percent of the value at 1 Hz.

Although not wholly applicable for the kinds of impacts experienced on high speed planing craft in a seaway, ISO 2631 provides a basis for comparing data relative to the effects of human exposure to whole-body vibration. First issued in 1985, ISO 2631 defines the limits of exposure within the frequency range 1 to 80 Hz to periodic vibrations and random vibrations with a distributed frequency spectrum. Provisionally, it may also be applied to continuous shock-type excitation within the same frequency range described above. To conform with the provisions of ISO 2631, acceleration amplitudes should be expressed as an RMS value and evaluated in one-third octave frequency bands.

Figure 7 provides an example of the way vibration data can be analyzed to evaluate its effect on human vibration exposure. The bucket shaped curves represent times of constant limiting exposure from 24 hours to just 1 minute. The RMS acceleration data has been analyzed in 1/3 octave bandwidths and overlaid on the graph. In this example, the data falls completely under the 2.5 hour curve, indicating that for this particular situation, vibration exposure should be limited to no more than 2.5 hours.

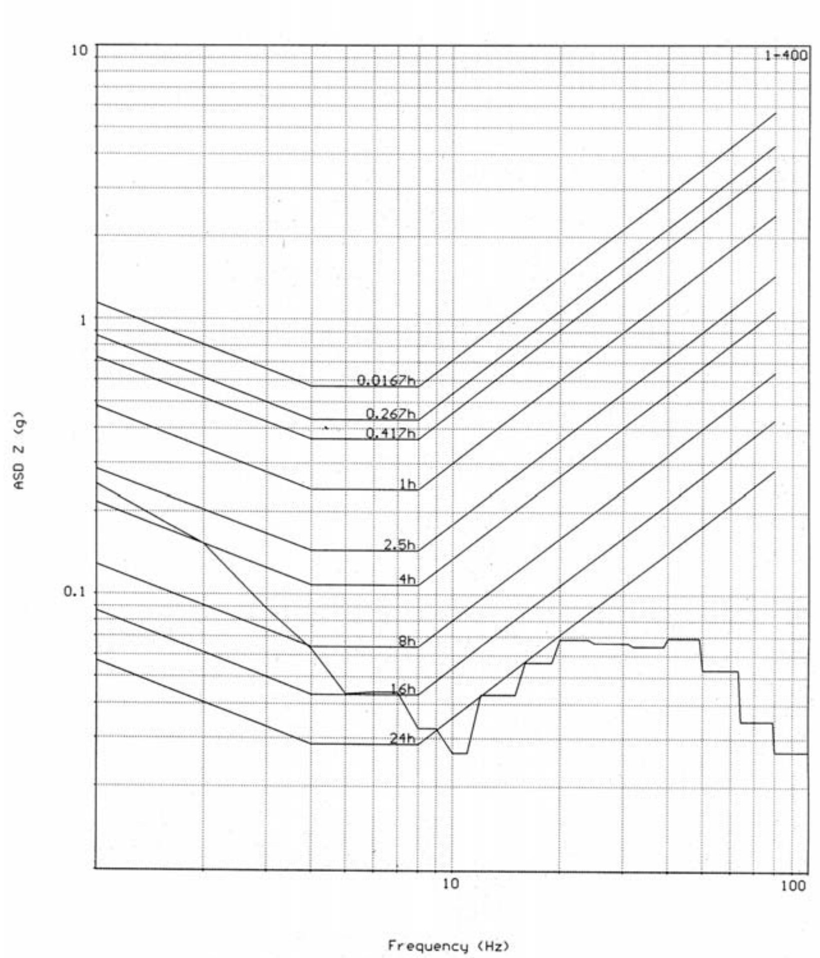

Figure 7. Example of Acceleration Spectral Density Results

Other Analysis Methods

In addition to the analysis methods already discussed, accelerations data can be analyzed to provide an understanding of seasickness tolerance within the frequency range 0.1 – 1.0 Hz. Data can also be low-pass filtered to remove high-frequency components to allow an analysis of the whole-body craft motions without the influence of vibration. Depending on the requirement, a need may exist to integrate the acceleration data to obtain velocity or displacement information, or to differentiate the acceleration data to obtain jerk.

CHALLENGES AND CONCLUDING REMARKS

As described in this paper, acceleration levels can be significant even for moderate craft speeds and seas. The data acquired during these tests was collected at an average speed of 35 knots in 3-foot seas. The MKV is routinely subjected to operations at faster speeds in considerably higher seas. These accelerations impose considerable strain on craft structure, equipment, and personnel. As new craft designs allow even higher speeds in more severe sea conditions, the demands on the craft and its occupants will quickly reach physical limits. The challenge for naval architects is to design craft that will meet operational requirements while at the same time minimizing the harmful effects of slamming loads on equipment and personnel.

A number of standards exist that define the requirements for structural adequacy and equipment, including those published by American Bureau of Shipping, American National Standards Institute, Det Norske Veritas, and others.

Commercial and military standards for vibration exposure and seasickness tolerance are also available including ISO 2631 and MIL-STD-1472. Unfortunately, a standard has yet to be established that defines the exposure criteria for slamming or impact loads imposed on personnel riding in high-speed planing craft. Although such a standard may be in the process of development, problems associated with complex postures, (that is, combinations of standing and seated) will make its development time consuming. Without standards against which to compare these acceleration results, it is difficult at best to qualify their effects on human occupants. ISO 2631 suggests that a single value of the frequency weighted overall RMS acceleration may be appropriate for evaluating vibration tolerance when compared against the 4 to 8 Hz criteria. Even still, the limits of the standard may not be appropriate for Naval Special Warfare personnel as they are generally well acclimated to craft motions produced during high speed transits in a seaway (and consequently have a higher tolerance for these extreme acceleration levels) and are in superior physical condition as compared with the general population for which the standard was developed.

The measurement, interpretation, and reporting of shock and vibration data on Naval Special Warfare craft is increasingly more important as these craft become faster and conduct missions in harsher environments. Because a single series of acceleration measurements cannot capture the variety of conditions under which a craft like the MKV is likely to operate, continued testing should be conducted on as many craft as become available. The more data collected on a particular craft class, the more likely that a better understanding of the cause and effect relationship between impact and damage to the craft, equipment, and personnel will result.