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Ride Quality Criteria and Assessment for Advanced Marine Vehicles

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RIDE QUALITY CRITERIA AND ASSESSMENT FOR ADVANCED MARINE VEHICLES

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Abstract

The purpose of this paper is to review some of the contemporary ride quality criteria which have evolved from laboratory experiments and from experience over a wide range of transport vehicles, with particular attention to those elements that are applicable to advanced marine vehicles. Techniques for ride quality assessments and comparisons among different advanced marine vehicle hull forms and methods of dynamic support are suggested. Practical applications of these techniques will be demonstrated in two examples. It should be noted that research on this subject is far from complete and that the criteria and assessment methods used here will be refined or revised over time as practical experience is attained.

Introduction and Definitions

In the context of this paper, ride quality is defined as the measure of the effects of vehicle motions on the safety, performance and comfort of human occupants. Ride quality is included in the class of characteristics of a seagoing vehicle entitled seakeeping which describes the relationship between a ship- and its operating environment.

The design and testing practices for conventional displacement ships are well developed and a few easily applied rules have been derived to assess ride quality and seakeeping. These rules have validity by the fact that the operating speeds and motion signatures of these vessels are usually quite similar. Thus the numerical quantities and ratios determined for one vessel may be directly compared to those from another vessel. However, with the introduction of so-called novel craft into military and commercial service, both the operating speeds and the ship motions characteristics have diverged from their traditional ranges. What is required then, is a more general method which can accommodate different motion waveforms and a wider range of frequencies.

In the present discussion we will be concerned with the effects of motion on the overall comfort, performance and safety of human occupants rather than with the detailed physiological mechanisms involved., Motion sickness is confined to the very low frequency regime and is the result of disturbances to the vestibular system. At higher frequencies the viscera seem to become the most sensitive to motion and then the muscles and skeleton come into play as they work to resist or adapt to the disturbance forces. Indeed, a given number of individuals may feel the effects of motions in as many different ways and may adapt at varying rates. Thus, there are many descriptions of the perceived response to the same motion profile.

Contemporary Limits and Criteria

In the following we will review some of the ride quality investigations and human response characteristics derived therefrom that would be applicable to advanced marine vehicles. A comprehensive overview of the subject has been given by Stark,[1]. Each of the many studies conducted and reported to date concentrated on only a few of the variables affecting human perception of motion. Major variables included the frequency spectrum, intensity and duration of test motions. Certainly, the position and posture of the subject influence the perception of motion. The type and amount of support provided by the structure on which the subject stands, sits or reclines alter the input to the body. The point at which the motion input to the body is measured affects the evaluation of experimental results. Test results were undoubtedly influenced by the design of the experiments as well as by the selection of the subject population and the instructions given to and the questions asked of the subjects.

The results of experimental investigations into human responses to motion have indicated that the most significant motions are linear accelerations, with the vertical direction being the most important, followed by lateral and then longitudinal. Although one might feel intuitively that angular motions would be a consideration, most studies relegated these to a secondary role based on early results. However this area is constantly being examined and as the ride quality database continues to increase and experimental apparatus and methods become more sophisticated, the relationship of angular motions will be better understood.

Despite the above caveats and qualifications that tend to cloud the picture, it is possible to extract some key elements that can be blended to achieve practical guidance for advanced marine vehicles. The following review is divided according to the applicable frequency ranges.

High Frequency

In the context of human response to motion, the high frequency range is that from approximately 1 Hertz (Hz) and up. In general, the physiological associations are visceral, spinal and then whole body as frequency increases.

The most often cited reference is International Standard IS0 2631 Guide for the Evaluation of Human Exposure to Whole Body Vibration', which is sponsored by the International Organization for Standardization. Despite its limitations, this document is remarkable in that it represents an international consensus in the interpretation and application of data available at the time and provides the foundation and guidance for subsequent investigations. The format of IS0 2631 covers human sensitivity to vertical and horizontal motions in terms of the root-mean squared (rms) values of acceleration in one-third octave bands as functions of the center frequencies of the bands. Three levels of severity are given as Exposure Limit, Fatigue Decreased Proficiency and Reduced Comfort Boundary and are generally applicable to seated and standing positions. The concept of frequency weighting for broadband accelerations was presented and the recommendation for its use was reinforced in Amendment 1. Amendment 1 also presented a method for evaluating multi-axis motions and provided a tentative recommendation to extend the curves down to 0.63 Hz at the same level as 1.0 Hz for some applications. On this latter point, the works of Miwa[3] and Shoenberger[4] indicate that the levels decrease with decreasing frequency in this range.

The salient points of IS0 2631 are illustrated in Figures 1 and 2 for the Fatigue Decreased Proficiency levels of vertical and horizontal accelerations, respectively, for durations of 1 minute and 1, 4 and 8 hours. These figures include the extensions from 1.0 to 0.63 Hz at constant levels per the tentative suggestion of Amendment 1. The Fatigue Decreased Proficiency levels are increased by a factor of 2 for Exposure Limits and decreased by a factor of 3.15 for the Reduced Comfort Boundary.

FIGURE 1 - VERTICAL ACCELERATION LIMITS

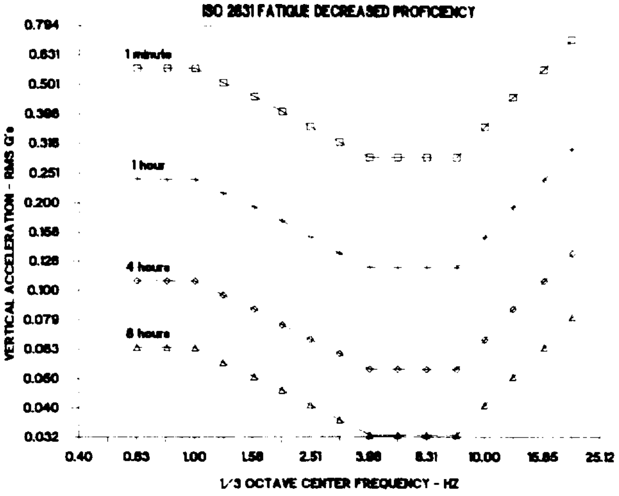
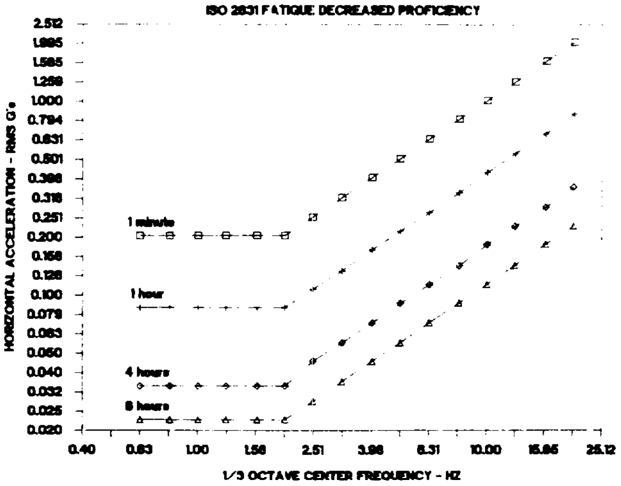


FIGURE 2-HORIZONTAL ACCELERATION LIMITS



MIL-STD-1472C Human Engineering Design Criteria for Military Systems, Equipment and Facilities[5] incorporates the basic vertical and horizontal acceleration limits of IS0 2631 without comments or qualifications regardiing applications.

The vertical and lateral weighting functions used for the Ride Comfort Index of MIL-F-9490D Flight Control Systems - Design, Installation and Test of Piloted Aircraft, General Specification For[6], also follow the shape of the curves of IS0 2631 above 1 Hz.

A slightly different method of ride quality classification which concentrates on passenger comfort in transportation systems has been developed at the NASA Langley Research Center[7]. In this approach, discomfort values are computed from an empirically derived model using frequency weighted accelerations in each linear and rotational. axis, either singly or in combination. 'This model, which is applicable to the frequency range of 1 to 30 Hz, also has provisions for including the effect of noise on ride comfort and includes a method for assessing the effects of exposure duration.

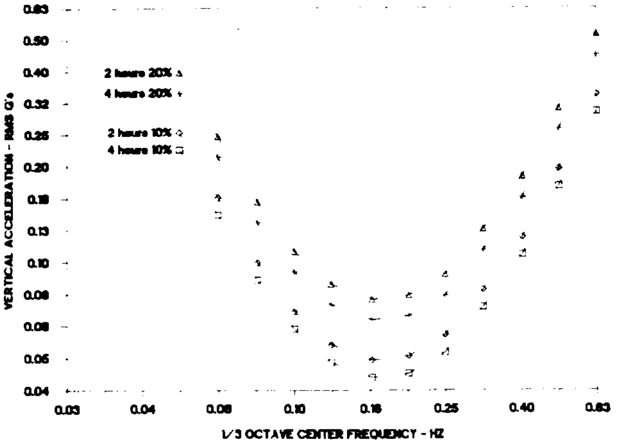
Low Frequency

The predominant effect of low frequency motion on humans is kinetosis, or motion sickness. Kinetosis has been described as a disease of information processing where the sensations from the vestibular system, or inner ear, and from visual cues are at odds with the spatial environment. Many ships seem to have natural resonant responses which fall within the frequency range of maximum human susceptibility to motion sickness. This has led to the suspicion on the part of some that seasickness is a phenomenon inflicted on the population by naval architects!

The work of O'Hanlon and McCauley' has provided the most comprehensive investigation of the motion sickness response characteristics for humans. Susceptibility appears to be associated primarily with vertical accelerations. Figure 3 summarizes the resulting description which includes the effect of exposure duration and quantifies the degree of sickness in per cent of subjects affected. As with ISO 2631, this description is given in terms of the rms value of vertical acceleration in one-third octave bands as a function of the center frequencies of the bands. Experience and subsequent studies, such as those discussed by Lawther and Griffin', have generally validated these results.

FIGURE 3 - MOTION SICKNESS INCIDENCE

FROM RESULTS OF O'HANLON AND MCCAULEY



MIL-STD-1472C incorporates the summary curves of O'Hanlon and McCauley for 10% motion sickness as functions of exposure time, again without comments or qualifications regarding applications.

Addendum 2 to ISO 2631 provides a recommendation for an extension of vertical acceleration criteria to the frequency range of 0.1 to 0.63 Hertz. The only degree of severity here is termed "severe discomfort or malaise" and the given limits roughly follow the lower limits of the O'Hanlon and McCauley curves for 10% sickness.

Current Activities

Happily, this field of endeavor is not static but continues to receive considerable attention. New investigations are being reported and refinements to existing thought are under consideration as illustrated by the following.

University of Southampton

Another variation in the process of establishing ride quality standards has been developed through investigations by Griffin at the Institute of Sound and Vibration Research of the University of Southampton[10]. This method advocates the concept of a Vibration Dose Value which addresses both acceleration intensity and exposure duration. For a given vibration dose value, a reduction in the weighted rms value of fifty per cent would increase the allowable exposure time by a factor of sixteen. Frequency weighting functions are given for vertical, horizontal and angular motions and for different points of input to the body. By basing the evaluations on root-mean-quad (nnq) computations, rather than on rms, this method reportedly provides a more accurate assessment for motions with higher crest factors and for impulsive accelerations.

ISO 2631 Revision

Experience with the current version of ISO 2631 has established the merits of the general approach, identified some of the shortcomings and limitations for practical applications and helped stimulate new research. Draft revisions to ISO 2631 have been circulating among committee members in the participating countries for some time. The publication of a revised standard is not expected for a few more years, but some clues as to its format and features are contained in an earlier paper by Allen[11]. The final version possibly could incorporate some of the concepts developed by Griffin, as mentioned above, and will contain weighting functions for additional axes of motion, for different postures and body supports and for different input points to the body. Recommendations for instrumentation, analysis and evaluation also may be included. More comprehensive guidance may be provided for the assessment of ride quality but fewer specific limits may be imposed.

Frequency Weighting

One feature common to all of the studies described above is the concept of frequency weighting for applications involving motions over a broad frequency range. This technique adjusts, or weights, the rms magnitude of the motion variable in each of several narrow frequency bands in inverse proportion to the human sensitivity. Then the weighted rms value over the entire frequency range of interest is computed and compared to the allowable. This is completely analogous to the standard method for acoustic measurements where the weighting functions such as those specified by ANSI S1.4-1971[12] for example, often are incorporated in the measuring equipment.

Most of the early ride quality research was performed with test subjects exposed to a series of single frequency or very narrow band motions, and in many cases the data were reported in terms of the rms values of the acceleration levels. The resulting tolerance boundaries had the appearance of continuous curves, whereas they actually represented the collection of the individual rms values for each discrete frequency band, usually one-third octave in width. In its initial version, ISO 2631 recommended that the effects of complex motions be evaluated in each one-third octave band independent of any other band. Later research with multiple frequency, or wide band motions, indicated that a more accurate assessment of the effects on test subjects was obtained if the rms value of acceleration in each one-third octave band were first weighted according to the relative sensitivity in that band as determined from the discrete frequency results. The total weighted rms value was then determined as the square root of the sum of the squares of the one-third octave weighted values. The contemporary approaches to ride quality evaluation presented above, including the current revision of IS0 2631, now recommend the frequency weighting method.

The general method for frequency weighting as discussed herein and as presented in IS0 2631 is as follows. A frequency weighting function for a given motion is obtained by computing the inverse of the response sensitivity curves such as those of Figures 1, 2 or 3. The results then are normalized to achieve a value of unity at a selected frequency by dividing by the inverse of the response sensitivity at that frequency. This process yields the normalized frequency weighting function. Weighted rms values are computed by multiplying the vehicle acceleration response rms value by the normalized weighting function value at each of the one-third octave center frequencies. The total weighted rms value over the frequency range of interest is the square root of the sum of the squares of the individual one-third octave weighted rms values . The total weighted rms value is then compared to the reference rms value of the response sensitivity curve at the frequency for which the weighting function was normalized.

Ride Quality Criteria for Advanced Marine Vehicles

It would be desirable to have available a few easily applied criteria to guide the development and evaluation of new vessels and to compare the ride qualities of existing vehicles of different types and speeds. These criteria should span the complete frequency range of interest and should be applicable to the different physiological-phenomena encountered over that range. Impulsive type motions and those with high crest factors should be covered. The effects of duration of exposure and the degrees of severity of the perceived motions should be addressed.

It is quite obvious from the preceding review that the development of universal criteria will not be easy nor will it be accomplished in a short time. However, with the information and methods available today, we can begin to develop the framework of an interim approach. By application of these quantitative methods each time an advanced marine vehicle is tested, an expanding data base can be compiled. If this accumulating data base is continually reviewed with subjective assessments correlated with the measured ride quality, adjustments can be made until a consistent set of criteria are achieved.

Since different physiological phenomena appear to be associated with human response to vibration in the high and low frequency ranges as defined above, a reasonable step would be to evaluate ride quality in each range separately.

Low Freuuencv

The relationships developed from the results of O'Hanlon and McCauley have been generally accepted as defining motion sickness incidence (MSI) as a function of frequency, vertical acceleration level and exposure time. Thus, it is recommended that the ride quality of advanced marine vehicles for vertical motions in the low frequency range up to 0.63 Hz be evaluated using these curves as the basis of the frequency weighting method. A frequency weighted rms value which produces a predicted MSI of 10% for a four hour exposure would seem to be a reasonable limit. Four hours corresponds to the traditional watch period for military vessels and could represent a typical trip duration for commercial travel. The frequency at which the weighting function is normalized is 0.2 Hz and the corresponding reference rms value for a four hour 10% MSI is 0.045 g.

High Frequency

The international contributions and agreements represented by IS0 2631 strongly recommend it as the starting point for evaluations of ride quality in the higher frequency range. Admittedly, the effects of exposure time contained therein are controversial and the definition of fatigue decreased proficiency (FDP) may be lacking precision. However, the levels defined by the FDP boundaries for four hour exposures to vertical and lateral motions represent a reasonable range between comfort and safety. Therefore it is recommended that the high frequency ride quality of advanced marine vehicles for vertical and horizontal motions be evaluated using the 4 hour FDP curves of IS0 2631, as extended to 0.63 Hz, as the basis for the frequency weighting method. The designation of FDP is retained for convenience in reference to these specific IS0 2631 curves. The weighting functions are normalized at 4.0 Hz and at 2.0 Hz for vertical and horizontal accelerations, respectively. The corresponding reference rms values for 4 hour durations are 0.054 g and 0.036 g for vertical and horizontal accelerations, respectively.

Composite

The above approach will result in two quantities for each vehicle examined. If, in comparing two or more vehicles, the motion signatures of some are predominantly in the low frequency region and for the others mostly in the high frequency range, there is still no method to evaluate the relative ride qualities. To close this gap and to supplement the separate high and low frequency evaluation methods with a composite method covering the total frequency range, the following approach is offered.

At least four versions of recommended limits for human exposure to vertical and horizontal accelerations over an extended frequency range for missions of four hour duration have been proposed in recent years. Each of these has drawn heavily on the source material which provided the foundations for the separate high and low frequency criteria discussed above. Three of these versions are contained in the previously cited references by Stark and MIL-F-9490D and in the paper by Skolnick[13] (for vertical acceleration only). The limits from MIL-F-9490D have been adjusted from 3 hours, as. given, to 4 hours per the method of IS0 2631. The fourth version was developed under the auspices of NATO by the David W. Taylor Naval Ship Research and Development Center in Study Guidance Document Annex I to AC/141(SWG/6)[14] specifically for application to Advanced Naval Vehicles and will be referred to herein as SWG/6. The 4 hour vertical and horizontal acceleration limits proposed by these four are shown in Figures 4 and 5, respectively. As can be noted from these figures, each version generally follows the shape and magnitude of the IS0 2631 FDP 4 hour exposure curves above 1 Hz and, in the low frequency region for vertical accelerations, tends to avoid the 4 hour 10%, or greater, MSI levels defined by O'Hanlon and McCauley .

FIGURE 4 - VERTICAL ACCELERATION LIMITS

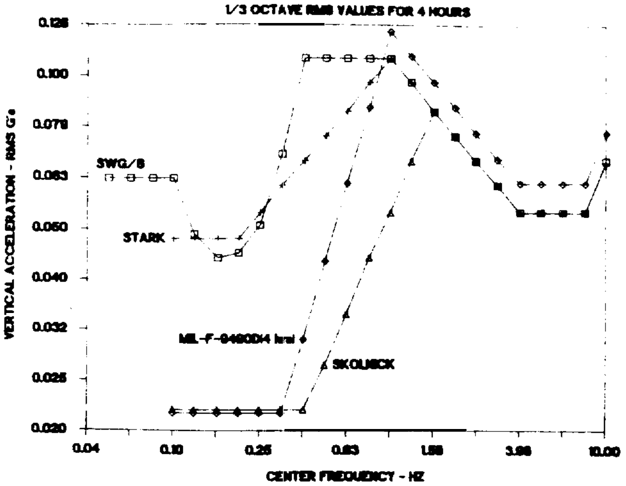
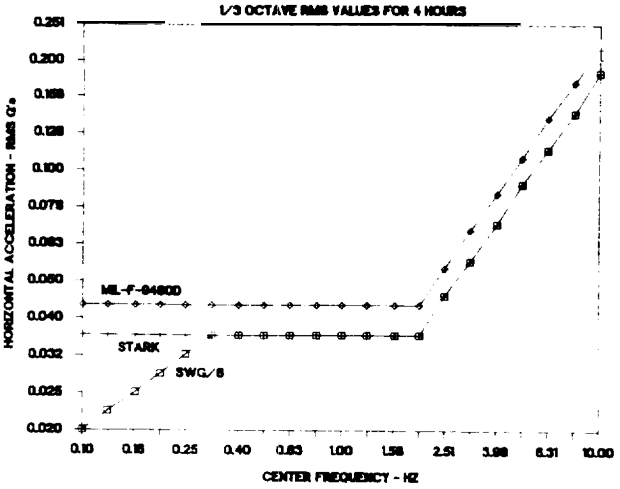


FIGURE 5—HORIZONTAL ACCELERATION LIMITS



It is suggested here that the limits proposed by SWG/6 for a 4 hour duration be chosen as the initial wideband curves for evaluating the overall ride quality of advanced marine vehicles with the frequency weighting method. These limits were determined from examinations of existing ride quality research as applied specifically to contemporary advanced marine vehicles and presumably represents the consensus of participating NATO nations. The frequency weighting functions for vertical and horizontal. accelerations are normalized at 4.0 Hz and 2.0 Hz,respectively and the reference rms values are 0.054 g and 0.036 g, respectively.

Criteria Summary

In summary, a complete-description of the ride quality of advanced marine vehicles as suggested in the foregoing discussions will consist of five parts as follows:

a. A description of the frequency content of the motions in each direction of interest by either a power spectral density plot or by a presentation of one-third octave rms values.

b. The frequency weighted rms value of vertical accelerations in the low frequency range 0.05 to 0.63 Hz using weighting functions based on the O'Hanlon and McCauley data for 10% MSI in four hours.

c. The frequency weighted rms values of motions in each direction in the high frequency range from 0.63 Hz to the highest frequency of interest using weighting functions based on ISO 2631 for four hour FDP.

d. The wide band frequency weighted rms value of motions in each direction using weighting functions based on SWG/6 for four hours.

e. The overall, unweighted rms value of the motion in each direction.

Examples of Assessment Methods

Two examples are offered below to demonstrate applications of the techniques of the preceding discussions. The first presents data gathered during underway trials of three different types of advanced marine vehicles operating in similar seaways, although in separate locations. The three chosen for this example are not necessarily competitive for the same mission. Two of the vehicles are dynamically supported and all three have active ride control systems. These vehicles are the SES 200, a 200 ton surface effect ship at a test speed of 20 knots: the FLYING PRINCESS, a 100 ton Boeing JETFOIL at a test speed of 38 knots and the HALCYON, a 60 ton SWATH vessel at a test speed of 18 knots.

FIGURE 6 - RIDE QUALITY IN SEA STATE 4

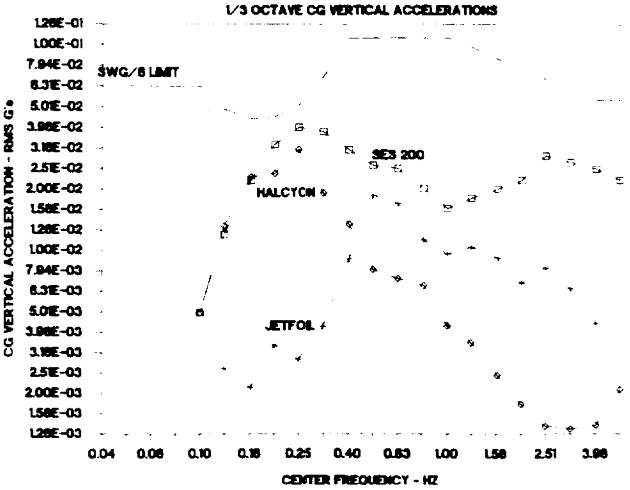


Figure 6 presents the one-third octave rms values for vertical accelerations at, the centers of gravity for the three vehicles and the SWG/6 four hour limit as functions of center frequency on log-log scales. Although these are discrete points representing the rms value over each band, as mentioned earlier, they are shown here connected by lines to better define the data for each vehicle. This presentation illustrates the differences in the vertical motion characteristics. **The SWATH vessel HALCYON tends** to follow the low frequency waves with some measure of attenuation in vertical amplitude while showing very little tendency to generate high frequency motions. The hydrofoil FLYING PRINCESS, travelling at a much higher speed,, generally platforms the waves which it encounters at a higher frequency as shown by the first peak. The dynamic characteristics associated with the active stabilization and ride control system create additional higher frequency responses. The surface effects ship SES 200 shows the basic wave following tendency of this type vessel as well as the higher frequency responses associated with the dynamics of the air handling and ride control systems.

The MSI, FDP and SWG/6 weighted rms values and the unweighted rms values for center of gravity vertical accelerations which quantify the observations from Figure 6 are given in Table 1. The MSI value for the HALCYON slightly exceeds the limit for a predicted motion sickness incidence of 10% in four hours, which also causes the overall SWG/6 value to exceed the four hour limit, while the FDP value is quite low. For the SES 200, both the MSI and FDP values exceed the four hour limits and consequently the overall SWG/6 value exceeds the four hour limit by a significant margin. It should be noted that, although in each case no single one-third octave value exceeds a limit, when these discrete rms values are considered together and appropriately weighted as they would be experienced simultaneously by a human occupant, the total value does exceed the limits.

Table I Comparative Ride Quality for Three Advanced Marine Vehicles in Sea State 4

	SES 200	HALCYON	JETFOIL	Criteria
Wave Height	6.3 ft	7.3 ft	6.5 ft	N/A
Speed	20 kts	18 kts	38 kts	N/A
MSI rms	0.061 g	0.047 g	0.009 g	0.045 g
MSI 4 hours	16%	11%	<1%	10%
FDP rms	0.056 g	0.007 g	0.018 g	0.054 g
SWG/6 rms	0.093 g	0.057 g	0.022 g	0.054 g
Total rms	0.108 g	0.055 g	0.037 g	N/A

The second example examines the predicted vertical motion ride quality of two simulated dynamically supported vehicles of generic designs. They are operating in the same seaway and at the same speed of approximately 40 knots in performing the same military mission. One vehicle is a 550 ton surface effects ship with an automatic ride control system which is assumed to reduce the vertical accelerations in a seaway to one half the uncontrolled levels. The other is a 250 ton fully submerged foil hydrofoil with a full time stabilization and ride control system representative of current technology.

Figure 7 presents the predicted power spectral densities (PSD) for center of gravity vertical acceleration responses in Sea State 4 in log-log scales. The corresponding rms values in one-third octave bands versus center frequency are shown in Figure 8 again in log-log form. As in the previous example these points are shown connected only as an aid in defining the data for each vehicle.

FIGURE 7 - POWER SPECTRAL DENSITY

VERTICAL ACCELERATIONS AT CG IN S/S 3

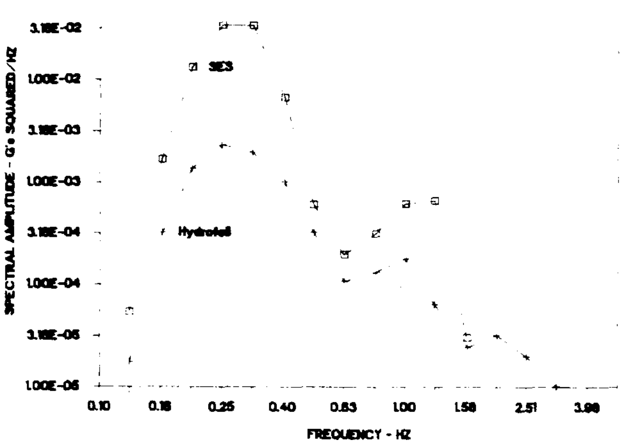
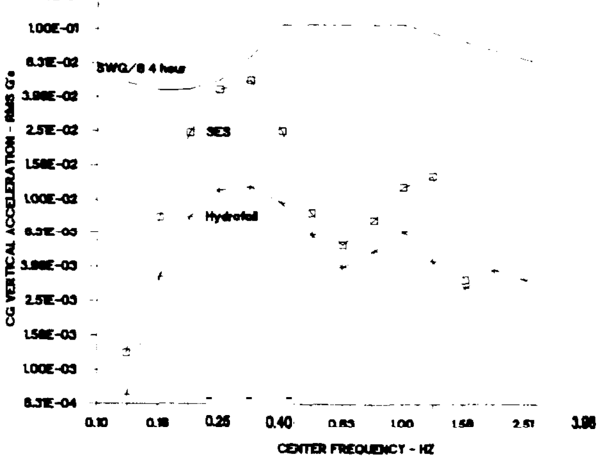


FIGURE 8 -ESTIMATED RDE QUALITY S/S 3

1/3 OCTAVE CG VERTICAL ACCELERATIONS



These figures illustrate the general dynamic characteristics of these types of vehicles. In the low frequency range each shows wave following tendencies by the peaks in the 0.2 to 0.4 Hz range with the hydrofoil acceleration values approximately one fourth those of the SES. The peaks at higher frequencies demonstrate the typical responses associated with the dynamics of the lift and ride control systems.

The vertical ride qualities are quantified by the suggested methods and tabulated in Table 2. It can be seen that the wave following characteristic of the SES.results in a predicted MSI which exceeds the 4 hour 10% limit, while the ride control system can maintain the cg vertical accelerations at the higher frequencies well below the FDP 4 hour limit. Again, as in the previous example, no individual one-third octave rms value for the SES exceeds the limiting boundary but the total weighted rms value predicts levels which exceed both the MSI and SWG/6 limits.

Table 2 Comparative Ride Quality for SES and Hydrofoil in Sea State 3

	SES 550T	Hydrofoil 250T	Criteria
Wave Height	4 ft	4 ft	N/A
Speed	40 kts	40 kts	N/A
MSI rms	0.05: g	0.016 g	0.045 g
MSI 4 hours	15%	<2%	10%
FDP rms	0.011 g	0.007 g	0.054 g
SWG/6 rms	0.071 g	0.021 g	0.054 g
Total rms	0.090 g	0.025 g	N/A

If the vehicles under consideration experience significant pitching motions, then the vertical accelerations at remote locations can be 'considerably greater than at the cg . The analysis of these examples should be repeated for each manned station in the vehicles to assess the overall ride quality.

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