AN APPROACH TO HIGH SPEED SHIP
RIDE QUALITY SIMULATION

W. L. Malone and J. M. Vickery*

Naval Sea Systems Command (PMS304)

SUMMARY

The high speeds attained by certain advanced surface ships result in a spectrum of motion which is higher in frequency than that of conventional ships. This fact along with the inclusion of advanced ride control features in the design of these ships has resulted in an increased awareness of the need for ride criteria. Such criteria can be developed using data from actual ship operations in varied sea states or from clinical laboratory experiments. A third approach is to simulate ship conditions using measured or calculated ship motion data.

Recent simulations have used data derived from a math model of Surface Effect Ship (SES) motion. The model in turn is based on equations of motion which have been refined with data from scale models and SES of up to 101 600-kg (100-ton) displacement.

Employment of broad band motion emphasizes the use of the simulators as a design tool to evaluate a given ship configuration in several operational situations and also serves to provide data as to the overall effect of a given motion on crew performance and physiological status. It additionally averts to a degree the more clinical problem of predicting reaction data from single frequency experiments. The long term exposure (currently up to 48 hours per simulation) was chosen to evaluate any cumulative effects of fatigue or stress that might be induced by the motion.

The particular motion simulated to date is especially interesting because its spectrum of 0.1 to 5 Hz covers both the classical motion sickness region and the mechanical interference region. The tendency of the low frequency motion to induce kinetosis and the transient nature of kinetosis leads to special problems in experimental design and to the interpretation of data as required for fine tuning of ride control.

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*Royal Navy

INTRODUCTION

Ship Motion, or ride quality, is the result of excitation of ships' response characteristics by energy contained in the wave train through which the ship passes. The major factors influencing ride quality in any given hull form are:

(a) Wave height and period

(b) Distribution of energy within an encountered sea condition

(c) Relative speed between the ship and the sea surface

(d) The ships response characteristics in all six degrees-of-freedom

These elements interact to alter the magnitude and frequency of the ship motion and as a consequence to effect personnel aboard the ship. The "effects" either manifest themselves as discomfort (in severe cases leading to extreme nausea and vomitting) or performance degradation (or both). Compared to other external factors affecting human behavior such as noise, temperature, and vibration, minimal quantative data is available on ship motion either in respect to acceptable levels or sensitive frequencies. Discomfort has been accepted, at least militarily, as part of the cost of operation at sea while little or no account has been taken of crew performance degradation (other than in extreme conditions).

Thus, with the advent of new ship forms, there is little or no basis upon which to judge possible crew problems arising from the ship motion environment - not even from that part of the predicted motion spectra which is similar to conventional hulled ships, let alone from that part of the spectra which is new.

Various means of achieving the desired knowledge are available. The approach taken to assessing the motion predicted for the SES has been to simulate the ride environment with observation and measurement of the effects on volunteer subjects. However, before proceeding with the selection of a suitable simulator, it is necessary to understand something of the characteristics of the motion environment to be reproduced.

THE FORCING FUNCTION

The distribution of wave amplitude as a function of frequency for a fully wind developed sea is described by the Pierson-Moskowitz distribution (ref. 1), $S(\omega)$, in terms of dimensionless empirical constants, α and β, the gravitational constant g, the wind velocity u, and the angular frequency of the wave, ω, as

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\beta\left(\frac{\omega_u}{\omega}\right)^4\right]$$

where $\alpha = 0.0081$
$\beta = 0.74$
$\omega_u = g/u$

According to this distribution, the energy peak of the sea occurs at a frequency depending only on the wind velocity:

$$\omega_p = \frac{g}{u}\left(\frac{4}{5}\beta\right)^{\frac{1}{4}}$$

Since a ship traveling across the surface of the sea experiences a wave encounter frequency, ω_e, which is related to the actual wave frequency, ω, ship velocity, V, and ship heading angle with respect to the wave velocity vector, χ, by

$$\omega_e = \omega - \omega^2\frac{V}{g}\cos\chi$$

it follows that the ship will be driven by a forcing function with apparent spectral distribution:

$$S(\omega_e) = S(\omega)\frac{\partial\omega}{\partial\omega_e}$$

$$= \frac{S(\omega)}{[1 - \frac{2\omega V}{g}\cos\chi]}$$

and energy peak whose frequency varies with sea state and ship speed as indicated in figure 1.

The significance of this fact is that ships traveling at speeds in the range of 20 knots routinely experience this peak in the energy spectrum at encounter frequencies of the order of 0.16 Hz to 0.6 Hz while high speed ships currently under design and potentially capable of speeds on the order of 100 knots can be expected to experience these energy peaks at encounter

frequencies as great as 1.9 Hz. These ships, of which the SES is an example, will thus operate in a motion region which falls well above that of conventional ships and for which neither extensive practical or laboratory experience exists.

THE SURFACE EFFECT SHIP

The SES itself is unique. Its general features are depicted in figure 2. An SES travels across the surface of the water supported by a cushion of air. The air is contained on two sides by the ship's rigid side walls and at the bow and stern by the ship's flexible bow and stern seals. Air escapes around these surfaces and through controlled openings in the form of valves or louvers in the deck or sidewalls of the ship.

Forces on both the seals and sidewalls affect the quality of the SES ride, but the predominant force and nature of the ride results from the confined air cushion. The nature of the cushion is in turn determined by the system of fans which supply pressure to the plenum, the variable deck openings which vent air from the plenum, and the surface of the sea whose rough contour results in a pumping action as the SES traverses its surface.

The general nature of the SES has been modeled extensively (for example, see ref. 2 and ref. 3.) The modeling starts by developing the basic physics of the individual forces alluded to above and by then coupling them into a central mathematical equation of motion. The equation is then driven by an irregular wave forcing function and the resulting time varying 6-degree-of-freedom (DOF) motion of the ship is used to study the ship characteristics.

The previously described Pierson-Moskowitz distribution has been used to describe the irregular wave driving function in all of our simulations to date. (Any forcing function can be used to drive the equation. The Pierson-Moskowitz distribution has been used because it is considered a good general representation of a fully developed sea.) The continuous distribution is approximated with a discrete series by dividing the wave spectrum into logarithmic intervals such that:

$$\ln \omega_i - \ln \omega_{i-1} = \frac{1}{N} (\ln \omega_N - \ln \omega_o)$$

where

N = total number of frequency intervals.

According to this approximation, the time varying wave amplitude y(t) can be represented as an 8-element trigonometric series:

$$y(t) = \sum_{i=1}^{8} A_i \cos \overline{\omega}_{ei} t$$

$$\overline{\omega_i}^2 \equiv \omega_i \omega_{i-1}$$

where the encounter frequency, $\overline{\omega}_{ei}$, explicitly takes into account the shift in the apparent wave energy spectrum $S(\overline{\omega}_{ei})$ due to ship speed. The coefficients A_i define the peak amplitude at frequency elements ω_i and are determined from:

$$A_i^2 \simeq 2S(\overline{\omega}_i) \, [\omega_i - \omega_{i-1}]$$

THE RESULTANT MOTIONS

When this discrete representation of $S(\omega_e)$ is utilized in the equation of motion and the time varying solution of the 6-DOF motion is analyzed in the frequency plane, the one-third octave heave acceleration spectra depicted in figure 3 results. These spectra represent the motion at the center of gravity of an early conceptual SES model (configuration A) traveling in a bow sea in various speed and sea state conditions. It is evident that the lower speed and higher sea state conditions produce a shift in the peak motion to lower frequencies and greater peak accelerations with the predominant energy of the motion falling in a spectral region which is midway between that of conventional ships and conventional surface vehicles. Figure 4 (data courtesy of Bell Aerospace Co.) indicates the predicted motions at the center of gravity of a more recent design. Note that this ship is predicted to have a better ride quality in terms of total acceleration and that the acceleration spectra undergo a major redistribution as a result of the use of a Ride Control System (RCS). (The term Ride Control System refers to those general features of the SES that are used to control the ride quality. They may be either active or passive in nature and are exemplified by the valves and louvers mentioned previously.)

The statistics of the motions are summarized in table 1. The expected frequency, f_e, the predicted number of maxima per unit time, N_1, and the spectral broadness factor, ε, are computed from the power spectral density for acceleration, $\phi(f)$, the one-third octave acceleration amplitude $A_j(1/3)$ and one-third octave center frequency f_{cj} by

$$m_k = \int_0^\infty \phi(f) f^k df \approx \sum_{i=1}^{N} A_j^2 (\tfrac{1}{3}) f_{cj}$$

$$f_e = (m_2/m_o)^{\frac{1}{2}}$$

$$N_1 = (m_4/m_2)^{\frac{1}{2}}$$

$$\varepsilon = [1-(f_e/N_1)^2]^{\frac{1}{2}}$$

Note the broad band nature of the motion as made evident by the relatively large value of ε. The heave motion of the SES when excited by a sea with Pierson-Moskowitz distribution is also predicted to have a reasonably Gaussian amplitude distribution despite the high degree of non-linearity present in the equations of motions. (See fig. 5.)

A further feature of the motion is indicated in Table 2 which compares the Root Mean Square (RMS) acceleration in heave surge, and sway for configuration A traveling in a bow sea. As is the case for most other operating conditions, the vertical acceleration (the combination of heave and pitch motion at the point undergoing motion) greatly exceeds the other motion components. This is a result of two conditions: (1) the sidewalls and seals of the SES have a minimal immersion and consequently very small side forces are generated in surge and sway; (2) as the SES begins to pitch or roll extensively the sidewalls or seals begin to vent air and are quickly restored to the water surfaces.

MOTION SIMULATION

The initial objective of developing a motion simulation program was to test for the presence of any gross physiological or performance changes attributable to exposure to the "new" high speed ship environment. At the planning stage, certain minimum requirements were identified and certain constraints were recognized which are worth some discussion before proceeding to a description of the simulations run to date. Included are

(a) The Simulator

(b) The Subjects

(c) The Experimental Design

(d) The Task Battery

The Simulator. The first requirement of the simulator (or Motion Generator) was that it should faithfully reproduce either real world or predicted motion in as many degrees of freedom as possible. This was by no means a simple requirement to meet. The absence of data on the comparative importance of subsets of motion within the total bandwidth and the significance of cross coupling effects between the various axes suggested a machine having a broad bandwidth and flat response characteristic in all six degrees of freedom, but no such machine existed. A compromise was, therefore, immediately necessary. Since initial concern was with high speed operation, a relatively small displacement (in heave) 6-DOF machine with good high frequency (0.1 to 10 Hz) characteristics was chosen and is described in more detail later. As it became evident that slower speed higher sea states posed problems similar to those experienced in conventional ships, the need for a "rough water" simulator (larger displacement, lower bandwidth) was also identified. Such a machine is also described in more detail later.

Whatever the specific physical limitations of any particular machine, it was rapidly evident that the ability to faithfully reproduce the commanded input was essential when dealing with broad band multi-axis motions. A subtle reason for placing emphasis on high fidelity is that it soon became evident that human response appeared to be very sensitive to certain characteristics (e.g. wave crests and troughs) and any tendency to "wash out" such characteristics rapidly removed realism from the simulation. In the same vein, it is of interest to know whether the motion character can be described simply in RMS terms or whether some weight needs to be given to the ratio of peaks to average values, etc. Interpretation is discussed in more detail in a later section and is mentioned here simply to underline the requirement for a "quality" simulation.

The simulator was also required to support a load representing a ship compartment which ideally would include at least two crewmen, a variety of tasks and life support facilities.

Since human volunteers were to be used, considerable emphasis was placed on safety features of the chosen machine(s) although time and space do not permit further discussion here.

The Subjects. The use of human volunteers for work of the proposed nature is strictly controlled to ensure the safety of the individual whether or not he appreciates the potential hazards of the position to which he is exposed. The protocol includes rigorous medical screening prior to acceptance as a volunteer, pre and post exposure medical examination, medical observation whenever in motion, and complete freedom to leave the simulation at any time without cause or explanation.

Subjects to be "scientifically" acceptable should be either carefully selected average people or part of a sufficiently large sample size to represent the population at large. Again, compromise has been necessary and the various simulations have used some 35 subjects at one time or another ranging from naive to experienced seamen.

Motivation is a major consideration. Motion sickness if experienced is not a minor event. The freedom to leave the simulation at any time makes it extremely difficult to ensure that volunteers "live through" the experience as they would in the real world. Significant emphasis is therefore placed on maintaining crew morale by (among others) having a two man crew, providing a busy, realistic work schedule and scenario, allowing considerable choice of food and drink, and maintaining an informal relationship between subjects and test administrators.

Subjects are constrained not to drink alcoholic beverages during time out of the simulator, to maintain a defined sleep cycle and to avoid any pastime which may interfere with their ability to maintain a positive attitude to the simulation.

The constraints imposed by confinement, the latent fear of vomitting, and the artificial nature of the motion generator's mechanical driving system are frequently commented upon by volunteers and are judged to produce the most difficulty in maintaining a smooth and orderly simulation series.

The Experimental Design. SES motion simulations to date can best be summarized as "exploratory" rather than "experimental". As stated earlier, the initial objective has been to assess the effects of SES motions in a gross manner related to physiological and performance changes. More recently an attempt has been made to establish ride quality criteria at least to a level of confidence which assures that a ship having a RMS acceleration less than some given value will have no major problems resulting from ship motions.

The simulation of high speed ship motion as currently undertaken is highly complex. It uses broad band, quasi-random motion, human volunteers, a battery of real world related and scientific tasks all of which come together within the limits of a 2.4 m by 2.4 m (8 ft by 8 ft) cabin. Refinements continue to evolve at every stage to improve the acceptability of data collected but it should be understood that the current program involves many variables and constraints which are difficult to filter out with total confidence. Simulations are planned ahead of their actual execution; therefore, they have certain fixed aspects: duration, conditions to be tested, measurements and observations to be made, etc. The arrangement attempts to follow a balanced design of motion and control conditions; however, while the most recent series has a set of protocols governing contingencies for various deviations from the test plan, structure is still fairly loose and provides for opportunities to explore targets of opportunity. The overall plan calls for exploration of extended periods of exposure (currently out to 48 hr continuous in one condition) and for comparison of effects in a variety of sea state/speed conditions. (Simulated conditions are chosen to bound the speed and sea state parameters set for a 2000-ton SES.) Therefore, when control conditions are added, the simulation program becomes extensive and difficulty in maintaining crew motivation and morale can become significant due to their confinement in "unreal" surroundings and the repetitiveness of the daily routine.

The Task Battery. At the outset the primary objective of including crew tasks was to provide meaningful employment for the volunteer crews. Tasks were scored or commented on by crewmen as to their realism and difficulties encountered in their execution. Crewmen also completed questionnaires on such matters as the degree to which they were affected by the motion both personally and in their ability to carry out specified tasks.

As the program developed, a more sophisticated array of tasks and tests was produced. While always trying to maintain the cooperation and understanding of the volunteers by ensuring that tasks or tests do not become too esoteric, the battery (see table 3 for full details) currently includes measurement of sleep performance and measurement of head movement by means of a special mouth mounted 6-DOF accelerometer package (originally developed by the Naval Aerospace Medical Research Laboratory, Detachment, New Orleans) as well as the more real world (and popular) navigation plotting, and missile directing (XY tracking) tasks. Volunteers still complete questionnaires and considerable emphasis is placed on briefing, debriefing, and interaction between volunteer crews and the directing staff. Much valuable insight has been gained by observation - e.g., variation of head movement with motion states with and without headgear - and by subjective discussions with volunteer crews - e.g., techniques learned for accommodating mechanical interference, etc.

The lack of totally controlled conditions using a minimum number of variables presents difficulties when attempting to achieve maximum knowledge from task data; however, tasks and their scores have generally served the program well. Remarkable consistency has been seen in some scores; strong trends in others. Gross questions are being answered: crews can sleep, can perform life support functions, do experience kinetosis in some conditions and not in others, do have more difficulty performing fine motor tasks and so on.

NASA MARSHALL SPACE FLIGHT CENTER (MSFC) SIMULATION

As is evident from the preceding discussion, the predominant interest at the onset of the program was centered on the high speeds predicted for the SES and the corresponding high frequency motion as compared to that of conventional ships; accordingly, the motion generator at MSFC was selected for the first simulation of the 6-DOF motion of the SES. This work was performed in the fall of 1973 and has been described briefly in reference 4 and more extensively in reference 5. The MSFC motion generator is an early version of the "large-stroke" simulators used for flight training for large jet aircraft. The facility includes a closed circuit television system for simulation of external terrain viewing and, as configured for our test, the four-place cabin depicted in figure 6 (adapted from ref. 4).

The purposes of this initial simulation were fourfold: (1) to test for the presence of any gross physiological effect such as extreme fatigue or stress that might be correlated to the motion, (2) to test for the

presence and nature of any gross performance decrement, (3) to assure
that a simulation of SES ride quality could be provided which was subjectively
similar to that of an actual SES, and (4) to determine the relative importance
of the SES motion associated with a given DOF.

The first two objectives were realized by means of general medical
examinations before and after each motion exposure and by a battery of
tasks administered during the exposure. The third objective was achieved
by exposing the subjects to motions reproduced from recorded operations
of the SES-100B and obtaining their opinion of the ride quality. (The
SES-100B is one of two 101 600-kg (100-ton) SES test craft.) The final
objective was achieved by exposing the subjects to the 6-DOF motion pre-
dicted for the 2000-ton SES and selectively deactivating one or more DOF.
As indicated in the description of SES motion, the magnitude of the heave
acceleration significantly exceeds that of the other DOF. As a result of
this fact and on the basis of the MSFC results it has been deemed suffi-
ciently realistic to restrict future tests to 3 DOF, at least until our
knowledge of motion effects has increased considerably.

As it turns out, the fact that a 3-DOF simulation satisfies primary
requirements is fortunate since the MSFC motion generator introduced an
artifact into the high sea state simulations. The originally predicted
capability of the motion generator operating with a cabin of approximately
the same mass as used in our simulations is indicated in figure 7. The
motion generator was limited at low frequency by the stroke of the simulator
and at high frequency by the load capacity. In the intermediate region,
the capability was expected to be limited by the flow rate of the motion
generator's hydraulic system. This would have resulted in a "soft" limiting
occuring for any motion approaching 0.61 m/sec (2 ft/sec).

In fact, one of the system's safety features actuated a pressure surge
valve at any cabin velocity approaching 0.61 m/sec (2 ft/sec), resulting in
an impulse exceeding 1g amplitude and 0.10 second duration. In order to
avoid these impulses it was necessary to limit the motion more greatly
than had originally been intended. Because of these limitations, and based
on motion criteria available at that time, it was judged that no motion
effects were to be expected for the longest periods of motion exposure
used in the simulations (4 hours) and indeed no major effects were noted.
Accordingly, plans were initiated to carry out future simulations on the
Office of Naval Research (ONR) motion generator at Goleta, California.

THE ONR MOTION GENERATOR

The ONR motion generator has three DOF (heave, pitch, and roll). The
1358 to 1814 kg (3000 to 4000 lb) cabin is driven along the heave axis by an
8.9-cm (3.5-in.) diameter ram piston and in pitch and roll by two independent
piston systems (ref. 6) mounted on the base of the cabin. (See fig. 8.) The
general servo system (since modified) is indicated in figure 9 (drawing

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courtesy of Systems Technology Incorporated). Pressure to drive the ram was developed by a constant displacement, pressure-compensated hydraulic pump operating against a servo valve controlled variable restriction in the drain. The hydraulic servo valve was in turn controlled by a pneumatic transducer. Upward motion was produced by the servo valve closure and the corresponding increase in ram fluid pressure. Downward motion was generated by the cabin's own weight, the rate of fall being controlled by the servo valve and ultimately by back pressure in the drain line.

The pitch and roll servos were identical. They consisted of a constant pressure, variable volume pump providing 190 liters/min (5 gal/min) flow at 11 MPa (1600 psi) pressure. The pump drove a double acting Hana hydraulic cylinder which was in turn controlled by a Moog servo valve. Individual chain driven potentiometers provided the analog voltages corresponding to the respective displacements of the 3 DOF.

The original version of the motion generator suffered from several deficiencies with respect to our desired simulation. The output response was linear only to approximately 0.35g and demands for more acceleration resulted in greater lag through the system and an ever-increasing disparity between the phase of the heave motion and the phases of the pitch and roll motion. Structural resonances were present in both the pitch and roll axes resulting in cross-coupling between the heave motion and the pitch and roll motions. The heave motion excited these resonances at about 2.2 to 2.6 Hz depending on the weight of the cabin (ref. 7). Finally, a stiction-like motion was present which resulted in a deadband or region of insensitivity to drive commands whenever the heave motion crossed through zero velocity. The minimum sinusoidal command to which the heave servo would respond once the system had come to rest was approximately ±0.06g.

The motion generator has since been upgraded in two series of modifications. The first series of modifications occurred prior to the first two rounds of testing at Goleta (Phases I and IA), and consisted of the addition of phase compensations to match the pitch and roll servo control response to the heave response and the addition of a further compensation network to flatten the heave servo response.

Prior to the initial modification (ref. 6), the transfer function (ratio of angular rate command to angular rate realized) for pitch and roll could be approximated by

$$H_{po}(S) \simeq [(1+\tau_{p1}S)(1+\frac{2\zeta_p S}{\omega_p} + \frac{S^2}{\omega_p^2})2]-1$$

$$\simeq [1+\tau_{p1}S]^{-1} \text{ for } \omega < \omega_p$$

where $\tau_{p1} = 0.49$ seconds

$$\zeta_p = 0.35$$

$$\omega_p = 15.7 \text{ radian second}^{-1}$$

and the heave transfer function (ratio of acceleration commanded to acceleration realized) by

$$H_{Ho}(S) \simeq [(1+\frac{2\zeta_H S}{\omega_H} + \frac{S^2}{\omega_H^2})(1+\tau_1 S)(1+\tau_3 S)]^{-1}$$

$$\simeq e^{-\tau S}(1+\frac{2\zeta_H S}{\omega_H} + \frac{S^2}{\omega_H^2})^{-1} \text{ for } \omega < \tau_1^{-1}$$

where $\zeta_H = 0.707$

$$\omega_H = 2.5 \text{ radian second}^{-1}$$

$$\tau_1 = 0.08 \text{ second}$$

$$\tau_3 = 0.06 \text{ second}$$

$$\tau = 0.14 \text{ second}$$

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After addition of the compensator networks, the pitch transfer function became

$$H_p(S) \simeq \left[(1+\tau_{cp}S)\left(1+2\zeta_pS + \frac{S^2}{\omega_p}\right)\left(\frac{}{\omega_p^2}\right)\left(1+2\zeta_cS + \frac{S^2}{\omega_c^2}\right)\left(\frac{}{\omega_c^2}\right) \right]^{-1}$$

where $S_c = 0.707$

$\omega_c = 12.6$ radian second^{-1}

$\tau_{cp} = 3.2$ second

and the heave transfer function became

$$H_H(S) \simeq \left[\left(1+\frac{2\zeta_oS}{\omega_o} + \frac{S^2}{\omega_o^2}\right)(1+\tau_3S)(1+\tau_{cH}S) \right]^{-1}$$

where $\zeta_o = 0.707$

$\omega_o = 0.31$ radian-second^{-1}

$\tau_{cH} = 0.019$ second

The second series of modifications occurred following the Phase I and IA simulations. The pitch and roll servos were modified by the addition of non-linear feedback networks to suppress the effects of structural resonances in pitch and roll. The compensation networks were also modified by changing the break point of the second order filter from 2 to 4 Hz. The heave servo was modified extensively. The capacity of the main hydraulic reservoir was increased from 1041 to 3785 liters (275 to 1000 gal), the flow capacity from 1041 to 2271 liters/min (275 to 600 gal/min), the hydraulic pressure capability from 4.5 to 6.9 MPa (650 to 1000 psi), and the capacity of the heave drive pump from 56 to 149 kW (75 to 200 hp) by substitution of two pumps operating in parallel. The electropneumatic command transducer was replaced by a hydraulic controller and the servo control was modified to include both a pressure and position feedback as indicated schematically in figure 10.

These changes have resulted in a significant increase in the performance capability of the system as indicated in figures 11 and 12 and further summarized in table 4. The non-linear feedback network has reduced cross-coupling to a rather negligible value and the system coherence* has been improved from about 0.6 to 0.98 (the latter value corresponds to 2 percent harmonic distortion). Finally, the deadband has been decreased from ±0.06 to ±0.04g.

The primary results of the artifacts present in the pre-modification motion were to limit the magnitude of acceleration peaks to 0.6 instead of 1.0g and to introduce an unwanted high frequency component into the motion. These effects manifested themselves as a modification to the commanded amplitude distribution as indicated in figure 13. These effects are further indicated in figure 14 which compares the acceleration spectra for the output and commanded motions corresponding for the simulated 80 knot/sea state 3 running condition.

GOLETA SIMULATIONS

Despite the limitations inherent in the pre-modification simulator, it was possible to obtain certain tests on the partially upgraded simulator; accordingly, two rounds of testing (ref. 8) were initiated in August 1974 (Phase I) and October (Phase IA). The cabin used in these tests and the general layout of the test battery are indicated in figure 15. Testing was continued in a manner analogous to the MSFC tests.

During the August 1974, series four volunteer crewmen were used in two crew pairs. Each crew pair was subjected to an identical series of exposures, commencing with 30 minutes in each of three conditions (0.154, 0.238, 0.25g RM: across a frequency band of approximately 0.1 to 2 Hz.) The series culminated one 4 hour ensemble of the above conditions and one 3.5 hour continuous exposure to 0.25g RMS. While three out of four subjects suffered from motion sickness when first exposed to 0.25g only one did so during the 3.5 hour exposure. This fact together with other generally encouraging results led to a decision to expand the series to 48 hr exposure periods to be run during October 1974.

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*The system coherence, ρ^2, is defined for each DOF in terms of mean square power associated with that DOF and the degree of correlation between the commanded motion and the resultant motion as

$$\rho^2 = \frac{\text{total power} - \text{uncorrelated component}}{\text{total power}}$$

Once again, 4 subjects were used and both crew pairs commenced with 48 hr at 0.154g RMS. For their second period of exposure, the first crew received 0.12g RMS (approximately 50% of the 0.25 case used in August) while the second received 0.18g RMS. The results of these tasks are still under evaluation but are expected to be issued shortly in a consolidated report from the various participating members of the simulation team.*
The results that have been reduced were encouraging. However, confirmation of the trends indicated is required and, therefore, another round of testing (Phase II) commenced on 7 July 1975 using the fully modified simulator. The testing pattern will be basically the same as in Phase I and IA with the inclusion of a few new tasks and slight variations on some of the previous ones.

ON THE APPLICATION OF RIDE CRITERIA TO BROAD BAND MOTION

Although the immediate concern of this project is to gain first hand experience with predicted SES motion, it is highly desirable that a procedure be established for treating broad band motion in a general way. As a first step in achieving this goal, it is necessary to develop a method for establishing the equivalency of motion conditions with equal RMS value but different amplitude distributions. Jex and Allen (ref. 10) have indicated some of the problems involved in establishing this equivalency.

The importance of this issue centers on the effects of intermittent large amplitude accelerations and the degree of interaction or cross-coupling between motion effects resulting from different regions of the motion spectrum. As an example, one might evaluate the effects of the motion depicted in figure 4 against a particular motion criteria by considering the RMS spectra in any one-third octave spectral band and comparing it to the motion criteria for each corresponding one-third octave band. The motion could be judged acceptable or not depending on whether the motion of any given band exceeded the motion criteria for that band. This amounts to neglecting any interaction between the effects associated with other bands.

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*Members of the motion simulation team include personnel from
  PMS304 - Surface Effect Ship Project
  NAMRLD - Naval Aerospace Medical Research Laboratory Detachment
  SESTF - Surface Effect Ship Test Facility
  NASA - Science and Engineering Division (MSFC simulation only)
  NSRDC - Naval Research and Development Center
  ONR - Office of Naval Research (Goleta simulations only)
  STI - Systems Technology Incorporated
  HFR - Human Factors Research Incorporated (Goleta simulations only)

The other extreme is to consider coupling between all bands as in the following example* which weights the power spectral density of acceleration against the square of the allowable heave acceleration, $Z_L^2(f)$:

$$\int_{f_1}^{f_2} \frac{\phi(f)df}{\ddot{Z}_L^2(f)} \simeq \sum_{i=1}^{N} W_i^2(\tfrac{1}{3})A_i^2(\tfrac{1}{3}) \le C_j$$

where

$W_i(\tfrac{1}{3})$ = weighting function evaluated at the one-third octave center frequency

$W_i^2(\tfrac{1}{3}) \simeq \ddot{Z}_L^{-2}(f_{ci})$

C_j = a constant, usually less than 1.

Such a criteria may well be overly stringent. Consider the case where $A_i(1/3)$ is approximately zero except in two frequency bands, where

$$A_i(\tfrac{1}{3}) = 0.71 \ddot{Z}_L(f_{ci})$$

The above form of evaluation (with $C_j=1$) would indicate the motion exposure to be unacceptable despite the fact that the acceleration in both bands is 30 percent less than allowed with narrow band data.

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*An alternate interpretation of this evaluation rule is that it takes into account the additive nature of the motion and makes allowance for the extremely large amplitudes that could result if all of the low amplitude spectra were momentarily to add constructively.

The lack of well-defined physiological criteria and such <u>apparent</u> inadequacies of existing evaluation criteria for broad band motion as well as the desire to have a single number which evaluates or scores a given motion condition have led to experimentation with a variety of "figures of merit" (FOM) in trying to predict the effects of motion exposure in advance. The tendency to date has been to develop these FOM in terms of two spectral regions which bound the motion region of primary interest to the SES (the spectral range from about 0.1 to 10 Hz). The first range (about 0.1 to 0.8 Hz) involves primarily kinetosis while the second range (about 0.8 to 10 Hz) involves primarily what is referred to in the context of the SES as mechanical interference, (or more commonly in general as "the whole-body motion regime" (ref. 11).

The latter region is the most well studied and SES efforts with the FOM approach have consisted primarily of evaluating our own motion exposure results in terms of existing and proposed single frequency motion criteria and those methods proposed by various organizations for extension of this criteria to broad band motion.

In the kinetosis region, evaluation has proceeded in much the same way with the primary effort directed toward the extension of the work of O'Hanlon, et al. (ref. 12). This group has been working for some time under the sponsorship of ONR on an empirical model of motion sickness incidence. The result of their work is indicated in figure 16 (drawing courtesy of Human Factors Research, Inc.) which graphs the motion sickness incidence (MSI)*, as a function of the RMS acceleration when exposed to single frequency sinusoidal motion. These data give a good fit to a log-normal cumulative distribution:

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*The representation of MSI describes the cumulative percentage of frank emesis expected from young <u>unadapted</u> adult males within two hours after initial exposure to motion. More recent but preliminary work at HFR presents a dynamic model of MSI in terms of the asymptotic proportion of sick individuals, P_A, and the time dependent proportion, P_T, as

$$MSI = 100 \ P_A P_T$$

where $P_j = \dfrac{1}{\sigma_j \sqrt{2\pi}} \int_{-\infty}^{X_j} \exp \ \left[\dfrac{-(X-\mu_j)^2}{2\sigma_j{}^2} \right] dX$

$j = A,T$

$\mu_A = -0.80 + 2.73 \ (\log_{10} f + 0.77)^2$

$\mu_\beta = 2.00 - P_A$ $X_A =$ common logarithm of acceleration (RMS g's)

$\sigma_A = 0.46$ $X_T =$ common logarithm of time (minutes)

$\sigma_T = 0.36$

$$MSI = \frac{100}{\sigma\sqrt{2\pi}} \int_{-\infty}^{X} \exp\left[\frac{-(X-\mu)^2}{2\sigma^2}\right] dX$$

where $X = \log_{10} 0.901\ a_{RMS}$

$\sigma = 0.43$

$\mu = 1.032 + 5.132\ \log_{10}f + 3.562(\log_{10}f)^2$

$a_{RMS} =$ acceleration (RMS g's)

from which it can be determined that the curves of constant MSI (fig. 17) have a maximum at a frequency of 0.190 Hz.

These curves in turn have been normalized by J. George and H. Donnelly at the Applied Physics Laboratory, Johns Hopkins University, to form the single weighting function depicted in figure 18.

If now a weighted acceleration, a_w, is formed from this weighting function according to:

$$a_w = \left\{ \sum_{i=1}^{N} [W_i(f_{ci})A_i(\tfrac{1}{3})]^2 \right\}^{\frac{1}{2}}$$

and substituted for a_{RMS} in O'Hanlon's MSI, a FOM for kinetosis, D_k, can be developed which gives an intuitive feeling for the quality of the motion. The use of D_k as a rating of one motion condition relative to another seems quite justified; however, it is to be emphasized that D_k is not to be given a quantitative interpretation since insufficient data have been taken for such an assessment (the HFR group tested almost 600 subjects to develop their single frequency data) and also because the data do not adequately take into account the process of adaptation. The adaptation to sea motion is an accepted fact and preliminary work by the same group at HFR has noted definite trends in this process as a function of the amplitude and time of exposure. The significance of this fact is that a designer of passenger ships, which normally carry unadapted passengers, might strive to achieve a very small value of D_k while a designer of a military ship which carries only adapted personnel might find the effects of higher frequency motion (which might, for instance, interfere with operation of electronic equipment) to be much more important. This situation is depicted

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in figure 19 which compares iso-kinetosis curves to hypothetical fatigue criteria developed by fitting contours of equal sensations (ref. 13) to curves of Fatigue Decreased Proficiency (ref. 11). It is apparent that a criterion such as D_k which is based strictly on kinetosis in unadapted males might be impractical for a military ship.

It is hoped that continuing work will help to clarify some of these issues. In the meantime, the newly modified ONR motion generator represents a significant new capability for investigating these and other effects of motion exposure.

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TABLE 1.- SUMMARY OF THE MOTION STATISTICS PREDICTED TO OCCUR AT THE

CENTER OF GRAVITY OF A 2000-TON SES (CONFIGURATION A) OPERATING

WITHOUT RIDE CONTROL

[Data describe the acceleration, a, expected frequency, f_e, number
of maxima per unit time, N_1, and broadness factor, ϵ]

Tape No.	Speed/Sea State	a (RMSg)	f_e (Hz)	N_1 (second^{-1})	ϵ
JR21	80/3	0.194	0.88	1.56	0.82
JR19	60/4	0.248	0.78	1.27	0.79
JR12	40/5	0.278	0.72	1.16	0.79

TABLE 2.- COMPARISON OF THE RMS ACCELERATION (g) IN HEAVE, SURGE,

AND SWAY AT A POSITION 23.5 m (77 ft) FORWARD OF THE CENTER

OF GRAVITY FOR A 2000-TON SES (CONFIGURATION A) WITH RIDE

CONTROL IN A BOW SEA

Sea State/Speed	5/40	4/60	3/80
Component			
Surge	0.036	0.016	0.01
Sway	0.033	0.02	0.01
Heave	0.24	0.14	0.09

TABLE 3.- SUMMARY OF TASKS AND TESTS

PHASES	NAME		ACTIVITY (C = Primarily Cognitive; M = Primarily Motor)	SCORING MEASUREMENTS
I, IA II	Navigation	C	Plotting own ship's and radar target positions and courses from verbal information	Fraction of radar contacts not plotted
I, IA II	Cryptography	C	Manual decoding of written messages	Time to completion or fraction of message decoded at mandatory termination
II	Radar Task I	C/M	Monitor PPI radar detect incoming missile and provide discrete motor response	Fraction of targets missed; fraction of targets in error
II	Radar Task II	C/M	Monitor PPI radar, detect collision hazards and provide discrete motor response	Fraction of targets missed; fraction of targets in error
IA, II	Visual Acuity	C	Read optometric near-point and far-point material	Acuity levels, list reading
II	Dual Axis Weapon Track-ing	M	Maintain control over simulated weapon flight by initiating commands via two axis electrical joy stick	Vertical control signal; vertical display error Horizontal control signal; horizontal display error Zero crossings for all of above
I, IA II	ECM Tracking	M	Antijam Frequency Meter tracking, MK VIII first-order autopaced critical task, dial display, unrestrained knob control	Critical instability score (median of 3 trials)
I, IA II	Equipment Handling	M	Take 59 kg (13 lb) case from rack and reinstall in rack; perform in both sitting, standing positions	Time to completion (table to table) and subjective rating
I, IA II	Fine-Motor Lock	M	Combination lock opening with one hand	Time to completion
IA II	Keyboard Operation	C/M	Calculating own ship's course and speed from timed samples of position using mini-calculator	Fraction of incorrect results and time to completion
II	Maintenance Task	M	Strip typical electro-mechanical circuit board using standard tools	Time to complete; number of components damaged during removal
I, IA II	Questionnaires	C/M	Complete selected sections of questionnaires when directed	Subjective rating
I	Eating, Drinking	M	Eating sandwiches, drinking milk, cola	Subjective rating
IA II	Complete Housekeeping	C/M	Food preparation, cleanup, personal hygiene, sleeping, R & R	Subjective rating
II	Head Motion Measurement	-	Using head mounted 6-DOF accelerometer package measure head motion	Correlation of head motion with commanded motion and with other motion effects
I, IA II	Stress Hormone Analysis	-	Regular, periodic urine sampling and analysis for stress hormones	Levels of stress hormones present at periods throughout simulation
II	Blood Pressure and Oral Temperatures	M	Interactive/self administered checks of B.P. & body temperatures	Regular record plot to show any unusual trends
IA II	Sleep Data Measurement Analysis	-	Automatic collection of EES EMG data whenever crewmen are at rest or sleeping	Comparison of sleep performance control/ motion conditions by hand scoring and computer scoring techniques

TABLE 4.- PERFORMANCE CAPABILITY OF ONR MOTION GENERATOR
PRE- AND POST-MODIFICATION

	Units	Unmodified	Modified
Heave Performance			
a. Amplitude	m (ft)	±3.4 (±11)	±3.1 (±10)
b. Velocity	m-sec^{-1} (ft-sec^{-1})	±2.4 (± 8)	±5.5 (±18)
c. Acceleration	g's	±0.6	±1.2
			±0.9
d. Compensated Bandwidth (3db)	Hz	0.5 to 5	–
e. Linearity, accelerator		0.6 to 0.7	±2db to 5 Hz
f. Coherency		0.6 to 0.7	0.98
g. Deadband	g	0.06	±0.04
Pitch and Roll			
a. Amplitude	deg	±15	±15
b. Velocity	deg-sec^{-1}	±25	±25
c. Acceleration	deg-sec^{-2}	±180	±180
d. Compensated Bandwidth (3db)	Hz	0.06 to 2	0.06 to 2
e. Phase Matching to Heave	deg	see test	<36°
f. Coherency	–	0.96	0.96
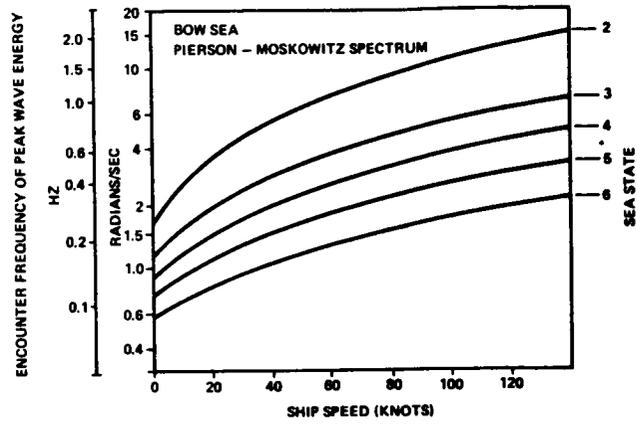
Figure 1. Encounter frequency of peak wave energy as a function
of ship speed and sea state for a bow sea and a
Pierson-Moskowitz sea spectrum.
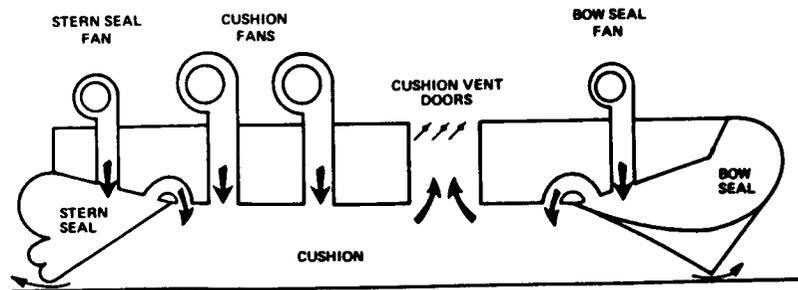
Figure 2. The nature of SES Lift and Ride Control System elements.

☐ CG JR21 80KNOTS SS3 TAPE 0.194RMS g
O CG JR19 60KNOTS SS4 TAPE 0.248RMS g
△ CG JR12 40KNOTS SS5 TAPE 0.278RMS g
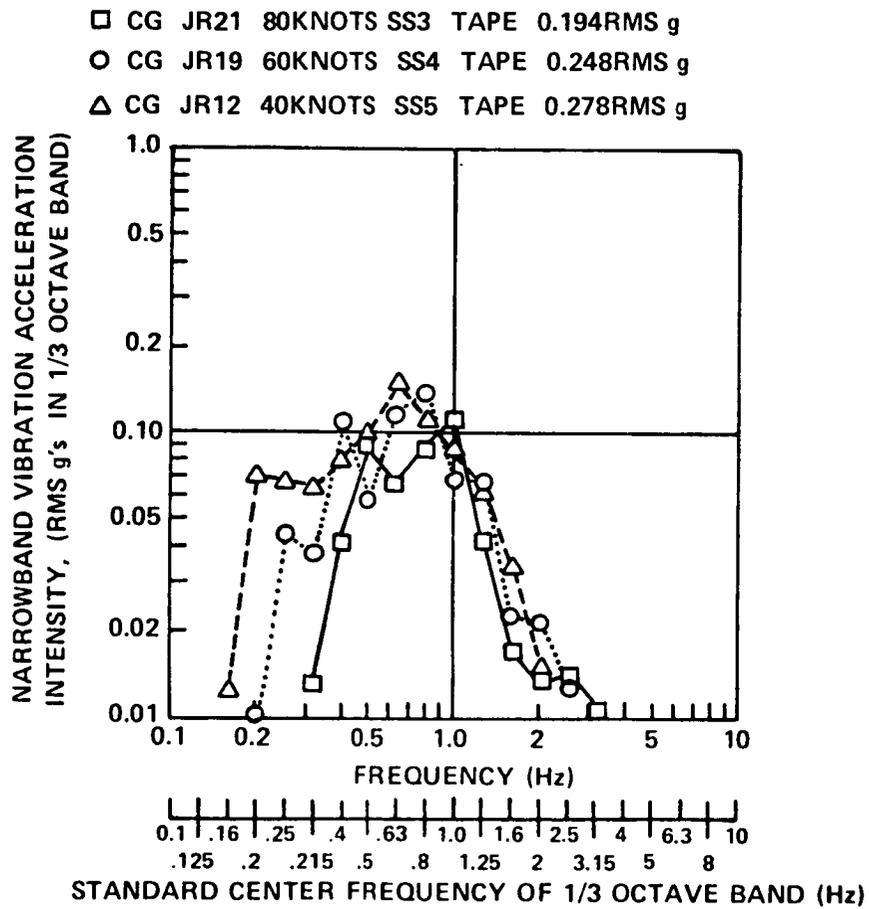
Figure 3. Mathematical prediction of acceleration intensity at the center of gravity of a generic SES (Configuration A) without Ride Control.
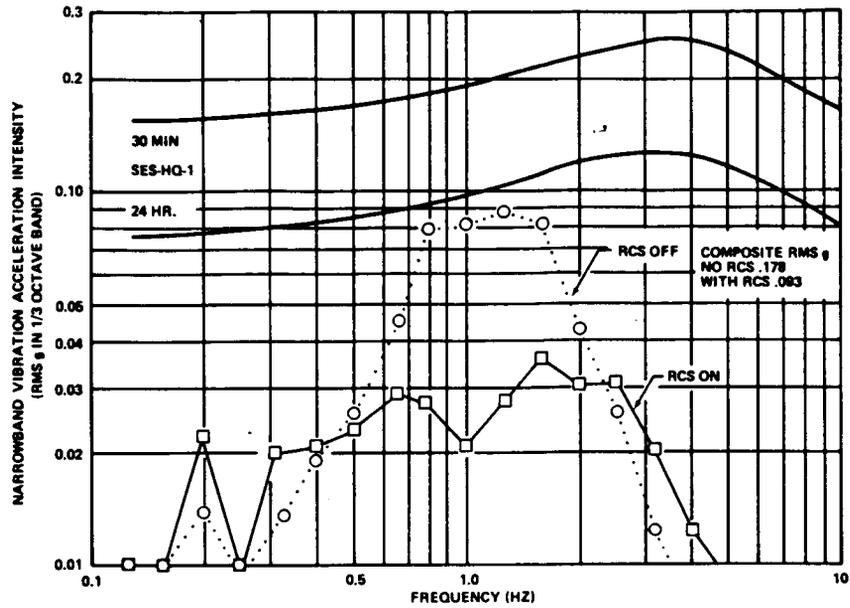
Figure 4. Math model predictions of the ride quality of a more recent SES design with and without Ride Control System activated. Condition is 65 knots and sea state 4.
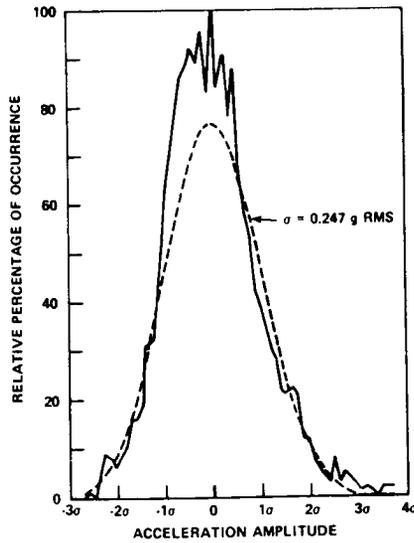
Figure 5. The acceleration amplitude distribution for Configuration A at 60 knots in Sea State 4.
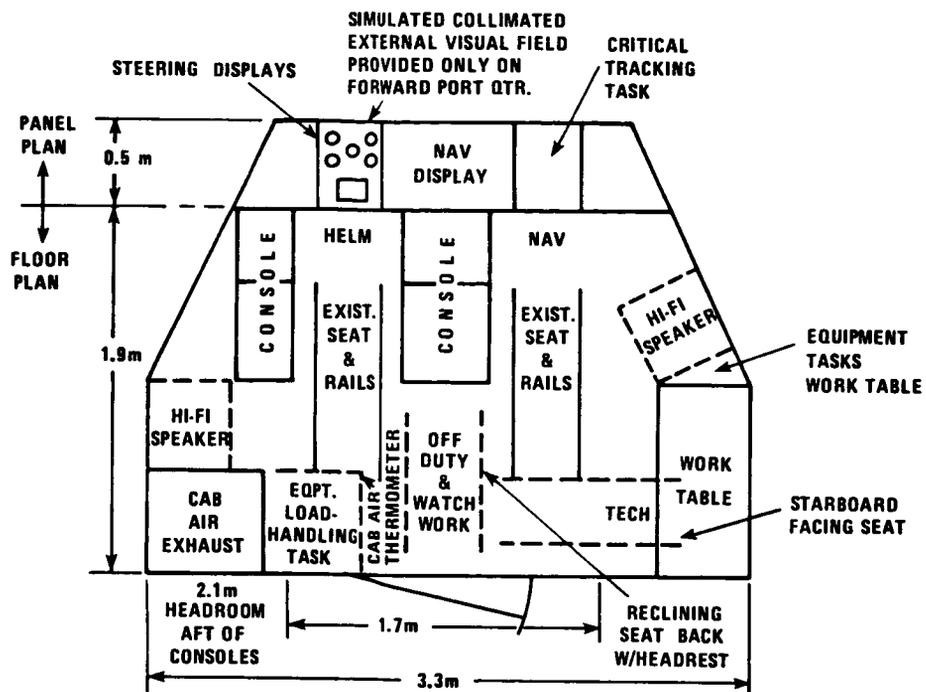
Figure 6. The configuration of the SES cabin during the MSFC simulation; Helm, Nav, Tech, and Off Duty indicates positions of subjects during motion exposure.
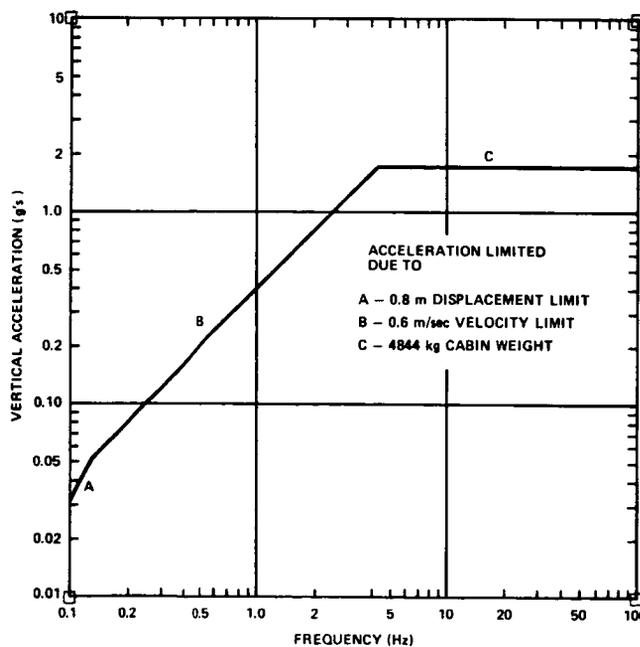
Figure 7. Performance of MSFC motion generator in vertical acceleration for sinusoidal input.

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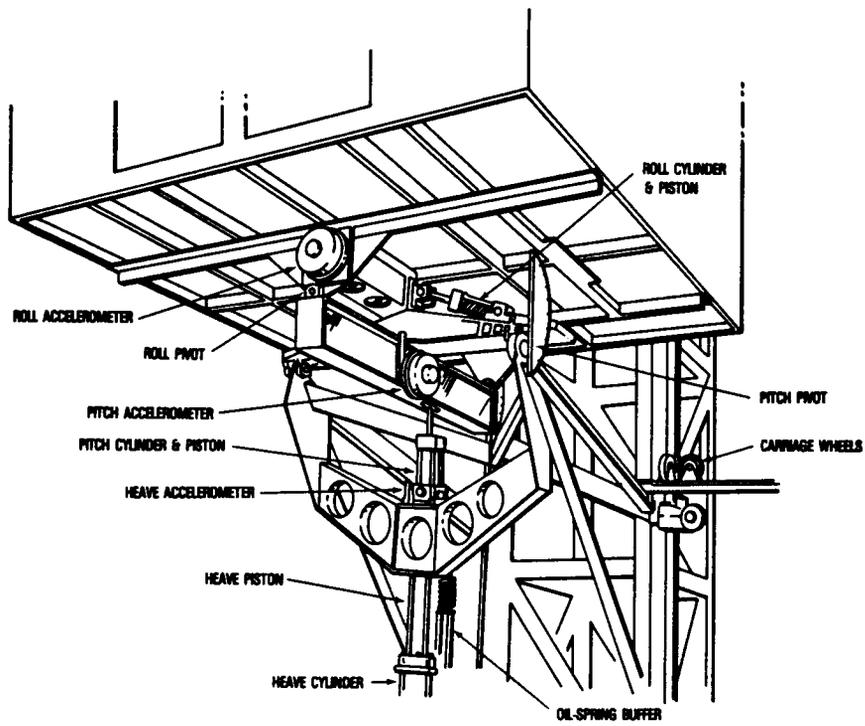
Figure 8. The moving carriage, gimbal, and associated structures of the ONR Motion Generator.

Figure 9. ONR Motion Generator heave drive hydraulic
system functional schematic.

Figure 10. Control loop for modified heave servo system.

Figure 11. Bode comparison of angular rate and heave response.

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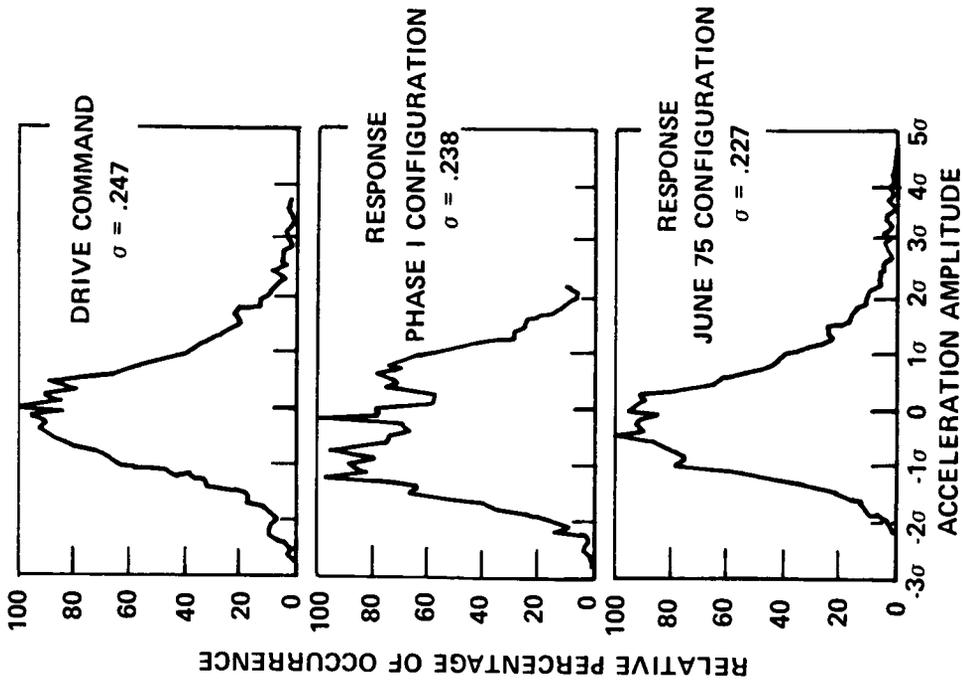
Figure 13. Alteration of the acceleration amplitude distribution by the ONR motion generator for 60 knot/sea state 4 case.
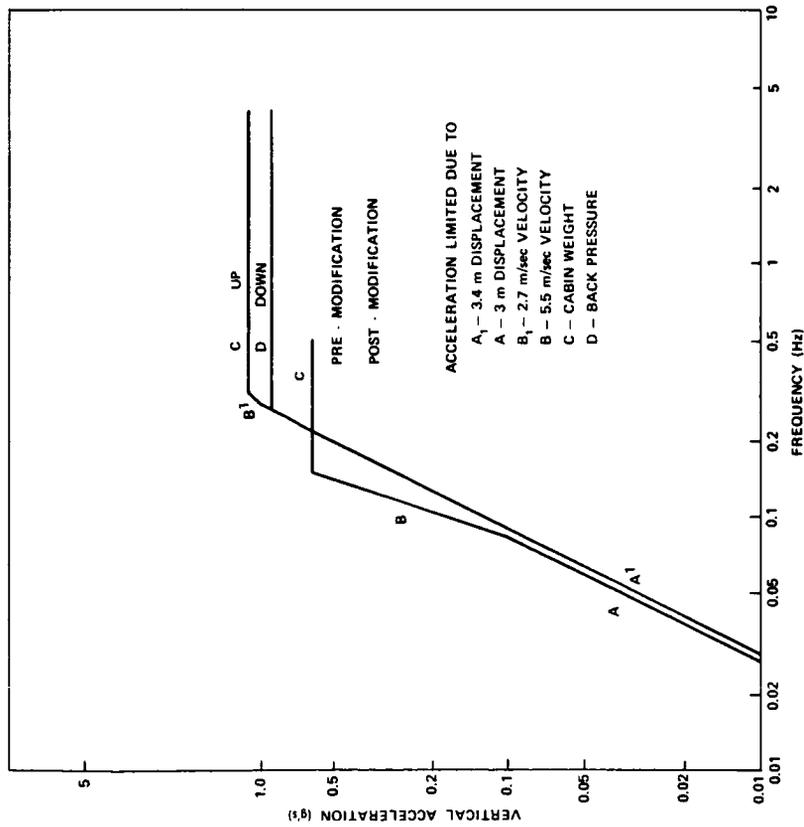
Figure 12. Performance of the ONR Motion Generator pre- and post-modification with 1724 kg (3800 lb) cabin.

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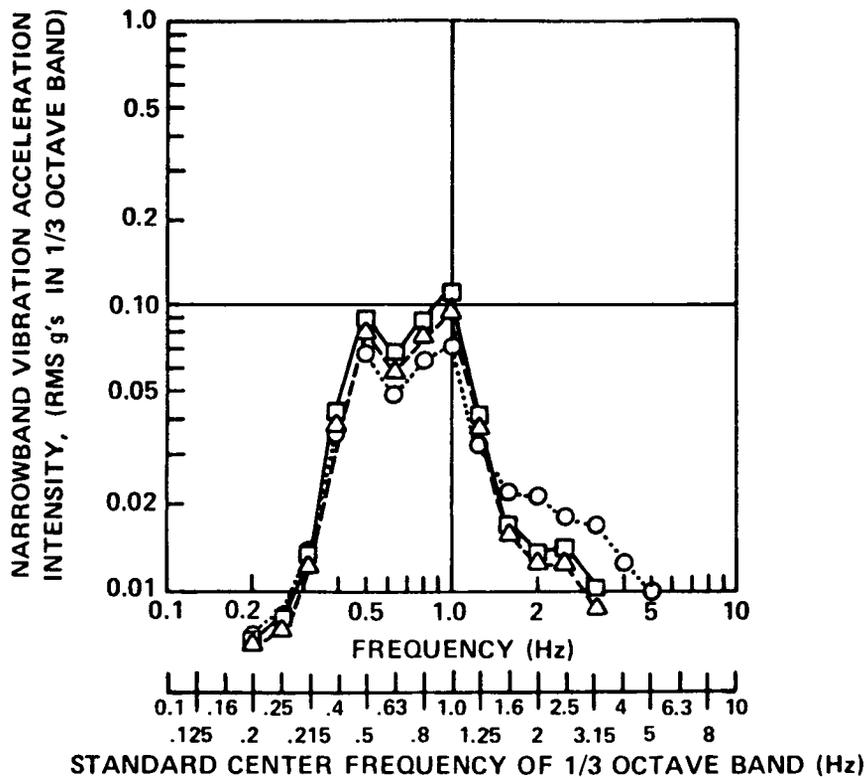
Figure 14. Pre- and post modifications response of
ONR Motion Generator to 80 knot/sea state 3
motions.
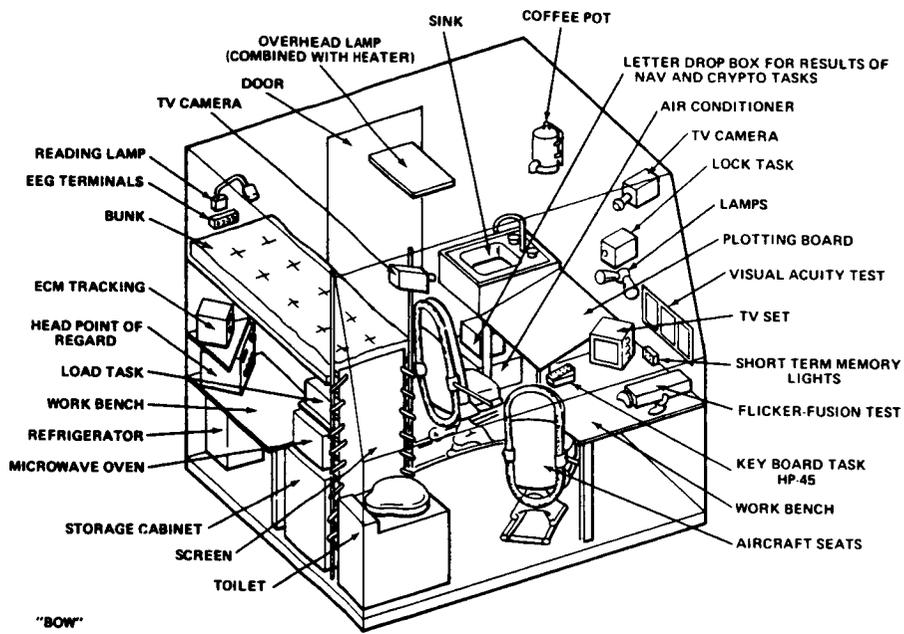
Figure 15. Large cabin for Phase IA.
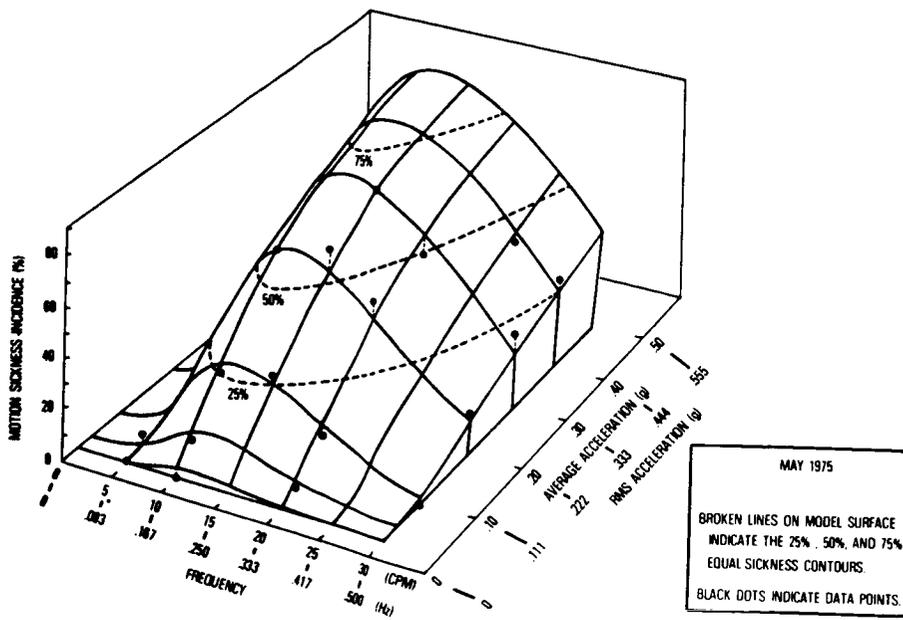
Figure 16. Empirically derived model of motion sickness incidence.

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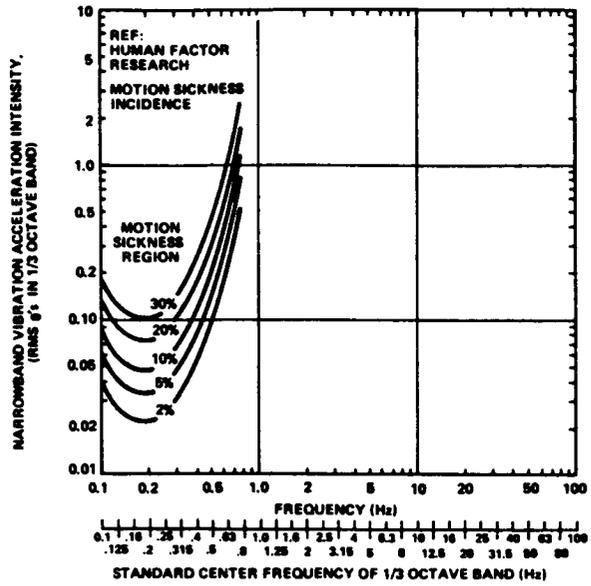
Figure 17. Curves of constant MSI as
a function of frequency.
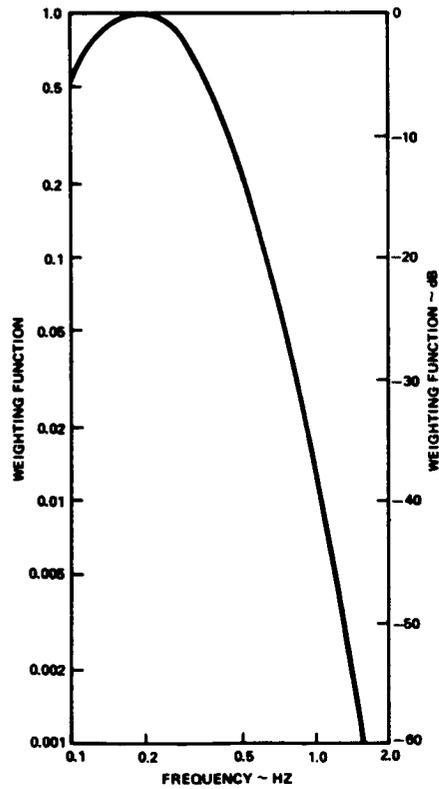
Figure 18. Broadband acceleration weighting
function for kinetosis.

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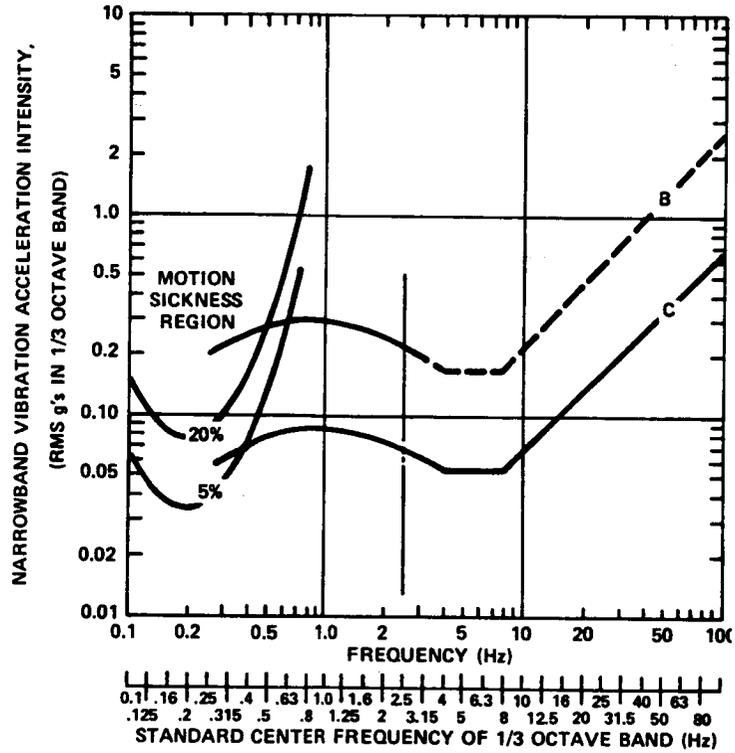
Figure 19. A hypothetical criteria for fatigue developed by
fitting an Equal Sensation Contour to a Fatigue
Decreased Proficiency curve at 2.5 Hz.