VALIDATING A MODEL OF THE EFFECTS OF SHIP MOTION ON POSTURAL STABILITY

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INTRODUCTION

Excessive ship motions in rough weather impair the fighting ability of a warship; these motions will degrade the crew's ability to operate ships' systems. Manual tasks requiring balance and coordination are most likely affected by severe motions. It has long been recognized that quantifying the seakeeping performance of new and innovative ship designs is difficult because of the inability to quantify ship motion effects on human performance. Models have been developed that predict the rate at which crewmembers will slide or lose their balance as a function of the ship motions. These events are called Motion Induced Interruptions (MIIs). Baitis and Applebee introduced the concept of MIIs (as a function of the lateral acceleration in the plane of the deck) as an approach for quantifying ship motion effects on personnel (1).

MOTION INDUCED INTERRUPTIONS

The definition of an MII is an incident where the accelerations due to the ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to make a postural adjustment in order to remain upright. MIIs include the ship motion induced interruptions of the crew in all non-seated tasks such as standing, walking, lifting and moving objects. A simple mathematical model was derived by Graham (2). This model predicts the number of MIIs in a given motion environment for simple standing tasks. The full formulation of the equations are given by Graham et al. (3) and shown here as a tip (in a standing person) will occur if

$$\left(\frac{1}{3}h\ddot{\eta}_4 - \ddot{D}_2 - g\eta_4\right) - \frac{l}{h}\ddot{D}_3 > \frac{l}{h}g \quad \text{or} \quad \left(-\frac{1}{3}h\ddot{\eta}_4 + \ddot{D}_2 + g\eta_4\right) - \frac{l}{h}\ddot{D}_3 > \frac{l}{h}g$$

where $\ddot{D}_3$ is the vertical acceleration, $\ddot{D}_2$ is the lateral acceleration, g is the acceleration due to gravity, η_4 is the instantaneous roll angle, $\ddot{\eta}_4$ is the instantaneous roll acceleration, h is the height of the subjects' center of gravity from the deck and l is half the subjects' base of support. $\frac{l}{h}$ is known as the theoretical tipping coefficient. This tipping coefficient essentially defines the acceleration thresholds above which an MII will occur. This simple model can be validated by undertaking postural stability experiments on volunteers by measuring the instantaneous accelerations on the subjects and by recording the MIIs as they occur. This procedure will also yield empirically derived tipping coefficients, which can be substituted for the theoretical tipping coefficients in the MII model. This would only be valid for the simple standing tasks. However, by performing the same procedure on more complex tasks (e.g., walking), acceleration thresholds, and hence empirical tipping coefficients, can also be derived for those tasks.

SIMULATOR EXPERIMENTS

Two MII experiments were performed using the Large Motion Simulator (LMS) at DERA Bedford, United Kingdom. These experiments were conducted to investigate the effects of ship motion on the postural stability of Royal Navy personnel and to provide data for validating the predictive MII model. In each MII experiment, every volunteer was asked to perform a simple task routine lasting about 15 min. This was then repeated 3 more times (setting a total of 1 h per condition). The task routine was the 5 tasks listed in Table 1.

The 1st experiment used motion profiles that were representative of the United States FFG8 (OLIVER HAZARD PERRY class frigate) and the 2nd experiment used profiles representative of a Royal Navy Type 23 (DUKE class frigate). For the US FFG8, 2 time histories were taken from a simulation of the unstabilized ship in a mid-sea state 5. For the RN frigate, 2 time histories were taken from a simulation of the unstabilized ship in high-sea state 5 and low-sea state 6. Sea-state 5 means waves with significant wave height in the range 2.5 to 4.0 m or about a Force 7 on the Beaufort wind scale (the sea appearance is described as white foam from breaking waves, blown in streaks along the direction of the wind). The motion profiles were random in their nature and appeared "shiplike" to the subjects. Moreover, they were representative of the real ship, resulting in little or no loss of fidelity from the point of view of validating the MII model.

Table 1. Empirical tipping coefficients

Task	Average empirical $\frac{l}{h}$	Theoretical $\frac{l}{h}$
1. Standing facing stern	0.270	0.250
2. Weapon loading task	0.200	
3. Standing facing stern, arms aloft	0.292	0.250
4. Walking on treadmill	0.273	
5. Standing facing starboard	0.182	0.150
All tasks	0.243	

DISCUSSION

Table 1 shows the average empirical tipping coefficients obtained from the 2 experiments for each task.

The lower the tipping coefficient the harder the task is to perform. The general trends are as expected: it was harder to stand facing starboard than facing the stern. This agrees quite strikingly with the experimental observations, in that all subjects had more trouble maintaining their balance during task 5. The empirical tipping coefficients are greater than equivalent theoretical, which means that the human is better able to cope with the motion than the model would suggest. The experiment also found that there was a large variation in the tipping coefficients between subjects, which was expected. One aim of these experiments is to establish a sufficiently large database to quantify this variability. The empirical tipping coefficients found from both the FFG8 and T23 experiments, for each subject, task and motion condition were used in the MII model described earlier to predict MII rates.

Figure 1 shows that the model is generally good at predicting MIIs per min for all tasks for both ship types. However, the model generally underpredicts at high MII rates. Very high levels of association between actual and predicted number of MIIs per minute (based upon empirical tipping coefficients found for each subject) have been demonstrated in all 4 motion conditions. Observed learning effects indicate that improvements in subject performance may reduce the actual MII rate, which would provide a closer correlation with the model predictions, yet, testing this hypothesis would be costly.

A task specific MII model (rather than the generic one presented here) based upon measured empirical tipping coefficients for each task may be feasible pro-

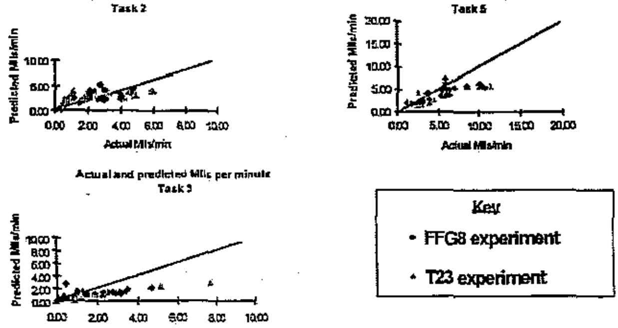

Figure 1. Predicted vs. Actual MIIs

vided that the acceleration thresholds for that task have been determined empirically. Therefore, if a specific task was of interest, experiments would be performed using a representation of that task in a simulator.

CONCLUSIONS

The MII model predicts when a person will lose balance due to high accelerations caused by a moving platform. In this model, the ratio of half stance width over the vertical height of the person's center of gravity, the theoretical tipping coefficient, is a key term in evaluating the probability of a MII occurring. The experiments described here have illustrated the difference between taking a theoretical tipping coefficient found from the geometrical representation in the model and from human studies that yield so-called empirical tipping coefficients.

The authors' recommend that the average empirical tipping coefficients shown in Table 1 be used when predicting MII frequency with the mathematical model. For general seakeeping assessment purposes, it is recommended that only the empirical tipping coefficient for task 1 is used as people would adopt this most motion-resistant stance (if able to choose) by standing sideways to the predominant accelerations (usually those associated with the ship rolling). In cases where detailed task assessment is required or if a person is unable to change stance to make them more comfortable, then a more complex analysis should be performed. If the complex shipboard task can be broken down into representative tasks then perhaps a weighted average for the empirical tipping coefficient can be determined. The weighting could be derived from the relative importance of the representative task (i.e., mission criticality). Another approach could use the time taken to complete a representative task as a proportion of the time taken to complete the whole, complex task.

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