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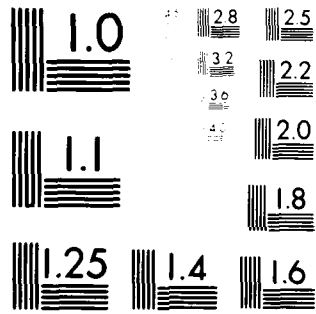
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Phone: (814) 238-9621

Applied Research in Statistics - Mathematics - Operations Research

ACCELERATION MEASURES AND
MOTION SICKNESS INCIDENCE

by

Carl A. Mauro
and
Dennis E. Smith

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I. INTRODUCTION

An important objective of motion sickness research is to establish quantitative relationships between sickness incidence and various parameters of the physical motions that induce sickness. An integral part of this objective is selecting the appropriate motion parameters upon which to build a predictive motion sickness incidence (MSI) model. Motions conducive to motion sickness, however, are rather diverse and invariably complex; at present, only whole-body vertical sinusoidal motion has been studied to any reasonable degree.

In the case of vertical sinusoidal motion, research has linked MSI to the frequency, acceleration, and duration of exposure. The apparent relationship between these variables and the resultant motion sickness has been formally described by an empirically based predictive model developed by Human Factors Research (HFR), Inc. [3]. Using the occurrence of frank emesis as the diagnostic motion sickness criterion, the HFR model predicts the cumulative probability of emesis as a function of wave frequency, root-mean-square (rms) acceleration, and an exposure time of not more than two hours duration. Initial results have indicated that the effects of vertical sinusoidal motion on MSI are fairly well described by this model.

Because vehicular motion, be it on land, sea, or air, tends to be broadband, the real-world practicality of the HFR single frequency model is limited. Of greater practical application is a means to predict MSI from the complex motions more characteristic of operational environments. Unfortunately, the current paucity of data regarding the

effects of complex motion spectra on motion sickness has precluded the development of a predictive MSI model for general motion; it is not yet known what characteristics of broadband motion, aside from frequency and acceleration, may be key contributors to motion sickness. Furthermore, it is not even clear for broadband motion how the frequency and acceleration stimuli might best be quantified. Further research is needed to resolve this perplexing, but important problem.

Although it is customary during sinusoidal motion to characterize the dynamic stimulus in terms of wave frequency and rms acceleration, other equally attractive characterizations do exist. In this paper the predictive utility of six such characterizations is examined. Three of these representations are based on frequency and acceleration; the other three are based on frequency and jerk, i.e., the rate of change of acceleration. Although each representation is readily generalizable to broadband motion, none completely characterizes the more complex stimulus present in broadband motion. Thus, any assessment of their utility for predicting MSI in complex motion environments will be tenuous at best.

An assessment of predictive utility is further complicated by the lack of complex motion data. However, to obtain some preliminary indication of their utility for predicting MSI in broadband motion, an experiment involving four dual frequency waveforms is analyzed in this report. Based on the results of this analysis, possible implications for future research and model construction are discussed.

II. SINUSOIDAL DISPLACEMENT

The displacement function of simple harmonic motion is given by an equation such as

$$x(t) = A \sin(\omega t) \quad (2.1)$$

where A denotes the wave amplitude, $\omega = 2\pi f$ ($\omega \geq 0$) denotes the angular frequency, f denotes the wave frequency, and $x(t)$ denotes the displacement at time t . Equation (2.1) does not include a phase constant since such a constant depends only on the initial position and is not important for the description of sinusoidal motion.

The acceleration $a(t)$ corresponding to the displacement $x(t)$ is given by

$$a(t) = x''(t) = -\omega^2 A \sin(\omega t) . \quad (2.2)$$

In sinusoidal motion, therefore, the acceleration is proportional to the displacement and in the opposite direction. Typical parameters for measuring acceleration have included the absolute value of peak acceleration (a_{\max}), the root-mean-square of acceleration in each half-wave cycle (a_{rms}), and the time integral of the absolute value of acceleration imparted in each half-wave cycle (\bar{a}). Applying these definitions to (2.2) yields

$$a_{\max} = \omega^2 |A| , \quad (2.3)$$

$$a_{\text{rms}} = \left[\frac{\omega}{\pi} \int_0^{\pi/\omega} a^2(t) dt \right]^{\frac{1}{2}} = \sqrt{.5} \omega^2 |A| , \quad (2.4)$$

and

$$\bar{a} = \frac{\omega}{\pi} \int_0^{\pi/\omega} |a(t)| dt = (2/\pi) \omega^2 |A| . \quad (2.5)$$

It is clear from equations (2.3), (2.4), and (2.5) that a predictive

MSI model based on a_{\max} , a_{rms} , or \bar{a} could just as easily be based, via a simple transformation, on either of the other two measures. In this sense, then, a_{\max} , a_{rms} , and \bar{a} have the same predictive utility for vertical sinusoidal motion.

Consider next the jerk $j(t)$ (i.e., the rate of change of acceleration) corresponding to the displacement $x(t)$:

$$j(t) = a'(t) = -\omega^3 A \cos(\omega t) . \quad (2.6)$$

As measures of jerk, let j_{\max} , j_{rms} , and \bar{j} denote the analogs of a_{\max} , a_{rms} , and \bar{a} , respectively. It is not hard to show that

$$j_{\max} = \omega^3 |A| , \quad (2.7)$$

$$j_{\text{rms}} = \sqrt{.5} \omega^3 |A| , \quad (2.8)$$

and

$$\bar{j} = (2/\pi) \omega^3 |A| . \quad (2.9)$$

As was the case for a_{\max} , a_{rms} , and \bar{a} , it is evident from equations (2.7), (2.8), and (2.9) that j_{\max} , j_{rms} , and \bar{j} are also equivalent in their predictive utility for vertical sinusoidal motion. Furthermore, it is clear that conditional on frequency the predictive utility of j_{\max} , j_{rms} , or \bar{j} is equivalent to that of a_{\max} , a_{rms} , or \bar{a} . It is immaterial, therefore, which of these six motion parameters is used in conjunction with the wave frequency f as a basis for characterization or prediction. A list of the defining relationships in which all the measures are equated to a_{rms} is presented in Table 1. It is interesting to note that for sinusoidal motion jerk can more simply be regarded as the interaction between frequency and acceleration.

In summary, then, the researcher has at his disposal a number of two-dimensional characterizations of sinusoidal motion that are seemingly

$$a_{\text{rms}} = \sqrt{.5} a_{\text{max}}$$

$$a_{\text{rms}} = (\pi/\sqrt{8}) \bar{a}$$

$$a_{\text{rms}} = j_{\text{max}}/(\sqrt{8}\pi f)$$

$$a_{\text{rms}} = j_{\text{rms}}/(2\pi f)$$

$$a_{\text{rms}} = \bar{j}/(\sqrt{32} f)$$

$$a_{\text{rms}} = \sqrt{.5} \omega^2 |A|$$

Table 1. Defining Relationships for Sinusoidal Motion

different but essentially equivalent (up to a change of units); accordingly, these representations offer the same degree of predictive utility for vertical sinusoidal motion.

The HFR single frequency model can be used as a predictive basis in actually making a quantitative assessment of the common predictive utility of a_{\max} , a_{rms} , \bar{a} , j_{\max} , j_{rms} , and \bar{j} . For example, combinations of frequency and acceleration for which data is available can be substituted into the HFR model to obtain predicted MSI values. These values can then be compared to the corresponding observed MSI values; the apparent degree of agreement between the observed and predicted MSI values is a measure of predictive utility. Such an analysis was undertaken in [3] where a 6.1% rms deviation between predicted and observed MSIs for a number of data conditions was observed. This represented, in the opinion of the authors of that paper, "a reasonably good fit to the data". Their analysis, however, was made on the same data that went into developing the HFR model. Hence, the apparent degree of fit is most likely an exaggerated indication of actual fit. A truer assessment of predictive utility would best be made on data independent of that used in model construction.

After discussing vertical sinusoidal motion, it is natural to investigate the utility that the various parameters may have for predicting MSI in motions more complex than sinusoidal motion. There are three, immediate impediments to such an investigation:

- (1) The insufficient data base for complex motion precludes a thorough assessment and comparison of the predictive utility of any motion parameters.
- (2) Predictive utility is contingent on other motion variables

present, and characterizing the pathogenic effects of broadband motion probably requires more than frequency and acceleration or frequency and jerk components.

- (3) The transformational properties that played a key role in sinusoidal motion (cf. Table 1) do not hold for more complex motion. Thus, a_{rms} , for instance, will not reflect the peak (a_{max}) or average (\bar{a}) acceleration during broadband motion in precisely the same way that it does in sinusoidal motion.

In the next section a preliminary analysis of some existing dual frequency data is undertaken. In order to assess predictive utility, it was necessary to relate dual frequency to single frequency motion and then apply the HFR single wave model. Although this weakens the analysis, it may provide some preliminary indication of predictive utility. At this juncture, there seems little else that can be done in view of the above impediments.

III. DUAL FREQUENCY DISPLACEMENT

The displacement function $y(t)$ of compound harmonic motion is given by an equation such as

$$y(t) = A_1 \sin(\omega_1 t + \delta_1) + A_2 \sin(\omega_2 t + \delta_2) \quad (3.1)$$

where A_i denotes the wave amplitude, $\omega_i = 2\pi f_i$ ($\omega_i \geq 0$) denotes the angular frequency, f_i denotes the wave frequency, and δ_i denotes the phase constant of the i^{th} ($i=1,2$) component sinusoid. Without loss of generality, it can be assumed that one of the phase constants can be set to zero and therefore omitted from equation (3.1). Hence five parameters are needed to characterize dual frequency displacement. For predicting motion sickness, however, it is presently unknown what characteristics (i.e., motion parameters) of dual frequency motion are important predictors.

Table 2 contains data from a pilot study, the so-called "Correlation Study" [1], designed to determine some of the effects on human response of four selected dual frequency waveforms. The four waveforms studied were created by summing two harmonically related sinusoids. The resultant waveforms are pictured in Figure 1.

In the "Correlation Study" the subjects assigned to Condition I (not presented here) constituted a control group exposed to sinusoidal motion at the fundamental frequency of .17 Hz. Condition II and III added a second harmonic (.33 Hz), differing only in the phasing between the fundamental and harmonic. In Condition II, 0° phasing was chosen to minimize the peak acceleration of the resultant waveform; in Condition

	MOTION CONDITION (1)			
	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>
Fundamental :				
Frequency (Hz)	.16	.16	.17	.16
rms Acceleration (g)	.14	.14	.12	.08
Harmonic:				
Frequency (Hz)	.32	.33	.50	.33
rms Acceleration (g)	.15	.14	.29	.26
Phase Angle (degrees)	0	+ 90	0	0

Number of Subjects:

Total Tested (2)	34	34	40	40
Quit	2	3	9	8
Emesis	16	20	21	25
No Emesis	16	11	10	7

MSI (3)	.53	.68	.75	.83
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- (1) In this study, Condition I was a single frequency control.
 (2) The duration of exposure to the motion was 120 minutes unless vomiting or quitting occurred earlier.
 (3) Quitters included as part of the emesis group in calculating MSI.

Table 2. Results of "Correlation Study": Delivered motion parameters; number of subjects who yielded data or quit; MSI in each condition.

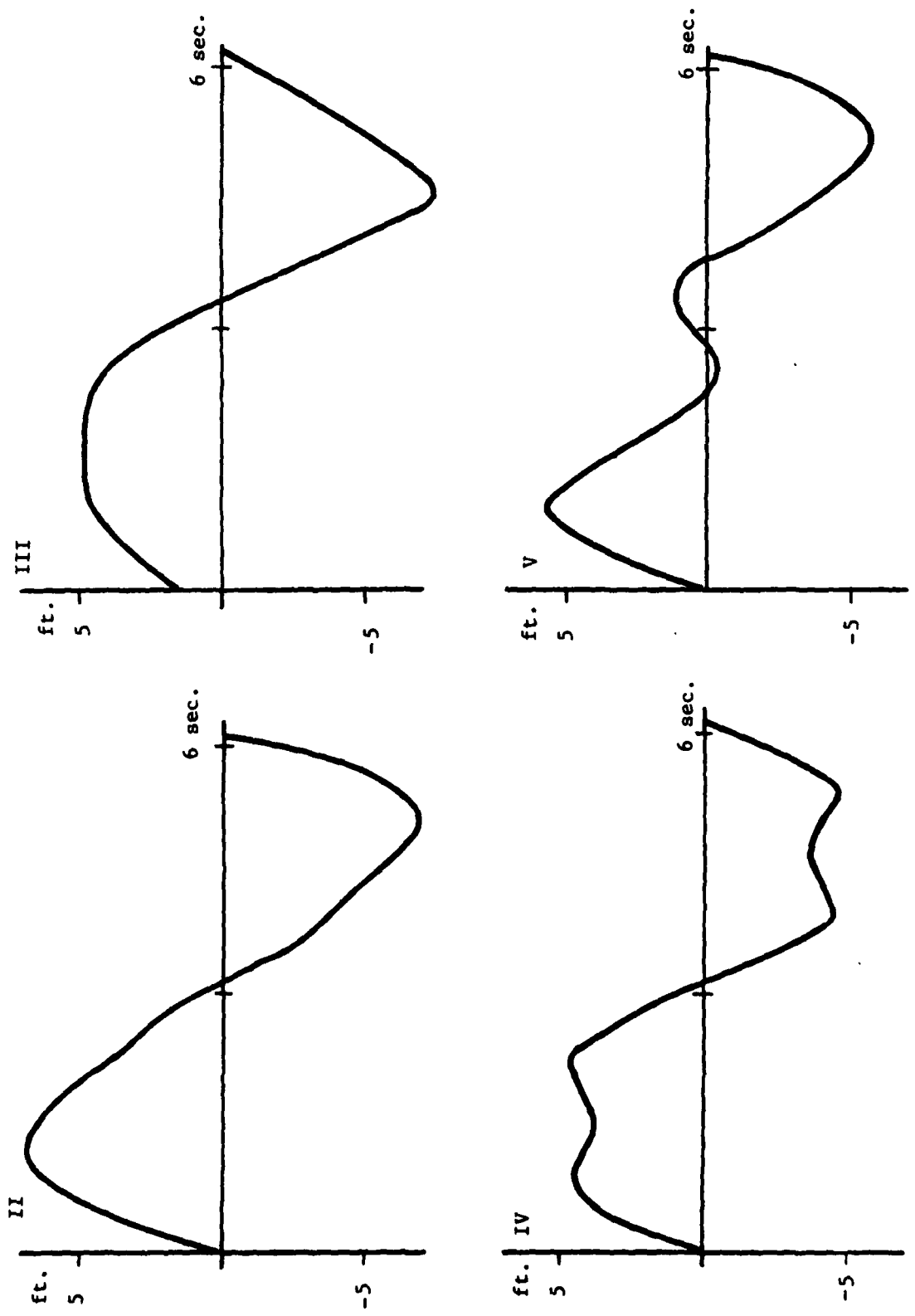


Figure 1. "Correlation Study" Waveforms: Plots of displacement versus time over first six seconds (approximately one period).

III, 90° phasing was chosen to maximize the peak acceleration. Condition IV combined the fundamental frequency of .17 Hz in phase with the third harmonic (.50 Hz). Condition V resembled II except that the level of acceleration of the fundamental was reduced while the level of acceleration of the harmonic was increased.

Subjects were exposed to the motion for 120 minutes unless they quit or vomited. It should be noted that a supplemental analysis [5] to the "Correlation Study" has studied the pattern of quits and concluded that "quitting may appropriately be regarded as part of the motion sickness-prone population". Thus, in the analysis presented here, quitters were included as part of the emesis group in calculating the MSI values for each of the four conditions. In effect, it is assumed that quitters quit because emesis was imminent.

In order to relate dual frequency to single frequency motion it is necessary to reduce dimensionality from five to two dimensions. This requires trying to represent the spectral content of dual frequency motion in terms of a frequency and either an acceleration or a jerk component. To represent the frequency dimension consider the mean frequency, \bar{f} , as determined from the spectral density function for compound harmonic motion:

$$\bar{f} = (A_1^2 f_1 + A_2^2 f_2) / (A_1^2 + A_2^2) . \quad (3.2)$$

To represent acceleration or jerk, a_{\max} , a_{rms} , \bar{a} , j_{\max} , j_{rms} , and \bar{j} can be calculated directly from $y(t)$. These six parameters together with \bar{f} were calculated for each of the four motion conditions; the corresponding values are presented in Table 3.

Parameter:	MOTION CONDITION			
	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>
\bar{f} (Hz)	.170	.169	.186	.222
\bar{a} (g)	.161	.151	.271	.238
a_{rms} (g)	.201	.195	.314	.272
a_{max} (g)	.354	.389	.506	.461
\bar{j} (g-Hz)	.278	.271	.844	.500
j_{rms} (g-Hz)	.323	.321	.920	.545
j_{max} (g-Hz)	.610	.568	1.464	.876

Table 3. Values of motion parameters.

For each motion condition, the values of \bar{f} and each of the three acceleration and jerk parameters were substituted into the HFR single frequency model, suitably reparameterized, to obtain predicted MSI values. The predicted values and corresponding p-values are given in Table 4. The p-value is the smallest significance level for which one can still reject the hypothesis that a given parameter combination results in the prediction of a true MSI value. In general, the smaller the p-value the poorer the agreement between the predicted and observed MSI values.

Inspection of the p-values reveals that of the six parameter combinations, Conditions II and IV are fit best by \bar{f} and \bar{a} , Condition III by \bar{f} and a_{\max} , and Condition V by \bar{f} and j_{\max} . The latter is perhaps an indication of a shifting mechanism. Note that for each condition there is the same ordering of predictions by the six parameter combinations.

In order to obtain an overall indication of how well each parameter combination can predict MSI, goodness-of-fit tests based on data from all four conditions were performed. The resulting p-values were as follows: \bar{f} and a_{rms} had a p-value equal to .21, \bar{f} and a_{\max} had a p-value equal to .15, \bar{f} and \bar{a} had a p-value equal to .12, \bar{f} and j_{\max} , \bar{f} and \bar{j} , and \bar{f} and j_{rms} each had a p-value less than .001. Overall, therefore, \bar{f} and a_{rms} had the most success at predicting MSI in the four dual frequency motions. Figure 2 presents a plot of the p-values for each of the four motion conditions, as well as on an overall basis.

MOTION CONDITION

	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>
Observed MSI	.53	.68	.75	.83
Predicted MSI:				
\bar{f} and a_{\max}	.69 (p=.038)	.73 (p=.515)*	.80 (p=.440)	.74 (p=.221)
\bar{f} and \bar{a}	.56 (p=.692)*	.54 (p=.103)	.75 (p=.971)*	.67 (p=.034)
\bar{f} and a_{rms}	.61 (p=.332)	.60 (p=.355)	.76 (p=.873)	.68 (p=.046)
\bar{f} and j_{\max}	.84 (p<.001)	.82 (p=.029)	.96 (p<.001)	.83 (p=.951)*
\bar{f} and \bar{j}	.74 (p=.005)	.74 (p=.430)	.95 (p<.001)	.80 (p=.694)
\bar{f} and j_{rms}	.76 (p=.002)	.76 (p=.276)	.94 (p<.001)	.79 (p=.637)

* Parameter combination producing largest p-value.

Table 4. Predicted MSI values.

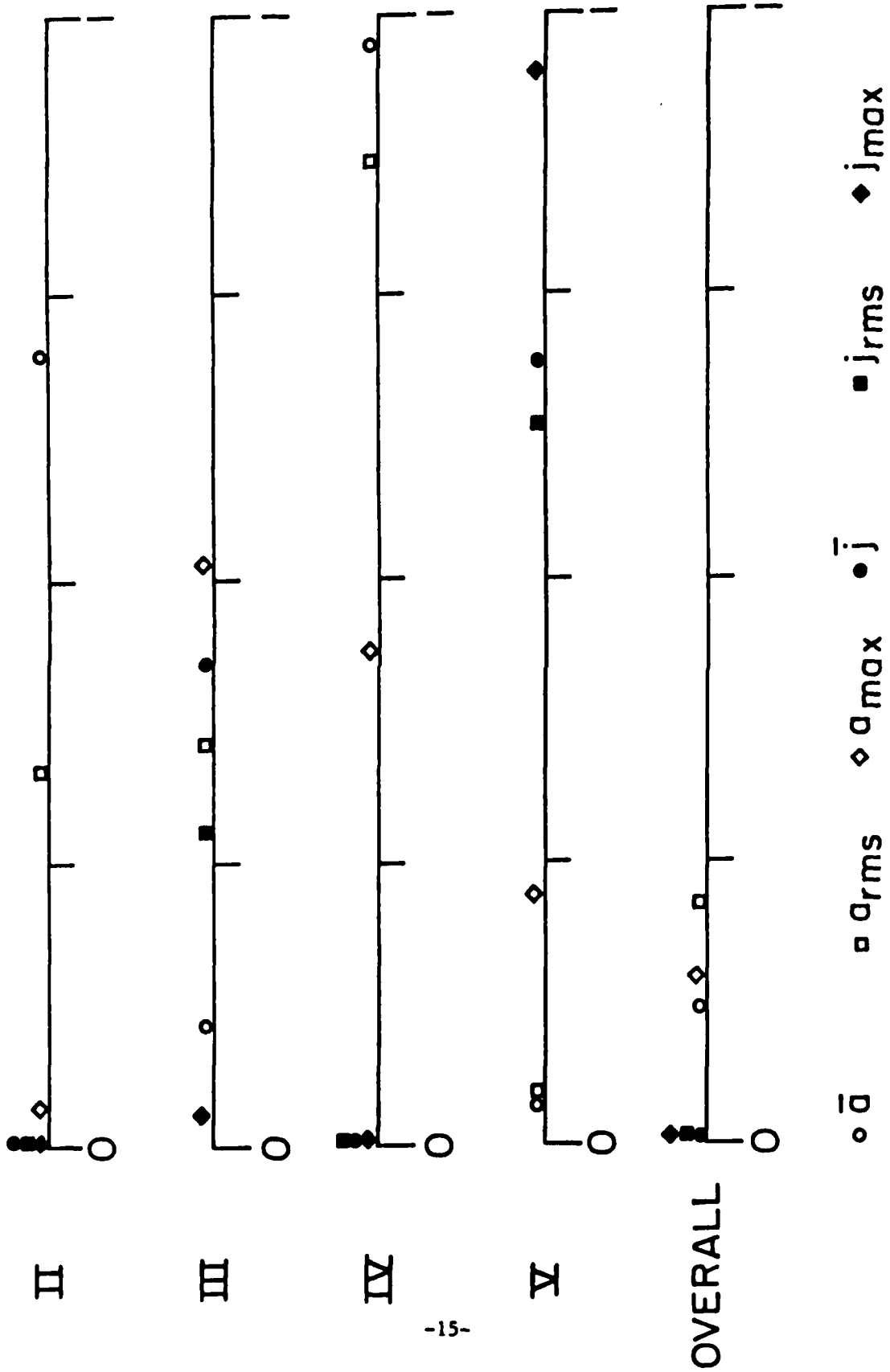


Figure 2. Plot of p-values.

IV. IMPLICATIONS AND FURTHER DISCUSSION

For Conditions II and IV, the acceleration parameters result in reasonably good predictions, while the jerk parameters do not. The opposite is true for Condition V; for Condition III, both types of parameters provide roughly equivalent results. It would appear, then, that both acceleration and jerk warrant consideration in characterizing the motion sickness mechanism. It should be stressed, however, that much more data is needed in order to explore and determine fully the relationship between dual frequency motion and the resultant motion sickness.

Unlike other approaches which have been proposed [4], the use of \bar{f} and a_{rms} , discussed herein, results in creditable predictions that cannot be rejected at conventional significance levels. Nonetheless, not enough evidence exists to conclude with a high degree of confidence that the HFR single frequency model can indeed be satisfactorily extended to dual frequency motion.

Although the approaches examined in [4] were found lacking, it should be borne in mind that the apparent inability of a weighting scheme to relate dual frequency to single frequency motion for the purpose of obtaining MSI predictions could imply that:

- (a) the weighting scheme is inappropriate,
- (b) the HFR model is being extrapolated beyond its scope,
- or (c) the relationship between dual frequency motion and the resultant motion sickness is simply too complex to be described by a predictive MSI model developed solely from single frequency data.

Because of data limitations, the results of this paper are preliminary in nature. With the aid of additional data, however, a more rigorous investigation of predictive utility could be made. Ideally, a predictive MSI model based directly on broadband motion data could then be developed. Of course, indirect procedures could continue to be refined and examined for their feasibility.

In either case, serious consideration must be given to the design of future motion sickness experiments, as well as to the analysis of the resulting data. From an analysis and model development standpoint, it may be advantageous to place more emphasis on the actual time to emesis, rather than concentrating only on the occurrence or nonoccurrence of emesis within a given period of time. This is particularly true in view of evidence that time-to-emesis may be regarded as a random variable arising from a mixture of two probability distributions [2]. The problem of predicting MSI can then be reduced to estimating the parameters of these distributions.

From the experimental design viewpoint, not only must the motion parameters of major interest be specified, but also the applicable parameter space must be well covered. Figure 3 illustrates this point for the single frequency case. Consider the rectangular region illustrated in the frequency and a_{rms} space. If subjects are run at motion conditions corresponding to the four vertices, the resulting experiment is orthogonal in the frequency and a_{rms} parameters. However, if the region is mapped into the frequency and j_{rms} space, the rectangular region is deformed into a trapezoid, resulting in the loss of orthogonality in this parameter space. This might pose serious difficulties in model construction and analysis, particularly if j_{rms} were of more interest than a_{rms} .

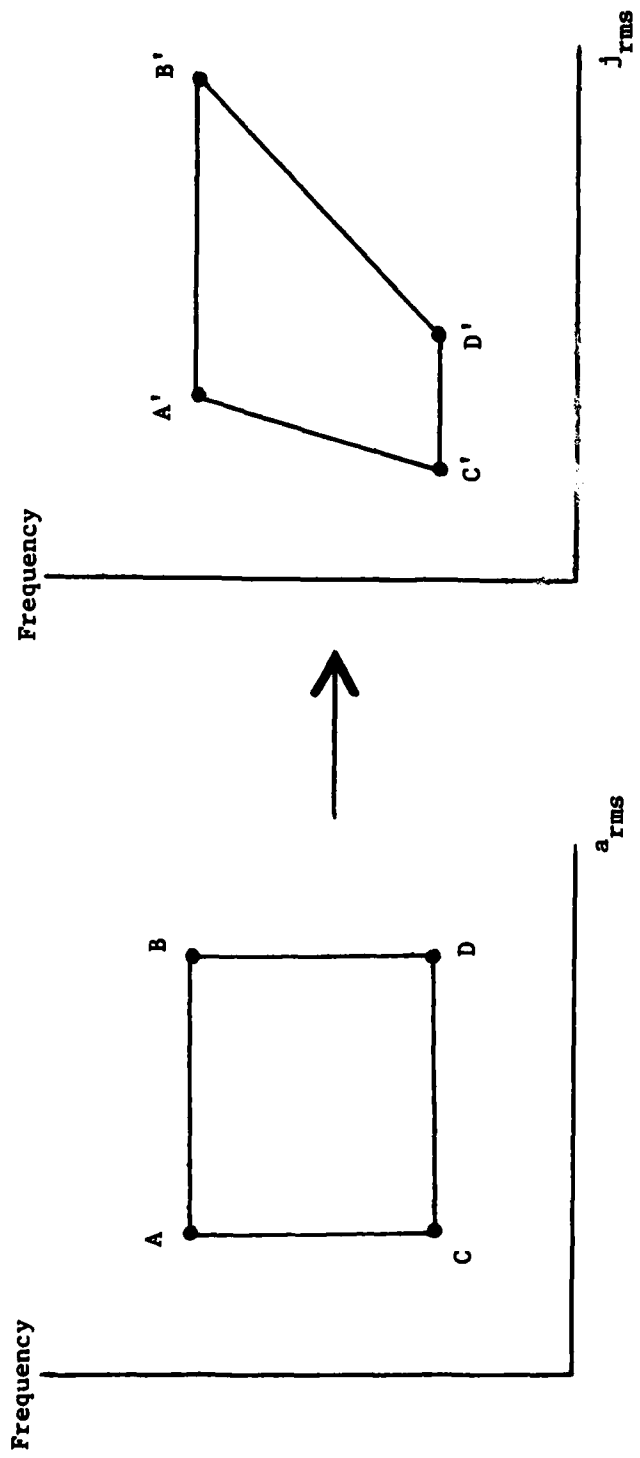


Figure 3: Mapping of a region from one parameter space to another.

In addition to the problem of defining the most appropriate parameters (and the region of interest within the parameter space), a number of trade-offs must be made in the quest for an experimental framework which would provide the most useful information for a fixed cost. As one example, consider two experiments, one of which involves many experimental conditions with few subjects per condition and the other which involves only a few experimental conditions, but with many subjects per condition. In this situation the experimenter is faced with the dilemma of balancing local accuracy against global coverage. Unfortunately, the effects of such trade-offs are not always easily quantifiable. Research on the impact of such considerations in the motion sickness prediction framework is currently in its preliminary stages.

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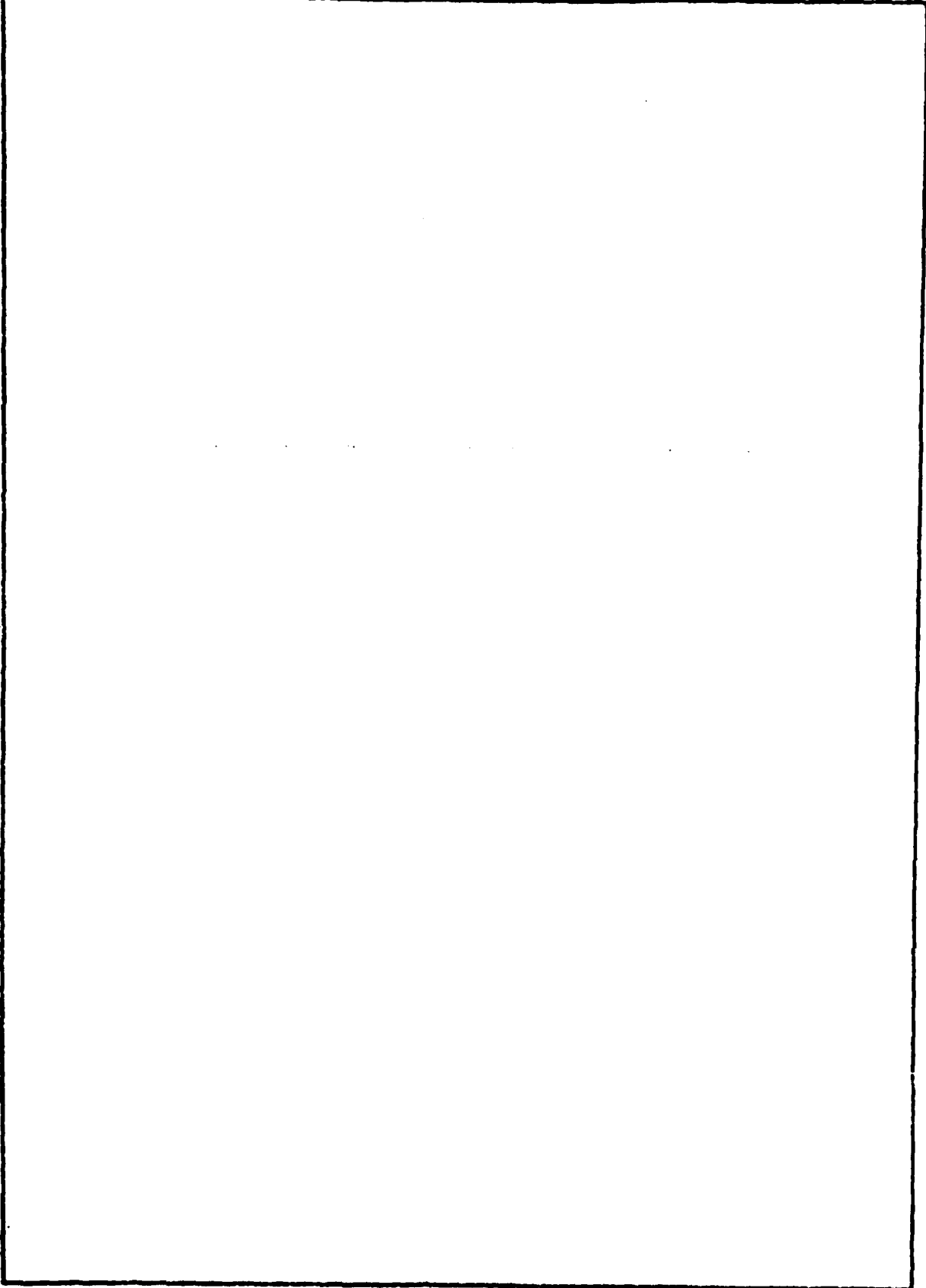
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