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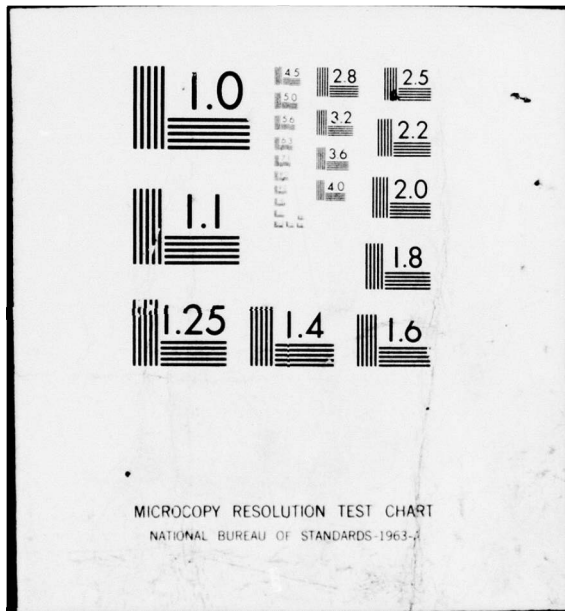
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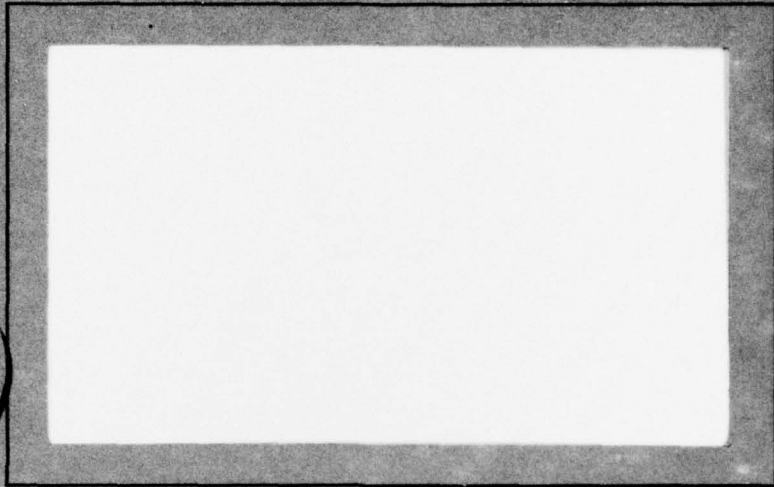
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Applied Research in Statistics - Mathematics - Operations Research

PREDICTION OF MOTION SICKNESS
INCIDENCE: A STATISTICAL
EXAMINATION OF THREE APPROACHES

by

Dennis E. Smith

TECHNICAL REPORT NO. 102-4

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I. INTRODUCTION

Based on a fairly extensive set of empirical data, two motion sickness incidence (MSI) predictive models [4,5] have been developed for subjects exposed to sinusoidal motion. (In essence, MSI is the probability of emesis.) One model [5], which will be referred to as MSI Model I, was developed for a fixed exposure time of two hours. The other model [4], which will be referred to as MSI Model II, includes exposure time as an independent variable. Both of these models appear to yield relatively accurate MSI predictions in those cases where motion is defined by a single sinusoid. However, neither model can be used directly in predicting MSI for ship motion, because that motion tends to be broadband. Needless to say, the problem of obtaining accurate MSI predictions for actual or simulated ship motion must be considered.

This technical report summarizes three approaches for obtaining such predictions, and examines them in light of the observed MSI data from an experiment [3] in which subjects were exposed for two hours to motion produced by the sum of two sinusoids. These approaches will be referred to as (1) the independent effects approach, (2) the Donnelly weighting approach, and (3) the least squares weighting approach. Before these approaches are defined and examined, the two MSI models will be discussed, and the experimental results will be presented.

II. THE MSI MODELS

Because the two MSI models [4,5] as originally stated define an MSI value as a percentage, a multiplicative factor of 100 is required. In this report, however, the alternative (and more convenient) expression of an MSI value as a decimal fraction is used. Thus, an MSI value of .426 in this report is equivalent to an MSI value of 42.6 (which must be regarded as a percentage) derived from an MSI model in its original form.

Both of the MSI models involve the cumulative distribution function Φ of a standard normal random variable, where

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z \exp[-t^2/2] dt$$

MSI Model I [5] predicts MSI for two hour exposure to sinusoidal motion with frequency f and acceleration \bar{a} , which is defined as "... the time integral of the absolute value of acceleration imparted in each half-wave cycle." The MSI prediction is given as

$$\text{MSI} = \Phi[(w - \mu_w)/\sigma_w] \quad (1)$$

where¹

$$w = \log \bar{a}$$

$$\mu_w = \mu_w(f) = .654 + 3.697 \log f + 2.320(\log f)^2$$

$$\text{and } \sigma_w = .40 .$$

¹ In reference [5], the value of σ_w is specified as $.40 \log \bar{a}$. This is evidently a misprint, with the correct value being $\sigma_w = .40$.

Because MSI Model II is expressed in terms of rms acceleration, which is in more common usage than \bar{a} , MSI Model I will be transformed into terms of rms acceleration (denoted by a) for comparison purposes. Thus, in place of the variable $w = \log \bar{a}$, a new variable $x = \log a$ is required.

As indicated in reference [5], the equality $\bar{a} = .901 a$ holds for sinusoidal motion. Therefore, it follows that

$$\begin{aligned} w &= \log \bar{a} \\ &= \log(.901 a) \\ &= \log a + \log(.901) \\ &= x - .045 \end{aligned}$$

Thus, by transforming from variable w to variable x in equation 1, MSI Model I may be expressed in terms of rms acceleration (a) as

$$\text{MSI} = \Phi[(x - \mu_1)/\sigma] \quad (2)$$

where

$$\begin{aligned} x &= \log a \\ \mu_1 &= \mu_1(f) = \mu_w(f) + .045 \\ &= .699 + 3.697 \log f + 2.320(\log f)^2 \\ \text{and } \sigma &= \sigma_w = .40 \end{aligned}$$

MSI Model II [4] predicts MSI for t minutes of exposure to that sinusoidal motion. Its predictions require the definition of the following quantities:

$$\begin{aligned} z &= (x - \mu_2)/\sigma \\ z_t &= (y - \mu_t)/\sigma_t \\ z'_t &= (z_t - \rho z)/(1 - \rho^2)^{1/2} \end{aligned}$$

where

$$x = \log a$$

$$\mu_2 = \mu_2(f) = .87 + 4.36 \log f + 2.73(\log f)^2$$

$$\sigma = .47$$

$$y = \log t$$

$$\mu_t = 1.46$$

$$\sigma_t = .76$$

$$\text{and } \rho = -.75 .$$

The resulting MSI prediction is:

$$\text{MSI} = \phi(z)\phi(z'_t) . \quad (3)$$

III. THREE APPROACHES

Assuming that the two models described in the previous section provide accurate MSI predictions for motion defined by a single sinusoid, a major question is whether these models may be used in some way to yield MSI values for broadband motion. The following sections outline three possible approaches for obtaining such predictions from the MSI models.

A. THE INDEPENDENT EFFECTS APPROACH

The independent effects approach assumes that when motion results from a combination of sinusoids, there is no interaction (i.e., synergism) between them relative to MSI. Let S_i denote a sinusoid with frequency f_i and rms acceleration a_i . (This notation will be used throughout the remainder of this technical report.) Under the assumption of independent effects, it follows in the simplest case of two sinusoids that

$$\begin{aligned} \text{MSI}(S_1, S_2) &= \text{MSI}(S_1) + [1 - \text{MSI}(S_1)] \text{MSI}(S_2) \\ &= \text{MSI}(S_1) + \text{MSI}(S_2) - \text{MSI}(S_1)\text{MSI}(S_2) \end{aligned} \quad (4)$$

where $\text{MSI}(S_i)$ denotes the MSI for the single sine wave S_i and $\text{MSI}(S_i, S_j)$ denotes the MSI for a combination of the two sine waves S_i and S_j .

B. THE DONNELLY WEIGHTING APPROACH

Donnelly [1] suggested that a qualitative assessment of MSI for broadband motion may be made by weighting all frequencies back to a single

frequency f_o . He proposed defining f_o to be the "most critical frequency", that is, the frequency which results in the largest MSI prediction. Based on this approach, a weighting function w_i may be defined such that

$$MSI(S_i) = MSI(S_o)$$

where $a_o = a_i w_i$.

To determine a motion sickness rating when a number of frequencies are present, Donnelly used the weighted rms acceleration

$$a_o = (\sum_i w_i^2 a_i^2)^{1/2}$$

and the frequency f_o in a single sinusoid MSI model. It should be noted that he stressed that this motion rating should be considered qualitative rather than quantitative. However, there is little doubt that there will often be the temptation to use his weighting procedure as a quantitative measure of MSI.

Although Donnelly emphasized this weighting approach for data expressed in 1/3 octave format, there is nothing in his derivation that restricts it to this situation. For motion which is defined by the sum of two sinusoids, this approach, used quantitatively, would define

$$MSI(S_1, S_2) = MSI(S_o) \quad (5)$$

where f_o is the most critical frequency

and

$$a_o = (w_1^2 a_1^2 + w_2^2 a_2^2)^{1/2}$$

The weights used by Donnelly were

$$\log w_i = -2.73(.77 + \log f_i)^2$$

with f_o defined to correspond to the weight $w_o = 1.00$ (i.e., $f_o = .170$ Hz). These weights, however, were evidently based on a partially developed version of MSI Model II.

For the two models considered in this technical report, the weights corresponding to each must be defined. For MSI Model I (equation 2),

$$\begin{aligned}\mu_1 &= \mu_1(f_i) \\ &= .699 + 3.697 \log f_i + 2.320(\log f_i)^2 \\ &= -.774 + 2.320(.797 + \log f_i)^2\end{aligned}$$

from which it follows that

$$\log w_i = -2.320(.797 + \log f_i)^2 \quad (6)$$

and $f_o = .160$ Hz .

For MSI Model II (equation 3),

$$\begin{aligned}\mu_2 &= \mu_2(f_i) \\ &= .87 + 4.36 \log f_i + 2.73(\log f_i)^2 \\ &= -.871 + 2.730(.799 + \log f_i)^2\end{aligned}$$

from which it follows that

$$\log w_i = -2.730(.799 + \log f_i)^2 \quad (7)$$

and $f_o = .159$ Hz .

C. THE EMPIRICAL LEAST SQUARES WEIGHTING APPROACH

The third approach, like the one described previously, also weights all frequencies back to a single frequency f_o . However, whereas the previous approach specifies the weights w_i a priori based on an existing sinusoid model, the empirical least squares weighting approach determines them a posteriori from experimental MSI data resulting from motion corresponding to complex waveforms. Thus, this approach, unlike the other two, requires access to MSI data from motion that is other than sinusoidal. The following paragraph summarizes the empirical least squares weighting approach.

Given motion described by k frequencies f_1, \dots, f_k and corresponding rms accelerations a_1, \dots, a_k , determine (from the sinusoid MSI model) the value of a_o that corresponds to the observed MSI for frequency f_o . Then set

$$w_1^2 a_1^2 + \dots + w_k^2 a_k^2 = a_o^2 \quad (8)$$

By considering $n \geq k$ of these cases (for the same k frequencies), values of the weights may be determined by solving the resulting set of equations by least squares. Thus, if an MSI estimate is required for motion described by the same k frequencies, but not necessarily the same accelerations, the values of w_i may be used to predict (via equation 8) the equivalent a_o . A predicted MSI value may then be obtained by substituting a_o and f_o in the appropriate MSI model.

IV. EXPERIMENTAL RESULTS AND PREDICTIONS

Table 1 summarizes the results of an experiment [3] involving motion produced by the sum of two sine waves. In addition to providing observed MSI data, this table lists the frequencies and rms accelerations which were reported in this experiment. (It will be noted that results are given for conditions II, III, IV and V only, since condition I corresponded to a single sinusoid used as a control.) These reported frequencies and accelerations are the ones used in this technical report in the examination of the three approaches for obtaining MSI predictions for motion produced by complex waveforms.

Table 2 summarizes the MSI predictions obtained by applying each of the three approaches to the frequency and acceleration data of the four conditions in Table 1. As an example of how the entries in this table were derived, the calculation of predicted MSI values for condition II based on MSI Model I is outlined in the following paragraphs. MSI predictions for the other conditions and/or for MSI Model II (using $t = 120$ minutes) may be obtained in a similar manner.

Condition II is defined by motion which is the sum of two sine waves S_1 and S_2 . The corresponding frequencies and rms accelerations are

$$\begin{array}{ll} f_1 = .16 & a_1 = .14 \\ f_2 = .32 & a_2 = .15 \end{array}$$

For MSI Model I (equation 2), it follows that for S_1 ,

	Condition				
	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	
Fundamental:					
Frequency	.16	.16	.17	.16	
rms Acceleration	.14	.14	.12	.08	
Harmonic:					
Frequency	.32	.33	.50	.33	
rms Acceleration	.15	.14	.29	.26	
No. of Subjects	32	31	31	32	
Emesis	16	20	21	25	
No Emesis	16	11	10	7	
Observed MSI	.500	.645	.677	.781	

Table 1: Results of the Two Sine Wave Experiment

Predicted $MSI(S_1, S_2)^*$

<u>Condition</u>	<u>Observed $MSI(S_1, S_2)$</u>	<u>Independent Effects</u>	<u>Donnelly Weighting</u>	<u>Empirical Least Squares Weighting</u>
II	.500	.569(.600)	.498(.528)	.599(.600)
III	.645	.547(.577)	.485(.515)	.574(.575)
IV	.677	.485(.487)	.429(.444)	-----**
V	.781	.572(.586)	.511(.518)	.780(.780)

*The first value is obtained using MSI Model I (equation 2).
The value in parentheses is obtained using MSI Model II (equation 3).

**See text.

Table 2: Predicted MSI Results

$$\begin{aligned}
x &= \log(.14) \\
&= -.854 \\
\mu &= \mu_1(.16) \\
&= .699 + 3.697 \log(.16) + 2.320[\log(.16)]^2 \\
&= -.774 .
\end{aligned}$$

so that

$$\begin{aligned}
\text{MSI}(S_1) &= \Phi[(-.854 + .774)/.40] \\
&= \Phi(-.200) \\
&= .421
\end{aligned}$$

Similarly,

$$\begin{aligned}
\text{MSI}(S_2) &= \Phi[(-.824 + .562)/.40] \\
&= \Phi(-.655) \\
&= .256
\end{aligned}$$

Therefore, from the independent effects approach used in conjunction with Model I, the predicted MSI (from equation 4) is

$$\begin{aligned}
\text{MSI}(S_1, S_2) &= .421 + .256 - (.421)(.256) \\
&= .569
\end{aligned}$$

Based on the a priori weighting (equation 6) for MSI Model I where $f_o = .160$, it follows that

$$\begin{aligned}
\log w_1 &= -2.320[.797 + \log(.16)]^2 \\
&= -2.320(.797 - .796)^2 \\
&= 0
\end{aligned}$$

$$\begin{aligned}
 \log w_2 &= -2.320[.797 + \log(.32)]^2 \\
 &= -2.320(.797 - .495)^2 \\
 &= -.2116
 \end{aligned}$$

From this it follows that

$$w_1 = 1.000$$

$$w_2 = .614$$

and

$$\begin{aligned}
 a_o &= [(1.000)^2(.14)^2 + (.614)^2(.15)^2]^{1/2} \\
 &= .168
 \end{aligned}$$

The predicted MSI (equation 5) from the Donnelly weighting approach is calculated by using MSI Model I (equation 2) where

$$\begin{aligned}
 x &= \log a_o \\
 &= \log(.168) \\
 &= -.775
 \end{aligned}$$

$$\begin{aligned}
 \mu_1 &= \mu_1(f_o) \\
 &= \mu_1(.160) \\
 &= -.774
 \end{aligned}$$

so that

$$\begin{aligned}
\text{MSI}(S_1, S_2) &= \text{MSI}(S_0) \\
&= \Phi[(-.775 + .774)/.40] \\
&= \Phi(-.003) \\
&= .498 .
\end{aligned}$$

In order to apply the least squares weighting approach, a set of observed MSI results corresponding a number of cases of motion described by the same k frequencies is required. Since each of conditions II, III, and V correspond (approximately) to frequencies $f_1 = .16$ and $f_2 = .33$, this approach may be applied to the data from these three conditions.

The observed MSI for these three conditions were .500, .645, and .781, respectively, for which the corresponding values of a_0 must be determined. From MSI Model I (equation 2), the value of a_0 corresponding to an observed MSI value MSI_0 is given by

$$\Phi[(x - \mu)/\sigma] = \text{MSI}_0$$

where

$$x = \log a_0$$

$$\mu = \mu_1(f_0)$$

$$= \mu_1(.160)$$

$$= -.774$$

$$\sigma = .40$$

The resulting solutions are:

$$a_o = .168 \text{ for } MSI_o = .500$$

$$a_o = .237 \text{ for } MSI_o = .645$$

$$a_o = .344 \text{ for } MSI_o = .781$$

Therefore, based on the least squares weighting approach (equation 8), the following set of equations results:

$$w_1^2(.14)^2 + w_2^2(.15)^2 = (.168)^2$$

$$w_1^2(.14)^2 + w_2^2(.14)^2 = (.237)^2$$

$$w_1^2(.08)^2 + w_2^2(.26)^2 = (.344)^2$$

The least squares solution yields the weights¹

$$w_1 = (.325)^{1/2}$$

and

$$w_2 = (1.708)^{1/2}$$

By using these estimated weights for f_1 and f_2 , the predicted value of a_o to be used in conjunction with $f_o = .160$ is given by

$$a_o = (w_1^2 a_1^2 + w_2^2 a_2^2)^{1/2}$$

These values of a_o and f_o would then be used in MSI Model I (equation 2) to

¹ For comparison, the weights obtained using MSI Model II are $w_1 = (.153)^{1/2}$
 $w_2 = (1.548)^{1/2}$.

obtain predictions of MSI. For example, based on these weights the predicted MSI for condition II would correspond to

$$\begin{aligned} a_o &= [.325(.14)^2 + 1.708(.15)^2]^{1/2} \\ &= .212 \end{aligned}$$

Thus,

$$\begin{aligned} x &= \log a_o \\ &= \log(.212) \\ &= -.674 \end{aligned}$$

$$\begin{aligned} \mu_1 &= \mu_1(f_o) \\ &= \mu_1(.160) \\ &= -.774 \end{aligned}$$

so that

$$\begin{aligned} \text{MSI}(S_1, S_2) &= \Phi[(-.674 + .774)/.40] \\ &= \Phi(.250) \\ &= .599 \end{aligned}$$

V. A STATISTICAL EXAMINATION OF THE MSI PREDICTIONS

In this section the observed data will be used to examine the validity of the three approaches which have been discussed. Under the hypothesis that a given approach results in the prediction of the true MSI value (denoted by MSI_0) for a duration of two hours under specific motion conditions,

$$z = \frac{x - n(MSI_0)}{\sqrt{n(MSI_0)(1 - MSI_0)}}$$

would be approximately distributed as a standard normal random variable, where

n = the number of subjects observed under this motion condition

and

x = the number of subjects who were overcome by emesis within two hours.

Based on the observed values of z , a test of the hypothesis may be made using the data summarized in Table 1 and Table 2. For example, the results¹ for the independent effects assumption using MSI Model I are:

$$\text{For condition II, } z = \frac{16 - 32(.569)}{\sqrt{32(.569)(.431)}} = -.788, p = .431$$

$$\text{For condition III, } z = \frac{20 - 31(.547)}{\sqrt{31(.547)(.453)}} = 1.098, p = .272$$

¹

It should be noted that since a two-sided test is appropriate here, the observed p-values reflect this.

$$\text{For condition IV, } z = \frac{21 - 31(.485)}{\sqrt{31(.485)(.515)}} = 2.144, p = .032$$

$$\text{For condition V, } z = \frac{25 - 32(.572)}{\sqrt{32(.572)(.428)}} = 2.392, p = .017$$

Thus, the hypothesis is rejected for condition IV and V at a 5% significance level. It should be noted, however, that when a number of tests are made, the problem of multi-test bias arises. Multi-test bias refers to the phenomenon that as the number of tests made increases, the chances of making at least one type I error also increases. To avoid this sort of contamination, it is desirable to use a single overall test.

Such a test, developed by Fisher [2], may be based on the statistic

$$X = -2 \sum_{i=1}^N \ln(p_i)$$

where p_i denotes the probability of the observed outcome of the i^{th} individual test in a total of N tests. Under the hypothesis, the statistic X has an approximate Chi-square distribution with $2N$ degrees of freedom.

For the data under consideration,

$$\begin{aligned} X &= -2[\ln(.431) + \ln(.272) + \ln(.032) + \ln(.017)] \\ &= 19.348 \quad (p = .014) \end{aligned}$$

Thus, there is convincing evidence that the independent effects approach, based on the single sine wave MSI Model I, cannot be used to predict MSI for a combination of sine waves. It follows, therefore, that either (a) the single sine wave MSI model is incorrect, (b) the independent effects approach is incorrect, or (c) both are incorrect.

Tests involving the Donnelly weighting approach and/or MSI Model II may be carried out in a similar manner. Table 3 summarizes the results of these tests. As can be seen from this table, the experimental results shed serious doubt on the usefulness of both the independent effects approach and the Donnelly weighting approach as methods of predicting MSI. Tests of the least squares weighting approach are inappropriate and therefore not included in the table. For that approach, extremely good agreement between observed and predicted MSI values is to be expected because two weights were estimated based on a total of only three observations. Furthermore, predicted MSI values would be compared with the observed MSI values from which the weights had been estimated. A valid test of this approach would require a larger set of observed data.

It is interesting to note, however, that the weights estimated by this approach are reversed in magnitude from the weights determined by the approach suggested by Donnelly. Whereas the weight his approach assigns to a frequency is a monotonic decreasing function of the distance of that frequency from approximately .160 Hz, the weight assigned to .330 Hz by the least squares approach is greater¹ than the weight assigned to .160 Hz.

Not enough data exists with which to test the use of MSI predictions from the Donnelly weighting approach as qualitative (i.e., ranking), rather than quantitative, indices. However, the observed and predicted MSI values listed in Table 2 indicate that the Donnelly approach ranks (in order of increasing MSI) conditions IV, III, II, V based on Model I, and conditions IV, III, V, II based on Model II, while the observed results indicate the ranking II, III, IV, V, instead.

1

Two times greater using MSI Model I and over three times greater using MSI Model II.

<u>Condition</u>	<u>Independent Effects Approach*</u>	<u>Donnelly Weighting Approach*</u>
II	z = -.788(-1.155) p = .431(.248)	z = .023(-.317) p = .982(.751)
III	z = 1.098(.768) p = .272(.442)	z = 1.784(1.450) p = .074(.147)
IV	z = 2.144(2.121) p = .032(.034)	z = 2.795(2.616) p = .005(.009)
V	z = 2.392(2.242) p = .017(.025)	z = 3.058(2.980) p = .002(.003)
Overall	X = 19.348(18.570) p = .014(.018)	X = 27.970(25.548) p = .001(.001)

* The first value is obtained using MSI Model I (equation 2). The value in parentheses is obtained using MSI Model II (equation 3).

Table 3: Summary of Statistical Tests

VI. SUMMARY AND DISCUSSION

Although only a small amount of empirical MSI data exists for motion other than that produced by a single sinusoid, that data provides a strong indication that neither the independent effects approach nor the Donnelly weighting approach produces accurate MSI prediction. (Judgment about the least squares weighting approach must be reserved until enough empirical data exists to provide an adequate test.)

It should be pointed out that the statistical analysis carried out in this technical report was approximate. Although the analysis did use the pair of observed frequencies and their associated rms accelerations as stated in reference [3], use of the actual frequency spectrum might have produced slightly different results. Furthermore, the analysis assumed that the predictions obtained from MSI Model I or II were true MSI values, devoid of variability. Since the development of each of these models was based on a relatively large number of observations, the effects of such variability should be negligible. In any event, with results as extreme as those observed, it is highly doubtful that these two approximations would have changed the conclusions which were reached.

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20. Abstract (continued)

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Although only a small amount of empirical MSI data exists for motion other than that produced by a single sinusoid, this data provides strong statistical evidence that the two approaches based on the single sinusoid models fail to produce accurate predictions. Statistical judgments about the least squares weighting approach must be reserved until enough empirical data exists to provide an adequate test.

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