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Session 3aNS: Noise

3aNS6. Significant infrasound levels a previously unrecognized contaminant in landmark motion sickness studies

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Airborne Infrasound at any given point can be accurately described as fluctuations or cyclic changes in the local barometric pressure. Variations in a motion sickness test subject's elevation, result in fluctuations in the surrounding barometric pressure by a similar amount to that experienced on a ship in high seas. Cyclic variation in the lateral or linear velocity of a subject in a vehicle or platform in atmospheric air may also be subject to infrasonic pressure fluctuations due to the Bernoulli principle and associated with vortex shedding effects. Calculations presented demonstrate that in at least one landmark study (McCauley et al 1976) test subjects were exposed to infrasonic sound pressure levels in excess of 105 dB at discrete frequencies between 0.063 Hz and 0.7Hz. The infrasonic sound pressure level necessarily present in cyclic motion in free atmospheric air does not appear to have been accounted for as a nausea influencing factor in the McCauley et al (1976) motion sickness studies.

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Introduction

This study is a relatively brief examination of the potential relationship between infrasound and nauseogenicity, with respect to previous work that has been carried out on Motion Sickness by McCauley et al. 1976 (Ref 1) and others (Ref 3,4,5,6).

According to comments in reference 8 the potential for infrasound to cause nausea was probably just becoming known at the time that some very substantial research on motion sickness was being performed. However, infrasonic pressure fluctuations were apparently not considered in any of the motion sickness studies of the day (Ref 1, 3, 4, 5, 6).

It can, however, be shown that motion in a free atmosphere will result in pressure fluctuations around the moving bodies and this is particularly well defined for vertical motion, because the Geopotential Pressure, more commonly known as Barometric Pressure, is an inverse function of altitude. The Bernoulli principle, which relates velocity and pressure to motion in a gas or fluid may also result in infrasonic pressures being developed, particularly in the case where vortex shedding or turbulence may be present in linear motion, however this study considers only the infrasound generated as a result of cyclic vertical displacement.

Vertical displacement in a cyclic pattern will result in the subject involved in the motion being exposed to a variation in the barometric pressure as an inverse function of the vertical displacement. Motion sickness trials have not taken this potential biodynamic stimulus into account when investigating vertical motion sickness and nausea, but appear to have paid close attention to the acceleration and frequency effects.

Background

In more recent times, infrasound has been implicated in various complaints related to discomfort and sometimes nausea, and have recently been directly compared to motion sickness symptoms (Ref 7, 8). The well-known and highly cited study, led by Michael E. McCauley in the 1970’s (Ref 1), has been examined. Data provided in the report on test frequencies and acceleration levels have been used to back-calculate the vertical displacements and resulting infrasonic pressures to which the many test subjects were exposed during the investigation into the relationship between acceleration, frequency and Motion Sickness Index (MSI). It was a partial aim of the McCauley team to validate and improve a model for MSI that had been partially developed from data generated in previous investigations (Ref 3, 4, 5, 6).

Infrasonic Pressure Magnitudes

According to the tables of reference 2, the variation in barometric pressure for a change in vertical position of 1000 Feet is 0.53 PSI, or equivalently a change of 304.8 meters will result in a pressure change of 3654.2 Pascal's, which is about 12 Pa/meter. The whole body of a subject undergoing a +/-1 meter vertical displacement at any frequency is essentially being exposed to an infrasonic sound pressure (at the same frequency) of about 8.5 Pascal's RMS. In un-weighted decibel terms this is equal to about 112dB.

Back-calculation of infrasonic pressure

All of the test point motion generator settings used to develop the McCauley model (which were tabulated in appendix B of Ref 1) were used to calculate the vertical displacements the test subjects were exposed to, as a method of establishing the magnitude of infrasonic pressures the motion sickness subjects were exposed to during the testing that simultaneously recorded nausea (actually emesis).

The vertical displacements were calculated by extracting the second integral of acceleration with reference to frequency (1.1).

Figure 1 is a 3D bar graph of the results of the infrasonic pressure calculations for all points provided in Ref 1 appendix B. The 0.166Hz line is of particular interest in the graph of figure 1, since it is the highest infrasound pressure at any given acceleration level except for a single point at .083Hz (5CPM) where a very low subject response was measured.

A 3D graph of the McCauley model output is shown (Fig 2) in comparison to the back-calculated infrasonic pressure values from the various test points used to develop the McCauley model. The McCauley et al. model was developed based on the nauseogenic response of about 2000 test subjects. The 3D graph scanned from Ref 1 (left image of Fig 2), shows an exaggerated nauseogenicity at exactly the frequency which would have consistently produced the highest infrasonic pressure values for a given acceleration, based on the motion generator settings used during the study. The McCauley study did show a response at a single point below 0.167Hz frequency which was a 5% MSI at 0.083Hz after 115 minutes. The general trend indicated by the McCauley et al. MSI model is clearly present in the infrasound pressure graph of figure 1.

The test subject displacement is calculated by:

$$D = \frac{a}{\omega^2} \qquad 1.1$$

where: D: is displacement

a: is acceleration in g's: 1.0 g $= 9.806 \frac{m}{Sec^2}$

ω: is $2\pi f$: f is the frequency of the acceleration in Hz.

The infrasonic pressure magnitude p is calculated by:

$$p = 11.99 \frac{a}{\omega^2} \qquad 1.2$$

where:

p: is the cyclic pressure change in Pascal's due to a cyclic change in vertical position.

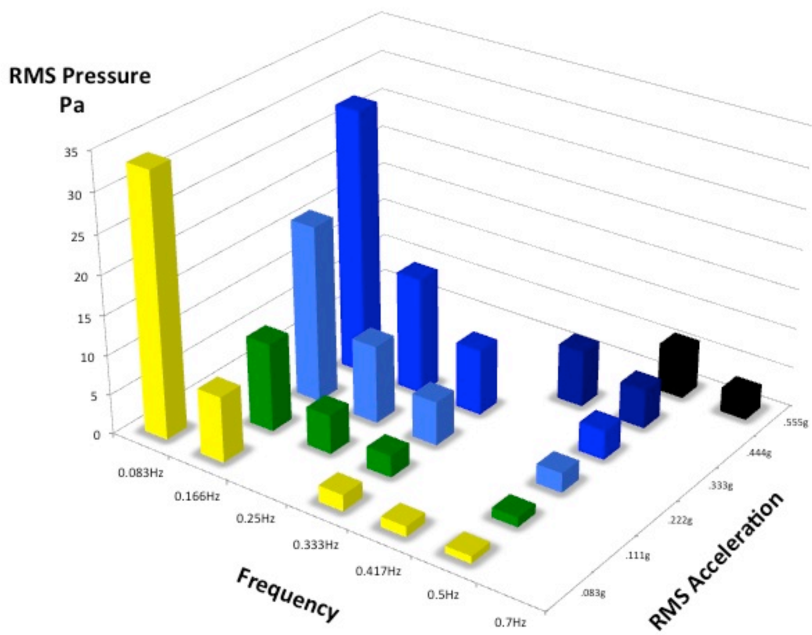
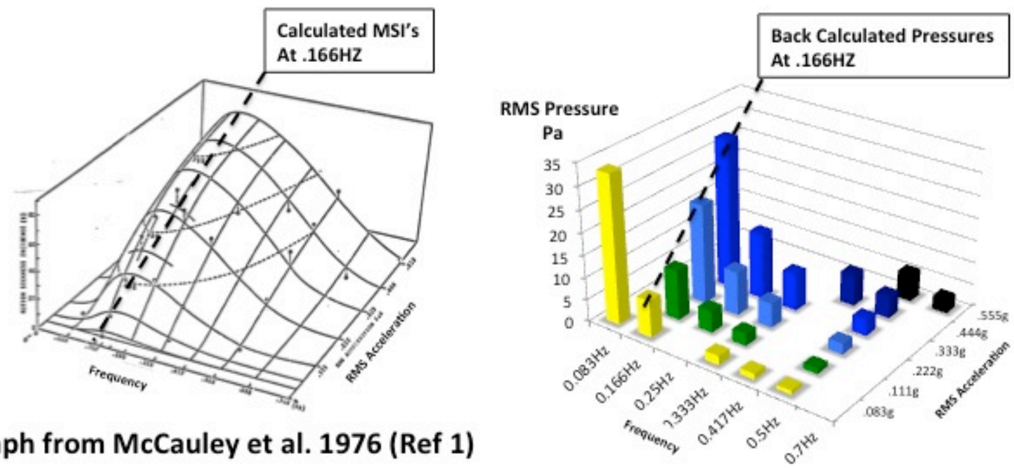


Figure 1

Figure 1 represents the results of back-calculating the vertical displacement and the resulting infrasound pressures (y axis), from the frequency (x axis) and acceleration data (z axis) provided in appendix B of ref 1, by applying equation 1.2 which converts cyclic vertical displacement into the resulting infrasonic pressure.

Comparison between the McCauley MSI model, and the Back Calculated Pressures from the McCauley data (data which was used to develop the McCauley model for MSI)



Graph from McCauley et al. 1976 (Ref 1)

The above comparisons between the McCauley model for MSI based on acceleration & Frequency (Left), to the back calculated Pressures (Right), based on the data points used to develop the McCauley MSI model, clearly show that the maximum Nauseogenicity at 0.166Hz is coincident with the maximum infrasonic pressure levels that the test subjects were exposed to above .09Hz (5.4 CPM).

Figure 2

A model for MSI based on Infrasonic Pressure alone

The strong similarity (Fig 2) between the MSI of Ref 1 and the back-calculated infrasonic pressure data at the most sensitive frequency (0.166Hz) and the general similarity of the trends at all frequencies between the data sets, prompted a study to evaluate the potential accuracy of a simple model developed here to express MSI as a function of exposure to infrasonic pressure only (no acceleration motion), as given by:

$$MSI = kP\sqrt{f}\,\ln(t) \qquad 2.1$$

Where:
P is the RMS pressure Pa
f is frequency of displacement
t is the exposure time in minutes
k is a proportionality factor of 1.8
MSI is Motion Sickness Index in %

Equation 2.1 was developed with the availability of the MSI response data provided in Ref 1 appendix B, and the understanding provided by McCauley et al. that the log of exposure time appeared to have a material influence on MSI.

Figure 3 and figure 4 are graphic results of a comparison between the simple infrasonic pressure based MSI model of equation 2.1 and real MSI results from Ref 1 appendix B.

Figure 3 is the graph of the complete data set from Ref 1 appendix B that was used to develop the McCauley et al. model, figure 4 is the same data except with the 0.167Hz and below data points removed, figure 5 is a similar graph showing the McCauley et al. predictions versus the observed MSI.

The 0.167Hz data points were excluded in the figure 4 graph because close examination of the MSI data (Fig 6 and Fig 7) seems to reveal a discontinuity when comparing observed MSI to pressure. The discontinuity is limited to the 0.167Hz data (this is based on the assumption that the presented hypothesis is correct). The apparent "resonance" at 0.166Hz shown in the McCauley 3D graph (Fig 2), also does not seem to be the cause of the discontinuity, since the McCauley et al. data is lower at the 0.166Hz frequency than the infrasonic pressure model (2.1) predicts it would be. The possibility that the test chamber leakage rate suddenly changed as the g level was increased from 0.111g to 0.222g (the response in MSI jumped up by a factor of at least 10 at this transition), or that an undetected Helmholtz resonance was altered cannot be discounted. The McCauley et al. data table did not include MSI data at the 15minute exposure interval for the 0.111g acceleration level, so it may have actually been zero (i.e. no MSI response from test subjects).

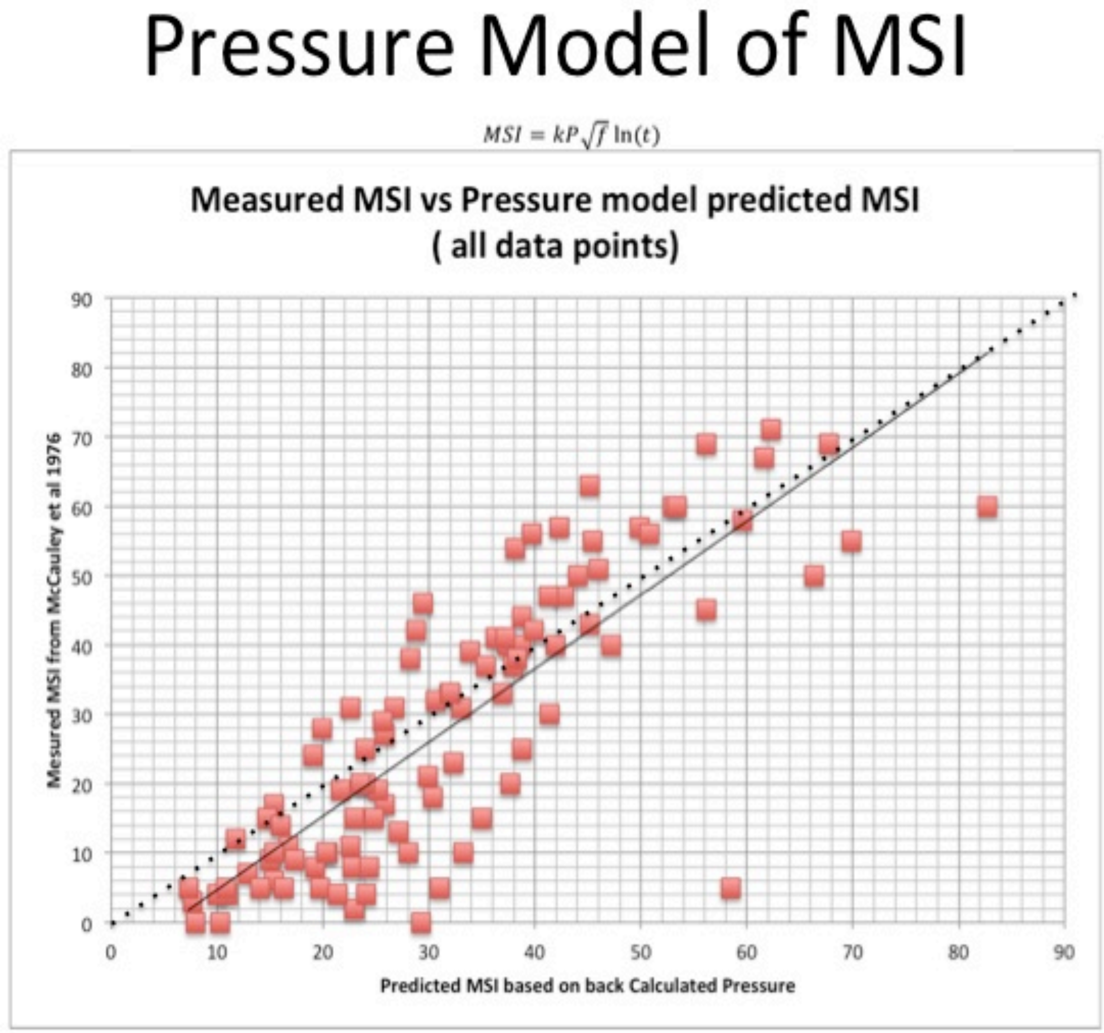


Figure 3

Figure 3 is a graph of all MSI experimental data provided in appendix B of reference 1 plotted against the infrasonic pressure model developed here.

The dotted line on the graph is the pressure model predictions (based on subject exposure to infrasonic pressure alone). The solid line is the mean value of all data points based on infrasonic pressure.

It was noticed during examination of the data as a function of calculated pressure, that an apparent discontinuity was exhibited in the 0.167Hz data alone (ref fig 6). The data is re-plotted in Figure 4 with the 0.167Hz and below data points excluded.

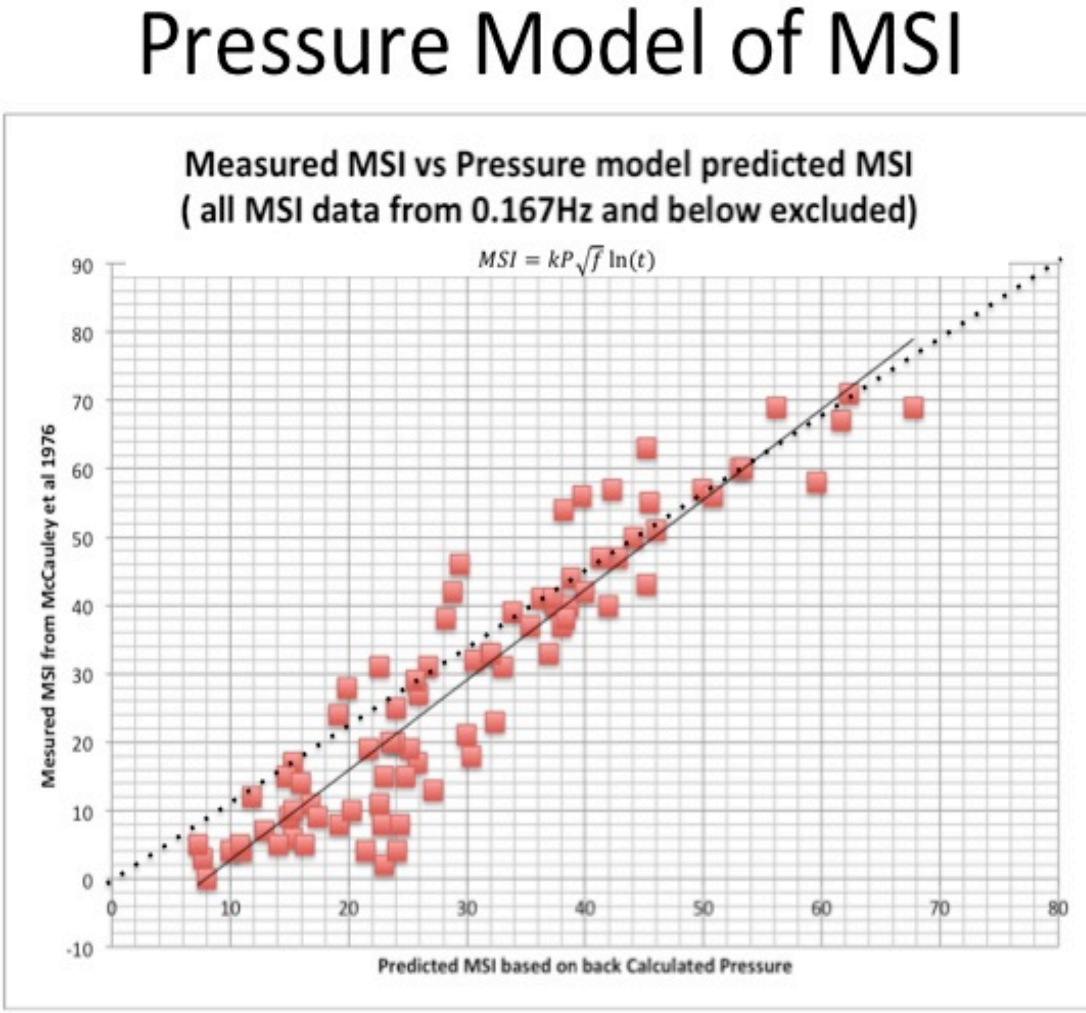
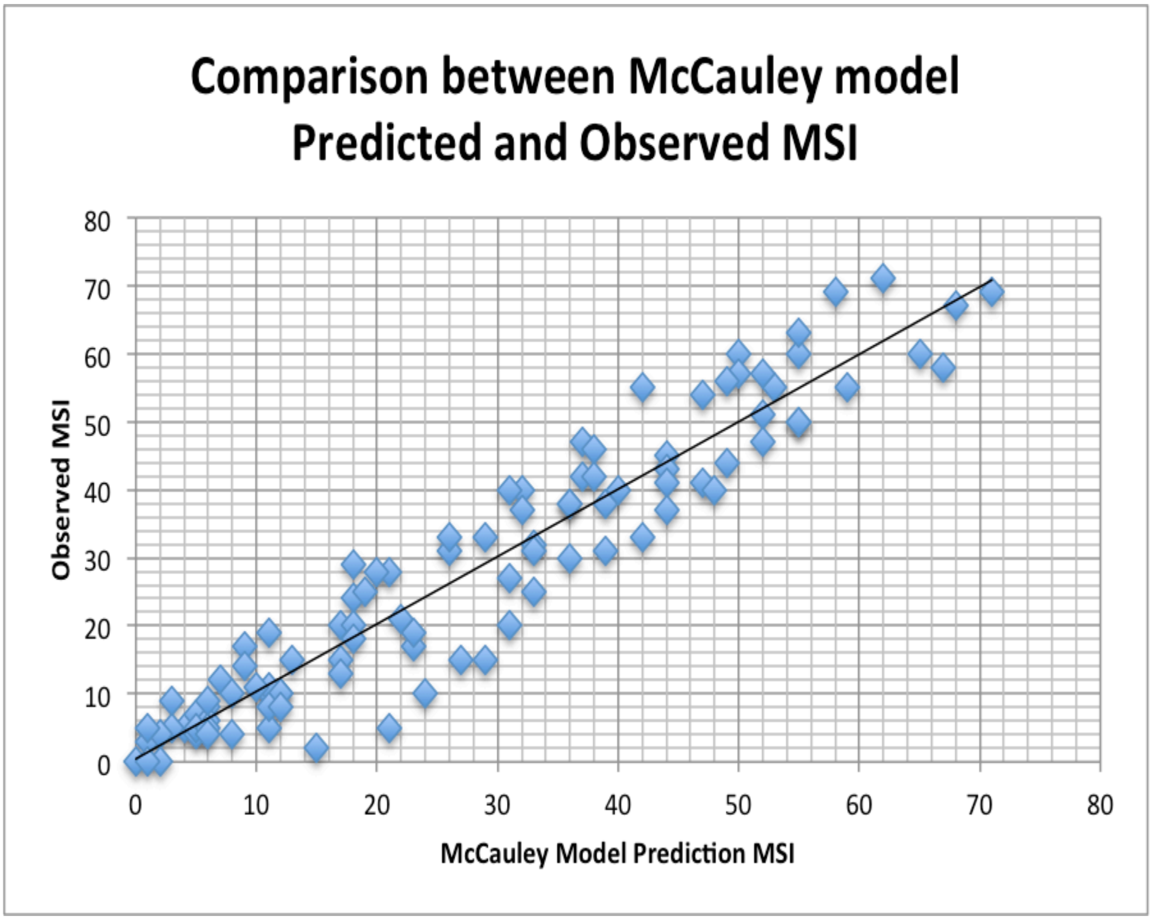


Figure 4

Figure 4 is a graph of all MSI experimental data provided in appendix B of reference 1, except data at 0.167 Hz and below have been excluded. The experimental MSI responses are plotted against the pressure model developed here.
The dotted line on the graph is the pressure model prediction (based on subject exposure to infrasonic pressure alone). The solid line is the mean value of all data points included, based on the pressure model.



Model Proposed by McCauley et al. for a 2 Hour exposure

$$MSI = \frac{100}{2\pi\sigma_a\sigma_t\sqrt{1-\rho^2}}\int_{-\infty}^{\log_{10}a}\int_{-\infty}^{\log_{10}t}\exp\left\{\frac{-1}{2(1-\rho^2)}\left[\left(\frac{x-\mu_a(f)}{\sigma_a}\right)^2 - 2\rho\left(\frac{x-\mu_a(f)}{\sigma_a}\right)\left(\frac{y-\mu_t}{\sigma_t}\right)+\left(\frac{y-\mu_t}{\sigma_t}\right)^2\right]\right\}dy\,dx = 100\,\Phi(a,t) \quad (1)$$

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Pressure Model for MSI

Implied by the back calculation of pressure from McCauley et al. test data based on the assumption that MSI is due only to Infrasonic pressure fluctuations.

$$MSI = 1.8\,p\,\sqrt{f}\,\ln(t)$$

: where MSI is Motion Sickness Index %
P is RMS pressure in Pascal's (Pa)
f is fluctuation frequency Hz
t is the of exposure time in minutes

Figure 5

The graph of figure 5 shows the comparison between the McCauley et al. model predicted MSI (x axis) versus the observed MSI values (Y axis). Below the graph is a comparison between the McCauley et al. MSI model and the pressure MSI model.

Potential Discontinuity in data in 0.167Hz data set

A potential discontinuity is revealed when analyzing MSI data as a function of back-calculated pressure related to vertical motion versus MSI divided by f^0.5 * log (t), which is effectively an alternate method of back calculation of un scaled pressure based on the hypothesis presented.

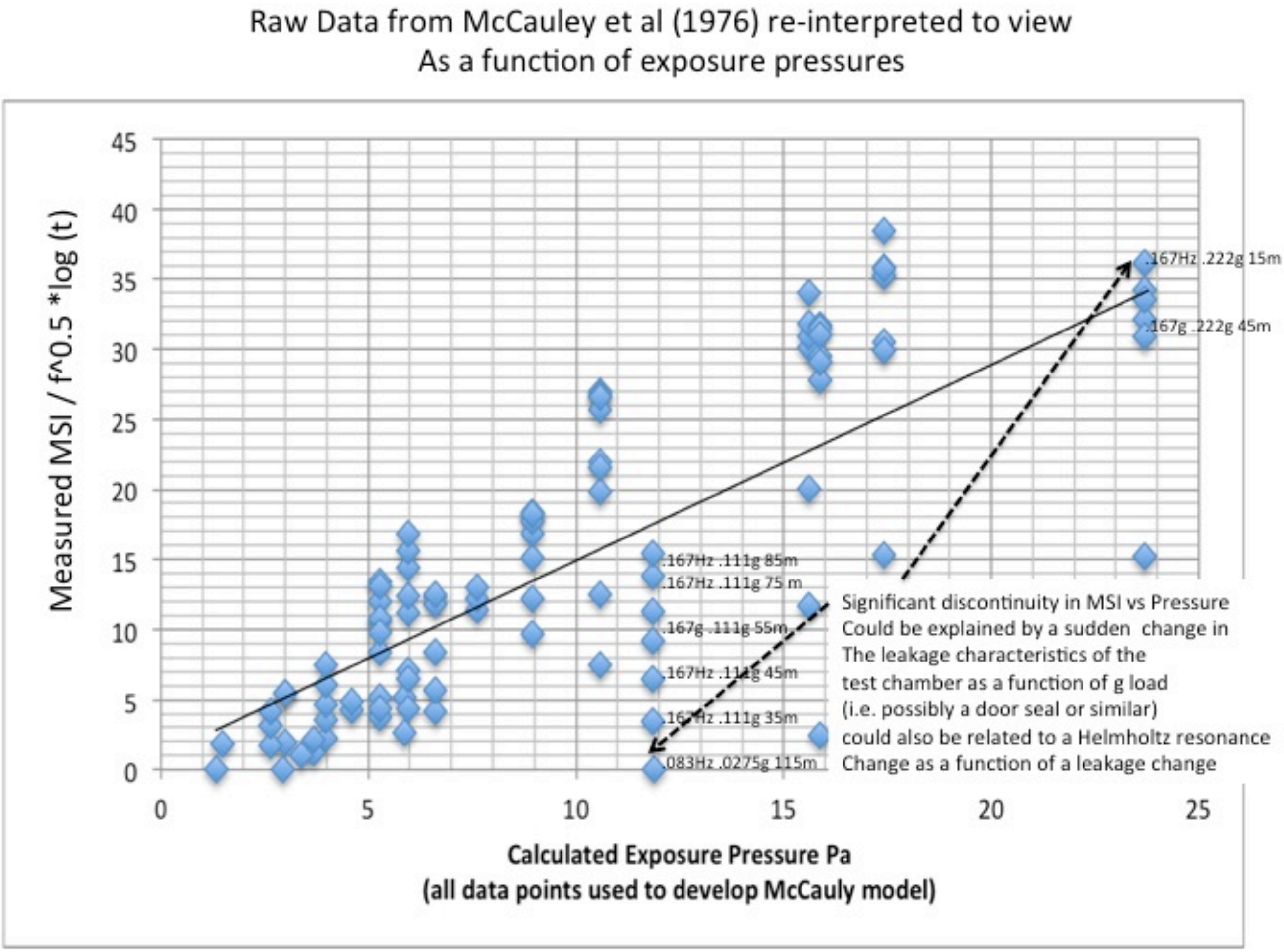

Figure 6

Figure 6 is a graph of all MSI data provided in ref 1 appendix B, which were used to develop the McCauley model for MSI and were used here to calibrate the Pressure model for MSI. The MSI data has been divided by log time and square root of frequency. A discontinuity seems to show up in the MSI response data from the 0.167 Hz data group (no 15 minute point at .111g and .167 Hz included in the McCauley et al data).

The MSI response jumps up by a factor of ten between the 0.167 Hz at 0.111g and the 0.167Hz at 0.222g (see arrows on graph).

This result could be explained by a sudden increase in the leakage rate of the test subject compartment of the motion generator at 0.222g, or possibly a change in a Helmholtz resonance due to a change in leakage characteristics at one of the conditions. Since the equipment was not designed with pressure response to the environment as a design parameter, this explanation may be reasonable.

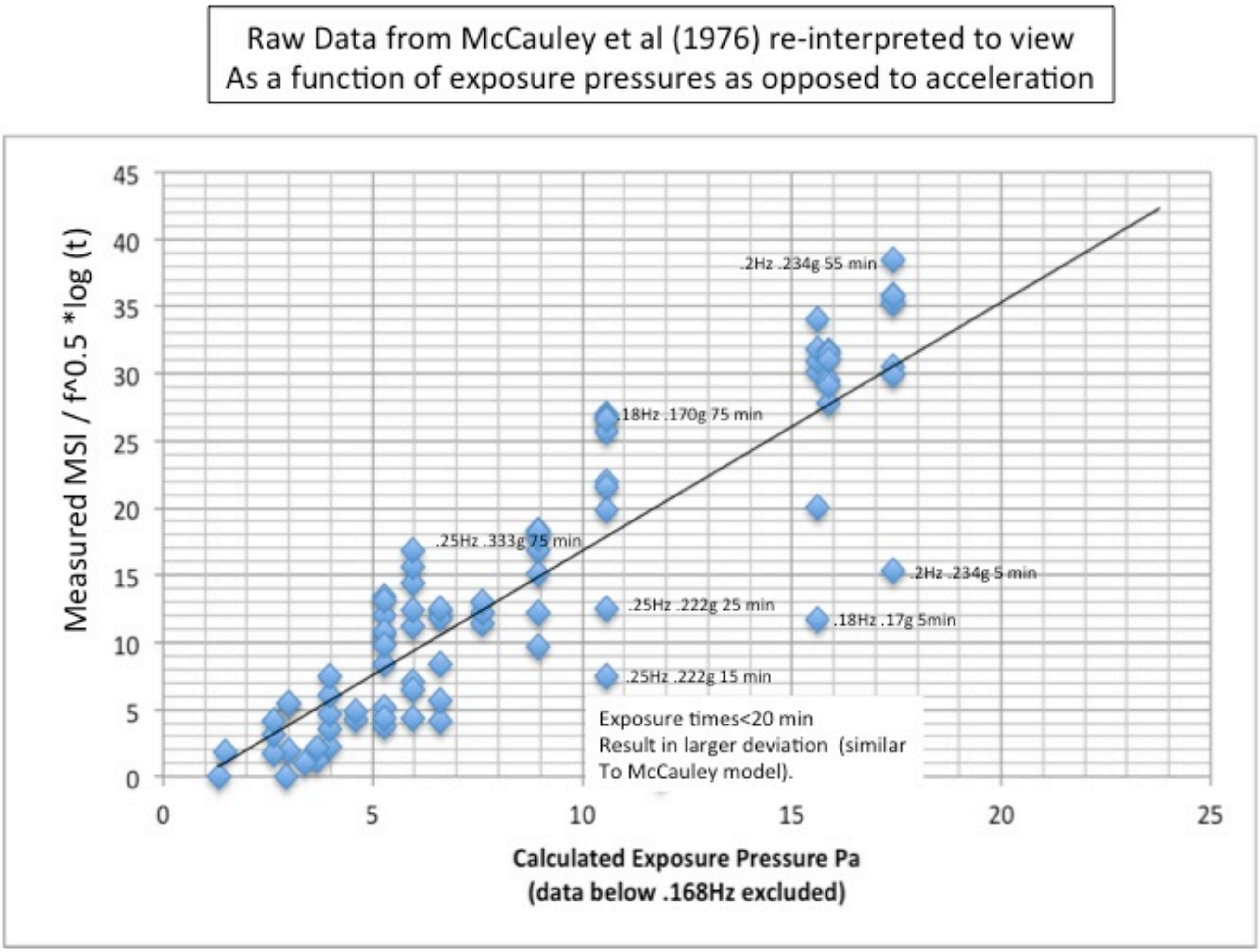

Figure 7

Figure 7 is a graph similar to Figure 6 except the 0.167 Hz data has been excluded. This illustrates the possible discontinuity of the 0.167Hz experimental data, by significantly reducing the scatter between experimentally measured pressure (based on the hypothesis) and MSI, and calculated infrasonic pressure fluctuations based on vertical motion.

Summary

In general the simple pressure model developed here correlates well with the experimental data from Ref 1 as shown by figure 3. A reduced overall scatter is realized when apparently discontinuous data points from 0.167 Hz are excluded as shown by figure 4. The slight droop in MSI data in the lower pressure range relative to calculated values visible in figures 3 and 4, could easily be explained as being due to the slower pressure equalization time of the test compartment with the outside infrasonic pressure, at lower pressure differentials (i.e. partial compartment sealing). The infrasonic pressure model for MSI (or nausea) developed here may provide insight into several areas. If applied to improving the comfort of passengers and crew in ships or other vehicles, a semi-sealed compartment where the external infrasound levels due to vertical (or other) motion may be prevented from communicating to the inside of the compartment easily, or an active infrasound cancellation system may be employed to attenuate the infrasonic pressures.

Although further research will be required to establish the validity of this model, its simplicity and accuracy relative to the existing MSI model (Fig 5), in conjunction with separate reports of infrasound related nausea and discomfort, tends to support the validity of the model concept.

At a risk of over extending the usefulness of the model in its present form, calculations of MSI for much lower infrasonic pressure levels over significantly longer time periods reveal an interesting trend. A calculation performed at 0.72Hz with an un-weighted SPL of 60dB yields an MSI of 0.35% after 2.5 months.
At 20 Hz and the same SPL of 60dB the model predicts an MSI of 1.9% after 2.5 Months.

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