# Technological Evaluation of the MIM (TEM & TEM-2)
## Final Research Report

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September 6, 2000

**INTRODUCTION**

Low-gravity fluid physics experiments are generally designed to investigate phenomena which is of second order relative to gravitational effects. It follows then, that these phenomena may easily be affected by g-jitter (Nelson, 1991). For example, shaking a container which is completely filled with liquid may result in convective flows; a phenomenon known as streaming. Therefore, understanding g-jitter effects is extremely important in the design of both fluid physics experiments and low-gravity fluids management systems.

There are several ways to avoid detrimental g-jitter effects on fluid physics experiments. The first is to design the experiment such that the experiment's natural frequency in not close to any strong environment frequencies. Unfortunately, research often requires a specific container size and fluid which is sensitive to the acceleration environment. If the fluids system or experiment may not be modified, then the only alternative is to alter or control the acceleration environment. In the case of fluid physics experiments, the PI will often specify that the experiment be run during "quiet" periods, such as when the astronauts are sleeping. However, this is not always sufficient and the only non-trivial solution remaining is vibration isolation.

Isolating fluid physics experiments from g-jitter is especially difficult because these experiments generally respond at frequencies on the order of one Hertz or less. Since passive isolation systems do not usually damp out sub-hertz oscillations, an active vibration isolation system is required. The Microgravity Isolation Mount (MIM) is one such active vibration isolation system.

The Technological Evaluation of the MIM (TEM) was a technology demonstration experiment designed to investigate the feasibility of using the MIM for vibration isolation of fluid physics experiments in a low-gravity environment. TEM was designed to investigate both the vibration isolation and the controlled motion capabilities of the MIM. The evaluation of the MIM was to be accomplished by studying the natural frequency and damping characteristics of a low-gravity free surface.

The second Technological Evaluation of the MIM, or TEM-2, was designed to evaluate the capabilities of the MIM in a different parameter range than TEM. TEM-2 was essentially the same as TEM. The difference being that TEM-2 was a much less viscous system and was susceptible to g-jitter at lower energy levels than TEM. TEM-2 was also to be performed on the MIM and used the TEM baseplate.

In addition to evaluating the MIM capabilities, TEM was also to gather information on low-gravity liquid surface sloshing which would be of interest to the design of low-gravity fluid physics experiments.

*Description of MIM*

The Microgravity Isolation Mount (MIM), developed by the Canadian Space Agency, provides active vibration isolation through the use of Lorentz coils. In addition to isolating experiments from vibrations, the MIM can also superimpose controlled oscillations on an isolated experiment. The MIM flotor is approximately 14 inches square and the working volume for an experiment is the size of a single middeck locker. The frequency range of isolation is 0.01 Hz to 100 Hz subject to a flotor displacement of ± 9 mm.

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A force of up to 10 N can be exerted on an experiment package perpendicular to the flotor and up to 5 N in the plane of flotor. The MIM can interact with an experiment through 4 control channels and can record experiment data through 8 data channels. In addition, the MIM can record flotor/stator accelerometer data and flotor position data.

*Description of TEM*

TEM evaluated the MIM's capabilities by studying the natural frequency and damping characteristics of a low-gravity free surface. A free surface oscillation experiment was chosen as the evaluation tool because a liquid surface is the extremely sensitive to residual accelerations, especially at the natural frequency of the surface, and the diagnostics required to view the experiment response to g-jitter is can be as simple as a video camera. The basis of the experiment is a cylinder half-filled with liquid exposed to the residual accelerations of the Mir. The response of the free surface to g-jitter is recorded on video.

TEM consists of two test cells and a baseplate. The baseplate attaches to the MIM flotor and provides a temperature readout and lighting for the test cell. Also, the baseplate receives an event signal from one of the MIM control channels which flashes a pattern via an LED. The event signal is used to correlate video data to the accelerometer data stored on the MIM harddrive. Each test cell is an aluminum/polycarbonate housing which contains a fluid reservoir and a cylindrical test chamber. The two test cells are identical except for an interior coating on one test cell which results in a change in the contact angle. The fluid used in the TEM test cells is a Cargille 5040 immersion oil which is indexed matched to the acrylic test chamber. The index matching allows for an undistorted view of the free surface behavior. Attached to the exterior of the housing is a CCD camera sensor and lens. The CCD camera is connected to the Mir Glovebox facility for video recording. The event signal, the temperature, and the free surface response are recorded on video. After securing the test cell to the baseplate, the fluid is transferred from the reservoir to the cylindrical test chamber; filling the chamber approximately half full. The TEM control files are then loaded into the MIM and the experiment begins.

The MIM and TEM were launched from Russia in March, 1996 as part of the Priroda Module which docked with the Mir space station. Astronaut Shannon Lucid performed the TEM experiment in July and August of 1996.

*Description of TEM-2*

TEM-2 was designed to investigate the MIM capabilities in a different parameter range than that of TEM. Again, both vibration isolation and induced vibration capabilities will be tested.

As with TEM, TEM-2 has two identical test cells differing only in contact angle. The test cells will be very similar to TEM in that the fluid will be stored in a reservoir and then transferred to the test chamber just prior to testing. The test cells will also have the CCD camera and lens which connect to the Mir Glovebox facility. The TEM baseplate will be reused for securing the TEM-2 test cells to the MIM. The test fluid is a mixture of decalin and tetralin and is indexed matched to the acrylic test chamber so as to allow for clear observation of the oscillating free surface. Variations in surface curvature between the test cells occurs as a result of the difference in contact angle.

TEM-2 is a much less viscous system than TEM. This was accomplished by enlarging the test chamber diameter and by using a different fluid. TEM uses an immersion oil and TEM-2 uses a mixture of decalin and tetralin. Both test fluids are indexed matched to the acrylic test chamber. The immersion oil has a viscosity of about 27 cSt and the decalin/tetralin mixture has a viscosity of about 2 cSt. In all other aspects TEM-2 is the same as TEM.

TEM-2 was transferred to Mir from STS-79 in September, 1996 and remained on Mir through the NASA 6 increment, but was never conducted.

*Technical Objectives of TEM and TEM-2*

The technical objectives of TEM are:

- demonstrate the effect of g-jitter on low-gravity fluid physics experiments,
- demonstrate utility of MIM to isolate fluid physics experiments from g-jitter, and
- demonstrate the controlled displacement capabilities of the MIM.

The first objective was tested by operating TEM with the MIM flotor locked down. In this mode, the TEM vessel was exposed directly to the Mir g-jitter. The second objective was tested by unlocking the MIM flotor and allowing the MIM to perform as a vibration isolation platform.

The third objective evaluates the MIM's capability to isolate an experiment while simultaneously inducing a controlled oscillation on the experiment. The level of vibration isolation capable by the MIM is reduced as the size of the controlled displacement is increased. This occurs because there is less flotor "rattlespace" available for isolation when a portion of that rattlespace is used for the controlled oscillations.
The results of the TEM experiment will be used to evaluate the relationship between the degree of vibration isolation and the g-level of the MIM induced oscillation. To do this, TEM specific configuration files were loaded into the MIM processor. These files instructed the MIM to oscillate sinusoidally at a fixed frequency, amplitude, and direction for a short period of time and then return to the vibration isolation mode. This sequence of oscillation/isolation was repeated for a wide range of oscillation frequencies and g-levels.

The TEM experiment is a relatively viscous system which allows for evaluating the MIM at the higher g-levels without the liquid surface breaking up. The MIM was evaluated up to the 12 mg saturation limit of the MIM flotor accelerometers. However, TEM was not able to evaluate the entire MIM vibration isolation spectrum because of the viscous damping. The test fluid used in the TEM experiment, Cargille 5040 immersion oil, was selected because:

- It is indexed matched to the acrylic which allows for an undistorted view of the free surface.
- Its prior use in manned environment expedited getting through all the safety reviews.
- The free surface response of this fluid has been characterized in previous drop tower experiments.

The TEM-2 experiment has the same three technical objectives as TEM. However, TEM-2 is much more sensitive to g-jitter than TEM by virtue of the lower viscosity fluid. The TEM-2 experiment used a mixture of tetralin and decaline which would have allowed for evaluating the vibration isolation capabilities of the MIM to a much lower g-level than the TEM experiment. Operationally, the TEM-2 experiment will proceed in similar fashion to the TEM experiment.

*Science Overview*

There are many analytical and numerical studies which attempt to calculate the natural frequency damping characteristics of a free surface. In nearly all of the analysis to date, the fluid system is assumed to be an inviscid, flat interface with a 90° contact angle which moves freely along the wall. In real capillary, or low Bond number, systems the interface has some curvature associated with a contact angle that is not 90° and there are energy losses due to viscosity and contact line dynamics.

The most difficult aspect in the analysis of an oscillating free surface is the boundary condition at the container wall. Analysis of free surface oscillations generally utilized the "free contact line" condition which equates the dynamic contact angle with the static contact angle and ignores any wall effects on the moving contact line. Therefore, damping of oscillations due to contact line motion is completely neglected and there is ample evidence that the energy dissipation near the contact line may be equal to or greater than that dissipated by viscosity in the bulk fluid (Hocking, 1987). Compounding the problem of the free contact line model is that nearly all of the analysis use a contact angle of 90° which results in a flat interface. Exceptions to the free contact line analysis use a pinned contact line, but again, the interface is flat. Thus, the effect of curvature on the natural frequency and damping characteristics of free surface oscillations has been virtually ignored. All of these simplifications are unfortunate since it is known that the overall damping of free surface oscillations is 2 to 20 times greater in low gravity than for the same system in normal gravity (Hocking, 1987).

The principle reason the contact line and curvature effects have been neglected in analytical studies is that there is no reliable model of the moving contact line. Inclusion of viscous effects is also difficult since it renders the governing equations nonlinear. The conclusion is that accurate modeling of an oscillating capillary free surface is extremely difficult and thus necessitates experimentation. A scaling analysis of the minimum acceleration level required in order for free surface oscillations to occur has been performed (Kamotani & Ostrach, 1991), but this work has not been experimentally verified. Finally, there has been very little analysis of the damping mechanisms associated with non-linear (large amplitude) oscillations. Some limited numerical work has been performed, but again the results have been hampered due to an inadequate model of the contact line condition.

*TEM and TEM-2 Science Objectives*

The first science objective of TEM and TEM-2 experiments was to determine the natural frequency of a low gravity free surface. The effect of curvature and contact angle on the natural frequency was studied in only the axial directions (the lateral slosh test points were lost, see Section III.A) and the results will be compared to current analytical models. This portion of the experiment was performed by shaking the test cell at a range of frequencies which span the predicted natural frequency. The test cells were shaken at a various g-levels ($10^{-2}$ to $10^{-4}$ g) and the natural frequency can be determined by observing the response of the liquid surface.

The second science objective is to determine the threshold Bond number, $Bo_t$. The Bond number is a ratio of capillary effects to gravitational effects on a free surface. The threshold bond number, $Bo_t$, is defined as the Bond number at which the liquid surface begins to have an observable response to the input acceleration.

$$Bo_t = \frac{r r^2 a_t}{s} \quad (1)$$

In equation 1, σ is surface tension, ρ is liquid density, *r* is the radius of curvature of the surface, and $a_t$ is the acceleration at which an observable response occurs on the liquid surface. Thus, $Bo_t$ gives the minimum acceleration at which the free surface will respond; i.e., when the system becomes critically damped. The threshold Bond number was to be determined as a function of frequency, contact angle, and direction of oscillation (lateral and axial).

The first and second objectives were investigated using the same test sequence; starting at low Bond numbers where no response should be visible except at the natural frequency and increasing the Bond number until a response was visible at all frequencies.

The third science objective of the TEM and TEM-2 experiments was to investigate the effect of contact angle and curvature on damping of free surface oscillations. The frequency of the forced oscillations was varied so as to excite different modes of oscillations in both the lateral and axial directions. The damping rates of each of the modes of oscillation will be studied.

**METHODS/RESEARCH OPERATIONS**

**Functional Objectives:**

N/A

**Hardware Items**

1. TEM Baseplate Assembly
2. TEM Electrical Cable
3. TEM Vessel Assembly 1
4. TEM Vessel Assembly 2
5. TEM Optical Disks (2)
6. Microgravity Isolation Mount (MIM)
7. MIM Video Cable
8. Mir GloveBoX (MGBX)
9. Mir Interface Payload System Laptop (MIPS-2L)
10. MIPS Optical Drive
11. TEM-2 Vessel Assembly 3
12. TEM-2 Vessel Assembly 4

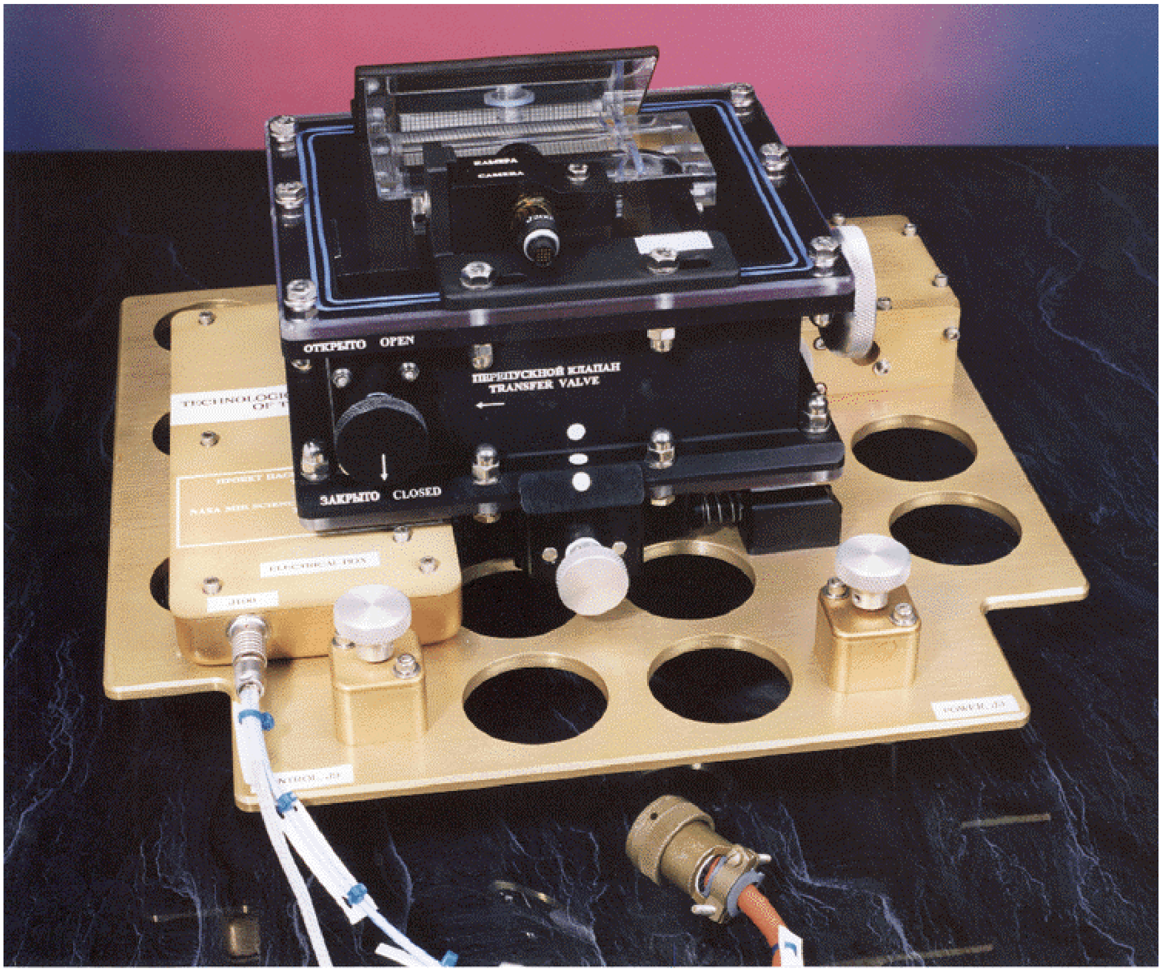



Figure 1. TEM-2 Vessel Assembly attached to TEM Baseplate Assembly and TEM Electrical Cable

## Method/Protocol

N/A

## RESULTS

### List of Pre-, In-, Post-flight Anomalies

Initially, the TEM experiment was designed so that the astronaut would download an entire test matrix, reboot the MIM and then return in two hours. Just prior to shipment to Baikanor, it was discovered that the MIM memory buffer could only hold approximately 15 test points of the 180 points in the test matrix. At the end of the first 15 test points the MIM computer would "lock up". Therefore, the TEM test matrix had to be divided into many segments which the crew member would have to load individually. The additional crew time associated with the loading of small test files instead of one large test files necessitated the removal of half of the test points from the test matrix. Therefore, all of the lateral slosh oscillations were lost. The loss of half of the test matrix was been very detrimental to the science objectives.

At the conclusion of the first run with TEM Vessel 1, the wrong command was used for transferring MIM data to the MIPS optical drive. Subsequently, data was not transferred and all of the MIM accelerometer and flotor position data was lost for TEM Vessel 1. The miscue with the transfer command was due to an error in the TEM On-Board Procedure. This procedure error was corrected twice before the launch, but was missed the third time when an extensive radiogram was sent to Mir in order to fix other errors in the TEM On-Board Procedures.

TEM Vessel 1 was rerun later, but by this time the liquid was completely broken up into drops on the wall and in liquid bridges across the cylinder. The liquid breakup was due to a combination of the original Impulse Experiment and the 70° contact angle in TEM Vessel 1. As a result of the liquid breakup, the experiment rerun did not produce any useable video results.

### Completeness/Quality of Data

The two TEM optical disks from TEM Vessel 1 and TEM Vessel 2 were sent to the Canadian Space Agency for analysis. Copies of the data from the optical disks were being returned to the principal investigator on a CD format. All TEM videotapes have been received and copied. Analysis of the videotapes is complete. However, the MIM data from the second run of TEM Vessel 1 could not be correlated to the video data from the first run of TEM Vessel 1.

## DISCUSSION

### Status of Data Analysis

The TEM videotapes have been reviewed to see at which test points the liquid surface responded to MIM flotor oscillations. The test points which show a response were being analyzed to determine the frequency, amplitude, and mode of the liquid surface response. The MIM flotor acceleration and position was not correlated to the video data.

### Final Research Findings

There is a strong correlation of damping of free surface oscillations to the contact angle. Figure 2 shows the low gravity configuration for TEM Vessel 1 and for TEM Vessel 2. The images are shown with the test cylinder oriented horizontally and the test fluid located at the left of the image. The location of the fluid may be determined by the clarity of the grid lines in the background. In the lower left corner is an LED readout of the baseplate temperature. TEM Vessel 1 has a 70° contact angle and has a relatively flat liquid surface (Figure 2a). TEM Vessel 2 has a contact angle less than 5° and has a hemispherical liquid surface (Figure 2b).

The response of the liquid surface to the MIM flotor oscillations is depicted in Figure 3. These response plots illustrate the test matrix of the TEM experiment on log-log plot of frequency v. g-level. The 12 mg saturation limit of the MIM flotor accelerometers is shown as the dark, horizontal line at the top of the plot. The 5 mm amplitude limit of the MIM flotor rattlespace is shown as the dark, diagonal line. The additional dashed diagonal lines represent constant amplitudes of 4 mm, 3 mm, 2 mm, and 1 mm from left to right, respectively. All of the test points lie under the two limit lines. Test points for which no liquid surface response was observed are shown as diamonds. Test points where the liquid surface was observed to respond to the MIM flotor oscillations are shown as circles. These plots illustrate the g-level and frequency domain where the free surface is susceptible to g-jitter. For example, the natural frequency of the liquid surface in TEM Vessel 1 (70° contact angle) is 3 Hz. At this frequency, the liquid surface was susceptible to accelerations at least as low as $10^{-4}$ g and the response of the liquid surface at this g-level was strong enough to indicate that the susceptibility would occur at a much lower accelerations. As the frequency deviated from 3 Hz, the acceleration at which the liquid surface was susceptible increased dramatically. At 1.5 Hz, the liquid surface did not respond until the acceleration increase to $10^{-3}$ g and at 6 Hz the liquid surface had to be excited at $10^{-2}$ g before a response was observed. These early results indicate that the susceptibility of a low-gravity liquid surface is strongly dependent upon the frequency of the acceleration as well as the magnitude of that acceleration. The results parallel the stability analysis of the Mathieu equation (Dodge, Kana, and Abramson, 1965 and Benjamin and Ursell, 1954).

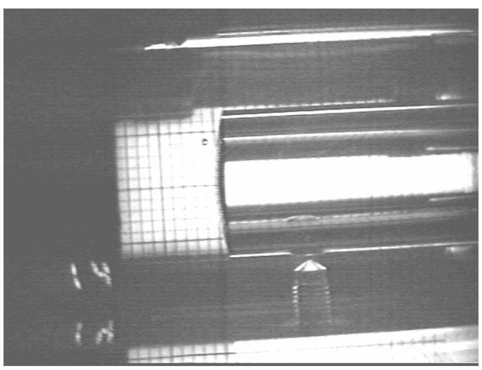


Figure 2a. TEM Vessel 1, ~70$^{o}$ contact angle

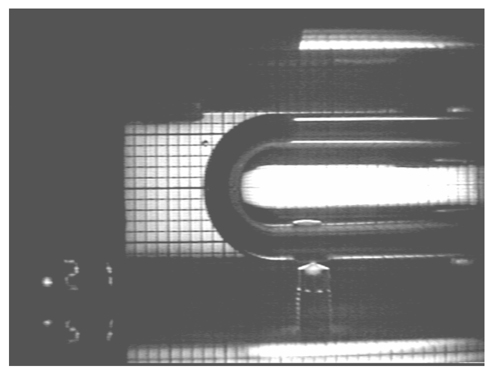


Figure 2b. TEM Vessel 2, < 5$^{o}$ contact angle

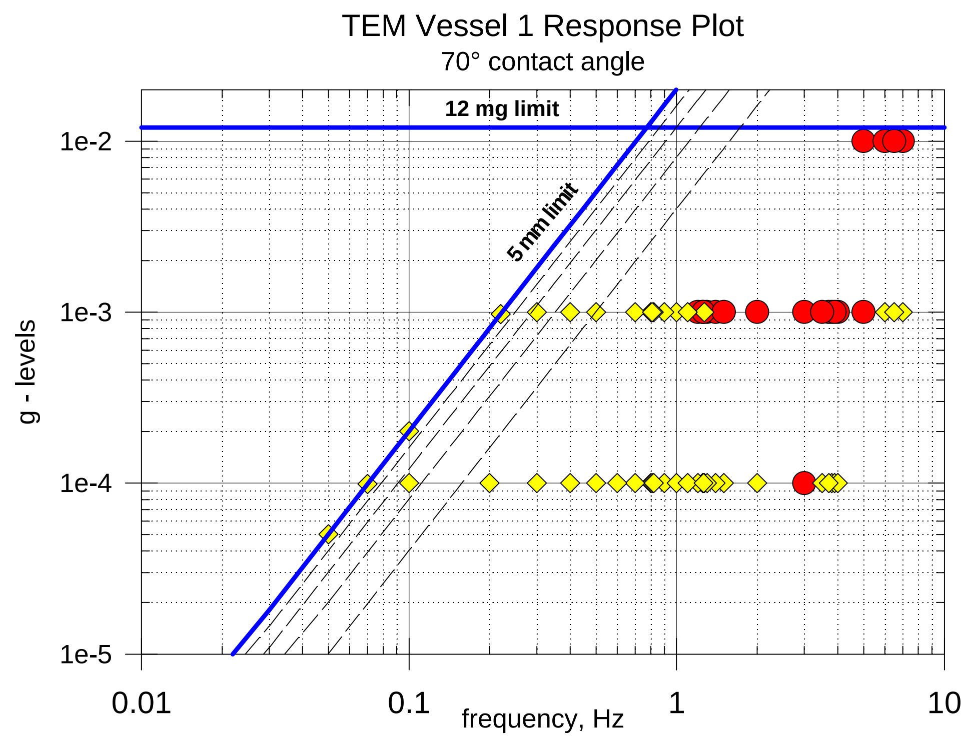
TEM Vessel 2 (< 5° contact angle) is also shown in Figure 3. The natural frequency of the liquid surface in this test cell is 1 Hz and no response of the liquid surface was observed for accelerations less than $10^{-3}$ g. This indicates that the dissipation of energy, or damping, is greater in the low contact angle system than in the high contact angle system. In addition, the natural frequency of the low contact angle system was lower than that of the high contact angle system ( 1 Hz v. 3 Hz). No data is available for the TEM-2 experiment since that experiment was never conducted.

**Conclusion**

Both the pre-flight anomaly and the loss of MIM data for TEM Vessel 1 during Increment 2 have resulted in an extreme degradation of the quality of the TEM experiment. There was some hope for recovery from the loss of data. If the MIM data sets for TEM Vessel 2 and for the rerun of TEM Vessel 1 could be correlated, then it might have been possible to extrapolate the MIM data for the TEM Vessel 1 rerun (performed in August) to the video data of the original fun of TEM Vessel 1 (performed in July). Unfortunately, the data could not be correlated and the results of the TEM experiment remain qualitative. It was hoped that this loss of data could be overcome with the TEM-2 experiment, but TEM-2 was not performed.

**REFEREMCES**

Benjamin, T.B. and Ursell, F., *Proc. Royal Soc.* (1954) *London*, A225, 505-515.
Dodge, F.T., Kana, D.D., and Abramson, H.N., *AIAA Journal* (1965), vol. 3, 685-694.
Hocking, L.M., *J. Fluid Mech.* (1987), vol. 179, 253-256.
Kamotani & Ostrach, “Effects of G-Jitter on Liquid Free Surfaces”, presented at the IUTAM Symposium on Microgravity Fluid Mechanics, Bremen (1991).
Nelson, E., NASA TM 103775 (1991).



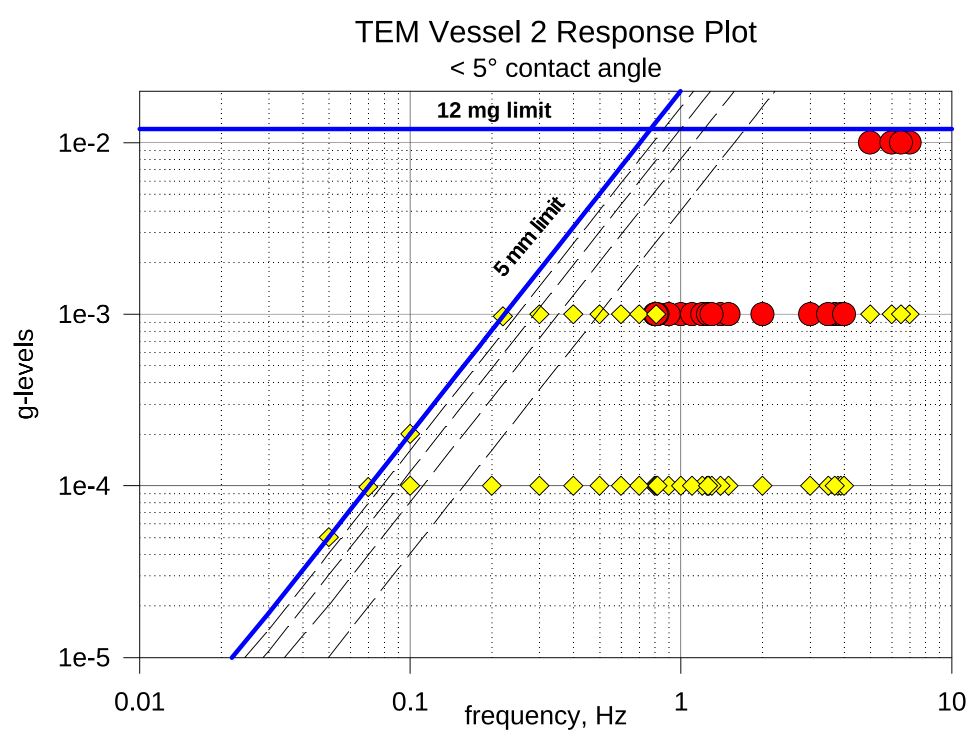




Figure 3. Response of liquid surface to MIM flotor oscillations for TEM Vessels 1 and 2