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Technical Support Package

Radio-Frequency Tank Eigenmode Sensor for Propellant Quantity Gauging

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Technical Support Package

for

RADIO-FREQUENCY TANK EIGENMODE SENSOR FOR PROPELLANT QUANTITY GAUGING

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Radio-Frequency Tank Eigenmode Sensor for Propellant Quantity Gauging

Brief Abstract

A method for rapidly determing the quantity of dielectric propellant in a metal tank has been developed and tested that utilizes measurement of the electromagnetic eigenmodes of the propellant tank. The device is known as a Radio Frequency Mass Gauge, or RFMG, and is applicable to propellants such as liquid hydrogen, oxygen, and methane. The RFMG sensor has been successfully tested as a propellant quantity sensor in a 1g settled liquid test, and also has the capability of measuring the amount of propellant in a tank in low-gravity, where the liquid-vapor interface location is unknown, or in applications where the propellant is sloshing in the tank. The RFMG sensor uses a very low power radio frequency signal, and requires only a small antenna internal to the tank which can be wetted by the fluid.

Section I — Description of the Problem

A key problem in spacecraft systems operating in a low-gravity environment is the mass gauging of liquid propellants in the propellant tanks. Accurate gauging of the liquid propellants in the tanks is an important requirement, the results of which can impact mission success. Although there are several methods for determining liquid level in a tank, there are no proven methods to quickly gauge the amount of propellant in a tank while it is in low gravity, or under low-settling thrust conditions where propellant sloshing is an issue. Propellant gauging in low-gravity or under low-settling thrust conditions can be critical to mission success and will be required for the new class of Exporation Vehicles under development for future missions to the Moon and beyond. Currently, the methods available for gauging the amount of propellant in low-gravity are only applied to storable (hypergolic) propellants, and suffer from the drawback of being time consuming along with other limitations. Having the ability to quickly and accurately gauge propellant tanks in low-gravity is an enabling technology that would allow the crew or mission control to always know the amount of propellant onboard, thus increasing the chances for a successful mission. Most propellant quantity gauging sensors operate as liquid-level sensors, whereby a sufficiently long period of a relatively large settling thrust is needed to produce a flat liquid-vapor interface that can be sensed by some means such as a capacitance probe, wet-dry sensors, or a delta-P sensor which measures the pressure head due to the liquid. The problem in relying solely on level sensors on a vehicle such as the Space Shuttle or the new Explration Vehicles is that in low-gravity the level sensors do not give an accurate propellant quantity reading, because the liquid can easily move to other parts of the tank and produce a false reading. Thus, when employing only a level sensor, it is necessary to provide a large settling thrust from the main engines for a pre-determined amount of time (which is typically 18 seconds for Space Shuttle OMS tanks) before the level sensor reading can be trusted. At that point, however, a large amount of propellant has already been consumed and the main purpose of the engine burn (such as a de-orbit burn) has already been commited to. There are two methods available for gauging the amount of propellant while in low gravity that have been applied to storable propellants, namely the pressure-volume-temperature (PVT) method and a thermal propellant gauging technique which effectively measures the heat capacity of the tanks. Both methods have drawbacks: PVT uses conservation of a helium pressurant, works best under high helium partial-pressure, and cannot separately gauge multiple tanks from one helium supply bottle; the thermal method requires adding heat to the tank which is very undesirable for cryogenic propellant tanks where long-term storage and heat leaks are important. In addition, both methods require near-equilibrium conditions for high accuracy which can take hours to days or weeks to achieve.

In the new class of Exploration missions and vehicles, there will be certain critical times that the amount of propellant in the tanks needs to be accurately gauged, such as before critical engine burns. Having the ability to accurately know the quantity of propellant in each tank even while in low-gravity will enable mission related decisions to be based on actual measurements. Low-gravity mass gauging of propellants was identified in the Exploration Systems Architecture Study (ESAS) report as a crtical technology that needed further research and development (ESAS report, NASA-TM-2005-214062, section 9.3.3, p. 630, see http://klabs.org/richcontent/Reports/NASA_Reports/esas/index.htm). The RFMG offers a potential solution to this problem which has been a concern since nearly the beginning of the space program.

Section II — Technical Description

The Radio Frequency Mass Gauge is more thoroughly described in NASA/TM-2007-214907 (see attachment).

Briefly, the RFMG technique measures the electromagnetic eigenmodes, or natural resonant frequencies, of a tank containing a dielectric fluid, and compares the measured spectra of eigenmodes with a database of eigenmode frequencies at various fluid fill levels. A pattern matching algorithm is used to match the measured spectra of eigenmodes with the database, thereby finding a good match at some fill level.

The essential hardware components consist of a RF network analyzer which measures the reflected power from an antenna mounted internal to the tank. At a resonant frequency there is a drop in the reflected power, and these inverted peaks in the reflected power spectrum are identified as the tank eigenmodes using a peak detection software algorithm. This information is passed to the pattern matching algorithm, which compares the measured eigenmodes with a database of eigenmode simulations at various fill levels. A best match between the simulated eigenmodes and measured values occurs at some fill level, which is then reported back as the gauged fill level.

The database of eigenmode simulations is created by using RF simualtion software to calculate the tank eigenmodes at various fill levels. The input to the simulations consists of a fairly high-fidelity tank model with proper dimensions and including internal tank hardware, the dielectric properties of the fluid, and a defined liquid/vapor interface. Because of small discrepancies between the model and actual hardware, the measured empty tank spectra and simulations are used to create a set of correction factors for each mode (typically in the range of 0.999 - 1.001), which effectively accounts for the small discrepancies. These correction factors are multiplied to the modes at all fill levels. By comparing several measured modes with the simulations, it is possible to accurately gauge the amount of propellant in the tank. Accuracy verification tests using liquid oxygen as the test fluid indicate that the RFMG accurately gauged the fluid quantity such that the root-mean-square deviation between the RFMG value and a reference weighing system was less than 1% of the full-scale mass over a wide range of conditions in this settled-fluid test configuration.

Section III — Unique or Novel Features of the Innovation

The concept of measuring the RF tank eigenmodes as a possible way to gauge propellant quantity dates back to the 1960's, with a significant amount of work following in the 1970's and 1980's. However, due to the complexity of the tank geometry and two-phase fluid distribution, the tank eigenmode spectra could not be calculated and therefore there was no way to predict or match a tank RF spectrum with theory. The innovative concept behind the RFMG is to apply numerical simulations to solve for the tank eigenmodes, and compare the measured tank spectrum with simulations using a pattern matching algorithm to gauge the amount of propellant in the tank.

The advantage of the RFMG approach of applying computer simulations and a pattern matching algorithm is that the predictions can be verified through testing on Earth, and the results can be extrapolated to low-gravity liquid configurations using simulations of liquid configurations that would be likely to occur in low-gravity. Such liquid configurations can also be solved using other computer software tools such as the Surface Evolver code. RF computer simulations are routinely used in the RF and communications industry to design or predict performance of RF devices. The same software tools can be used to calculate the electromagnetic eigenmodes of large tanks with a two-phase fluid distribution. By having a pre-built library of tank eigenmode simulations, the measured eigenmode spectra can be compared with the library of spectra to determine the unknown amount of propellant in the tank.

Recent liquid oxygen tests in a 58 cu. ft. test tank at NASA Glenn Research Center (Jan-Feb 2008) have verified the capabilities of the RFMG. When comparing the RFMG reading of liquid mass in the test tank to a high-accuracy load cell reference weighing system, it was found that the RFMG reading compared to the reference system was within 1% RMS full-scale mass. Although this was a settled gauging test, that is, the liquid was settled to the bottom of the test tank, it demonstrates the potential of the RFMG.

Section IV — Potential Commercial Applications

In addition to the space-based application of the RFMG measuring propellant quantity in liquid hydrogen, oxygen, and methane tanks, the RFMG principle could be applied to cryogenic liquid storage tanks on Earth to act as a level sensor.

There are various designs for radar level sensor that operate on the principle of measuring a radar reflection off a liquid/vapor interface. The radar level sensor does not typically work well with low dielectric constant fluids such as liquid hydrogen.

Radio Frequency Mass Gauging of Propellants

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Abstract

A combined experimental and computer simulation effort was conducted to measure radio frequency (RF) tank resonance modes in a dewar partially filled with liquid oxygen, and compare the measurements with numerical simulations. The goal of the effort was to demonstrate that computer simulations of a tank's electromagnetic eigenmodes can be used to accurately predict ground-based measurements, thereby providing a computational tool for predicting tank modes in a low-gravity environment. Matching the measured resonant frequencies of several tank modes with computer simulations can be used to gauge the amount of liquid in a tank, thus providing a possible method to gauge cryogenic propellant tanks in low-gravity. Using a handheld RF spectrum analyzer and a small antenna in a 46 liter capacity dewar for experimental measurements, we have verified that the four lowest transverse magnetic eigenmodes can be accurately predicted as a function of liquid oxygen fill level using computer simulations. The input to the computer simulations consisted of tank dimensions, and the dielectric constant of the fluid. Without using any adjustable parameters, the calculated and measured frequencies agree such that the liquid oxygen fill level was gauged to within 2 percent full scale uncertainty. These results demonstrate the utility of using electromagnetic simulations to form the basis of an RF mass gauging technology with the power to simulate tank resonance frequencies from arbitrary fluid configurations.

Nomenclature

c	speed of light in vacuum
f	frequency
L	cylinder length
R	cylinder radius
m, n, p	indices of eigenmodes; integers
ε	dielectric constant
Z	impedance

I. Introduction

The concept of measuring the electromagnetic eigenmodes of a tank as a method to gauge the quantity of liquid in a propellant tank dates back to 1966, when Lockheed Missiles and Space Company first tested the technique as a level sensor in tanks partially filled with RP–1, liquid hydrogen, and liquid oxygen (ref. 1). Since that time, several others have contributed to both the theoretical and experimental development of RF gauging, especially towards the development of using the technique as a method to gauge propellants tanks in low-gravity, where the configuration of the liquid in the tank is uncertain (refs. 2 to 5). Despite success with breadboard tests, the technique has not advanced to a high Technology Readiness Level, perhaps due in part to the complexity of signal analysis which includes the difficult task of converting a tank RF spectrum into a propellant quantity reading. The computing power available today makes this a much less daunting problem than in previous investigations. Moreover, the field modes of a tank can now be accurately predicted using commercial software packages, something that was not possible 20 years ago.

In simple tank geometries with a high degree of symmetry the electromagnetic eigenmodes can be calculated analytically. For example, a cylinder of length *L* and radius *R* will have transverse magnetic (TM) resonant frequencies at

$$f = \frac{c}{2\pi\sqrt{\varepsilon}}\sqrt{\frac{x_{mn}^2}{R^2} + \frac{p^2\pi^2}{L^2}} \tag{1}$$

where $m = 0, 1, 2, ...$; $n = 1, 2, 3, \ldots$; $p = 0, 1, 2, \ldots$; x_{mn} is the *n*th root of the Bessel equation $J_m(x) = 0$, and ε is the dielectric constant of the medium uniformly distributed in the cylinder (ref. 6). The lowest resonant frequency of a cylindrical tank corresponds to $(m, n, p) = (0, 1, 0)$ and is denoted as the TM010 mode. If the tank has a 1 m radius, the lowest TM mode is at 114.8 MHz for an empty tank. Since typical tank sizes have resonant frequencies near the radio frequency spectrum, the technique is dubbed RF gauging. Filling a tank with liquid oxygen ($\varepsilon = 1.488$) or liquid hydrogen ($\varepsilon = 1.23$) would cause the resonant frequencies to decrease by 18 or 10 percent respectively from the empty tank value.

More complex tank geometries, such as a propellant tank with domed ends, internal tank hardware, and two-phase fluid distributions require computer simulations using finite element models which simultaneously solve Maxwell's equations in $10^4 – 10^6$ sub-volume elements. The accuracy of a computer simulation is likely limited by the fidelity of the tank and fluid model, numerical round-off errors, and available memory. Figure 1 shows a comparison of our measurements and simulations of RF resonances in an empty dewar. The simulations predict eigenmodes which are in good agreement with the measured resonances. Some of the eigenmodes predicted by the simulations (especially transverse electric modes) are not excited by the particular antenna geometry used in this measurement.

The goal of this work is to demonstrate that the first four TM eigenmodes measured in a small dewar can be accurately predicted at various liquid oxygen fill levels, thereby providing the basis for a low-gravity RF mass gauge technique. At a given fill level, the frequencies of the various modes will have some dependence on the fluid distribution in the tank. Thus, several modes would need to be analyzed

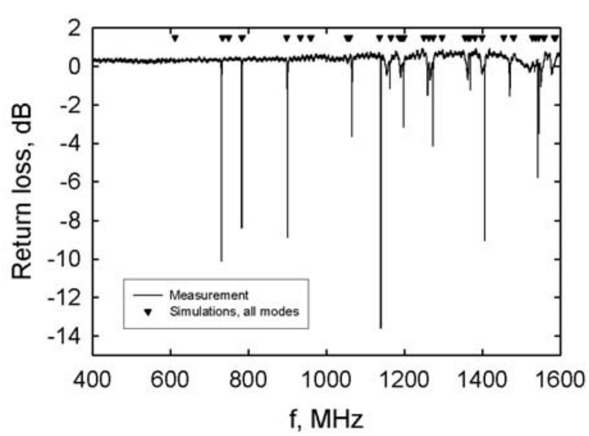

Figure 1.—Comparison of measured empty dewar RF resonance spectrum (solid line) with the first 50 eigenmodes calculated from numerical simulations (triangles). Not all of the eigenmodes were excited with the stub antenna, and several of the calculated eigenmodes are degenerate.

and compared to simulations in order for the RF technique to work as a low-gravity mass gauge. In principle, such a gauge could function by comparing the measured frequencies of several modes to a database of simulations at various fill levels and liquid configurations. By finding the best match between the measured and simulated frequencies, the percent fill-level could be determined. Although the test results presented here are for only one liquid configuration (liquid settled on the bottom of the dewar), the results provide a sound basis for a more exhaustive study.

II. Simulations

CST's Microwave Studio (MWS) software was used to perform the numerical simulations (refs. 7 and 8). Microwave Studio is a commercial, general-purpose, electromagnetic simulator that contains three different electromagnetic solvers (transient solver, frequency domain solver, and eigenmode solver) that can be used for various high frequency applications. The eigenmode module calculates a finite number of modes in a closed structure by solving the Helmholtz equation for electromagnetic waves. The eigenmode module provides two solver methods: the Advanced Krylov Subspace (AKS) method and the Jacobi-Davidson (JD) method. The AKS method is faster and recommended for calculating many modes in a loss-free structure. The JD solver is the more robust solver and can handle lossy materials; however, the solver time is much longer. The AKS method was used to provide initial results in a short amount of time, and the JD solver was used for more extensive analysis. The solvers were found to be in excellent agreement with each other, with discrepancies in mode frequencies typically being less than 0.2 percent.

The 3–D structural model used in the simulations was based on measurements of the cylindrical dewar having an elliptical base. The total axial length of the inner volume of the dewar is 61 cm, the radius is 15.7 cm, and the depth of the elliptical base is 4.5 cm. The empty dewar was modeled as a perfectly conducting electrical surface with an empty interior using 23,520 sub-volume elements. Figure 2 shows an example of the electric field vector amplitudes for the TM011 mode in the empty dewar. Liquid oxygen was characterized as an isotropic dielectric with a dielectric constant ε = 1.488 (ref. 9). Different liquid oxygen fill levels were modeled by intersecting a block of liquid oxygen with the interior of the dewar. The height of the liquid oxygen block was varied as a percentage of total dewar length from 10 to 100 percent, in 10 percent increments. The volume of the resultant liquid oxygen object was calculated using post-processing routines.

Each simulation run consisted of calculating the lowest 50 eigenmodes for each of the liquid oxygen fill levels. For the empty dewar, the 50th eigenmode occurs at 1587 MHz. Several of the calculated eigenmodes are degenerate (two modes having the same resonant frequency for a different field configuration). Using a workstation running Windows XP 64-bit edition with two dual core processors and 4 GB of RAM, the total simulation time (11 runs) was less than 4 hr. Figure 3 shows the electric field amplitude contour plots of the four lowest TM modes as calculated by the simulations, for both an empty dewar and a ~50 percent liquid oxygen fill level. The amplitudes of the field plots are normalized such that each mode contains a total energy of 1 Joule.

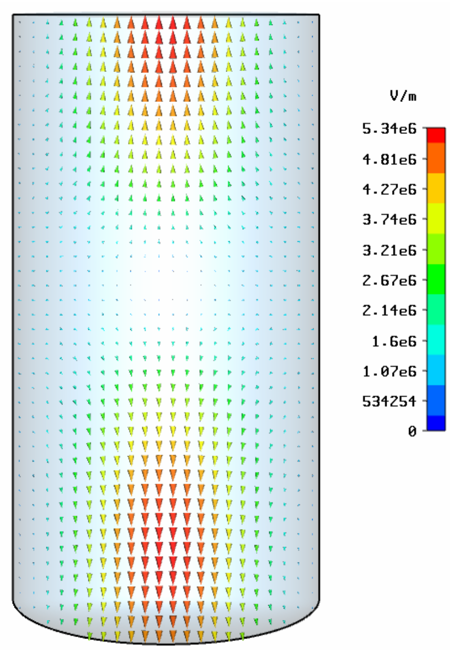

Figure 2.—Numerical simulations are used to calculate the electromagnetic eigenmodes of the dewar volume. Shown above is a plot of the electric field vector amplitude along the axial plane, computed for the empty tank TM011 mode.

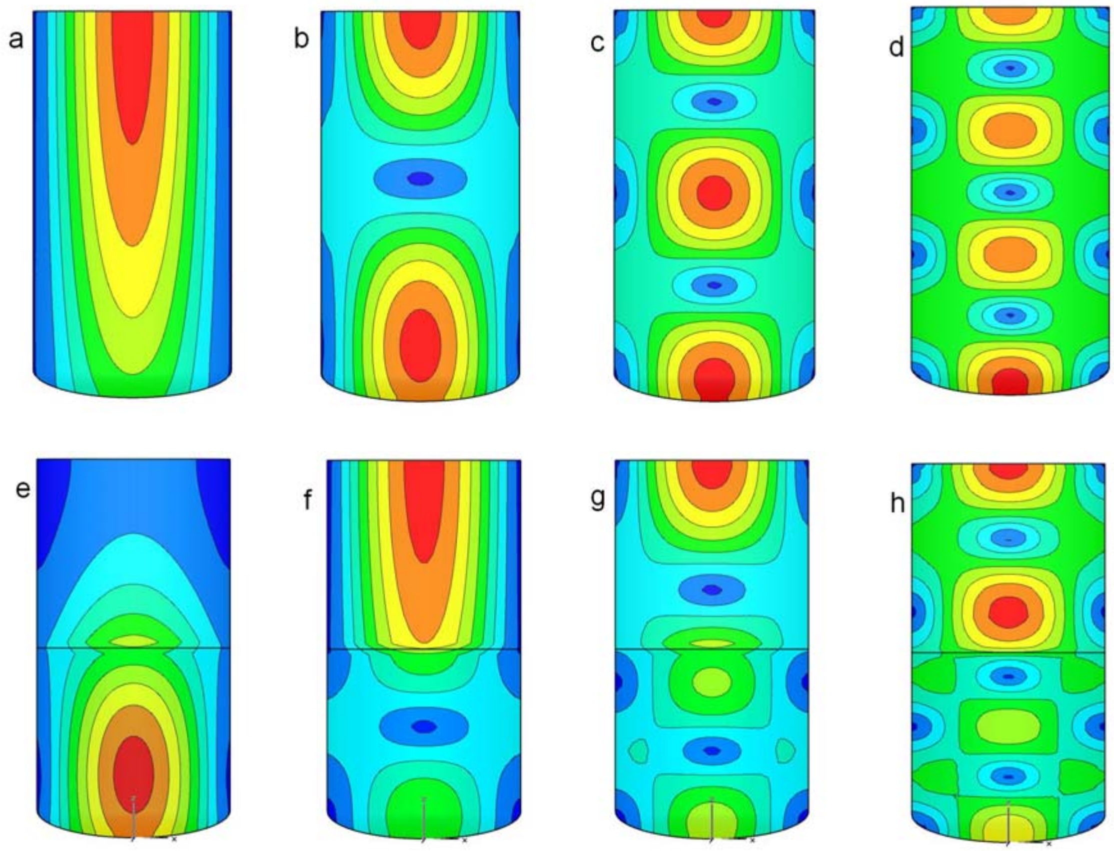

Figure 3.—Numerical simulations were used to generate these electric field amplitude contour plots of the four lowest TM modes [(a, e) - TM010; (b, f) - TM011; (c, g) - TM012; (d, h) -TM013] in the empty dewar (a-d) and at a 50 percent liquid oxygen fill level (e-h). High field regions are denoted in red.

III. Measurements and Analysis

A small dewar (46.1 liter capacity) was used as the test tank for the measurements. The dewar was placed on a calibrated floor scale, which provided the reference weighing system for determining the fill level (fig. 4). The percent fill level was determined by the ratio of the measured net weight of the liquid oxygen to the calculated full net weight, using 1.14 g/cc as the density of liquid oxygen. The liquid oxygen fill tube, which extended to near the bottom of the dewar, was removed during the frequency scans. The vent holes in the dewar lid were covered on the underside of the lid using a fine metal mesh screen tack welded to the lid to contain the RF energy.

A straight 4 cm long antenna probe was mounted to the underside of the dewar lid, approximately 10 cm off the central axis, using a Type-N feedthrough. The antenna was fabricated by removing the outer conductor and dielectric spacer from a section of rigid copper coax, leaving the center conductor as the radiating element. No other internal hardware was inside the tank, thus providing an idealized test configuration.

The RF measurement apparatus consisted of a spectrum analyzer with built-in tracking generator, an RF bridge, and a 12 m long coax cable connecting the instrumentation to the antenna. A 0 dBm source signal is output from the analyzer’s tracking generator, through the RF bridge, to the antenna inside the tank. The power reflected from the antenna travels back through the coupled port on the RF bridge to the

Figure 4.—The dewar was incrementally filled with liquid oxygen, and weighed using a floor scale to determine the fill level.

input of the analyzer. Prior to conducting measurements in the dewar, the RF measurement system was calibrated by successively attaching an electrical short, open, and 50 Ω load to the end of the coax cable (in place of the antenna) and creating a set of vector reflection calibration files over a range of frequencies. The analyzer stores the calibration information, and uses the calibration files to determine the return loss when the antenna is connected to the measurement system. The vector calibration procedure minimized the amount of ripple on the calibrated 0 dB reference line, thus making it easier to find weak resonance signals. The return loss is a measure of the reflected power relative to the incident power, and is defined as

$$\text{return loss}(\text{dB}) = 20\log_{10}\left|(Z - Z_0)/(Z + Z_0)\right| \quad (2)$$

where Z is the impedance of the load and Z_0 is the impedance looking towards the source. When the antenna is excited at a frequency far from a tank resonant frequency, the power is completely reflected and the return loss is 0 dB. At a resonant frequency, the RF energy may couple into the tank where it is dissipated in the tank walls, and the reflected power is low.

Figure 5 shows an example of the return loss spectrum from the tank at a liquid oxygen fill level of 38.1 percent. The resonant tank modes are clearly distinguished as sharp dips in the return loss. It is interesting to note that the TM010 mode (648.9 MHz), which was clearly visible in the empty tank spectrum (fig. 1), is barely detected at this fill level. This is consistent with figure 3(e), which shows that the electric field configuration of the TM010 mode at a 50 percent fill level has a weak electric field component at the top of the tank where the antenna is located. As expected, the antenna poorly couples to the TM010 mode over a range of fill levels.

Return loss spectra were recorded at liquid oxygen fill levels of 0 percent (empty tank), 9.7, 19.1, 38.1, 57.6, and 76.8 percent. The frequencies of the lowest four measured modes as a function of fill level are compared with the simulations in figure 6. The agreement between the simulations and measurements is excellent over the whole range of fill levels. As the tank fills with liquid oxygen, the frequencies of the various modes change in a complex, mode-dependent fashion. When the dielectric fluid intercepts the higher electric field regions of a mode, the frequency shift is larger. For example, the empty tank lowest

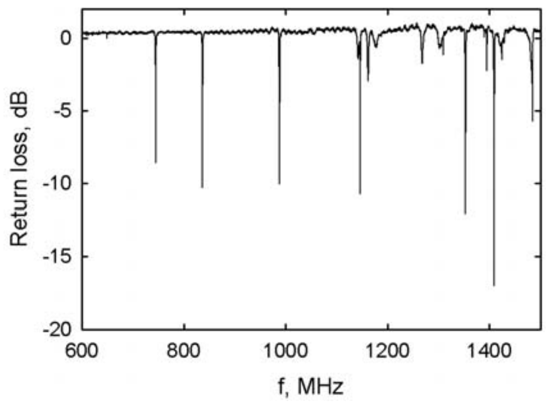

Figure 5.—Return loss spectrum of the dewar at 38.1 percent liquid oxygen fill level.

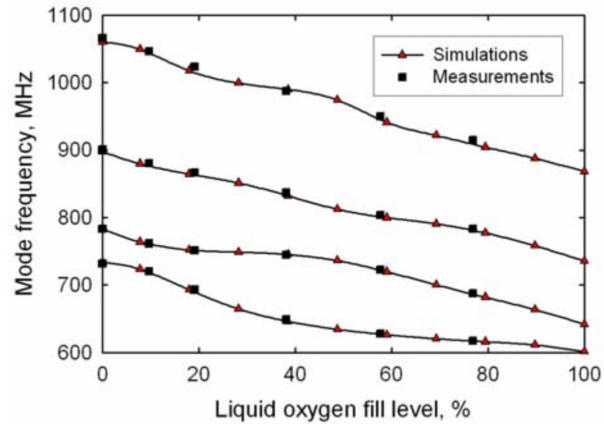

Figure 6.—Comparison of measured eigenmode frequencies (squares) with numerical simulations (triangles) as a function of liquid oxygen fill level. The solid lines are a smooth fit to the numerical simulation data. No adjustable parameters were used in the simulations.

mode has a relatively low-field region near the bottom of the tank (fig. 3(a)), so when the fluid begins to fill the tank, the frequency of that mode changes slowly at first. By the time the tank is half full of liquid oxygen, the electric field amplitude in the top half of the tank is relatively low (fig. 3(e)) so there is less frequency shift as the tank continues to fill. The TM011 mode (figs. 3(b) and (f)) displays the opposite trend. Higher order modes have regions of high electric field distributed more uniformly throughout the tank, and thus change in a more linear fashion as the tank is filled.

IV. Comments on Applying the Technique in Low-Gravity

In low-gravity a possible fluid configuration is that in which the tank walls are completely wetted by the fluid, leaving a vapor pocket in the interior. The frequency response of the modes as a function of fill level would be different for a wetted wall liquid configuration, since the electric field amplitudes near the walls is relatively low. Because the modes are sensitive to the fluid distribution, in order to be effective as a low-gravity RF mass gauge several tank modes would have to be monitored and compared to numerical simulations. Using interpolated values of the numerically calculated eigenmode frequencies as the basis for a translation from the measured frequencies to a percent fill value, as might be done when used as a low-gravity RF mass gauge, we find that the RF gauge predicts the fill level to within 2 percent full scale uncertainty without using any adjustable parameters.

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