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Development and Design of Zero-g Liquid Quantity Gauge for Solar Thermal Vehicle

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November 2002

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Summary

The development and design of a cryogenic liquid quantity gauge for zero-gravity (zero-g) applications are described. The gauge, named the compression mass gauge (CMG), operates on the principle of slightly changing the volume of the tank by an oscillating bellows. The resulting pressure change is measured and used to predict the volume of vapor in the tank, from which the volume of liquid is computed. For each gauging instance, pressures are measured for several different bellows frequencies to enable minor real-gas effects to be quantified and thereby to obtain a gauging accuracy of ±1 percent of tank volume.

The CMG was selected by NASA's Future-X program for a flight demonstration on the United States Air Force-Boeing Solar Orbit Transfer Vehicle Space Experiment (SOTVSE). This report reviews the CMG design trade studies needed to satisfy the SOTVSE limitations on power, volume, and mass and also describes the mechanical design of the CMG.

Introduction

The solution to the problem of accurately gauging the quantity of liquid in a tank in a weightless environment has eluded spacecraft designers for years. Clearly, Earth-based methods such as determining the location of the liquid interface or weighing the tank cannot be employed. Many innovative zero-g gauging methods have therefore been proposed. Several of the methods depend on imaging the shape of the liquid volume (somewhat similar to medical tomography), so they would require substantial instrumentation, long gauging times, and powerful computing resources. For some other methods (e.g., microwave excitation of cavity resonances), it is not evident how the measurements can be interpreted in terms of liquid quantity without calibrating the tank and liquid in weightlessness over a range of fill levels. The straightforward method of metering the outflow from the tank is generally not sufficiently accurate (especially for cryogens). Mord, et al. (1988) evaluated many of the proposed zero-g gauging methods and concluded that the compression mass gauge (CMG) method and the pressure-volume-temperature (PVT) method are the best choices. Southwest Research Institute and NASA Glenn Research Center have developed several breadboard and engineering development gauges of the CMG type and tested them in cryogenic hydrogen and nitrogen to establish the gauge capabilities, to resolve design issues, and to formulate data-processing algorithms.

The CMG method is illustrated schematically in figure 1. A bellows is used to change the tank volume slightly, and the resulting pressure change is measured. The tank gas volume V_g can then be inferred from thermodynamics:

$$V_g = -kP\left(\frac{\Delta V}{\Delta P}\right) \tag{1}$$

where k is the isentropic gas constant, P is the mean static pressure of the tank, ΔV is the change in volume of the tank (numerically equal to the swept volume of the CMG bellows), and ΔP is the change in tank pressure. The liquid volume is the difference between the tank volume V_T and V_g. Equation (1) assumes that the compression process is adiabatic, the compression is uniform over the entire fluid volume, the liquid is incompressible, and $\Delta V/V_g << 1$. (Some of these assumptions can be eliminated when they are not applicable; for example, equation (1) can easily include

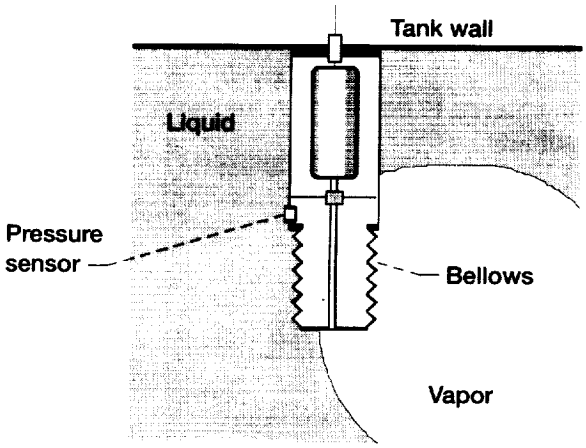

Figure 1.—Compression mass gauge (CMG).

liquid compressibility.) A CMG works as well in weightlessness as it does in normal gravity because the operating principle is not a function of the shape or orientation of the liquid or gas volumes or a function of the gauge orientation with respect to the liquid and gas locations in the tank.

The PVT method is somewhat similar to the CMG method except that the change in tank pressure is produced by injecting a small measured amount of gas into the tank. The CMG appears to be the better choice of the two because by oscillating the bellows at a known frequency, data processing techniques can be used to eliminate noise in the oscillatory pressure signal (which is quite small and challenging to measure), whereas the PVT pressure signal is a ramp to a new steady state for which the noise cannot easily be removed. Another potential limitation of the PVT method is that, when used with a cryogen, the increased pressure tends to decay back to the initial pressure. The PVT method and an analogous method in which a small measured pulse of heat is added to the tank fluid and the temperature change is measured (from which the mass of fluid can be inferred) are currently used to gauge the *storable* propellants of certain telecommunications satellites (Ounougha, Jallade, and Pigot (1998)). Since proposed solar thermal vehicles and other advanced reusable launch vehicles use *cryogenic* propellants, the compression mass gauge is especially relevant for them.

Symbols

C	empirical parameter related to viscous boundary layer temperature change, $Hz^{0.5}$
D	empirical parameter related to pressure magnification by acoustic resonances, Hz^{-2}
E	error, defined in equation (4)
F(geometry)	function relating acoustic mode standing wave shape to location of ΔP sensor
f	bellows frequency, Hz
f_a	acoustic resonant frequency, Hz
K	empirical parameter related to mass transfer at liquid-vapor interface, $Hz^{0.5}$
k	isentropic gas constant
P	mean static pressure in tank, Pa (psi)
ΔP	oscillating fluid pressure, zero to peak, Pa (psi)
ΔV	swept volume of the CMG bellows, zero to peak, m^3 (ft^3)
V_g	volume of vapor in tank, m^3 (ft^3)
V_T	tank volume, m^3 (ft^3)
$X(f)$	Fourier transform
δ_a	acoustic damping coefficient

Previous CMG Experiments

As part of their evaluation of zero-g gauges, Mord, et al (1988) constructed and tested a breadboard CMG in an oil-barrel-size tank containing water and air. The bellows was oscillated at a frequency f of a few hertz, and ΔV and ΔP were interpreted as the amplitudes of the corresponding sinusoidal signals. It was found that small nonideal gas effects prevented the desired ±1% gauging accuracy from being obtained unless the nonideal gas effects were accounted for in the data processing. In particular, equation (1) had to be modified to account for a nonuniform isentropic gas constant k caused by the temperature change in the viscous boundary layers; to the first order, the relation between the in-phase components of the oscillatory ΔV and ΔP signals was found to be

$$V_g = \frac{-kP\left(\frac{\Delta V}{\Delta P}\right)}{1 + \frac{C}{\sqrt{f}}} \qquad (2)$$

where C is a parameter that depends on fluid viscosity and liquid-gas-tank configuration. Although C cannot be predicted accurately, Mord, et al (1988) determined it empirically by measuring ΔP at two frequencies and using equation (2) twice to determine both C and V_g. As expected, the magnitude of $C/\sqrt{f}$ was found to be much smaller than unity.

Monti and Berry (1994) tested a breadboardlike CMG in a Get Away Special experiment during the space shuttle flight of STS–57 in 1993. They used equation (1) to analyze gauging data for a small tank containing the perfluorinated liquid Fluorinert FC75 (3M Electronic Materials, St. Paul, MN). Good accuracy was found. The value of $\Delta V/V_g$ used in these tests was, however, relatively large (compared to what would be practical for a space vehicle) so as to enable ΔP to be more easily measured.

Rogers, Dodge, and Behring (1995) used a breadboard CMG to investigate the effects of cryogenic liquids. Their tests employed an oil-barrel-sized tank containing saturated liquid and vapor Freon (DuPont, Wilmington, DE) to simulate a cryogenic propellant. The tests revealed that mass transfer of the near-boiling fluid at the liquid-vapor interface had a noticeable influence on gauging accuracy. During each bellows oscillation cycle, vapor tended to condense when the tank pressure increased and liquid tended to vaporize when the tank pressure decreased; in both cases, the pressure change was less than that predicted by the ideal gas law. Although mass transfer effects can be diminished by using a sufficiently high bellows frequency, there is a limit on the highest frequency that can be employed without introducing other unwanted effects, as is discussed in the section entitled "Compensation for Acoustic Effects in Very Large Tanks." By analyzing the heat transfer rate at the liquid-vapor interfaces, Saiyed (1993) predicted that the mass transfer effect could be treated by a further refinement of equation (2):

$$V_g = \frac{-kP}{1 + \frac{C}{\sqrt{f}}}\left(\frac{\Delta V}{\Delta P} - \frac{K}{\sqrt{f}}\right) \qquad (3)$$

where K is an empirical "mass-transfer" coefficient. Values for K, C, and V_g were established by using three or more distinct bellows frequencies for each gauging instance. The values of both $K/\sqrt{f}$ and $C/\sqrt{f}$ were small but crucial in obtaining good gauging accuracy.

Cryogenic Testing of CMG Engineering Development Model

Because of the applicability of a CMG to cryogenic propellants, Southwest Research Institute and NASA Glenn Research Center entered into a Space Act Agreement in the early 1990s to develop the CMG technology to the point where it could be realistically tested in a space experiment and then made available for advanced space vehicles. To that end, a CMG engineering development model was designed and fabricated to be suitable for service in cryogenic hydrogen or nitrogen and of a size to be compatible with an existing 0.167 m^3 (5.9 ft^3) Dewar at Glenn. Since the unit was meant only for development purposes, no attempt was made to minimize its size, weight, or power as would be required for a vehicle application. Figure 2 shows an exploded photograph of the CMG. The overall volume of the CMG is about 0.012 m^3 (0.42 ft^3).The bellows is welded stainless

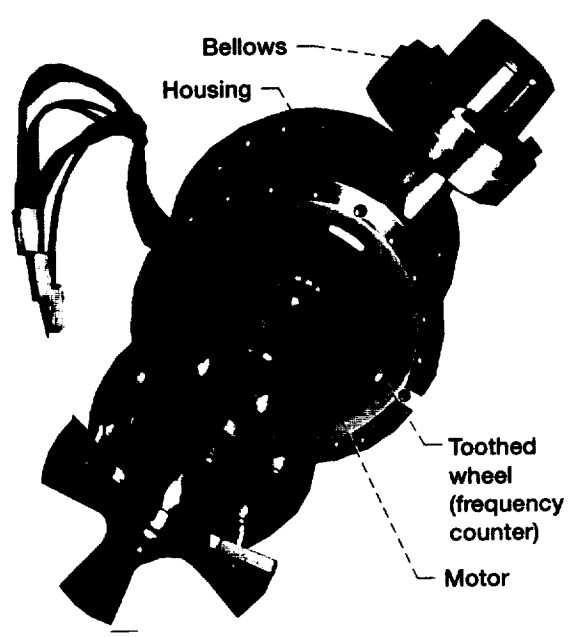

Figure 2.—CMG engineering development model.

steel and has a mean diameter of about 64 mm (2.5 in.) and a zero-to-peak stroke of about 8.1 mm (0.32 in.), which produced a bellows ΔV (zero to peak) of 0.011 percent of the net Dewar free volume. This ΔV is considered to be a representative value for an actual space vehicle application. A three-phase ac fractional-horsepower electric motor drives the bellows.

Several development problems had to be solved during the CMG design and testing. For example, oscillatory pressures of about 100 Pa (0.015 psi) had to be measured for frequencies as low as 3 Hz. Piezoelectric transducers for cryogenic service are commercially available with the required sensitivity, but developing a calibration curve for them at such low frequencies and low amplitudes was a challenge (Green (1998)). Other problems included developing a tank-to-gauge pressure-equalization system since a large pressure difference between the tank and the inside of the CMG would substantially increase the power required to drive the bellows and also might overstress the bellows.

A least-squares error algorithm was needed to analyze the ΔP measurements. However, the customary least-squares error methods could not be used because the desired quantity (the vapor volume V_g) was not available. In fact, because V_g is supposed to be determined by the gauge, its true value cannot be known to compare with the predicted V_g to determine the parameters (C and K) of the prediction equation. Various alternatives were investigated. For one alternative, the least-squares error method was based on a comparison of the true value of the derivative of V_g with respect to f since this derivative is physically equal to zero (i.e., V_g does not depend on bellows frequency); thus, the error could be defined as the difference between zero and the derivative of equation (3) with respect to f. This definition of the error gave a set of coupled equations nonlinear in C and K that could not be solved readily. After several alternatives were investigated, a method based on fitting a pressure parameter to the analytical model was developed from Eq. (3):

$$E = \sum \left[\left(\frac{kP\Delta V}{\Delta P} \right)_i - V_g - \frac{V_g C + kPK}{\sqrt{f_i}} \right]^2 \qquad (4)$$

where E is the error. A standard least-squares technique is used to determine the values of V_g and $(V_g C + kPK)$ which minimizes the error for all of the operating frequencies, f_i (Dodge and Kuhl (1997)). The procedure yields the best or true value of V_g, but it does not predict either C or K individually because in this form of the analytical model, both C and K are the same functions of $\sqrt{f}$ and thus cannot be distinguished; however, this indeterminateness of C and K is not a limitation on the determination of V_g.

Equation (4) fits the analytical model to a parameter based on the experimental ΔP_i amplitude data, which are computed from the digitized pressure time-history signal for each bellows frequency f_i. In processing the time histories, it was necessary to eliminate the high-frequency noise and low-frequency drift in the signal to obtain the desired gauging accuracy. Thus, the signal was first processed by LabVIEW (National Instruments Corporation, Austin, TX) Fourier transform to determine its amplitude and frequency content. The power spectrum $S_{xx}(f) = |X(f)|^2$ of the transformed signal was then computed, where $X(f)$ is the Fourier transform. The amplitude ΔP_i of the sine wave at the bellows frequency f_i was next computed as $\Delta P = 2\sqrt{S_{xx}(f_i)}$, and this was the value used in equation (4). There is one accuracy-limiting problem with this data reduction procedure. The time histories cannot generally be acquired over an integral number of bellows cycles, so some spectral power leaks to other frequencies as a consequence of the implicit assumption in the Fast Fourier Transform that a data time history represents a periodic function infinitely extended in time. For a time history that is not an integral number of cycles, the beginning and end points of the time history do not align, so when the data record is continued in time there is a discontinuity at the alignment point. To minimize the misalignment, power spectra of subsets of the time history were computed, starting with a single point and subsequently increasing the number of data points until the entire record was processed. The amplitude ΔP for each subset was stored as an array, and the maximum amplitude in the array was assigned as the true ΔP. This process in essence finds a subset of the record for which the end point is best aligned with the starting point of the record.

With these data-processing algorithms in place, an extensive series of tests were conducted with liquid hydrogen and liquid nitrogen for a variety of tank fill levels and static pressures (Jurns and Rogers (1995) and Dodge and Kuhl, (1997, 1998)). For some tests, helium gas was used to pressurize the tank above the saturation pressure of the cryogen. At least four bellows frequencies were used for most of the tests to obtain sufficient data for the data-reduction algorithm.

To establish the liquid volume independently of the CMG measurements, the Dewar was instrumented with an array of vertically oriented silicon diode temperature sensors, which determine the approximate liquid level during filling. The fluids in the Dewar were weighed by a load cell during each test. Nonetheless, because of heat leaks and other problems, there were questions about the accuracy of these determinations. In addition to the uncertainty introduced by the Dewar fluid measurement system, the linkage between the CMG motor and the bellows developed an excessive amount of "play" during the tests such that the actual ΔV varied slightly in an unknown way, as was shown by an examination of the CMG at the conclusion of the tests. These problems limited the degree to which the accuracy of the CMG could be established. (The CMG has since been upgraded and refurbished, and the reference measuring system at the NASA Glenn test facility has been greatly improved.)

Figures 3 and 4 give representative results, in this case for liquid nitrogen, from tests conducted over a period of months. Some of the results obtained near the end of the testing are marked as "degraded" for the reasons noted above. The averages of those tests considered to be valid are also indicated in the plots. In general, the averages predict the vapor volume to within ±2 percent, which is considered satisfactory agreement since there was probably at least ±1-percent error in the vapor volume determined by the Dewar load cell used for comparison with the CMG results.

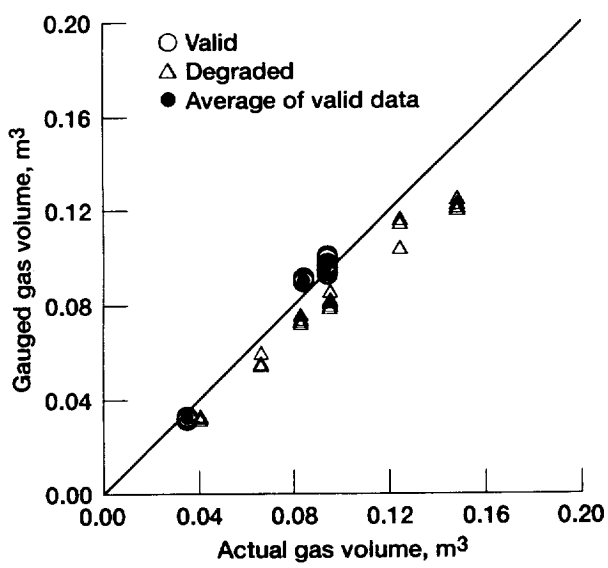

Figure 3.—Gauging results for liquid nitrogen (LN_2) at nominal tank pressure of 172 kPa (25 psia).

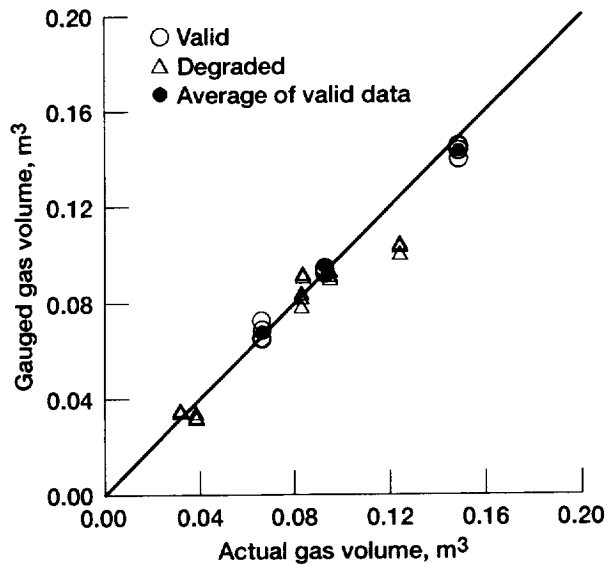

Figure 4.—Gauging results for LN_2 at nominal tank pressure of 255 kPa (37 psia).

Design of CMG for Solar Thermal Vehicle

Because of the CMG capabilities demonstrated by the cryogenic ground tests, a flight experiment was proposed to and was accepted by NASA's Future-X program. The vehicle selected for the experiment was the United States Air Force (USAF)-Boeing Solar Orbit Transfer Vehicle Space Experiment (SOTVSE), which employs liquid hydrogen (LH_2) as its propellant. The LH_2 tank volume is about 1.89 m^3 (66.7 ft^3). For the baseline SOTVSE design, the tank pressure at launch is about 124 kPa (18 psia), and the liquid fill percentage is about 89 percent. After reaching low Earth orbit, the tank remains in a locked-up configuration for several days while the propellant is heated to raise the tank pressure to about 310 kPa (45 psia), at which point the fill percentage has increased to 96 percent as a result of expansion of the LH_2. Thrusters are then activated during each orbit to raise the orbit until the LH_2 is exhausted. SOTVSE is an almost ideal vehicle to demonstrate the CMG technology for the following reasons:

(1) The fill level changes from 89 to 96 percent with no change in total mass; thus, the CMG accuracy can be verified under precisely known conditions over a wide range of fill levels.

(2) The tank contains an array of heated silicon diode sensors from which the settled liquid level (during thrusting) can be determined at a number of discrete locations; these measurements also allow the CMG accuracy to be determined for a variety of fill levels.

(3) The LH_2 is continually mixed to prevent stratification.

(4) The LH_2 is stored in a saturated condition without a noncondensable pressurizing gas.

SOTVSE does, however, impose limitations on the allowed power, volume, and weight of the CMG. In addition, the fairly large change in tank pressure from launch to operation and the fact that the tank is in an upside-down configuration at launch presented a challenge to the design of a pressure equalization method for the gauge, which is needed for reasons described in the Pressure Equalization Design section.

Objectives of CMG Space Experiment

The objective of the space experiment is to demonstrate the capability of the CMG in an actual space vehicle and thus, in NASA's terminology, to achieve a technology readiness level of 7. Specifically, the CMG design will incorporate all the features needed to make it flightlike, and the experiment will investigate, to the extent possible, all the relevant physical effects of microgravity that might influence the operation of a compression mass gauge in a space environment, especially those effects that cannot be reasonably simulated by ground tests. These zero-g effects, listed in the likely order of their importance, are

(1) Location and configuration of liquid and vapor zones—The configuration is unknown, and the bellows might be in liquid or vapor; while this is unlikely to cause a problem, it must be verified by zero-g tests.

(2) Multiple vapor bubble resonances—If the vapor space is composed of several large bubbles, the CMG oscillation may create a resonance in which one bubble compresses while another expands, with the result that the measured ΔP is distorted and cannot be interpreted.

(3) Creation of liquid sloshing by the CMG bellows—Since there are no large forces to prevent sloshing, the bellows oscillation may create sloshing and distort the ΔP measurements.

(4) Cavitation at the gauge head—When the bellows is in the liquid space, the liquid may not be able to follow the bellows motion because there are no strong gravity forces to restore the displaced liquid; hence, the liquid may cavitate and thereby distort the ΔP measurements.

(5) Thermal stratification—Stratification may be more pronounced in microgravity because of the absence of buoyancy forces to mix the fluid; if so, a representative fluid temperature may not be available to make accurate fluid property (e.g., k) determinations.

Because the extent of these effects cannot be predicted in the absence of microgravity test data, the flight gauge will be designed with enough intelligence to recognize the effect and compensate for it if necessary. For example, the software will filter out a cavitation pressure spike. Similarly, if the magnitude of ΔP changes significantly when f changes, which would indicate the occurrence of a multiple bubble resonance, the software will change the bellows oscillation frequency range.

Trade Studies

The SOTVSE design and operation put limits on the CMG power, mass, and volume: these limits are roughly 75 W peak power only for brief durations; total mass of 45 kg (100 lbs); and total volume of 1 percent of the tank volume. Trade studies were conducted to develop the flight hardware design such that the liquid volume could be gauged over a representative fill level range with the desired accuracy of ±1 percent of tank volume.

One of the important trade studies was to examine the usage of power to drive the CMG. The resolution of the ΔP sensor is finite, so the theoretically best resolution of the CMG is also finite. Figure 5, which is derived from equation (1), illustrates how the gauging accuracy varies with bellows ΔV, for a fixed, finite ΔP resolution of 1 Pa ($\sim 1\times10^{-4}$ psi), typical of a state-of-the-art cryogenic sensor. With other parameters held constant, the power required to drive the bellows increases with ΔV; thus, the figure demonstrates that the ΔV needed to obtain a given accuracy increases dramatically for small fill levels. Hence, for a given power budget, there is a lower limit on the tank fill level that can be gauged with the desired accuracy.

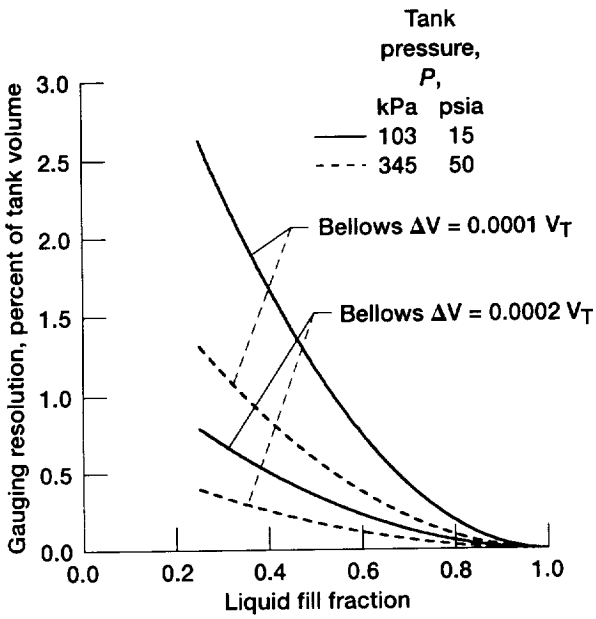

Figure 5.—CMG resolution as function of amplitude of oscillating fluid pressure, ΔP. ΔP resolution is 1 Pa (1×10^{-4} psi).

The power required to drive the gauge also depends on the bellows frequency f, the bellows spring stiffness, the internal volume of the gauge enclosure (since the internal gas is compressed as the bellows oscillates), the vapor volume of the tank, the pressure differential between the gauge internal volume and the tank, and the fluid properties. The authors developed an analytical model to relate these parameters to the electric motor power. The enclosed volume of the CMG was found to be an important parameter because the gas contained in the volume acted like a pneumatic spring during the bellows oscillation. The pressure differential between the CMG enclosed volume and the SOTVSE tank was also found to be quite important; for this reason, the design included a pressure equalization scheme (described in the next section) to maintain the pressure differential at near zero. To be conservative, the motor power expended on the outward part of the bellows stroke was assumed to be unrecoverable on the inward stroke, and the motor peak torque was chosen to meet the peak torque required to drive the bellows. This choice ensured the bellows oscillation would be sinusoidal to simplify the data analysis.

These trade studies indicated that to satisfy the CMG power, weight, and volume budgets, the gauged fill levels had to be greater than about 65 percent to meet the desired accuracy goal of ±1 percent of tank volume. It is expected that after the space experiment data are analyzed, less conservative design approaches will be feasible.

Pressure Equalization Design

The SOTVSE CMG is nominally a completely sealed enclosure. The CMG internal volume will be purged of air and filled with gaseous helium to 1 atm before being installed in the SOTVSE tank. (It is expected that the helium will be purged and replaced with hydrogen vapor on the launch pad.) When the SOTVSE tank is being loaded with LH_2 prior to launch, the CMG temperature and gas pressure decrease substantially, and a large pressure differential is therefore created between the tank and the CMG if the CMG remains sealed. Since this pressure differential is large enough to overstress the bellows, it must be prevented. As mentioned in the previous section, a pressure equalization method is also needed during flight (when the SOTVSE tank pressure changes) to minimize the power required to oscillate the bellows.

After numerous concepts were analyzed, the equalization method that was chosen employs vaporization and condensation of cryogenic hydrogen. A solenoid valve is incorporated in the CMG housing so that the internal volume can be opened to the SOTVSE tank volume when needed. During the tank filling prior to launch, liquid level sensors open the valve when the LH_2 in the tank reaches a location just above the bottom of the CMG; this ensures that the CMG hardware temperature is the same as the LH_2 temperature and that the tank has been sufficiently chilled so that only hydrogen vapor flows across the solenoid valve into the CMG. The vapor flow into the CMG keeps the CMG internal and tank pressure equalized. The CMG also incorporates a small internal standpipe connected to the solenoid valve. At some point during the filling, the valve inlet becomes submerged in liquid, and liquid flows from the tank through the valve into the CMG standpipe. At that point, both the tank and the CMG pressures are very close to the final tank pressure. After a small amount of liquid has flowed into the standpipe to fill it to a predetermined level, the solenoid valve closes. The internal and tank pressures remain equalized during the remainder of the tank loading.

When SOTVSE reaches its initial orbit, the propellant will have been heated over a number of days

to raise the tank pressure to 310 kPa (45 psia). The CMG temperature increases in lockstep with the tank, and the LH_2 in the CMG standpipe consequently evaporates into the internal volume to maintain the CMG pressure equal to the SOTVSE tank pressure. During any subsequent gauging operation when the tank pressure differs from the nominal 310 kPa pressure, the solenoid valve opens to admit fluid (liquid or vapor) or to expel vapor to maintain a zero pressure differential; the amount of fluid exchange needed is extremely small because the saturated liquid in the CMG standpipe evaporates or condenses in response to the SOTVSE tank temperature/pressure change to maintain pressure equalization. The solenoid valve is closed just before the actual gauging process.

Although this equalization process may appear to be unduly complicated, it is necessary to ensure that the SOTVSE CMG is self-contained (a project-imposed requirement) and can equalize the pressure differential regardless of whether the external fluid in contact with the CMG is vapor or liquid. For some applications, it may be sufficient to plumb the CMG to the tank gaseous pressurization supply to maintain the CMG internal pressure equal to the tank pressure.

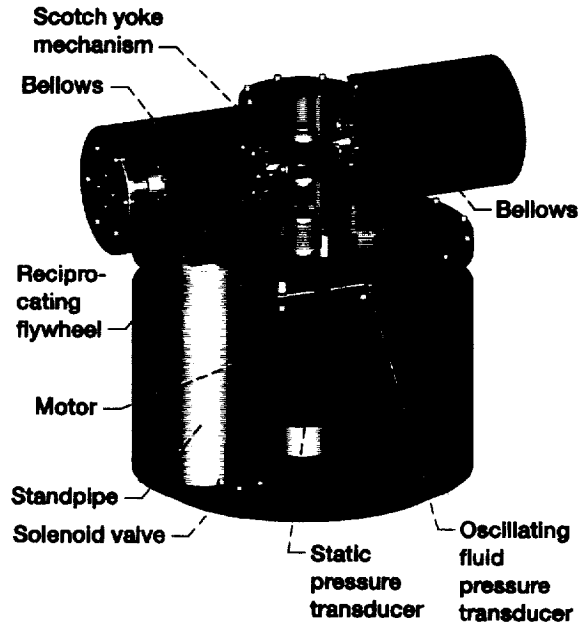

Figure 6.—Solid model of SOTVSE CMG.

SOTVSE Hardware Design

Figure 6 illustrates the SOTVSE CMG design. The CMG employs two identical but opposed bellows to minimize the net oscillatory force and torque exerted on the SOTVSE during the gauging. Both bellows are driven in phase by the same motor through a scotch yoke mechanism. Each bellows has an outside diameter of 126 mm (4.97 in.), and the length from the end of one bellows to the end of the other is 427 mm (16.8 in.). The overall axial length of the CMG is 401 mm (15.8 in.). The cylindrical barrel that houses the electric motor and standpipe has a diameter of 335 mm (13.2 in.) and a length of about 254 mm (10 in.). For the reasons discussed earlier in the section Trade Studies, the volume of this barrel was made as large as possible to minimize the effect of the hydraulic spring of the contained gas on the power requirements. Each bellows is also attached to an inertial mass (labeled the reciprocating "flywheel" in the figure) to help smooth out the load on the electric motor.

Figure 7 illustrates the installation of the CMG in the SOTVSE tank. The CMG is located at the end of the tank away from the outlet so as not to interfere with the pump mixer operation or impede the outflow; in addition, this location tends to keep the CMG in the vapor space during flight and thus simplifies the operation of the pressure equalization system. The relative sizes of the CMG and the tank are deceptive in this planar representation of a three-dimensional configuration. In fact, the CMG occupies only about 1 percent of the tank volume.

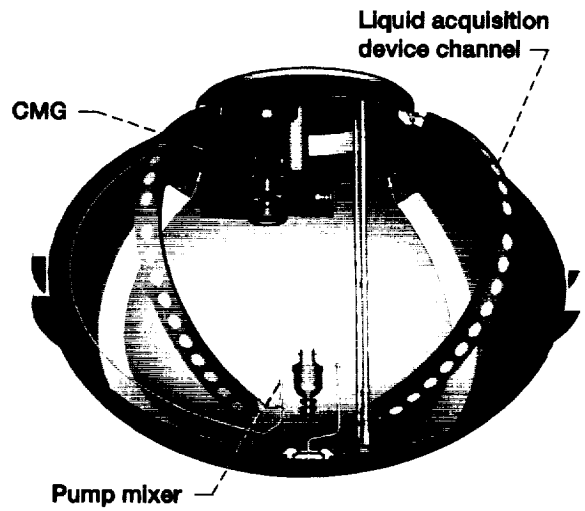

Figure 7.— CMG installation in SOTVSE tank.

All components of the CMG are commercially available and are compatible with cryogenic hydrogen. The bellows are welded stainless steel. For liquid oxygen service, the bellows may need to be of the convolute-formed type for ease of cleaning. Welded bellows generally have a considerably smaller spring constant than the convolute-formed, which is the reason the welded type was chosen for the SOTVSE CMG.

Compensation for Acoustic Effects in Very Large Tanks

For the reasons discussed earlier, the bellows must be operated at three or more frequencies during each gauging instance to determine V_g. Furthermore, it is greatly beneficial to separate the frequencies as widely as possible, since this reduces the uncertainty in the data analysis procedure. The ΔP dynamic pressure sensor, however, imposes a lower limit of about 3 Hz on the allowed bellows frequency, and the volume of the tank imposes an upper limit: if the frequency is too high compared to the acoustic resonance frequency of the gas volume, the acoustic wave travel time through the gas becomes comparable to the bellows oscillation period, and compression is not achieved uniformly throughout the tank. The fundamental CMG principle, equation (1) or (3), is not applicable when the compression is not uniform. The allowed frequency range must fit between these two limits.

A relatively simple, linearized, order-of-magnitude analytical model of the acoustic effects was used to determine the allowed frequency range of the SOTVSE gauge. This model predicts that the pressure amplitude ΔP_a of the acoustic standing wave at the sensor location is

$$\Delta P_a = \frac{\Delta P}{\sqrt{\left[1-(f/f_a)^2+(2\delta_a f/f_a)^2\right]}} F(\text{geometry}) \qquad (5)$$

Here, ΔP is the pressure predicted by equation (3) for uniform compression, f_a is the acoustic resonant frequency, δ_a is the acoustic damping, and F(geometry) is a function that relates the acoustic mode standing wave shape to the location of the ΔP sensor. For the SOTVSE tank, the lowest acoustic wave frequency was estimated to be about 120 Hz. Consequently, to maintain acoustic effects below the 1-percent level (so that $0.99 < |\Delta P/\Delta P_a| < 1.01$), equation (5) indicates that the maximum allowed value of f can be no higher than 12 Hz. A bellows frequency range of 3 to 12 Hz was therefore selected for the SOTVSE tank.

For tanks substantially larger than the SOTVSE tank, the spread between the lowest (3 Hz) and highest allowed frequencies as determined from the acoustic wave travel time will be too narrow for accurate gauging (Dodge (2000)). The mode of operation would either have to be changed (e.g., to a bellows step or pulse motion followed by a delay to let the acoustic ringing decay), or the data analysis would have to account for acoustic effects. Acoustic effects can be approximately accounted for in the analysis by a first-order correction to equation (3). To do so, equation (5) is expanded to a power series of $(f/f_a)^2$, and all but the first term are neglected. Then, by solving for ΔP, the data analysis model that incorporates acoustic effects is

$$V_g = \frac{-kP}{1+\left(C/\sqrt{f}+Df^2\right)}\left(\frac{\Delta V}{\Delta P}-\frac{K}{\sqrt{f}}\right) \qquad (6)$$

The empirical acoustic coefficient D can be determined during the data processing just as C and K are, although additional measurements of ΔP versus f would be required. By using equation (6) to analyze the gauging data, the bellows frequency can be as high as about one-third the acoustics frequency. Since a reasonably good bellows frequency range is 3 to 12 Hz, the tank volume could therefore be as large as about 28 m^3 (1000 ft^3), inasmuch as the acoustic resonant frequency would be then no smaller than 35 Hz. Although for tanks larger than about 28 m^3, which could have acoustic resonant frequencies below 35 Hz, the bellows frequency would have to be less than 12 Hz because when the bellows frequency is greater than one-third the acoustic resonant frequency, the first-order correction employed in equation (6) is not sufficiently accurate to represent the acoustic effects. Hence, the allowed frequency range could be so narrow for these very large tanks that a pulse mode of bellows operation might be necessary.

Concluding Remarks

An instrument to measure the volume of cryogenic liquids in zero-g applications, the compression mass gauge (CMG), has been the subject of a 10-year development process between Southwest Research Institute and the NASA Glenn Research Center. Breadboard and engineering development models of the gauge have been tested with cryogens in tanks of various sizes to establish the important parameters, resolve design issues, and validate data analysis algorithms. This development has shown that a compression mass gauge should be able to achieve an accuracy of ±1 percent of tank volume for cryogens. The size and power requirements of the gauge also appear to be practical for space vehicles.

Compared with most other zero-gravity gauging methods, the compression mass gauge has the great advantage that it does not have to be calibrated in the tank in zero-g as a function of fill level, tank shape, and liquid-vapor configuration. The only calibration required is that due to relatively minor real-gas effects, not by complicated tank shapes or liquid-vapor configurations. This calibration to accommodate real-gas effects can be easily accomplished during each gauging instance by operating the gauge at several bellows frequencies.

The compression mass gauge technology was selected by NASA's Future-X program for a flight demonstration on the United States Air Force-Boeing Solar Orbit Transfer Vehicle Space Experiment (SOTVSE). The SOTVSE propellant is liquid hydrogen. The SOTVSE CMG will be manufactured from flight-qualified components to aid in demonstrating a NASA technology readiness level of 7. The mechanical design of the CMG is complete, although the electronics design has been placed on hold until the SOTVSE electronics interfaces are defined more completely.

At this time, the flight date of the SOTVSE has been postponed for several years. As an interim measure, a smaller version of the SOTVSE CMG is currently being fabricated from non-flight-qualified components. This CMG will be suitable for further ground testing at Glenn and NASA Marshall Space Flight Center.

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John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135, April 25, 2002

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13. ABSTRACT ***(Maximum 200 words)***

The development and design of a cryogenic liquid quantity gauge for zero-gravity (zero-g) applications are described. The gauge, named the compression mass gauge (CMG), operates on the principle of slightly changing the volume of the tank by an oscillating bellows. The resulting pressure change is measured and used to predict the volume of vapor in the tank, from which the volume of liquid is computed. For each gauging instance, pressures are measured for several different bellows frequencies to enable minor real-gas effects to be quantified and thereby to obtain a gauging accuracy of ±1 percent of tank volume. The CMG has been selected by NASA's Future-X program for a flight demonstration on the United States Air Force-Boeing Solar Orbit Transfer Vehicle Space Experiment (SOTVSE). This report reviews the design trade studies needed for the CMG to satisfy the SOTVSE limitations on its power, volume, and mass and also describes the mechanical design of the CMG.

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