JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 48, No. 3, May–June 2011

Optical Mass Gauging System for Measuring Liquid Levels in a Reduced-Gravity Environment

Ryan M. Sullenberger,* Wesley M. Munoz,† Matt P. Lyon,† Kenny Vogel,† and Azer P. Yalin‡
Colorado State University, Fort Collins, Colorado 80523
Valentin Korman§
K Sciences GP, LLC, Huntville, Alabama 35814
and
Kurt A. Polzin¶
NASA Marshall Space Flight Center, Huntsville, Alabama 35812

DOI: 10.2514/1.51560

A compact and rugged fiber-coupled liquid volume sensor designed for flight on a sounding rocket platform is presented. The sensor consists of a Mach–Zehnder interferometer capable of measuring the amount of liquid contained in a tank under any gravitational conditions, including a microgravity environment, by detecting small changes in the index of refraction of the gas contained within a sensing region. By monitoring changes in the interference fringe pattern as the system undergoes a small compression provided by a piston, the ullage volume of a tank can be directly measured, allowing for a determination of the liquid volume. To demonstrate the technique, data are acquired using two tanks containing different volumes of liquid, which are representative of the levels of liquid in a tank at different time periods during a mission. The two tanks are independently exposed to the measurement apparatus, allowing for a determination of the liquid level in each. In a laboratory test of the unit, a liquid level of 11.2 ± 3.7 ml was measured, comparing favorably with the actual liquid volume level of 10.5 ml.

Nomenclature

A	=	molar refractivity, m^3/mol
l	=	length of the sensing path, m
n	=	optical refractive index
p	=	pressure, Pa
R	=	universal gas constant, $J/(K \cdot mol)$
T	=	temperature of working gas, K
V_{Cell}	=	volume of the reference gas cell, mL
V_P	=	volume of piston, mL
V_{Tank}	=	tank ullage, mL
Δm	=	fringe shift
Δn	=	change in refractive index
Δp_{Ref}	=	reference pressure change, Pa
Δp_{Tank}	=	tank ullage pressure change, Pa
$\Delta \Phi$	=	change in phase, rad

I. Introduction

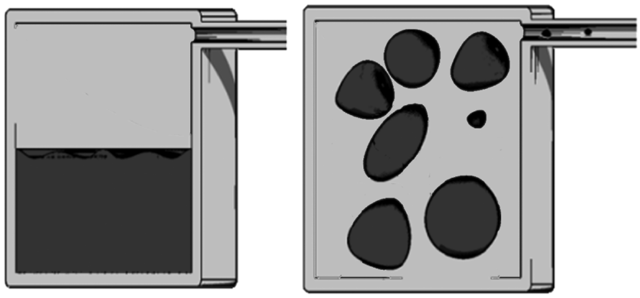
THE lack of gravity in the space environment makes it challenging to measure the amount of liquid propellant remaining in storage tanks. As shown in Fig. 1, liquid under microgravity conditions is free to float within the confines of its containment system. Various mass gauging systems have previously been attempted [1–5]. Typical volume compression/expansion systems either require complicated methods to avoid the acoustic sensitivities of a pressure transducer or require large displacement volumes (approximately one-third of the tank volume) [1]. Other methods avoid the complications of reduced-gravity effects by applying ground-based level measurements to a spacecraft [2], but this requires the craft to be under acceleration, to settle the fluid. Currently, there are no options that have the capability to determine the liquid volume in a microgravity environment without adding significant mass or complexity to the propellant tank or imposing requirements on mission flight parameters.

An optical mass gauging system equipped with a modified Michelson interferometer was recently developed at NASA's Marshall Space Flight Center and has been shown as a promising option to measure liquid volumes with high precision using a small, lightweight system [6]. The optical mass gauge is capable of monitoring critical on-orbit storables, such as cryogenic fluids (fuels or oxidizers), water, and other liquids. This paper describes recent follow-on efforts to those described in [6] where the aforementioned optical mass gauging system was modified to be compact and lightweight by using a free-space Mach–Zehnder interferometer that is fiber-coupled to a light source and detector. The sensor still uses a volume compression/expansion to measure the liquid level, but measuring changes in the index of refraction by observing shifts in the interference pattern is a much more sensitive method than the use of a pressure gauge (∼100–1000 times the sensitivity depending upon the magnification used for fringe detection) [7]. This implies that, relative to the pressure gauge compression/expansion system, the interferometric measurement can either be 100 to 100 times more accurate or the displacement tank can be $1/100$ to $1/1000$ the volume. The use of fiber-optics in place of traditional optics (mirrors and beam splitters) allows the sensor to be ruggedized to withstand the extreme vibrations and accelerations experienced during launch and flight. The new sensor was fabricated as a payload to be flight tested on a sounding rocket platform. The apparatus has been extensively tested in the lab to ensure successful operation under flight conditions.

It should be noted that the sensor we describe does not use a fiber optic as the sensing element. The sensor is a standard free-space Mach–Zehnder interferometer that uses fiber optics as "light pipes"

Presented as Paper 2010-7132 at the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville, TN, 25–28 July 2010; received 14 July 2010; revision received 14 January 2011; accepted for publication 15 January 2011.

*Undergraduate Student, Mechanical Engineering. Student Member AIAA.
†Undergraduate Student, Mechanical Engineering.
‡Associate Professor, Mechanical Engineering. Member AIAA.
§President and Director of Research.
¶Propulsion Research Engineer, Propulsion Research and Technology Applications Branch, Propulsion Systems Department. Senior Member AIAA.



a) b)

Fig. 1 Tank containing a liquid a) under Earth gravity conditions and b) in a microgravity environment.

or waveguides to direct light into the sensor and recollect the light once it has been split and recombined in the interferometer, with the interference fringe pattern naturally appearing when the two beams are recombined before their recollection by the fiber optic. Sensors that use fiber optics as the detector elements, which typically measure the phase shift in a light pulse as a function of time [8,9], have been tested in a lab environment and do exhibit much higher accuracies than those achievable with the fiber-coupled interferometer described in this paper [10,11]. However, such systems also require high laser output stability and phase-locking detection equipment, which can both be expensive and difficult to miniaturize and ruggedize for use on a rocket that experiences high vibrational loads. In addition, the sensitivity of the fiber-optic detector can be a detriment because its will also be susceptible to any external source that stresses the fiber (vibrational loads, for example).

The outline for the rest of this paper is as follows. The technique of interferometric measurement of gas properties (specifically pressure) is presented in Sec. II. The design of the fiber-coupled optical mass gauge sensor is given in Sec. III, while test results are presented and discussed in Sec. IV.

II. Interferometric Measurement of Gas Properties

The amount of liquid contained within a tank can be determined using an interferometer to measure the change in the index of refraction of the gas occupying the tank's ullage volume. A change in refractive index occurs as the gas is either compressed or expanded through the motion of a piston, changing the gas density (and also the pressure) and causing a shift in the interference pattern produced by the interferometer. In a Mach–Zehnder interferometer, a beam of light is first split into two equal halves. One path represents a reference beam that continues unaltered while the other beam passes through the medium being measured (sensing region). As the latter beam passes through the medium, a phase difference arises between the two beams. The phase difference between the two beams is a function of the gas density, as this affects the index of refraction.

Recombination of the two beams produces an interference pattern, which can be subsequently observed by pointing a photodetector at one point on the pattern. The photodetector measures the time-varying phase change between the two beams based on the passage of interference fringes (sequences of bright and dark regions) in front of the detector, which changes as the density in the gas varies. For a Mach–Zehnder interferometer, a Δn change in the index of refraction yields a Δm change in the interference order given by the equation [12]

$$\Delta m = \frac{\Delta \phi}{2\pi} = \frac{l \Delta n}{\lambda} \tag{1}$$

where l is the length of the sensing region, Δn is the change in refractive index of the gas in the sensing region, and λ is the wavelength of light being used. Measuring the ullage of a tank requires the ability to measure a pressure change by examining the fringe shift. Using the Lorentz–Lorenz relation and assuming an ideal-gas equation of state, the rate of change of pressure with respect to the order of interference is given as [12]

$$\frac{\partial p}{\partial m} = \frac{2RT\lambda}{3Al} \tag{2}$$

where R is the universal gas constant, and T and A are the temperature and molar refractivity, respectively, of the gas. Similar methods have demonstrated high volume sensitivity in other applications [7].

III. Mass Gauging Experiment Description

A. Sensor Design

A fiber-coupled Mach–Zehnder interferometer is used to perform measurements on a gas cell, which is connected to a piston and two liquid tanks. The system operates on a single tank at a time. For demonstration purposes we employed two liquid tanks containing different volumes of water (representing tank levels at different periods during a mission) that can be independently exposed to the measurement apparatus such that the liquid volume in each can be determined. A generalized schematic of the optical mass gauge system is shown in Fig. 2.

Initially, both tanks are isolated from the gas cell and the system undergoes a cycling to provide a reference measurement. During the reference cycle, when the piston compresses its volume (closed position), the measured gas occupies the volume V_{Cell}, which is comprised of the cell and associated gas lines. When the piston is moved, allowing the gas to expand (open position), the same mass of gas additionally occupies the volume V_P swept by the piston stroke

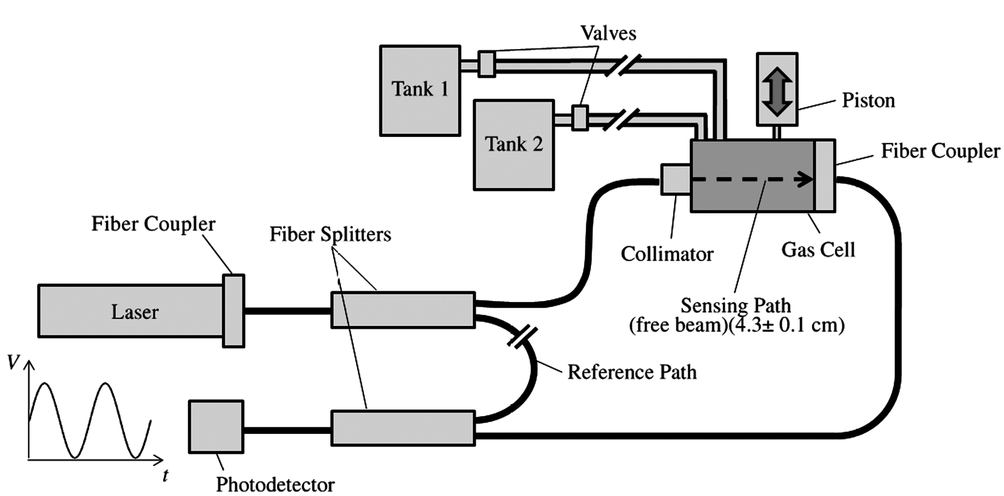


Fig. 2 Schematic of a fiber-coupled optical mass gauging system.

(i.e., a total volume of $V_P + V_{\text{Cell}}$). The actuation of the piston causes a shift in the interference fringes at the detector. The number of fringes that pass as the volume transitions from V_{Cell} to $V_P + V_{\text{Cell}}$ is designated as the reference fringe count Δm_{Ref}. The value of Δm_{Ref} can be related to the corresponding pressure change of the gas through Eq. (2). For tank volume measurements, the targeted tank (with unknown ullage volume V_{Tank}) is exposed to the gas cell and piston volume and a second piston cycle is performed, producing a second fringe shift Δm_{Tank}.

The exercise of relating the ratio of the fringe shifts to the ratio of either the pressure change or the tank volumes using Eq. (2) and an ideal-gas equation of state is found in the Appendix. The result of this analysis is

$$\frac{\Delta m_{\text{Ref}}}{\Delta m_{\text{Tank}}} = \frac{\Delta p_{\text{Ref}}}{\Delta p_{\text{Tank}}} = \frac{V_{\text{Cell}} + V_{\text{Tank}} + V_P}{V_{\text{Cell}} + V_P} \tag{3}$$

The ullage of the tank may be calculated knowing the volumes of the gas cell and piston, the reference fringe shift, and the new fringe shift. Knowledge of the theoretical volume of the entire tank allows for calculation of the volume of the liquid. In this work volumes of the gas cell and tanks are initially estimated and later determined experimentally.

B. Hardware and Layout

Drawings and a photograph of the optical mass gauge payload can be found in Fig. 3. The optical mass gauge sensor was designed as a sounding rocket payload and was subject to the constraints that the entire apparatus could be no larger than 23.62 cm in diameter and 12.1 cm tall, and mass limit was 2.97 kg. The final sensor design fits within the required dimensions and massed 2.90 kg.

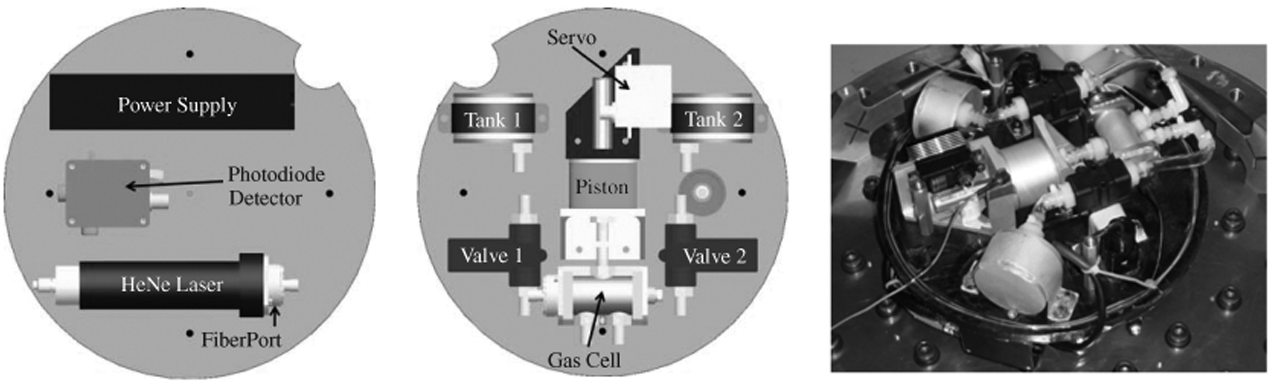
To withstand the extreme accelerations and vibrations of a typical launch, the sensor and light source were coupled using fiber-optic components. The use of fiber optics greatly increases the likelihood of maintaining optical alignment after launch (during free fall) when the sensor begins to operate. Single-mode fiber greatly reduces internal fiber interference between wave propagation modes, so the source of the interference pattern observed is primarily due only to the changing index of refraction [12]. A compact helium–neon (HeNe) laser with a wavelength of 632.8 nm was selected as the light source, due to the availability of both the laser and compatible fiber components at this wavelength. The laser provides a coherence length greater than 5 cm, which is sufficient for simple interferometry.

Due to size constraints, the piston was designed to have a 4.25 cm diameter, allowing for a minimization of the actuation distance. Piston actuation was controlled using a 3.4 $\text{N} \cdot \text{m}$ servo capable of delivering ~760 N of linear force through a rack and pinion design. The piston had approximately 1.25 cm of actuation, resulting in approximately 18 ml. During the course of several static tests the piston demonstrated the capacity to endure a pressure up to 267 kPa, which is much larger than the maximum 67 kPa encountered during dynamic actuation. The time interval for a compression was approximately 200 ms, while a reference and sample measurement could be completed in a total time of approximately 1.2 s. Interferometers like the one discussed in this paper can be sensitive to thermal drifts. This is especially possible in the case where the optical mass gauge is applied to the measurement of the levels in tanks containing cryogenic fluids. However, since a relative measurement technique is employed the effects of thermal drifts, which are typically expected on timescales longer than the ~1 s measurement duration, should be minimal.

The gas cell (including all associated tubing) has an internal volume of approximately 60 ml, and both tanks had a volume of approximately 50 ml. During validation testing, one of the tanks was kept completely empty while the other was filled with 10–30 ml of water. For initial tests air was used as the sample (cover) gas. Air has a molar refractivity of $4.606 \times 10^{-6}\ \text{m}^3/\text{mol}$ at 287.5 K (from [8]). The molar refractivity of air is relatively low compared to heavier gasses such as xenon, which has a molar refractivity of $11.04 \times 10^{-6}\ \text{m}^3/\text{mol}$ computed based on a refractive index $n \sim 1.0007$ (from [9]). While this does decrease the system sensitivity, the use of air as the sample gas greatly reduces the complexity of the device.

The HeNe laser (JDS model 1007) is powered at 12 VDC by the primary payload battery. Single-mode fiber splitters (Thorlabs, FC632-50B-FC) were used to construct the test apparatus. The hardware used for assembly of the optical system had limited angular adjustment capability for the fiber coupling hardware. Consequently, the fiber launch stages that coupled free-beam laser light into fiber optic cables were limited in their efficiency. Approximately 100 μW of the 800 μW laser (12.5%) was successfully coupled into the fiber connecting the laser to the interferometer using a FiberPort (Thorlabs, PAF-X-11-PC-B) mounted directly to the laser output. Roughly 5% of that light passed through the gas cell and was coupled into a second detection fiber using another FiberPort. The resulting final output of interferometer was about 4–6 μW. Despite all the losses, the photodiode detector (Thorlabs, PDA36A with built-in gain adjustment) used in the experiment was capable of measuring the interference pattern signal, yielding a high signal-to-noise ratio on the fringes.

The unfiltered signal was acquired using an analog input on the microcontroller operating in a DC-coupled mode. Filtering the signal or operating in an ac-coupled mode may have allowed for removal of noise from the measurement and is simple enough to implement on future iterations of this work. Another noise-rejection technique that may be employed is to pulse or chop a laser beam above the noise threshold of the system and then measure the signal using an ac-coupled scope or lock-in amplifier. This would allow filtering below the frequency threshold of the noise while passing the signal through to the data acquisition system, which could be very useful on a launch vehicle where vibrational noise can prove to be an impediment to performing optical interferometric measurements.



a) b) c)

Fig. 3 Solid model drawings of a) the bottom and b) the top of the sensor, and c) the fully assembled unit.

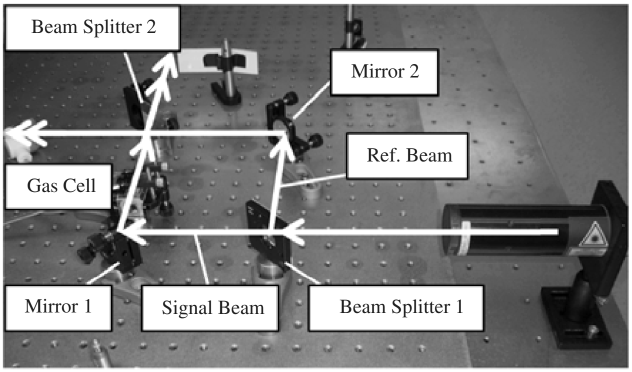


Fig. 4 Proof-of-concept experiment using free-space optics.

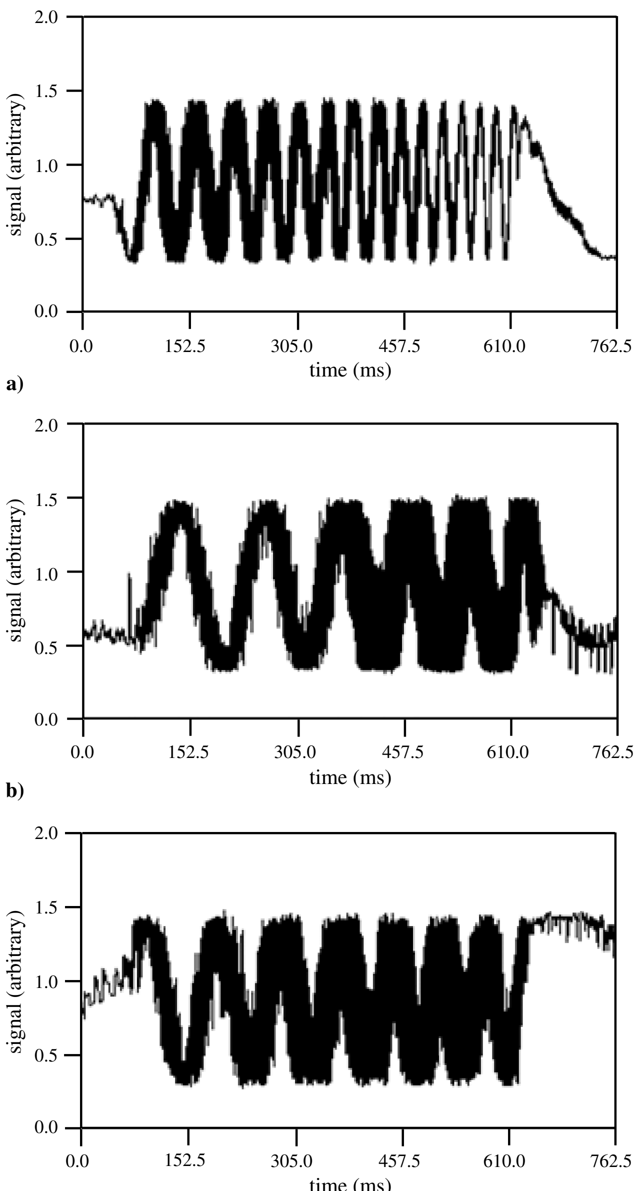


Fig. 5 Proof-of-concept fringe-shift measurements for the a) reference case, b) case where tank 1 (empty tank) was exposed to the apparatus, and c) case where tank 2 (partially filled tank) was exposed to the apparatus.

IV. Results and Discussion

A. Proof-of-Concept Testing

Proof-of-concept testing was conducted to show that the interferometry measurement method was viable and could accurately quantify tankage volumes to the level required. The testing used the setup shown in Fig. 4, employing a HeNe laser (Thorlabs, HGR005, 543.4 nm) and free-beam optics with a measurement path length l of 5 cm. The test setup consisted of two different tanks containing different volumes of liquid. Tank 1 was empty, and tank 2 contained 11.5 ml of water.

Three sets of fringe shifts were measured for this experiment and are presented in Fig. 5: the reference, the fringe shift that occurs when tank 1 is exposed to the system and the fringe shift that occurs when tank 2 is exposed to the system. These free-beam tests were performed without equalizing the pressure after each piston cycle as required by Eq. (3) making an analysis by this equation invalid. The unknown volumes in this case were calculated through Boyle's law, which is easier to use but not as accurate as the method assumed in the development of Eq. (3).

As expected according to Eq. (2), larger ullage volumes resulted in lower fringe counts. The isolated gas cell, having the smallest volume, has the greatest fringe count (15 fringes, 34 ml). The empty tank, having the largest ullage volume, yields the smallest number of fringes (5.75 fringes, 51 ml). The partially filled tank has an ullage volume in between the empty tank and the isolated gas cell, yielding fewer fringes than the former but more than the latter (7 fringes, 37 ml). The measurements indicate that the amount of liquid contained within this tank was 14 ml, which is a difference of roughly 20% compared to the actual volume of water.

The large error observed during proof-of-concept testing is mostly a result of the fringe counts being obtained visually, without the aid of computer software. Additional contributions to the uncertainty include assumptions regarding the pressure and temperature of the gas and the estimation of the sensing path length.

B. Laboratory Measurements Using Sounding Rocket Payload

In this section we describe test results from the fiber optic system fabricated for flight on a sounding rocket (system in Fig. 3). Experimental data are presented in Tables 1 and 2 and Fig. 6, where the value of A is obtained from [13]. Obtaining an accurate count of the number of fringes was a problematic issue in general, with accuracy on the fringe counts of 0.1 fringes. The volume of water in tank 2 as measured by the sensor was 11.2 ± 3.7 ml, while the actual volume of water was 10.5 ml. This result is significant not only in that the actual liquid volume falls within the measurement error bar, but also because the liquid level was computed using three separate volumes (V_{Cell}, V_{Tank}, and V_{Empty}) that were all determined using the

Table 1 Parameters for the testing of the payload apparatus

λ	632.8 nm
A	4.606×10^{-6} (m^3/mol) [13]
R	8.32 J/(K · mol)
l	0.043 m
T	297 K
p	101,900 Pa

Table 2 Number of fringe shifts measured for each test case from testing of the payload apparatus

	No. of fringes
Reference	5.35
Tank 1 (empty)	3.30
Tank 2 (water)	3.60

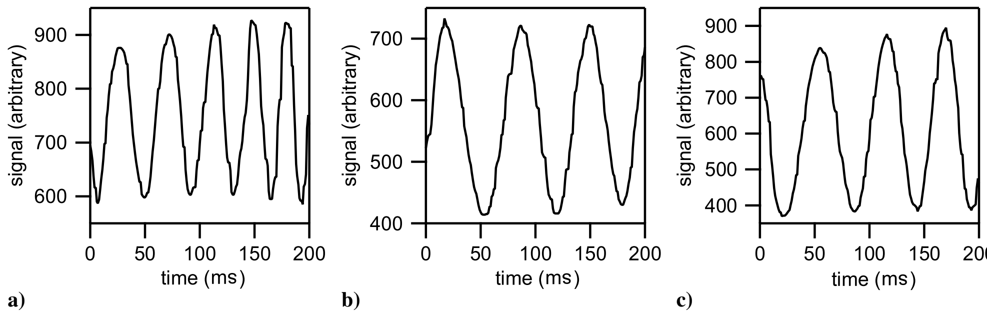


Fig. 6 Fringe shifts measured with the flight-test apparatus for the a) reference case, b) case where the liquid tank was empty, and c) case where the tank contained a level of liquid.

interferometric measurement technique (V_{Empty} is the empty volume of V_{Tank}).

Difficulty in obtaining an accurate fringe count was largely due to significant noise in the interferometer output caused by the mechanical vibrations of the servo used to actuate the piston. Measuring the low-power output signal required an increase in the photodetector gain from 50–70 dB, resulting in a poor signal-to-noise ratio. Recorded signals were filtered to remove high frequency noise and aid in fringe counting. The HeNe laser fluctuated in power during each piston cycle; these power fluctuations were most likely caused by back reflection in the fiber-optics, which could be alleviated in the future by installing a fiber-optic isolator. Even by visual inspection, it was readily seen that there were some inconsistencies in the fringe counts between each piston cycle. These inconsistencies were most likely due to a gas leak somewhere in the system, making it difficult to reproduce results with each piston cycle.

Accurate results were also difficult to obtain, since the volumes measured by our optical mass gauge were very small. This produced a relatively low number of fringes and a small difference between the measurements of tanks 1 (empty) and 2 (containing liquid), limiting the measurement sensitivity. In the future, using a sample gas with a higher index of refraction (therefore yielding higher fringe counts) could help alleviate this issue.

C. Vibration Test

A full-scale vibration test of the optical mass gauge payload was performed on a vibration table (Sierra Nevada Corporation). The payload was exposed to several different tests: two tests in the Z axis (sine sweep and random) and a random test in the X and Y axes. None of the components showed signs of damage upon visual inspection, and the optical components remained in alignment (although there was a slight laser coupling efficiency loss). In each test, the vibration table was ramped up to a maximum of 7 g for no more than 30 s. The payload's first mode of resonant frequency was at approximately 200 Hz and briefly experienced 25 g at this frequency.

V. Conclusions

A fiber optic-coupled interferometric mass gauging system was presented as a means of measuring the amount of liquid stored in a tank under any gravitational conditions, including microgravity, without requiring spacecraft acceleration (settling) before the measurement. Data were obtained using a prototypical fiber-coupled optical mass gauge coupled to two tanks containing different liquid volumes. The liquid volume measurement of 11.2 ± 3.7 ml compared favorably with the actual liquid volume of 10.5 ml. In general, the system shows good quantitative and excellent qualitative correlation between ullage volume and fringe count, consistently matching the theoretical description.

Appendix: Derivation of Eq. (3)

We proceed with a derivation of Eq. (3). In the reference state, the pressure levels in the open and closed configurations ($p_{\mathrm{Ref,Open}}$ and $p_{\mathrm{Ref,Closed}}$, respectively) are given as using an ideal-gas equation of state as

$$p_{\mathrm{Ref,Open}} = \frac{n_1 RT}{V_{\mathrm{Cell}} + V_P} \tag{A1}$$

$$p_{\mathrm{Ref,Closed}} = \frac{n_1 RT}{V_{\mathrm{Cell}}} \tag{A2}$$

where n_1 is the number of moles residing in the closed system. Assuming isothermal conditions, the system experiences a fringe shift Δm_{Ref} that results in the following pressure change during the reference cycle:

$$\Delta p_{\mathrm{Ref}} = p_{\mathrm{Ref,Closed}} \cdot \left(\frac{V_P}{V_{\mathrm{Cell}} + V_P} \right) \tag{A3}$$

A second fringe shift Δm_{Tank} is produced when the target tank (with unknown ullage volume V_{Tank}) is exposed to the gas cell and piston volume and a second piston cycle is performed. This fringe shift produces a pressure change in the system that can be written as

$$\Delta p_{\mathrm{Tank}} = p_{\mathrm{Tank,Closed}} \cdot \left(\frac{V_P}{V_{\mathrm{Tank}} + V_{\mathrm{Cell}} + V_P} \right) \tag{A4}$$

where

$$p_{\mathrm{Tank,Closed}} = \frac{n_2 RT}{V_{\mathrm{Tank}} + V_{\mathrm{Cell}}} \tag{A5}$$

and n_2 is the number of moles of gas in the full volume. Before any piston cycle is performed, gas pressure within all compartments of the system is equalized by opening and closing all solenoid valves so that

$$p_{\mathrm{Ref,Closed}} = p_{\mathrm{Tank,Closed}} \tag{A6}$$

The $p_{\mathrm{Tank,Closed}}$ and $p_{\mathrm{Ref,Closed}}$ terms are eliminated when taking a ratio of the two pressure changes. The fringe shifts can be related to the pressure changes in each cycle, yielding

$$\frac{\Delta m_{\mathrm{Ref}}}{\Delta m_{\mathrm{Tank}}} = \frac{\Delta p_{\mathrm{Ref}}}{\Delta p_{\mathrm{Tank}}} = \frac{V_{\mathrm{Cell}} + V_{\mathrm{Tank}} + V_P}{V_{\mathrm{Cell}} + V_P} \tag{A7}$$

which is the result given in Eq. (3) and provides a way to use the fringe shifts as a pressure or volume change measurement.

Acknowledgments

The authors of this paper would like to thank Omnis, Inc., for their generous financial donation that seeded our research efforts. Financial support was also received from the Colorado State University Senior Design Program, the Colorado State University NASA Space Grant Consortium, and Masten Space Systems, Inc. We would like to thank Jason Priebe, Dan Goodrich, and Lad Kurtis of Sierra Nevada Corporation for the use of their vibration table. We acknowledge technical guidance from John Williams, Sachin Joschi, and graduate students Lei Tao, Brian Lee, and Frank Loccisano.

References

[1] Jurns, J. M., and Rogers, A. C., "Compression Mass Gauge Testing in a Liquid Hydrogen Dewar," NASA Lewis Research Center, CR-198366, Cleveland, OH, July 1995.

[2] Haberbusch, M., "Flexible Cryogenic Temperature and Liquid-Level Probes," NASA John C. Stennis Space Center, Tech. Brief SSC-00191, Stennis Space Center, MS, Nov. 2005.

[3] Nurge, M., and Youngquist, R., "Capacitive Sensors for Measuring Masses of Cryogenic Fluids," NASA Kennedy Space Center, Tech. Brief KSC-12457, Cape Canaveral, FL, Sept. 2003.

[4] Dodge, F. T., Green, S. T., Petullo, S. P., and Van Dresar, N. T."Development and Design of a Zero-*g* Liquid Quantity Gauge for Solar Thermal Vehicle," NASA John H. Glenn Research Center at Lewis Field, TP-2002-211595, Cleveland, OH, Nov. 2002.

[5] Justak, J., Caimi, F. M., Bryant, C. B., and Hastings, L., "An Optical Mass Gauge Sensor for Zero-G Environments," *Advances in Cryogenic Engineering*, AIP Conference Proceedings, Vol. 710, 2004, pp. 451–460.

[6] Witherow, W., and Pedersen, K., "Mass Gauging Demonstrator for Any Gravitational Conditions," Internal Research and Development, NASA Marshall Space Flight Center, Huntsville, AL, Mar. 2007.

[7] Korman, V., Gregory, D. A., and Banish, R. M., "Phase Transition Thermal Expansion Measurement Technique Using a Modified Michelson Interferometer," *Journal of Optics A, Pure and Applied Optics*, Vol. 6, 2004, pp. 781–786. doi:10.1088/1464-4258/6/8/007

[8] Hariharan, P., *Basics of Interferometry*, 2nd ed, Elsevier, Burlington, MA, 2007.

[9] *Optical Fiber Sensor Technology*, edited by K. T. V. Grattan, and B. T. Meggitt, Kluwer Academic, Dordrecht, The Netherlands, 2000.

[10] Nash, P., "Review of Interferometric Optical Fibre Hydrophone Technology," *IEE Proceedings F, Radar and Signal Processing*, Vol. 143, No. 3, 1996, pp. 204–209.

[11] Parsons, J. E., Cain, C. A., and Fowlkes, J. B., "Cost-Effective Assembly of a Basic Fiber-Optic Hydrophone For Measurement of High-Amplitude Therapeutic Ultrasound Fields," *Journal of the Acoustical Society of America*, Vol. 119, No. 3, 2006, pp. 1432–1440. doi:10.1121/1.2166708

[12] Sinko, J. E., Korman, V., Hendrickson, A., and Polzin, K. A., "Miniaturized Optical Sensor for Leak Detection in a Space Environment," *Journal of Spacecraft and Rockets*, Vol. 47, No. 4, 2010, pp. 680–685. doi:10.2514/1.46693

[13] Born, M., and Wolf, E., *Principles of Optics*, 7th exp. ed., Cambridge Univ. Press, Cambridge, England, U.K., 1999.

J. Martin
Associate Editor