Analysis of fluid gauge sensor for zero or microgravity conditions using Finite Element Method

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Abstract: In this paper the Finite Element Method (FEM) is presented for mass/volume gauging of a fluid in a tank subjected to zero or microgravity conditions. In this approach first mutual capacitances between electrodes embedded inside the tank are measured. Assuming the medium properties the mutual capacitances are also estimated using FEM approach. Using proper non-linear optimization the assumed properties are updated by minimizing the mean square error between estimated and measured capacitances values. Numerical results are presented to validate the present approach.

Introduction: For future space explorations, an existence of an orbiting “gas station” supplying liquid hydrogen and oxygen to space crafts on their way to Moon, Mars, and other planets will make the future space missions more efficient and sustainable. These so called orbiting gas stations are envisioned to be able to store liquid hydrogen, oxygen, and other necessary liquids required for space travels. One of the important advantages of having such orbiting gas stations will be avoiding necessity of lifting heavy fuel loads out of the earth’s gravity for long duration missions. For construction of such orbiting gas stations, efficient and cost effective methods to store, supply and transfer these cryogenic liquids in adverse orbital environments are essential. Once these propellants liquids are stored in an orbital storage facility robust and reliable methods to measure the liquid fuel quantities in these storages are also essential. In low gravity orbital environment an accurate measurement of liquid contents in these tanks becomes problematic because of liquid in the tank is always unsettled, sloshing, not wall bounding, and flowing. Traditional ground based mass and volume gauging techniques [1-2] such as liquid level estimation using mechanical floats, Capacitance theory, Frequency Modulated Continuous Wave Radar (FMCW) techniques, and ultrasonic sensors fails in a zero gravity conditions due to uncertain behavior of liquids. In the recent past there have been attempts to apply these techniques to estimate liquid quantities in tanks subjected to zero gravity conditions [2-3]. These techniques especially those using electromagnetic waves employed in mass gauging have important shortcomings. In these techniques a change in electromagnetic characteristic such as a shift in resonance frequency is used to estimate mass of liquid in tank. However, due to the large size of storage tanks and existence of large number of higher order modes, electromagnetic field strength in side the tank varies in a random fashion. Hence, presence of in-homogeneity in the medium due to the liquid uncertainty makes it almost impossible in a deterministic way to relate amount of resonant frequency shifts to the liquid contents. In the mass gauges that estimate liquid quantities from measuring the amount of microwave energy absorptions, it is assumed that the electric field intensity is uniform in the medium. However, a random distribution of liquid inside microwave cavity (storage tank) causes to generate standing waves and hence assumption of an uniform field intensity may not achieve desire accuracy in the estimation.

In this paper the FEM approach is presented for mass/volume gauging of a fluid in a tank subjected to zero or microgravity conditions. For mass/volume gauging the tank is assumed to be
embedded evenly/randomly with multiple rods. In the presence of liquid inside the tanks, mutual capacities between the rods are measured. Also using the FEM the mutual capacities between the rods are estimated assuming the medium properties. Dielectric profile of medium inside the tank is then estimated using standard optimization procedure which will minimize the mean square error between the estimated and measured values of the mutual capacitances. From the knowledge of dielectric profile the volume of the liquid inside the tank can be estimated. The method suggested in this paper uses the electromagnetic principles (as has been used by earlier approaches) to develop a mass gauging system for microgravity conditions. However, in the proposed approach we take into account the random liquid distribution in the storage tank while estimating its responses. This makes the measurement system more robust and reliable under all conditions compared to the existing systems.

**Theory: Electrical Capacitance Tomography:** Figure 1 shows an arrangement of various components placed in a cryogenic tank to measure liquid quantities stored in the tank under microgravity conditions. This arrangement consists of number of thin metallic electrodes printed on inside surface of the tank. In order to avoid stray capacitance effect an electric field screen is inserted between the tank surface and electrodes as shown in Figure 1.

A pair from these electrodes is selected and mutual capacitance between the pair is measured by activating one and grounding the other electrode while other remaining electrodes may be free potential points. This will create $N(N-1)/2$ independent pair combinations where $N$ is total number of electrodes. These independent mutual capacitances $C_{ijm}$ where $i$ and $j$ are equal to 1, 2, 3, ...N can be used to extract the dielectric profile of the medium inside the tank using the following procedure. These mutual capacitances can also be estimated using the expressions

$$C_{ij} = Q_{ij}/V_i$$ (1)

$Q_{ij}$, the total charge collected by $j^{th}$ electrode when $V_i$ voltage is applied to the $i^{th}$ electrode and all other electrodes being grounded is obtained through
\[ Q_{ij} = \varepsilon_j \int_{\Gamma_j} \nabla \phi_i \cdot \hat{n} d\Gamma_j \]  \hspace{1cm} (2)

where \( \phi_i \) is the potential distribution when \( i^{th} \) electrode is excited by voltage \( V_i \) and all other electrodes grounded, \( \Gamma_j \) is the closed contour enclosing the \( j^{th} \) electrode, \( \varepsilon_j \) is the dielectric constant of medium surrounding the \( j^{th} \) electrode, and \( \hat{n} \) is the unit normal to the electrode contour. The electric potential \( \phi_i \) appearing in (2) can be obtained by solving Laplace’s equation

\[ \nabla^2 \phi_i = 0 \]  \hspace{1cm} (3)

Above equation is solved using the FEM approach by discretizing the medium into tetrahedrons. Numerical values of zero or one are assigned to each tetrahedron. Tetrahedron with value one corresponds to presence of liquid inside it. Where as a tetrahedron with zero value corresponds to presence of liquid inside it. Initially this assignment is arbitrary since the liquid distribution is unknown. With this assumed liquid distribution the mutual capacitances can be estimated. The mean squared error defined as

\[ Error(0) = \sum_i \sum_j \sqrt{(C_{ijm} - C_{ij})^2} \]

is minimized using nonlinear optimization procedure [4]. A liquid distribution that gives the error below some predetermined small value is most probable distribution from which liquid volume and mass can be estimated.

**Numerical Results:** For numerical validation a multi-electrode geometry embedded in an inhomogeneous media, as shown in Figure 2 is considered.

![Figure 2: Geometry of four sensor electrodes embedded in a stratified media.](image)

In this case we assume that the mutual capacitances between the sensor electrodes are known (obtained either through an experiment or through a numerical simulation). However, the media in which these sensor electrodes are embedded is assumed to be completely unknown. Using a non-linear optimization procedure and following the procedure described above medium parameters are estimated and are shown in Figure 3.
Conclusion: A finite element method approach has been presented for mass/volume gauging of a fluid stored in a cryogenic tank subjected to zero gravity or microgravity conditions. By embedding metal electrodes inside the tank measurement of mutual capacitances is performed. Also using the finite element approach the mutual capacitances are estimated as a function of dielectric profile of medium inside the tank. Using an appropriate non-linear optimization, most probable dielectric profile is estimated by minimizing the mean square error between measured and estimated capacitances. Numerical results are also presented to validate present approach.

References