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Modeling Aircraft Fuel Gauging Unit Using COMSOL Multi-Physics Software.

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Abstract:
Aircraft during flight missions are usually varied through various angular orientations and as such accurate measurement of fuel quantity on board is difficult to obtain. An investigation was undertaken into the suitability of using COMSOL multi-physics software for modeling a capacitive fuel gauging unit for an aircraft. A model of a sensor immersed in a fluid was developed for rectangular tank geometry with a range of fluid levels and sensor orientation using the electrostatics application mode in COMSOL's AC/DC module. The importance of modeling the capacitance of air was demonstrated. An initial offset of 16pF was corrected by modeling air capacitance into COMSOL model. Simulated results were validated experimentally. Experimental measurements and simulated COMSOL model results fitted closely within a limit of 6.83pF. These preliminary results indicate a good correlation between the COMSOL model simulations and experimental measurements, suggesting that the software is suitable for modeling aircraft fuel gauging unit.

Keywords: COMSOL model, Capacitance, Fuel gauging, Experiment, Aircraft

1.0 Introduction

The aircraft fuel system forms the largest fluid system in an aircraft. For decades, engineers have been working to improve the gauging system for measuring aircraft fluids. Accurate and reliable measurement of the available fuel quantity is crucial to aircraft safety considerations (Beeny, 1983 and Brahney, 1988). Any significant over-estimation of the aircraft fuel level during flight may lead to disastrous consequences, if the true available quantity is not adequate for the aircraft to reach its target location. A known fact in the aviation industry is the difficulty faced by designers and manufacturers of aircraft to eliminate any weight where possible even as small as 1kg. Normally, aircraft fuel gauging system is made up of several sensors which measure the available quantity of fuel onboard. Commercial airliners such as Boeing 747 may require up to 20-30 sensors per wing tank to accurately gauge the fuel quantity (Brahney, 1988). The present gauging units used in the industry have an accuracy of ±1-2% of the full tank capacity (Langton et al. 2009). Supposing, we have a gauging unit with a better accuracy in the region of ±0.8% of the total tank capacity, for example a commercial airliner such as Boeing 747-400ER which has a full tank capacity of 241140L (Boeing-online), this would have considerable impact in the estimation of the fuel level onboard the aircraft.

In 2005, a study reported that the aviation industry contributed 4.9% to global emissions causing climate change, and with air traffic increasing at a rate of 3-5% every year, this can only present further challenges in the fight to reduce global warming (Lee et al, 2005). Proactive steps are needed to contain this problem; one step in this direction would be the development of aircraft fuel gauging unit with improved accuracy. In the case of large commercial aircraft, if the sensors in the wing tank can be replaced with just one or two sensor(s) that can provide the same or better accuracy regarding the available fuel quantity in the aircraft, then the weight of the other sensors and their associated wiring would have been eliminated. Thus less fuel would be used for journeys from a weight perspective .The quantity of fuel in the tank is important, but so too is its position which affects the aircraft centre of gravity, and hence its range and stability. Pilots often move fuel from one physical location to another in the aircraft to improve the aircraft stability (Raymer, 1999); accurate information of the available fuel quantity will be useful when making this decision.

Capacitance probes are mostly used as sensors for aircraft fuel quantity measurement. Aircraft fuel tanks usually have complex shapes and during flight, aircraft can be maneuvered through various pitch, roll and yaw angles, as a result the accurate measurement of the fuel level becomes difficult to obtain (Pallet 1981; Mior and Seabridge, 2008). In this work, a virtual capacitive sensor is placed in a virtual aircraft tank and the effectiveness of COMSOL multi-physics software for developing aircraft fuel gauging unit was investigated.

1.1 Background Theory

The fuel used for this experiment is sunflower cooking oil. The capacitance, C_{NF}, developed by the sensor in the experiment is based on equation (1.1).

$$C_{NF}=n\,(K-1)\,C+C_{TA} \dots.\ (1.1)$$

Where n is the wetted length of the sensor

K is the dielectric constant of the fluid

C is the effective capacitance developed by the sensor

C_{TA} is the capacitance when the sensor is in air

The effective capacitance, C, developed by the sensor was calculated using the equation (1.2)

$$C=\frac{2\pi\varepsilon_0\varepsilon_r L}{\ln(B/b)} \dots\dots\dots\dots\dots\dots\dots (1.2)$$

Where C is the capacitance of the system
ε_0 is the permittivity of free space
ε_r is the relative permittivity
L is the length of the cylinders
B is the diameter of the bigger cylinder
b is the diameter of the smaller cylinder

The dielectric constant for sunflower oil was given as 2.45, (Akhtar et al. 2006). Analytically using equation (1.2), the capacitance of the sensor in air, C_{TA}, was determined as 15.69pF and with a dielectric constant of 2.45 for the fuel, the effective capacitance, C, was determined as 38.45pF

1.2 Experimental Process

The equipment used for the experiment was set-up as figure (1.0). Using a siphon, the fuel quantity in the tank (glass container) was varied. Data was acquired at a sampling frequency of 100kHz with 1000 samples. It should be noted that initially the sensor output voltage was constant even when the fuel level in the tank was varied. It was observed that the fuel level did not rise inside the sensor as the fuel height was increased. This was as a result of the air pressure inside the sensor been constant and as such there was no capillary action for the fuel. However, when four 2mm holes were drilled at the upper end of the sensor, the problem was corrected and the output voltage from the sensor varied as the fuel height was changed. Voltage (hence capacitance) measurements were obtained and the process was repeated for different fuel levels, angles of rotation and also when cooking salt was added to the working fluid.

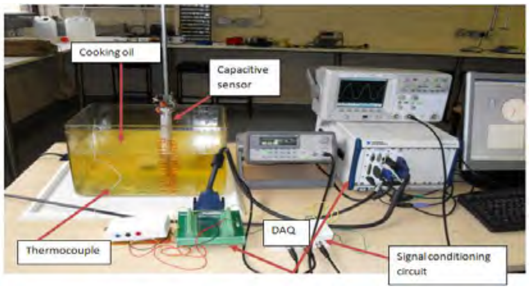

Figure (1.0) Experimental set-up

1.3 The Role of COMSOL Multi-physics

The AC/DC module in COMSOL was used in modeling of the sensor, fuel and tank assembly in 3D, both when the sensor was vertical, rotated 30^0 from its vertical position and when cooking salt was added to the fuel. This module has an electrostatic application mode which is the underlining principle of operation of a capacitance sensor, it is able to calculate and display the capacitance value developed in the model. It calculated the capacitance from the integral of the electrical energy density. The governing equations for the sub-domain and the boundary settings are given by (1.3) and (1.4) respectively.

$$-\nabla.\varepsilon_0\varepsilon_r\nabla V = \rho \text{......} \; (1.3)$$

$$n.(D1 - D2) = \varepsilon_0\varepsilon_r(Vref - V)/d \text{................} \; (1.4)$$

The Constitutive relation, *D*, is given by

$$D = \varepsilon_0\varepsilon_r E \text{........} \; (1.5)$$

Where ρ= space charge density, *d* = thickness, *Vref*= reference potential, *V*= Electrostatic potential, *E*= Electric field

The sensor, tank, insulation and air domain properties were specified in the **Subdomain** and **boundary Settings** dialogue box. The boundary conditions selected for the sides of the tank was **zero charge/Symmetry** and **Distributed Capacitance** was selected for fuel surface. The positive and negative terminals of the sensor were specified as **Port** and **Ground** respectively. An input voltage of 5V was used for the **Port**. The system had 10 sub-domains and 64 boundaries. The mesh created has number of elements up to 243333 when the tank is filled with fuel, a degree of freedom 352613 and mesh structure is tetrahedral.

Tank Dimension

Internal Volume= 0.23 x 0.34 x 0.225 m

Thickness =0.005m

Sensor Dimension

Sensor Height=0.19m

Internal rod diameter = 0.0128m

Outer cylinder diameter = 0.028m

Outer cylinder thickness =1mm

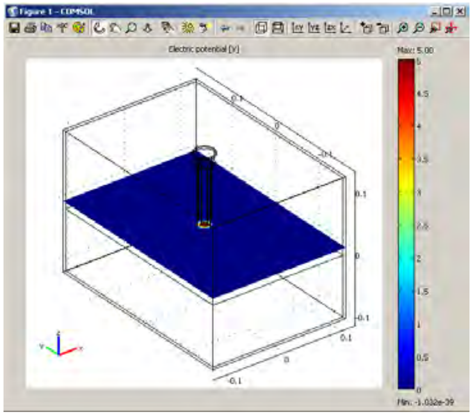

Figure (1.1) Post processing mode of the simulated COMSOL model when the sensor is vertical

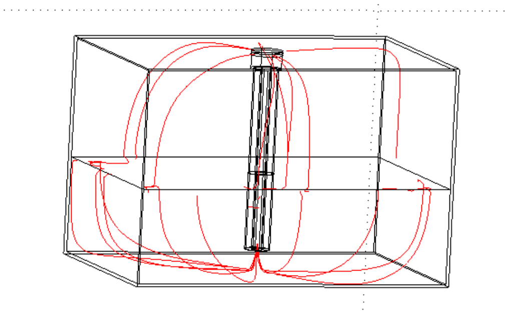

Figure (1.2) COMSOL model of the experimental set-up showing the electric flux lines in a 3D workspace

1.4 Results

The results obtained when the sensor is vertical, when rotated 30^0 from the vertical position and when cooking salt was added to the working fluid (fuel) is presented in this section.

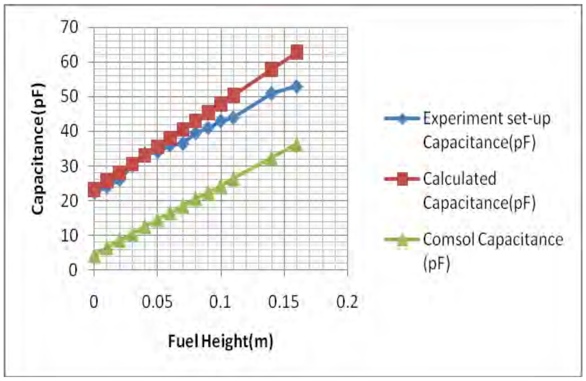

Figure (1.3) Comparison of capacitance results from the experiment, COMSOL model and analytical solution with the 16pF offset

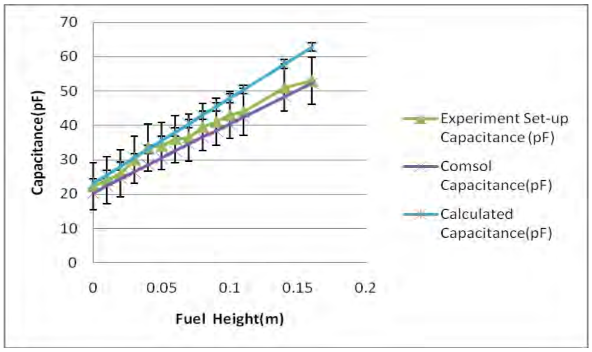

Figure (1.4) Correction of the off-set of the COMSOL capacitance

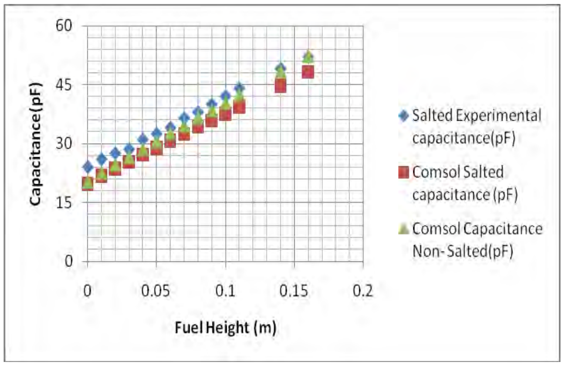

Figure (1.5) Results when cooking salt was added to the fuel

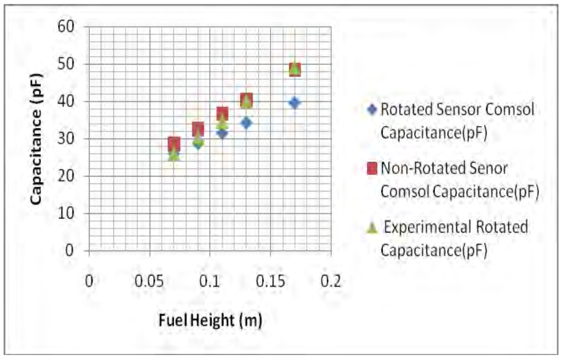

Figure (1.6) Results when the sensor is rotated at 30^0 from the vertical

1.5 Discussion

The next step is to ascertain whether the COMSOL model simulation can be validated from experimentation. From figure (1.3), it was observed that the calculated capacitance and the capacitance measured from the experiment were close. Lower range measurements of up to 0.06m of the fuel height suggested that the capacitance values for both are closely matched within a 1.53pF bracket. At the upper range of the measurements up to 0.16m of fuel height, the difference in the results became obvious with a value of up to 9.79pF. This deviation could be as a result of the fact that the calculated capacitance measurement is an idealized representation of the gauging information, whereas the experimental gauging set-up had its shortcomings. Uncertainties within the experimental process may have contributed to the deviation between the two set of capacitance measurements. These included parallax error in reading off the fuel height, small voltage drops in the electrical wiring connections of experimental set-up, measuring error associated with the measuring tape in marking out the height of the tank and system errors associated with the equipments used in the experiment.

A curious observation of figure (1.3) is the capacitance results obtained from the COMSOL model; it was clearly observed that COMSOL capacitance results had an off-set of 16pF relative to both the calculated capacitance results and the experimental capacitance measurements. Upon investigation, it was noticed that the COMSOL model was not adding the value of the sensor's air capacitance to the capacitance developed as a result of the wetted length of the sensor. When air was modeled alongside the fuel height, the off-set was largely reduced as shown in figure (1.4). It should be noted that when modeling the air into the tank, care must be taken so that there is no gap between the top surface of the fuel and the air. The presence of gap results in electric flux leakages, therefore causing erroneous capacitance readings from the COMSOL model.

From figure (1.4), it is observed that with reduction of the off-set, capacitance results from the COMSOL model closely approximated the results obtained from the experiment. However, the slight difference between the measurements can be largely attributed to the 4.4pF capacitance of the tee-connector used in the calibration of the sensor's signal conditioning circuit. Other potential sources of uncertainty in the measurement have been mentioned earlier in the paper. An error limit of 6.83pF was associated with the experimental measurements taken. Calculated capacitance result fitted with the experimental results except for three points when the fuel height was 0.14m, 0.17m, and 0.19m. This could be due to the idealized assumptions of the calculated capacitance values. As a rule, when an offset is noticed in the result obtained using COMSOL model, a good action will be to investigate if air has been added into the COMSOL model.

As demonstrated in figure (1.5), the addition of cooking salt to the fuel reduced its dielectric by 11.42%. Results obtained when the model was salted and not salted differed with an average off-set of 2.08pF indicating the effect of additives on the sensor's output. The measurements obtained from the experiment when cooking salt was added to the fuel had an average off-set of 3.65pF compared to the measurements obtained when the effect of the salt was added to the COMSOL, this off-set can be attributed non-uniform mixing of the salt particles in the fuel.

The number of measurements taken when the sensor was rotated 30^0 from the vertical was restricted to five due to the limitation of the tilting mechanism; the sensor did not come in contact with the working fluid in the tank when larger angular orientation was used. As shown in figure (1.6), the COMSOL measurements when the sensor is vertical and rotated 30^0 from vertical position indicated that the fuel quantity reduced by 13.93%. This can give an incorrect indication of the fuel quantity on board. There was an average off-set between the model measurements and experimental measurements by 4.27pF largely due to the inaccuracy in the measurement of the angular orientation of the clamp used in holding the sensor to position.

It is clear that the results of the COMSOL model produced a good fit with the results from the experiment.

1.6 Conclusion

An investigation into the suitability of using COMSOL multi-physics software for modeling an aircraft fuel capacitive gauging unit has been presented. Initial results of COMSOL model produced an offset of 16pF relative to the results from experimental measurements suggesting that the capacitance of the sensor in air was not added in computing the total capacitance as the fuel height was varied. Adding air to the model largely corrected the offset. As such a good action, when modeling capacitive fuel gauging units in COMSOL will be to add the air separately in to the model. Also, there should be no gap between the top surface of the fuel and the air.

These preliminary results show good correlation between the COMSOL simulation and experimental results, suggesting that the software is suitable for modeling aircraft fuel gauging unit. The results suggests that the software holds potential for developing aircraft gauging units with improved accuracy, this will ultimately have impact on the efforts to reduce the global emission associated with the aviation industry.

1.7 References

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