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# 항공기 보조연료탱크 연료량측정시스템 개발

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# Development of Fuel Quantity Measurement System for Aircraft Supplementary Fuel Tank

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## ABSTRACT

This paper presents a fuel quantity measurement system (FQMS) for an aircraft supplementary fuel tank considering the change of aircraft attitude. The developed FQMS consists of fuel sensors, a signal process unit, an indicator and a software to estimate the fuel quantity from the sensor data. To replicate the change of the roll and pitch attitude on the ground, the test simulator is developed in this work. Using the test simulator, the sensor data at various fuel quantities, roll and pitch angles are automatically measured to build a training data set. The data-driven software to estimate the fuel quantity is then developed using a trilinear interpolation method with the training data set. The developed FQMS is verified by investigating the fuel estimation error of the test data set that we know the true values. Through the test, it is confirmed that the error of the developed FQMS system satisfies the criteria of TSO-C55 document.

## 초 록

본 논문에서는 항공기 자세 변화를 고려한 항공기 보조연료탱크 연료량측정시스템을 제시하였다. 개발된 연료량측정시스템은 연료센서, 데이터 처리장치, 계기 및 센서 데이터로부터 연료량을 추정하는 소프트웨어로 구성되었다. 지상에서의 롤 및 피치 자세 변화를 모사하기 위해 모사시험장치가 개발되었다. 모사시험장치를 이용하여 다양한 연료량, 롤 및 피치 각도의 센서 데이터를 자동으로 측정하여 트레이닝 데이터 세트를 획득하였다. 연료량을 추정하는 연료량 측정 소프트웨어를 트레이닝 데이터 세트와 함께 삼선형보간법을 사용하여 개발하였다. 개발된 연료량측정시스템은 참값을 알고 있는 테스트 데이터 세트의 연료 추정 오차를 측정하여 검증하였다. 테스트를 통해 개발된 연료량측정시스템의 오차가 TSO-C55 문서의 기준을 충족하는 것을 확인하였다.

**Key Words :** Fuel Quantity Measurement System(FQMS, 연료량측정시스템), Supplementary Fuel Tank(보조연료탱크), Test Simulator(모사시험장치), Trilinear Interpolation (삼선형보간법)

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# Ⅰ. Introduction

An aerial refueling system and supplementary fuel tanks have been used to increase the range of aircraft and extend the amount of time in combat and surveillance[1,2]. In commercial aircrafts, the range of aircraft has been increased through supplementary fuel tanks[3]. To estimate the fuel quantity of the supplementary fuel tank, the fuel quantity measurement system (FQMS) needs to be developed[4]. The FQMS is generally composed of fuel sensors, a signal process unit, an indicator and software for the estimation. The accuracy of the FQMS is classified into the MIL-G-26988C for military and TSO-C55 used for civilian, as shown in Table 1[5,6].

In FQMS, the fuel quantity is generally estimated based on the capacitance gauging method that utilizes the difference of the dielectric properties between the air and fuel material[7-9]. In this method, the fuel height in the tank varies depending on the attitude of the aircraft changes, which should be considered in the fuel quantity estimation. To treat this problem, a device simulating the aircraft roll and pitch motion on the ground is required. In [10], a ground test system for a Miniature Unmanned Aerial Vehicle (MUAV) fuel system was developed. The test system[10] consists of a drive unit, a servo system, and an upper control. Using the developed device, the FQMS for MUAV was developed and its accuracy was verified through the test.

This paper presents the FQMS developed for an aircraft supplementary fuel tank. The developed FQMS uses a capacitance type fuel sensor with the signal processing device composed of the data acquisition (DAQ) and computer. The LabVIEW software are used for the indicator and measurement software. To treat the change of aircraft attitude, a test simulator is developed. The test simulator hardware consists of attitude simulation equipment, fueling equipment, and data acquisition equipment. To obtain the training data set composed of a sensor information at various fuel quantities and roll/pitch angles, the system for the automatic control of the fuel quantity and roll/pitch angles is developed in this work. A data-driven software using the trilinear interpolation[12] is developed using the obtained training data set to estimate the fuel quantity. The developed FQMS is verified in a test data set. The test data set is prepared by first suppling the fuel to the supplementary fuel tank and randomly operating the roll and pitch attitudes.

Table 1. Standard of FQMS Accuracy

| Section | Document | Standard | |
|---|---|---|---|
| Military | MIL-G-26988C | Class I | ±4% of Indication<br>±2% of Full Scale |
| | | Class II | ±2% of Indication<br>±0.75% of Full Scale |
| | | Class III | ±1% of Indication<br>±0.5% of Full Scale |
| Civilian | TSO-C55 | ±3% of Full Scale | |

# Ⅱ. Fuel Quantity Measurement System (FQMS)

## 2.1 Configuration of FQMS

The FQMS consists of fuel sensors, a signal process unit, an indicator, and software. As shown in Fig. 1, a passive DC capacitance type fuel sensor, P-300C, is used in this work to measure the capacitance that is determined by the height of the fuel in the tank. The output data of the P-300C fuel sensor is the form of the frequency and processed through a data acquisition (DAQ) system. The position of the sensor in the supplementary fuel tank is related to the accuracy of the FQMS. Through tank studies, the location of the sensor is optimized to minimize the quantity of fuel that cannot be measured. The optimized sensor location is obtained using parametric study. Fig. 2 shows the tank shape and sensor location[11].

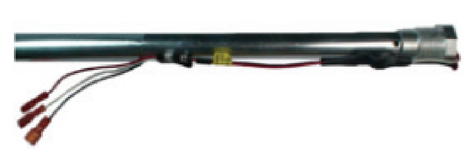

Fig. 1. P-300C fuel sensor

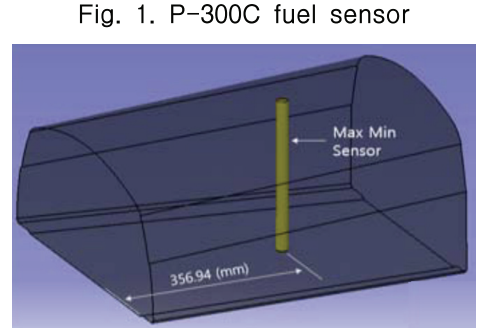


Fig. 2. Optimized Fuel Sensor Location

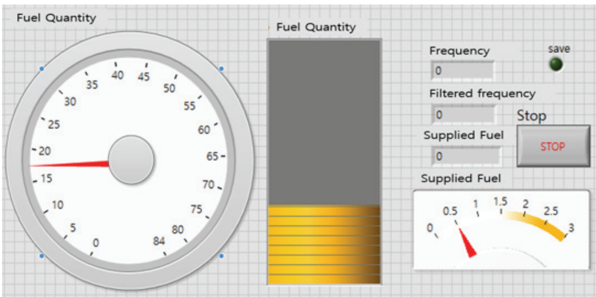


Fig. 3. Indicator GUI

The frequency data obtained from the sensor are passed into the DAQ system, and the signal processing is performed. Fig. 3 shows the indication, which is a graphic user interface developed using LabVIEW software. In the indication, the fuel quantity is estimated using the software based on the sensor frequency output and roll/pitch attitude data.

## 2.2 Fuel Quantity Estimation

The fuel quantity is estimated using the trilinear interpolation method. The trilinear interpolation is the extension of linear interpolation to deal with three-dimensional data. Using the data on the lattice points, the value of an intermediate point within the rectangular prism is linearly interpolated. In Equation (1), the frequency $f$ is expressed as a function of fuel quantity Q, roll angle $\phi$ and pitch angle $\theta$ of the supplementary fuel tank.

$$f = g(\phi, \theta, Q) \tag{1}$$

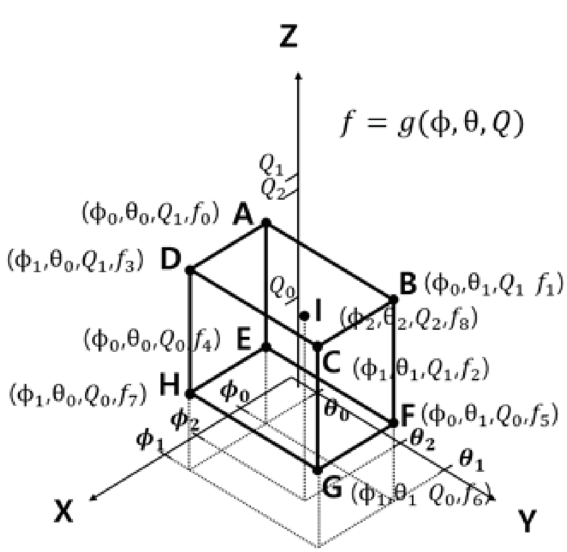


Fig. 4. Rectangular prism for trilinear interpolation

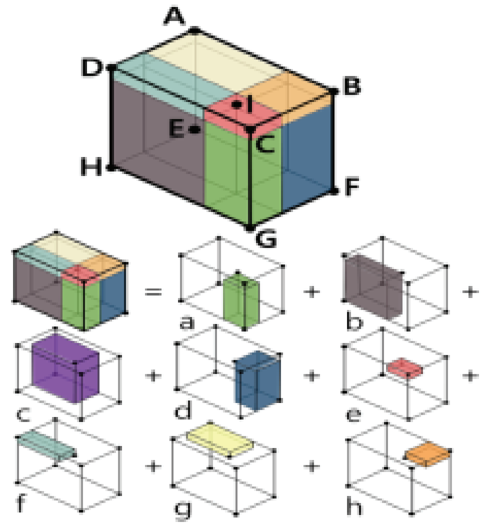


Fig. 5. Divided volumes

Figure 4 shows the rectangular prism for the trilinear interpolation. The first step of the interpolation is to find 8 adjacent predefined values (A,B,C,D,E,F,G,H) surrounding the interpolation point(I)[12]. The information of 8 adjacent points (A to H) surrounding the point I $(\phi_2, \theta_2, Q_2)$ are searched and stored. Next, the eight volumes around the point I is calculated as can be seen in Fig. 5. The divided eight volumes are then normalized using the whole volume of prism ABCDEFGH. Finally, the fuel quantity $Q_2$ can be calculated using Eq. (2).

$$f_8 = f_0 N_a + f_1 N_b + f_2 N_c + f_3 N_d + f_4 N_e + f_5 N_f + f_6 N_g + f_7 N_h \tag{2}$$

where $f_i$ is frequency of fuel sensor at the point $i$ $i = (0, 1, \cdots, 8)$, and $N_j (j = a, b \cdots h)$ is calculated as:

$$N_a = \frac{(\phi_1 - \phi_2)(\theta_1 - \theta_2)(Q_2 - Q_0)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_b = \frac{(\phi_1 - \phi_2)(\theta_2 - \theta_0)(Q_2 - Q_0)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_c = \frac{(\phi_2 - \phi_0)(\theta_2 - \theta_0)(Q_2 - Q_0)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_d = \frac{(\phi_2 - \phi_0)(\theta_1 - \theta_2)(Q_2 - Q_0)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_e = \frac{(\phi_1 - \phi_2)(\theta_1 - \theta_2)(Q_2 - Q_0)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_f = \frac{(\phi_1 - \phi_2)(\theta_2 - \theta_0)(Q_1 - Q_2)}{(\phi_1 - \phi_0)(\theta_1 - \theta_0)(Q_1 - Q_0)}$$

$$N_g = \frac{(\phi_2-\phi_0)(\theta_2-\theta_0)(Q_1-Q_2)}{(\phi_1-\phi_0)(\theta_1-\theta_0)(Q_1-Q_0)}$$

$$N_h = \frac{(\phi_2-\phi_0)(\theta_1-\theta_2)(Q_1-Q_2)}{(\phi_1-\phi_0)(\theta_1-\theta_0)(Q_1-Q_0)}$$

In order to apply the trilinear interpolation, it is necessary to acquire the training data set including the fuel quantity and frequencies together with the roll and pitch angles of the supplementary fuel tank.

## Ⅲ. Experimental Test

Figure 6 shows the entire structure of the test simulator. Fig. 7 shows the architecture of the developed test simulator with FQMS. As shown in Fig. 7, test simulator operates the following functions; <1> The roll and pitch motion to simulate the aircraft attitudes[13], <2> Automatic fuel supply into the supplementary fuel tank, <3> Data acquisition of the frequency of fuel sensor, attitudes, etc. The automation software controls the aforementioned functions of the test simulator.

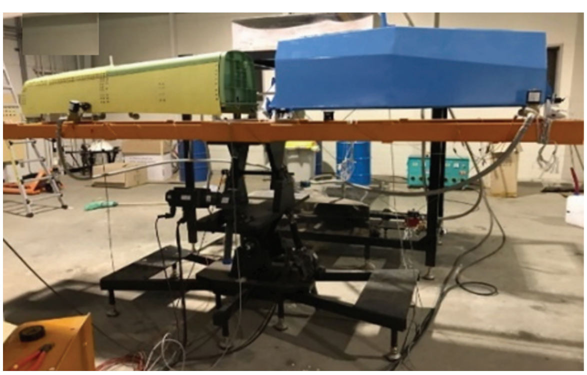

Fig. 6. Test Simulator

### 3.1 Data Acquisition

The training data at various conditions are acquired using the developed test simulator with automatic operation. For the roll and pitch movements, it is assumed that the attitudes of the operating aircraft ranges -3 to 8 degrees for pitch and -2 to 2 degrees for roll. The given ranges are divided by 0.5degree intervals. As a result, 23 data points for pitch and 9 data points for roll are chosen for the training data. In the case of the fuel quantity, 3L intervals are chosen as the data points. Since capacity of supplementary tank is 84L, 28 data points are selected for the fuel quantity. As a result, the data at total 5796 points (=23×9×28 points) are measured as the training data using the test simulator with an automation software[14].

The data measured at 5796 points is presented in Fig. 8. The frequency $f$ measured at the fuel sensor is little varied following the roll $\phi$ motion. The tendency of frequency $f$ for the pitch angles $\theta$ is demonstrated in Fig. 9. If the fuel quantity is between 9L and 72L, the relation between the frequency $f$ and the pitch angle $\theta$ is linearly proportional. When the fuel quantity is less than 9L or higher than 72L, the frequency $f$ is not linearly proportional to the pitch angle $\theta$ due to the shape effect of the supplementary fuel tank. As can be noticed in Fig. 10, the outer shape of the fuel tank is not rectangular shape, and there is an inner structure such as latticed bulkhead and the bolt structure and the fuel pipe connection parts. This shape causes the nonlinear relation between the frequency and pitch angle $\theta$ when the fuel quantity is less than 9L or higher than 72L.

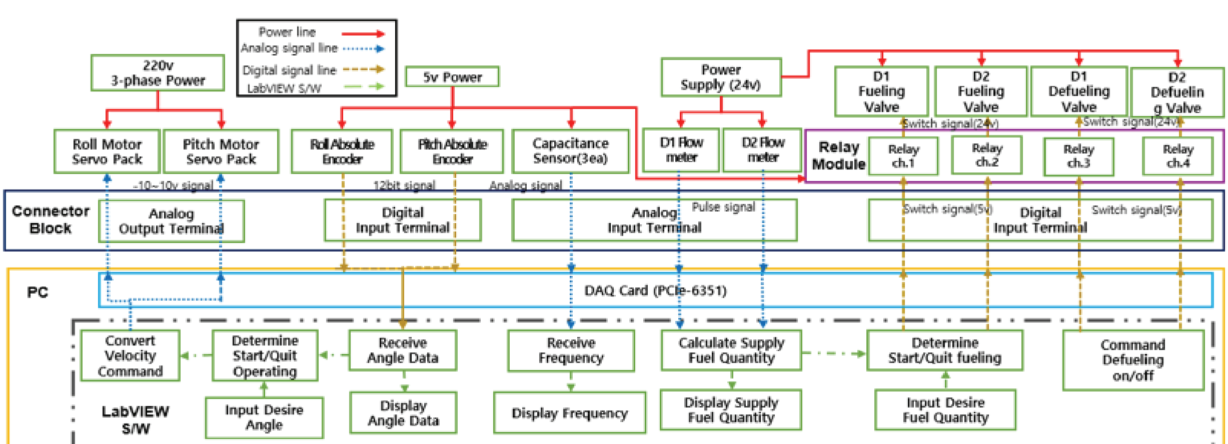


Fig. 7. Architecture of Test Simulator with FQMS

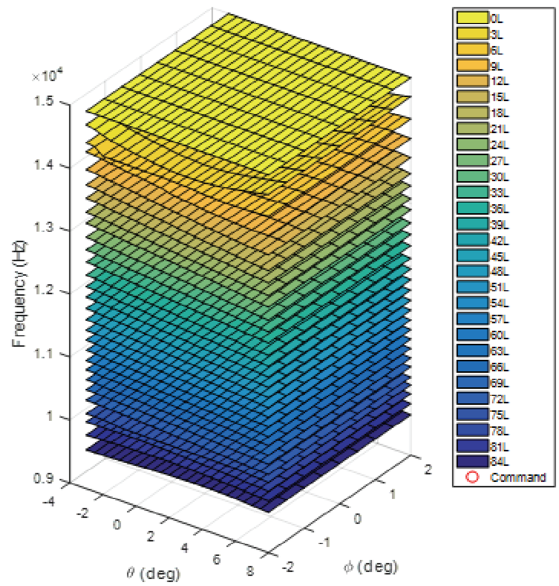


Fig. 8. Result of Data Acquisition

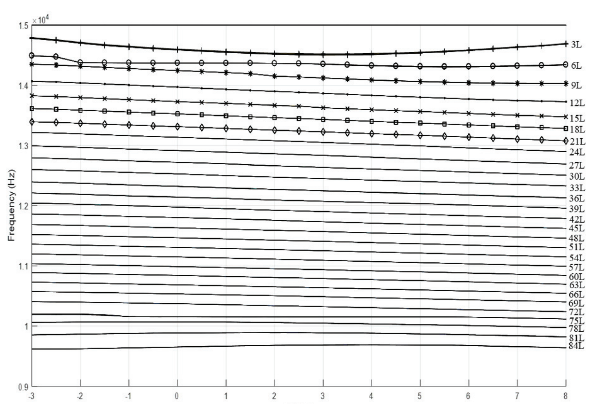


Fig. 9. Result of Data Acquisition (Tendency of frequency for pitch attitude)

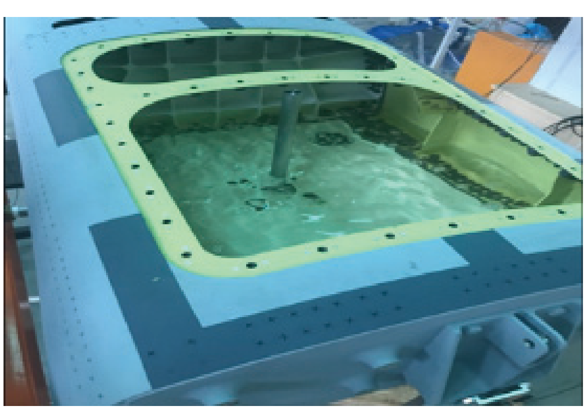

Fig. 10. Shape of supplementary fuel tank

## 3.2 Accuracy of Test Result

To verify the accuracy of developed FQMS, a test is conducted. Fuel is supplied by 5 liter (around 4kg) each using a beaker and an electronic scale. The performance of the electronic scale(HS5002) is shown in Table 2.

Table 2. Performance of HS5002

| | |
|---|---|
| Maximum capacity | 5100g |
| Minimum display | 0.01g |
| Reproducibility | 0.01g |
| Linearity | ±0.03g |
| Settling time | 1.5sec |

The quantity of fuel is set to 8 cases (5L, 15L, 25L, 35L, 45L, 55L, 65L, 75L). Then, the test data set is prepared by changing the roll and pitch attitude arbitrarily. Next, the error between the true and estimated fuel quantity is calculated to validate the accuracy of the developed FQMS.

Figures 11-18 presents the calculated error as a function of the roll angle $\phi$ and pitch angle $\theta$. Table 3 shows the maximum absolute error of fuel quantity calculated by the developed FQMS. When fuel quantity is 5L and 75L, respectively error is within 2.97% of full scale and 1.56% of full scale. The error caused by the shape effect of the auxiliary fuel tank becomes severe when the fuel quantity is very small or very large. The error of the other case is calculated within 1%. As shown in Figs. 11-18 and Table 3, the accuracy of developed FQMS satisfied ±3% of full scale and satisfied the criterion of TSO-C55.

Table 3. Result of FQMS

| True Fuel Quantity (L) | Maximum Absolute Error (L) | Full Scale (84L) Error (%) |
|---|---|---|
| 5 | 2.4978 | 2.97 |
| 15 | 0.3044 | 0.39 |
| 25 | 0.6450 | 0.77 |
| 35 | 0.1669 | 0.20 |
| 45 | 0.1530 | 0.18 |
| 55 | 0.2016 | 0.24 |
| 65 | 0.1837 | 0.22 |
| 75 | 1.3088 | 1.56 |

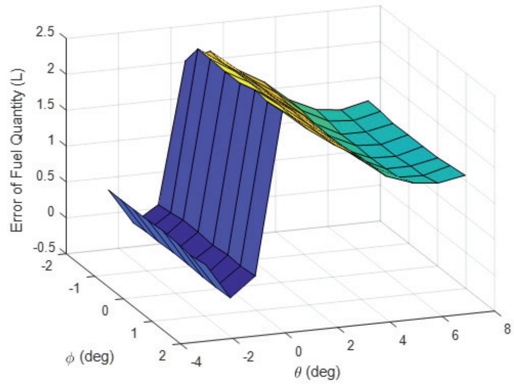


Fig. 11. Error of Fuel Quantity (5L)

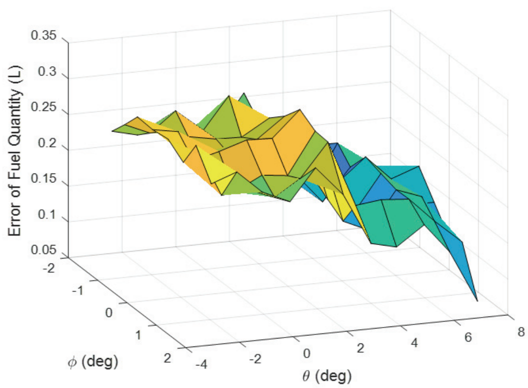


Fig. 12. Error of Fuel Quantity (15L)

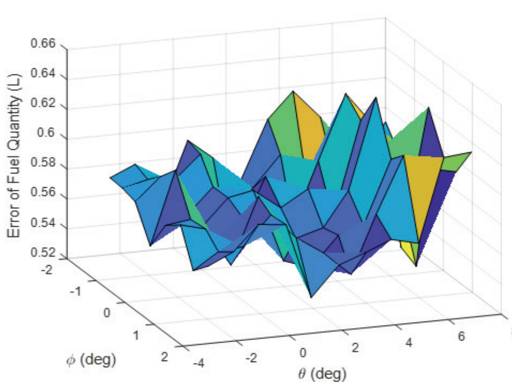


Fig. 13. Error of Fuel Quantity (25L)

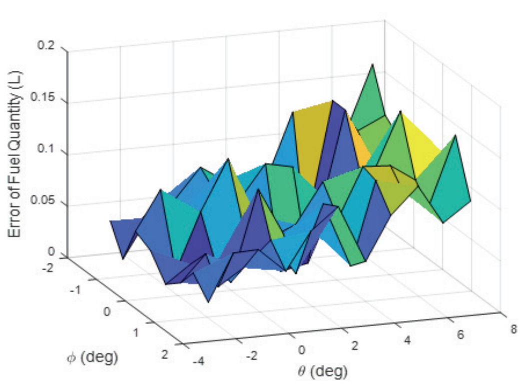


Fig. 14. Error of Fuel Quantity (35L)

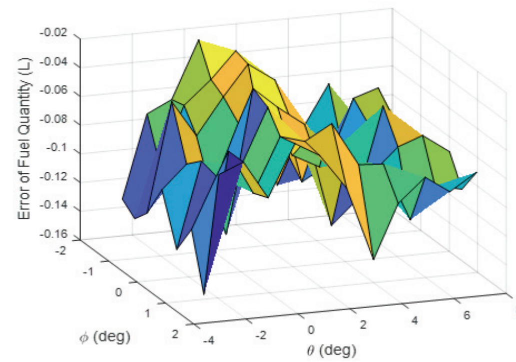


Fig. 15. Error of Fuel Quantity (45L)

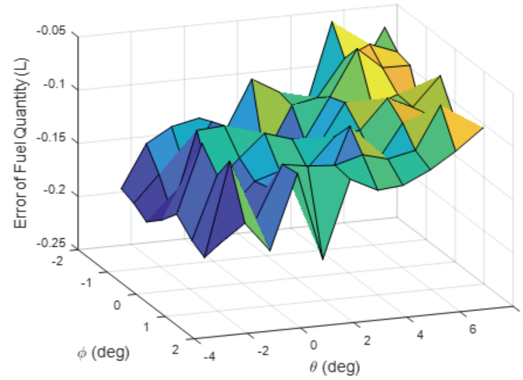


Fig. 16. Error of Fuel Quantity (55L)

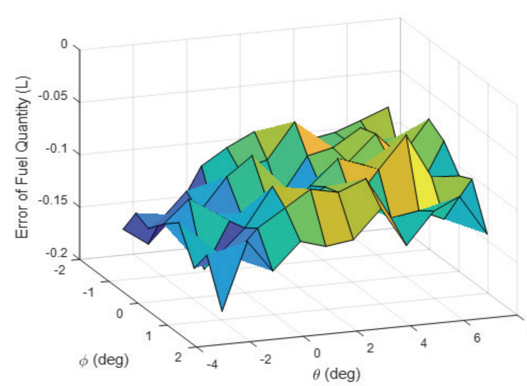


Fig. 17. Error of Fuel Quantity (65L)

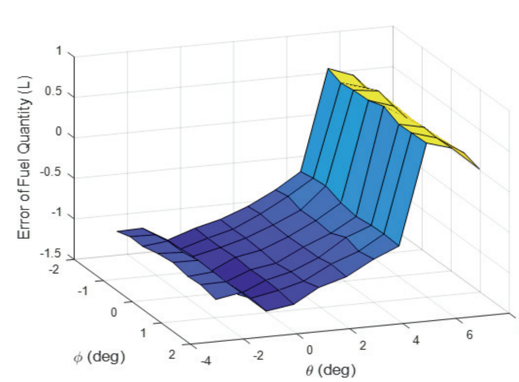


Fig. 18. Error of Fuel Quantity (75L)

## Ⅳ. Conclusion

This paper presents the development of the FQMS for a supplementary fuel tank. The developed FQMS consists of P-300C capacitance-type fuel sensor, a signal processor, and an indicator implemented using a LabVIEW software. The quantity of fuel was estimated using the trilinear interpolation method with the training data set. The training data set was prepared using the test simulator. Using the test simulator, the sensor frequency data at various fuel quantity and roll/pitch angles were automatically acquired. The developed FQMS was verified through the test. The test data set was obtained in arbitrarily changing roll/pitch attitudes. In the test data, the developed FQMS successfully estimated the fuel quantity. In the case of small and large fuel quantities, the estimation error became relatively high due to the shape of the supplementary fuel tank. However, the developed FQMS satisfied ±3% of the full scale specified by the FQMS accuracy of the TSO-C55 document.

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