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Performance evaluation of 80 GHz FMCW Radar for level measurement of cryogenic fluid

J. M. Mun[a], J. H. Lee[a], S. C. Lee[b], K. D. Sim[c], and S. H. Kim[*, a]

[a] *Changwon National University, Chgangwon, Korea*
[b] *HiTechLogic, co., Ltd., Busan, Korea*
[c] *Supergenics, co., Ltd., Changwon, Korea*

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Abstract

The microwave Radar used for special purposes in the past is being applied in various areas due to the technological advancement and cost reduction, and is particularly applied to autonomous driving in the automobile field. The FMCW (Frequency Modulated Continuous Wave) Radar can acquire level information of liquid in vessel based on the beat frequency obtained by continuously transmitting and receiving signals by modulating the frequency over time. However, for cryogenic fluids with small impedance differences between liquid medium and gas medium, such as liquid nitrogen and liquid hydrogen, it is difficult to apply a typical Radar-based level meter. In this study, we develop an 80 GHz FMCW Radar for level measurement of cryogenic fluids with small impedance differences between media and analyze its characteristics. Here, because of the low intrinsic impedance difference, most of the transmitted signal passes through the liquid nitrogen interface and is reflected at the bottom of the vessel. To solve this problem, a radar measurement algorithm was designed to detect multiple targets and separate the distance signal to the bottom of the vessel in order to estimate the precise position on the liquid nitrogen interface. Thereafter, performance verification experiments were performed according to the liquid nitrogen level using the developed radar level meter.

Keywords: cryogenic fluid, level meter, FMCW Radar, zoom FFT, multiple target detection

1. INTRODUCTION

Recently, the research on hydrogen fuel cells is actively underway due to the increase in the use of unmanned aerial vehicles and hydrogen electric vehicles [1-3]. Liquid hydrogen has a boiling point of 20 K at 1 atm and has a higher density than the gaseous state. Therefore, when hydrogen is stored in a liquid state in a transport and storage tank, it has better energy density and storage stability compared to high-pressure gaseous hydrogen. However, liquid hydrogen stored in a cryostat continuously vaporizes due to an external heat load. And since it is used as a fuel for drones and electric vehicles, it is necessary to accurately determine the amount of residual liquid hydrogen after charging and use. This can be quantitatively confirmed by measuring the level of liquid hydrogen inside the tank. In this study, 80 GHz FMCW Radar was introduced to measure the cryogenic fluid level inside the transfer and storage tanks.

The FMCW radar is a method of continuously transmitting and receiving signals by modulating the frequency according to time. These radars can get level information of fluid based on the beat frequency obtained through the transmitted/received signal [4-6]. In the liquid interface, the transmitted wave from the radar antenna is reflected at the interface due to the intrinsic impedance difference between the gas media and the liquid media. However, in the case of a cryogenic fluid with a small difference in intrinsic impedance between a liquid media and a gas media, such as liquid nitrogen and liquid hydrogen, it is difficult to detect a general radar-based target due to the low reflectivity [7]. And since the permeated signal is reflected from the bottom of the vessel, it is difficult to detect the interface of the cryogenic fluid with the conventional radar distance measurement method that detects the maximum intensity signal as the distance of the target. Therefore, multiple targets were tracked to estimate the precise location of the liquid nitrogen interface, and the radar measurement algorithm was designed to separate the distance signal corresponding to the bottom of the vessel and detect the liquid nitrogen interface as distance information.

In this paper, the FMCW radar was designed and manufactured to measure the level of cryogenic fluid, and the basic characteristics of FMCW Radar were experimentally analyzed by applying an improved algorithm to cryogenic fluid having a low impedance difference.

* Corresponding author: seokho@changwon.ac.kr

2. THEORY OF FMCW RADAR

2.1. Distance measurement principle of FMCW Radar

In general, in order to obtain distance information from a target, time information on a transmitted/received signal

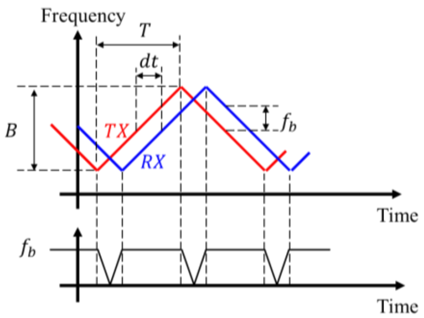

Fig. 1. The principle of FMCW Radar Distance Measurement.

is required. However, in the case of the FMCW radar, the frequency of a continuously transmitted signal is modulated with respect to time, and distance information is obtained by using the frequency difference between the transmitted signal and the received signal reflected from the target. This frequency difference is called beat frequency and is proportional to the distance to the target. Through the information extracted from the frequency difference in this way, the distance to the target is expressed as follows;

$$f_b = \frac{B}{T} dt \quad (1)$$

$$R = \frac{C_0 \cdot dt}{2} = \frac{C_0 \cdot T \cdot f_b}{2 \cdot B} \quad (2)$$

Where, f_b [Hz] is the beat frequency, B [Hz] is the modulated frequency, T [s] is modulation time, dt [s] is the delay time between transmitted and reflected signals, R [m] is distance between antenna and target and C_0 is the speed of light. Because B and T are design constants, the distance R is proportional to f_b.

2.2. Improvement of Distance Resolution by Zoom FFT

The distance information is proportional to the beat frequency, and the distance resolution is determined according to the frequency resolution in the FFT process [3].

$$f_{res} = \frac{f_s}{N} = \frac{1}{NT_s} = \frac{1}{T} \quad (3)$$

$$R_{res} = \frac{C_0 \cdot T}{2 \cdot B} f_{res} = \frac{C_0}{2 \cdot B} \quad (4)$$

Where, f_{res} is frequency resolution [Hz], f_s is sampling frequency [Hz], N is the sampling points, T_s is the sampling time [s] and R_{res} is the distance resolution [m].

In this paper, the distance resolution R_{res} is calculated as 37.5 mm using designed B of 4 GHz. However, this distance resolution is not suitable for precise level measurement of fluids, and in this study, the design distance resolution was selected as 5 mm and the resolution was improved by applying the zoom FFT method.

The zoom FFT method is a specific frequency band extension technique that can accurately analyze frequency information in a specific frequency band. The Fig. 2 shows the schematic of zoom FFT for a specific frequency band.

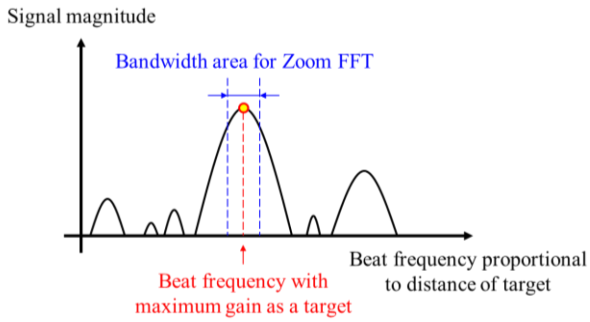

Fig. 2. The schematic of Zoom FFT.

The zoom FFT process for improving the distance resolution is as follows. First, coarse FFT is performed based on the maximum intensity f_b to obtain the first maximum gain frequency. And then f_{res} is modified by the decimation factor as follows;

$$f_{fin} = \frac{f_s/M}{N} = \frac{f_{res}}{M} \quad (5)$$

Where, f_{fin} is frequency resolution after zoom FFT and M is the decimation factor. M is set to 7.5 according to the design process and the distance resolution of 5 mm is obtained by equation (4) [8-10].

2.3. Signal reflection properties at the media boundary

In general, the propagation characteristics of electromagnetic waves in a media are determined by the intrinsic impedance, which is an intrinsic property of a material as follows;

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \quad (6)$$

Where, η [Ω] is the intrinsic impedance of media, ε [F/m] is permittivity, μ [H/m] is permeability and σ [Ω] is electrical conductivity.

When electromagnetic waves travel from media to media, some of them are reflected and some are transmitted at the interface. The degree of reflection is determined by the impedance difference between medium as follows;

$$E_{ro} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} E_{io} = \Gamma E_{io} \quad (7)$$

Where, Γ is the reflection coefficient.

For comparing the reflection properties, it is assumed that an incident wave of electromagnetic waves travels through media 1 (free space) and enters the interface of media 2 (water or liquid nitrogen). The impedance of media 1 is, by definition, 370 Ω. The intrinsic impedance of media 2 almost depends on the permittivity because water and liquid nitrogen have near zero electrical conductivity in a stable state and are not magnetized. Using the relative permittivity of water and liquid nitrogen of 80 and 1.4, the impedance of each media was calculated as 42.1 Ω, 318 Ω, respectively. Therefore, the reflection coefficients of water and liquid nitrogen are -0.8 and -0.08, respectively. Compared to metals with a reflection coefficient of -1 due to total reflection, in the case of water,

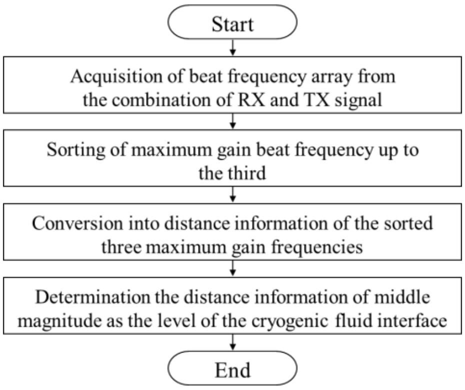

Fig. 3. Sequence for cryogenic fluid distance information acquisition.

most of the radar waves are reflected, so the signal reception characteristics are good. However, in the case of liquid nitrogen, it is estimated that the reception sensitivity of the signal is low because most of the waves are transmitted.

2.2.1 Algorithm Design for Distance Measurement of Cryogenic Fluid Interface

The existing distance estimation algorithm of FMCW Radar recognizes signals with maximum intensity as target distances out of all frequency information extracted through the transmit and receive antennas.
Unlike a media with high relative permittivity like water, liquid nitrogen and liquid hydrogen have low permittivity, so the reflection coefficient for the radar transmission wave and the reception wave sensitivity is low. Therefore, when measuring the interface to a media having a low impedance difference, the distance at the bottom of the vessel may be detected. As a solution to this, the algorithm was improved to measure the distance for multiple targets without performing distance measurement for a single target as shown Fig. 4.

First, the number of targets to be identified by the algorithm was selected as three targets in consideration of the lower bottom of the liquid nitrogen vessel, the liquid nitrogen interface and the upper flange. Next, in order to measure each distance to the three targets, a frequency band having the maximum intensity is extracted up to the third, and the frequencies of the corresponding band are converted into detailed distance information by performing zoom FFT. Thereafter, the maximum and minimum distance data were regarded as the bottom and upper flanges of the liquid nitrogen container, respectively, and the distance data having an intermediate value was finally selected as the liquid nitrogen interface. The schematic and flow chart for the above process is as follows;

3. PERFORMANCE EVAVUARION OF FMCW RADAR

Experiments were classified according to the medium to analyze the basic characteristics of FMCW radar, and the medium were selected as metal, water, and liquid nitrogen. Measurement result analysis was performed from the

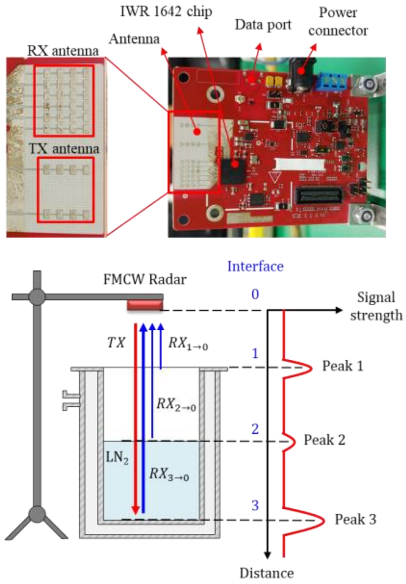

Fig. 4. Measurement results for media #1 (metal).

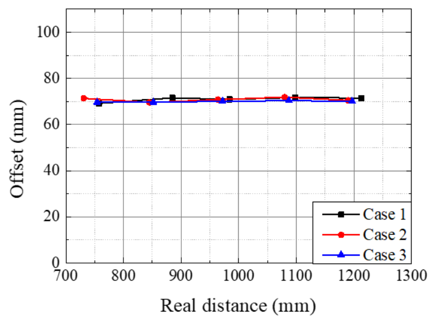

Fig. 5. Measurement results for media #1 (metal).

perspective of measurement accuracy and resolution. Measurement accuracy was defined as the average offset from the true value (real distance), and the measurement resolution was defined as the difference between the maximum offset and the minimum offset.

3.1. Performance Evaluation for Medium #1 (Metal)

In the case of medium #1, the incident electromagnetic wave is totally reflected due to its high electrical conductivity. Therefore, the basic properties of the FMCW Radar were evaluated prior to the liquid media experiment. And as the material of the media, STS 304, which is generally used for cryogenic vessel, was selected. The average offset for measurement accuracy of FMCW Radar for medium #1 was 70.5 mm. The measurement resolution was 2.8 mm as the maximum and minimum offset were measured as 71.9 mm and 69.1, respectively.

3.2. Performance Evaluation for Media #2 (Water)

The medium #2 (water) has a relatively high relative permittivity of 80 compared to liquids having a low permittivity such as liquid nitrogen and liquid hydrogen, and thus has good reflection characteristics for electromagnetic waves. And since it is thermally stable when exposed to room temperature, there is no bubble generation due to boiling, so there is little diffuse reflection.

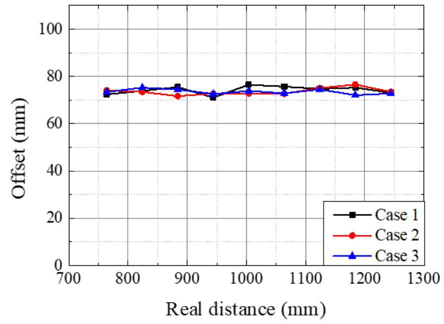

Fig. 6. Measurement results for media #2 (water).

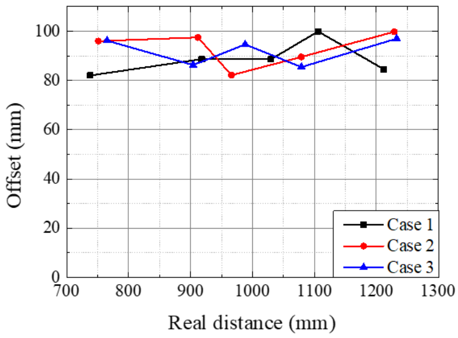

Fig. 7. Measurement results for media #3 (liquid nitrogen).

Therefore, water was previously selected as media #2 in order to analyze the basic characteristics for level measurement of a liquid medium.

The average offset for measurement accuracy for medium #2 was measured as 73.8 mm. The measurement resolution was 5.5 mm. In here, the maximum and minimum offset were measured as 76.6 mm and 71.1, respectively.

3.3. Performance Evaluation for Media #3 (Liquid Nitrogen)

In the case of media #3, basic characteristics of FMCW Radar were analyzed for medium having low dielectric constants. However, since liquid hydrogen has a handling risk, liquid nitrogen was selected as an alternative media.

The measurement results of FMCW Radar for media #3 was as follows; the average offset for measurement accuracy was 91.2 mm and the measurement resolution was 17.8 mm. The maximum and minimum offset were measured as 99.9 mm and 82.1, respectively.

4. CONCLUSION AND DISCUSSION

In this study, an FMCW radar was designed and fabricated for level measurement of cryogenic fluids with a small impedance difference between the mediums. As a result of the experiment, by detecting the level of the media #3, the measureability of the media having a low dielectric constant was confirmed. However, a difference between the maximum and minimum offsets of 17.8 mm was measured for media #3. This indicates that the distance resolution for liquid nitrogen is not enough even though the design distance resolution is improved by zoom FFT.

At first, liquid nitrogen, which is in a boiling point of 77 K at 1 atm, is boiled by the external heat load and bubbles are continuously generated. Therefore, the cause of the degradation of the FMCW radar can be estimated as follows;

1. The equivalent dielectric constant is lowered due to the numerous bubbles inside the liquid nitrogen.
2. The convection occurs due to boiling and the interface of liquid nitrogen is not maintained stably.
3. Evaporated gaseous nitrogen fills the free space medium that is distinct from the liquid medium, reducing the impedance difference between the two mediums.

Due to the above reasons, the distance resolution of the FMCW Radar did not satisfy the theoretical design value, and it can be solved by improving the concentration of the transmission/reception signal of the FMCW Radar. Currently, we are designing a horn antenna to improve the concentration of signal, and experiment was planned to evaluate Radar performance in near future.

Consequentially, liquid hydrogen has a low dielectric constant similar to liquid nitrogen, and level measurement for liquid hydrogen will also be possible depending on whether liquid nitrogen level is measured in this study.

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