A Microwave Technique for Detecting Water Deposits in an Air Flow Pipelines

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Abstract **-** A simple microwave method is used to determine thin layers of water inside the air or compressed-air carrying pipes of pneumatic systems. The technique proposed here is based on the shift in the resonant frequency with the changing air-water ratio within the pipe. A calibration chart relating the resonant frequency and thickness of water layer is presented and experimentally verified. Experimental results agreed well with the simulated response, particularly for thin water layers, which are difficult to detect accurately using existing methods.

Index Terms **-** Microwave, reflection, multiphase flow, water deposit.

I. INTRODUCTION

Measuring the liquid to air ratio is important in maintaining presssure and determining the flow rate and liquid buildup within a compressed-air transporting pipe, commonly employed in pneumatic systems. Popular methods of measuring the water level include mechanical, electrical, ultrasonic and optical techniques [1-3]. The most common electrical method excites the two-phase fluid with a low frequency signal and measures the electrical parameters between two electrodes. The measured parameters include capacitance, resistance and inductance, which can determine the dielectric properties (permittivity and conductivity) of the mixture. In the capacitance measurements, the fluids enter into the coaxial capacitor from one end and exit from other end. The dielectric constant (permittivity) of the fluids inside the capacitor is a function of the capacitance, which in turn helps in determining the resonance of an RC circuit [4]. The resistance measurements method mounts two electrodes in the pipe to monitor the conductance of the passing liquids, where the resistivity is a function of the liquid effective length between the electrodes and the electrodes cross sectional area [5].

Ultrasonic sensors, used in the water level determination, also suffer from highly undesirable fluctuation in the measurements due to multiple reflections of sound beams [6, 7]. Electrical two-phase level detectors that use high frequency signals include radio frequency radars and microwave sensors. Different types of RF radars are reported for two-phase level determination, such as multiple-frequency continuous wave (MFCW) radar [8, 9] and frequency step continuous wave (FSCW) radar [10]. But radar applications in level monitoring are subject to strong fluctuations caused by multiple reflections from surroundings. Another common disadvantage of all the methods listed above is their inability to accurately measure small water layer deposits in the pipeline. Measuring the effective dielectric constant of the air-water mixture, on the other hand, can correctly predict the contents of the pipeline.

Microwave signals are often used to distinguish between materials with different dielectric constants. Although the development of microwave sensors began in the 1950s [11], until recently these sensors have had limited application due to their high price and large component size. These sensors are mostly based on the interaction (refraction, scattering, absorption, etc.) between microwave signals and the composite dielectric media [12]. Thus, for a known structure containing a two phase mixture, simple microwave technique can be adopted to measure the content ratio of the mixture. But in multiphase scenarios, microwave multi-parameter measurements are required. Although free-space microwave transmission sensors employ complicated phase measurements to identify the content ratio of a two-phase mixture, the effects of guiding structure are ignored and averaging of multi-frequency responses is required [13, 14].

In this paper, waveguide modes are excited in the pipeline using a coaxial probe and the related reflection response is measured to calibrate of the air-water ratio, particularly for very thin layer of water deposits in the pipeline. This technique also allowed improved impedance matching compared to that of free space microwave sensors.

II. METHOD OF ANALYSIS

The propagation of electromagnetic waves in a pipeline is governed by the geometrical and electrical properties of the pipe and its contents. For a two-phase pipeline, the gas and liquid mixture constitute a composite dielectric material, where changing the percentage of any component modifies the effective dielectric constant of the mixture and influences its resonant response. This principle is adopted here to determine the water ($\bullet_r$=81) and air ($\bullet_r$=1) level within the pipeline.

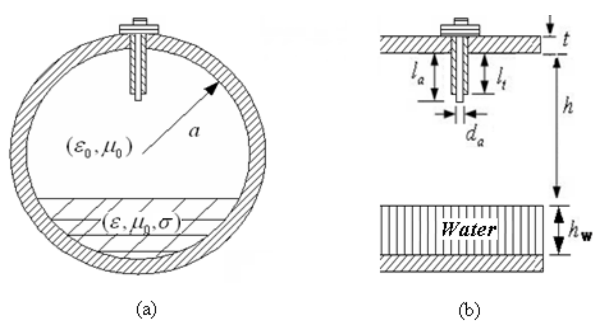


Fig. 1. (a) Cross section and (b) side view of the measurement unit. (a=21.89mm, l_a=14.68 mm, l_t=11.9 mm, d_a=1.3 mm).

The measurement unit used is illustrated in Fig. 1, where the pipe is represented by a circular aluminium waveguide with a diameter of 4.378 cm, length of 43 cm and terminated by matched loads. The length of the pipeline is selected to be long enough to minimize the affects of the reflected waves from the terminations. It is assumed that the micro-machined pipeline unit had no discontinuities (valves/bends) with minimal surface losses. The position and depth of the coaxial probes are selected to optimally monitor the cut-off behaviour of the mixture through measuring the reflection responses. The probe normally excites E-fields of the dominant TE_{11} mode and depending on its diameter and length, the impedance of the waveguide is matched to the desired coaxial prove impedance of 50 Ω. In this work, simulated S-parameter responses are monitored to find the optimal position of the excitation probe. For a homogenously loaded pipeline/waveguide, the cut-off frequency (f_c) and the wave impedance (Z_0) of the TE mode can be expressed as

$$f_c = \frac{S}{\pi D \sqrt{\varepsilon \, \mu}} \tag{1}$$

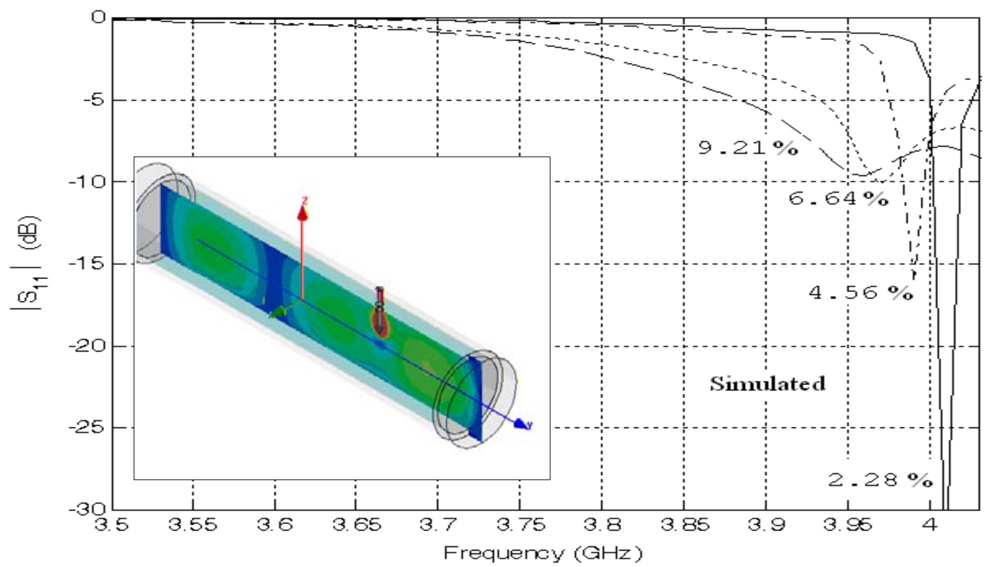
and

$$Z_0 = Z_{fs} \frac{\lambda_g}{\lambda_0} \ , \tag{2}$$

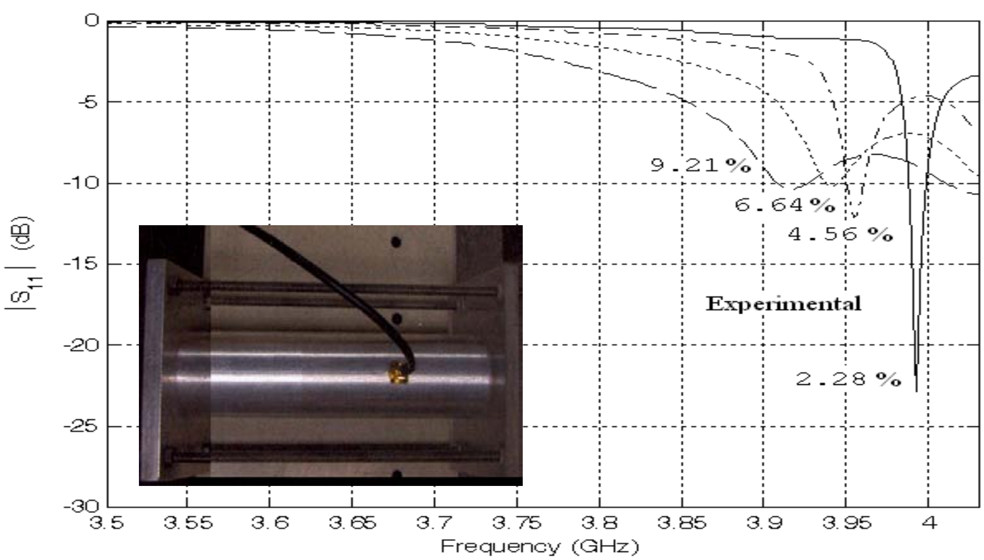
where, 'D' is the pipeline diameter, 'S' is the Bessel function constant, 'ε' and 'μ' are permittivity and permeability of the pipeline contents, Z_{fs} is the wave impedance in free space, λ_g and λ_0 are the guide and free-space wave lengths, respectively. The two phase (air-water) mixture within the pipe resembles an in-homogenously loaded waveguide, where cut-off frequency ranges between equivalent modes of the guide resulting from individual loading of the dielectrics [3]. Thus, limiting values of the modal characteristics, such as fc,TE_{11}(water only)=0.45 GHz and fc,TE_{11}(air only)=4.05 GHz, calculated using equation (1) are used to govern the simulation process.

III. RESULTS

A finite element solver is used to simulate the two-phase mixture within the pipe for various combinations of air and water contents. The simulated reflection responses (S11) of the pipe with various water levels are plotted in Fig. 2a. The air-water mixture demonstrated a cut-off response at 4.01 GHz, 3.9875 GHz, 3.977 GHz and 3.9575 GHz for water levels of 1 mm (2.28% of the pipe), 2 mm (4.57%), 3 mm (6.85%) and 4 mm (9.14%), respectively.



(a)



(b)

Fig. 2. Reflection response of the two-phase mixture (depth/diameter) within the pipe, for four different levels of water: (a) simulated response, (b) experimental response. The inset pictures show simulation and experimental process.

The percentage data is calculated here in terms of "depth-diameter" rather than a "filling by volume". Note that increasing water level increased the effective dielectric constant of the two-phase mixture and consequently reduced the cut-off frequency of the pipeline. The conductivity of the pipe metal is observed to affect the cut-off frequency in an inverse manner, although it has little effect on the changes in S11 response with changing water–air ratio.

The measured reflection responses are shown in Fig. 2b. The position, size, inset and alignment of the SMA probe are carefully selected to achieve best excitation. Reflections from side terminations

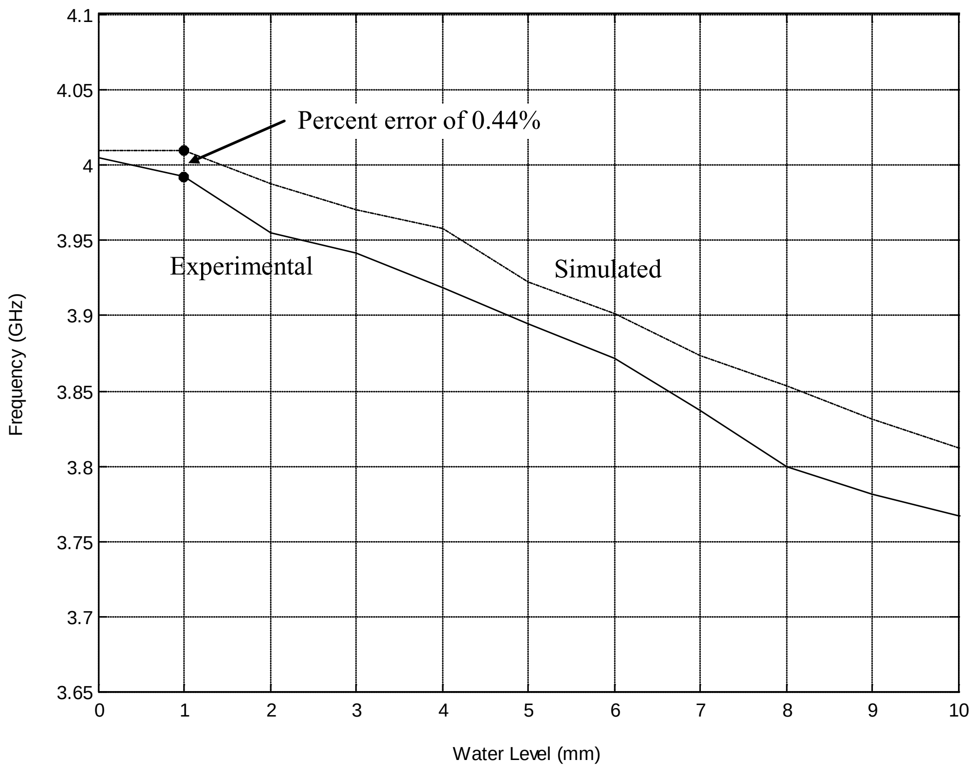


Fig 3. Measured and simulated responses to calibrate water level against the cut-off property of the two-phase mixture within the pipe.

are minimized by selecting absorbing terminators. The experimental results from the network analyzer exhibited similar trends of S11 response with cut-off frequencies of 3.99250 GHz, 3.95500 GHz, 3.94125 GHz and 3.91875 GHz for water levels of 1 mm (2.28%), 2 mm (4.57%), 3 mm (6.85%) and 4 mm (9.14%), respectively. Thus, this technique exhibited an error of 0.44%, 0.82%, 0.90% and 0.99% for water layers of 1 mm, 2 mm, 3 mm and 4 mm, respectively.

Figure 3 superimposes the simulated and experimental cut-off frequency response with respect to the water level in the pipe. Note that for small layers of water the normalized percentage error between the experimental and simulated results are very small (0.44% for 1 mm) with a maximum error of 1.9% occurring for a water layer of 12.9mm or 29.6%. In multiphase flow measurements, an error of 10% is common when one to the parameter is near its low values, i.e., layer of water or flow-rate etc. Therefore, the reproducible measurements results of this simple technique can be attractive for detecting a very thin film of water.

IV. CONCLUSION

A simple microwave technique for water level measurements in a compressed-air transporting pipe is demonstrated. The advantage of this method is its ability to accurately measure very small layers of water, which are often the reason for corrosion in pneumatic systems. The predicted calibration chart relating the water level with the cut-off frequencies of the two-phase pipe is experimentally verified.

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