Flow Measurement and Instrumentation 43 (2015) 14–22

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Improving the performance of an RF resonant cavity water-cut meter using an impedance matching network

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ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form
16 January 2015
Accepted 27 February 2015
Available online 25 March 2015

Keywords:
Impedance matching
Resonant cavity sensor
Two-phase flow
Radio frequency
Water-cut meter

ABSTRACT

In multiphase flow measurement, one of the most challenging issues is to define an adequate technology for a specific scenario, taking into account the measurement accuracy, implementation feasibility and costs. The electromagnetic technology based on resonant cavities is often employed in water-cut meters to measure two-phase flows such as water/oil and water/gas mixtures. The main disadvantage of this technology is the electromagnetic signal attenuation that occurs as the water content decreases. This undesirable behavior is amplified due to the impedance mismatch between the sensor ports and the transmitter/receiver modules. This paper presents a study to implement an impedance matching network in order to improve the instrument performance. Impedance matching networks were built, taking into account the matching for a 100%, 50% and, also, for the worst case of 0% of water fraction where there is a significant signal attenuation. The implemented networks improved the signal amplitude ratio between the first resonant mode and the other modes, increasing the identification accuracy of the first resonance peak.

1. Introduction

In almost all stages of the petroleum production, there are multiphase flows, such as water/oil/gas, or water/oil and water/gas mixtures. In order to evaluate the productivity of an oil field, it is important to monitor how much water, oil, and gas is being produced. Several technologies have been developed in order to estimate the relative quantities in a multiphase flow flowing in an oil pipe, such as electrical capacitance tomography [1], fiber optic reflectometer [2], ultrasound [3], and electromagnetic waves [4–7]. Sensors that employ electromagnetic technology, such as resonant cavity sensors, are based on dielectric properties of the multiphase flow in the RF and microwave frequency range [8,9,5]. They are usually used in flows containing water, due to the large difference between the electric permittivity of the water ($\varepsilon_{relative} \approx 81$ for frequencies below 1 GHz) and those of other flows, such as oil ($\varepsilon_{relative} \approx 2$).

The electromagnetic technology, based on resonant cavities employed in water-cut meters to measure two-phase flows, is the main issue of this paper. In this technology, the resonant frequency of the sensor depends on the effective permittivity of the multiphase flow inside the pipeline. By measuring the transmission coefficient of the sensor as a function of the frequency, we determine the frequency where the resonance occurs. This information is then processed in order to find a correspondence with a given multiphase flow pattern, which was previously established in a characterization procedure.

In order to measure the transmission coefficient, it is often employed a 50 Ω-based RF network analyzer. The accuracy of the measurement is strongly related to the signal-to-noise ratio at the receiver input, which is very dependent on the quality of the impedance matching at the instrument ports. Moreover, the port impedance of the sensor changes with the flow pattern. Thus, in order to minimize the reflections on the ports and consequently maximize the amplitude ratio between the first and the other signal peaks, the use of impedance matching networks is imperative to enhance the measurement accuracy. The problem of signal attenuation was also reported in an acoustic two-phase flow measurement system [10], where the amplitude ratio of the RF signal exponentially decreases as the gas flow rate increases. In [11], the problem of the instability on the resonance frequency measurement due to the increasing of the gas mass fraction was investigated. The two last references do not take into account the impedance matching approach.

The passive impedance matching networks are often used to maximize the power transfer between two devices. Several matching techniques have been employed in different applications, such as

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http://dx.doi.org/10.1016/j.flowmeasinst.2015.02.002
0955-5986/

in communication systems, wireless power transfer, and medicine [12–15]. A particular characteristic of the proposed water-cut meter is that the impedance of the ports varies according to the water content inside the cavity, thus an adaptive matching network should be employed in order to provide a complete solution.

In this paper, we present a study regarding the adoption of an impedance matching network to improve the measurement characteristic of a water-cut resonant cavity sensor. The proposed measurement system operates in the frequency range from 150 MHz to 300 MHz. Inside this frequency operating range, three impedance matching networks were implemented to match the impedance between the transmitter/receiver modules and the sensor RF antennas. In this sense, three different cases 0%, 50% and 100% of water fraction were evaluated, since it is enough to validate the proposed method.

It is noteworthy that the impedance matching method proposed in this paper improve remarkably the detection of the first resonant peak of the sensor response. This is the main contribution of this paper.

The paper is organized as follows. The working principle of the sensor and how its signal degrades with changes in the pipeline water fraction content are shown in Section 2. Section 3 presents the proposed impedance matching design through a circuit-level analysis. Simulation and experimental results are explained in Section 4. Finally, some conclusions are drawn in Section 5.

2. Working principle

Resonant cavities are closed metallic devices made in a rectangular or cylindrical shape, in which the energy is stored in the electromagnetic fields at a high frequency. The resonance occurs at the frequency in which the excitation field will be in phase with the reflection components, resulting in a high standing wave pattern inside the cavity. This phenomenon occurs at distinct frequencies corresponding to different propagation modes, denoted by Transversal Electric TE_{nml} and Transversal Magnetic TM_{nml}, where n, m, and l refer to a maximum electric field at a wave pattern in the cavity directions [8]. The resonance frequency of a cylindrical cavity can be determined by [8]

$$f_{r,nml} = \frac{1}{2\sqrt{\mu\varepsilon}}\left[\left(\frac{p_{nm}}{\pi a}\right)^2 + \left(\frac{l}{d}\right)^2\right]^{1/2}, \qquad (1)$$

where p_{nm} are mth-order Bessel functions of the first kind, that vary according to the propagation mode; a is the cavity radius and d is the cavity length; μ is the permeability of the material defined as $\mu = \mu_0\mu_r$, where μ_0 is the magnetic permeability of free space and μ_r is the relative permeability; ε is the electric permittivity of the material, being $\varepsilon = \varepsilon_0\varepsilon_r$, where ε_0 is the permittivity of free space, and ε_r is the relative permittivity. The relative permittivity ε_r is a complex value, usually represented by $\varepsilon_r = \varepsilon_r' + j\varepsilon_r''$, where the imaginary part stands for the losses of the material.

The sensor was built, as depicted in Fig. 1(a), using a 3 inches in diameter PVC pipe inside another 5 inches in diameter metallic pipe, both of them with 5.9 inches in length. The cavity was designed to resonate around 300 MHz for the TE111 resonant mode. A sketch and a photograph of the implemented sensor prototype are shown in Fig. 1 (a) and (b), respectively. Replacing the sensor parameter values in (1) we can find the resonance frequency as

$$f_{r,TE111} = \frac{kc}{\sqrt{\varepsilon_m}} \qquad (2)$$

where $k = 5.69\ \mathrm{m}^{-1}$ is a constant, c is the speed of the light in vacuum and ε_m is the relative permittivity of the mixture inside the sensor. Note that from Eq. (2), the resonant frequency of the cavity sensor is inversely proportional to the square root of the material's

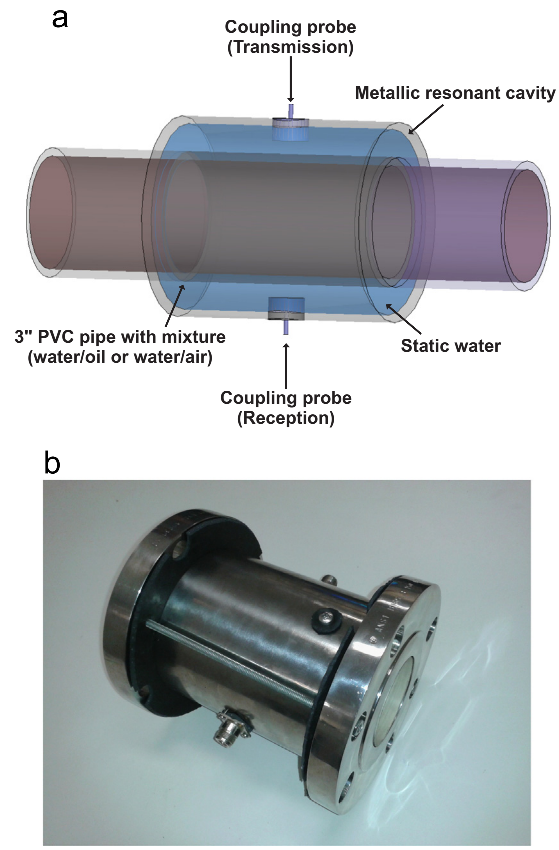

Fig. 1. Sketch (a) and photograph (b) of the resonant cavity sensor.

permittivity and that the permittivity varies with the fraction of water inside the cavity. This is the physical principle of the proposed water-cut meter.

The probe antennas are positioned on the metallic cavity wall where the electric field is maximum. The sensor response depends on the position of the antennas (vertical or horizontal, see Fig. 2). In a horizontal way the response curve of the sensor (resonant frequency versus water fraction) becomes more linear than in a vertical way. This result can be investigated by the resonant cavity perturbation method [8,16–18].

The resonant cavity perturbation method is useful to measure the material dielectric properties. In the material perturbation method, the material sample is inserted into the cavity, and so the resonant frequency and quality factor are measured.

A resonant cavity with volume V and partially filled with a material whose volume is V_s is characterized by means of the relative permittivity (ε_{r1}) and the relative permeability (μ_{r1}). The cavity designed to resonate at a specific resonant mode presents an electric field $\overline{\mathbf{E}}_1$ and a magnetic field $\overline{\mathbf{H}}_1$ at the resonance frequency ω_1. The electromagnetic fields ($\overline{\mathbf{E}}_2$ and $\overline{\mathbf{H}}_2$) together with the resonance frequency $\omega_2 = \omega_1 + \Delta\omega$ are modified when a perturbation of the permittivity $\Delta\varepsilon_r = \varepsilon_{r2} - \varepsilon_{r1}$ and permeability $\Delta\mu_r = \mu_{r2} - \mu_{r1}$ is induced in the material sample. The general formula of the perturbation method, taking into account perfect conductive cavity walls and a small perturbation, is given by [8]

$$\frac{\omega_2 - \omega_1}{\omega_2} = \frac{\int_{V_s}[(\varepsilon_{r2}\varepsilon_{r1})\varepsilon_o\overline{\mathbf{E}}_2\overline{\mathbf{E}}_1^* + (\mu_{r2} - \mu_{r1})\mu_o\overline{\mathbf{H}}_2\overline{\mathbf{H}}_1^*]\,dV}{\int_V[\varepsilon_{r1}\varepsilon_o\overline{\mathbf{E}}_2\overline{\mathbf{E}}_1^* + \mu_{r1}\mu_o\overline{\mathbf{H}}_2\overline{\mathbf{H}}_1^*]\,dV}, \qquad (3)$$

where the indexes 1 and 2 represent the results before and after the insertion of the sample into the cavity.

Assuming that the original medium in the cavity is lossless and considering a small and homogeneous volume fraction of the