An electromagnetic cavity sensor for multiphase measurement in the oil and gas industry

S Al-Hajeri, S R Wylie, R A Stuart and A I Al-Shamma’a
Liverpool John Moores University, General Engineering Research Institute, RF and Microwave Group, Byrom Street, Liverpool, L3 3AF, UK

E-mail: S.R.Wylie@ljmu.ac.uk

Abstract. The oil and gas industry require accurate sensors to monitor fluid flow in pipelines in order to manage wells efficiently. The sensor described in this paper uses the different relative permittivity values for the three phases: oil, gas and water to help determine the fraction of each phase in the pipeline, by monitoring the resonant frequencies that occur within an electromagnetic cavity. The sensor has been designed to be non-intrusive. This is advantageous, as it will prevent the sensor being damaged by the flow through the pipeline and allow pigging, the technique used for cleaning rust and wax from the inside of the pipeline using blades or brushes.

1. Introduction
Multiphase metering provides valuable information for the management of oil and gas fields. It enables decisions to be made that can maximise the hydrocarbons that are extracted from each well in the most efficient manner. Accurately measuring the amount of oil, gas and water flowing in a single conduit is challenging and a wide range of techniques have been adopted in the search for a reliable meter [1]. The sensor discussed in this paper is based upon a cylindrical cavity and it uses the relationship between the resonant frequencies that occur and the permittivity of the fluid flowing through it. The resonant frequency for a $\text{TM}_{nm\ell}$ mode in a cylindrical cavity [2] can be calculated using equation (1).

$$f_{nm\ell} = \frac{c}{2\pi \sqrt{\mu_r \varepsilon_r}} \left[ \left( \frac{p_{nm}}{b} \right)^2 + \left( \frac{l}{d} \right)^2 \right]^{1/2}$$

where $c$ is the velocity of light
$\mu_r$ is the relative permeability
$\varepsilon_r$ is the relative permittivity
$p_{nm}$ is the $m^{th}$ root of the Bessel function of the $n^{th}$ order
$b$ is the radius of the cavity
$d$ is the depth

© 2007 IOP Publishing Ltd
For this application, the sensor has to be fitted to a pipeline, so the cavity must be open at both ends. By making the cavity diameter larger than the pipeline diameter, and by using a dielectric liner, the pipeline can be made to appear continuous [3] as shown in Figure 1. Using this technique allows the antennae, which are used to excite the resonant modes, to be separate from the fluid in the pipeline. This both protects the antennae from the moving fluid and enables the pipeline to be cleaned with the sensor in place. The permittivity of the outer cavity is therefore independent of the fluid inside the pipeline, aside from possible temperature dependence, so the simple relationship between the permittivity and the resonant frequency described by equation (1) must be reconsidered. This paper will consider using either air or water in this outer section.

![Figure 1. Pipeline cavity sensor](image1)

![Figure 2. Coaxial cavity](image2)

2. Mathematical Model
Figure 2 shows a cross-section of a coaxial electromagnetic cavity of radius $b$ that contains the smaller radius $a$, which represents the boundary between two different permittivities. A dispersion curve for this cavity [4] can be calculated for azimuthally symmetric modes by first considering the wave equation shown in equation (2).

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} E_z + \left[ \frac{\omega}{c} \right]^2 \varepsilon - \beta^2 E_z = 0$$  \hspace{1cm} (2)
The electric field along the length of the cavity, $E_z$, can then be expressed in terms of Bessel functions before the boundary conditions are applied. The two cases considered here will be the two extremes i.e. air in the outer section ($\varepsilon_r = 1$) and water in the inner section ($\varepsilon_r = 81$) and vice versa. The boundary conditions require that $E_z = 0$ when the radius $r = b$, $E_z$ be equal for both solutions at $r = a$, as should the magnetic field component $B_\phi$ at the same radius.

The non-trivial solution can therefore be found using equation (3) for air in the outer part of the cavity (water on the inner) and using equation (4) for the reverse case.

$$\frac{J_0(\Gamma_1 a) Y_0(\Gamma_2 b) - J_0(\Gamma_1 b) Y_0(\Gamma_2 a)}{J_1(\Gamma_1 a) Y_0(\Gamma_2 b) - J_1(\Gamma_1 b) Y_0(\Gamma_2 a)} - \frac{\Gamma_1}{\varepsilon_r \Gamma_2} \frac{J_0(\Gamma_1 a)}{J_1(\Gamma_2 a)} = 0$$

(3)

$$\frac{J_1(\Gamma_2 a) Y_0(\Gamma_2 b) - J_0(\Gamma_2 b) Y_1(\Gamma_2 a)}{J_0(\Gamma_2 a) Y_0(\Gamma_2 b) - J_0(\Gamma_2 b) Y_0(\Gamma_2 a)} - \frac{\Gamma_2}{\varepsilon_r \Gamma_1} \frac{J_1(\Gamma_1 a)}{J_0(\Gamma_1 a)} = 0$$

(4)

where $\Gamma_1 = \left(\frac{\omega}{c}\right)^2 - \beta^2$ and $\Gamma_2 = \left(\frac{\omega}{c}\right)^2 \varepsilon_r - \beta^2$.

$\omega$ is the angular frequency
$\beta$ is the propagation constant, from the sinusoidal dependence $e^{j(\omega t - \beta z)}$

---

**Figure 3.** Dispersion curves with HFSS simulations for TM01 modes for $a = 21\text{mm}$, $b = 65\text{mm}$

Figure 3 shows the dispersion curves for a cavity with an outer radius, $b = 65\text{mm}$. The results using equation (1) for an entirely air filled cavity and an entirely water filled cavity for TM01 modes, are asymptotic with the dashed light lines described by equation (5). Results found using equation (3) and
equation (4) are also plotted for a pipeline radius \( a = 21 \text{ mm} \), along with the \( \text{TM}_{010} \) results obtained using the Ansoft’s HFSS simulation software [5] for the same two cases, which are in good agreement.

\[
f = \frac{\beta c}{2\pi\sqrt{\varepsilon_r}}
\]

The cut-off frequencies for these curves (\( \beta = 0 \)) are also the resonant frequencies for the \( \text{TM}_{010} \) mode in each case. The simulated \( E_z \) field results for this mode are shown in figure 4 for the two cases and the frequencies are summarized in table 1.

![Figure 4a. HFSS simulated E-field with air in the outer cavity and water in the pipeline](image)

![Figure 4b. HFSS simulated E-field with water in the outer cavity and air in the pipeline](image)

| Cavity Description                              | Resonant Frequency (MHz) for \( \text{TM}_{010} \) |
|------------------------------------------------|--------------------------------------------------|
| Air-filled cavity                              | 1765.4                                           |
| Water-filled cavity                            | 196.2                                            |
| Air in outer, water in pipeline                 | 301.2 (at \( \beta = 0.465 \))                   |
| Air in outer, water in pipeline (HFSS)          | 299.8                                            |
| Water in outer, air in pipeline                 | 231.6 (at \( \beta = 0.086 \))                   |
| Water in outer, air in pipeline (HFSS)          | 231.7                                            |

It can be seen that an air-filled outer cavity offers a large frequency shift - in excess of 1.4GHz if the relative permittivity inside the pipeline varied from 1 to 81 – but experiments showed that this also led to a very large variation in amplitude. This made the peak more difficult to track, so a decision was made to concentrate on a water-filled outer cavity. The frequency shift is reduced to 36MHz for the same variation in permittivity, but the amplitude variation is also much less, and using a liquid has the added advantage of supporting the dielectric liner from pressure changes that would be expected in a real pipeline.

3. Experimental Results
A prototype sensor, shown in figure 5, was constructed from brass with the dimensions used above. A PVC tube (50mm O.D., 42mm I.D.) was used to represent the pipeline. The depth of the cavity, \( d = 80\text{mm} \), was chosen so that the \( \text{TM}_{010} \) mode would occur at a lower frequency than any other mode to make it easy to identify on the spectrum analyzer. The cavity was sealed to allow it to be filled with water.
As the prototype was to be initially tested in a static condition by raising the water level in the horizontal pipeline, an HFSS simulation was used to predict the TM_{010} frequencies. The presence of the PVC tube in the real cavity displaces the material in the outer cavity (water) when compared with the simplified model discussed previously, so a second simulation that included it was also completed. The results with and without the PVC liner are shown in figure 6.

Spectrums captured during testing of the prototype sensor are shown in figure 7. There are two peaks for each percentage of water, except for 0% where the peaks overlap. A shift in frequency caused by the change in permittivity can clearly be seen in the smaller of the two peaks, which up to 20% corresponds closely with the frequencies predicted by HFSS for the TM_{010} mode. As the water volume is increased the frequency shifts are lower than expected. The larger peak is assumed to be the TE_{111} mode as the simple cavity theory predicts a frequency of 256.7MHz for a water-filled cavity, although HFSS indicates that the PVC liner should shift the resonant frequency to 293MHz. This
discrepancy may be caused by the partially open ends of the cavity as, unlike the TM\textsubscript{010} mode for which the depth of the cavity ($d$) has no effect, the frequency of the TE\textsubscript{111} mode will be decreased as $d$ is increased.

![Figure 7](image_url)  

**Figure 7.** Experimental results from the prototype sensor as the volume of water is varied in the pipeline

4. Conclusion
A sensor design based on a cylindrical resonant cavity has been investigated for detecting changes in permittivity within a pipeline for multiphase metering purposes. The non-intrusive antenna design requires an equation, which takes account of the two coaxial dielectrics within the cavity to predict the resonant frequency of the TM\textsubscript{010} mode. The results are compared with simulations using Ansoft’s HFSS software and with measurements from a prototype sensor.

References
[1] Thorn R, Johansen G A and Hammer E A 1997 Recent developments in three-phase flow measurement, *Meas. Sci. Technology* **8** 691-701
[2] Pozar D M 2005 *Microwave Engineering* (John Wiley and Sons)
[3] Wylie S R, Shaw A and Al-Shamma’a A I 2006 RF sensor for multiphase flow measurement through an oil pipeline *Meas. Sci. Technol.* **17** 2141-9
[4] Tripathi V K and Lui C S 1989 A slow wave free-electron laser IEEE *Trans. Plasma Sci* **17** 583-7
[5] www.ansoft.com/products/hf/hfss/