Integrated Microwave Sensor for Cavity-Length Measurement with Sub-Millimeter Accuracy

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***Abstract* — A novel measurement procedure using microwaves is presented. The implemented sensor determines the length of a cylindrical cavity (e. g. hydraulic system) with sub-millimeter accuracy in real time. The principle of operation is based on the detection of the resonance-frequency distribution in a cavity resonator.**

I. Introduction

Microwave sensors offer a possibility to implement novel and cost-effective measurement systems for science and industrial applications. Extensive use of microwave monolithic integrated circuits allows one to enable contact-less, non-destructive, and real-time measurements.

Depending on how the measurement is arranged and which physical phenomenon is used, microwave sensors may be divided in some groups [1]. This paper deals with a measurement system that is based on the resonance principle. There has been a number of sensors employing this phenomenon (e. g. [2–4]).

Figure 1 shows a schematic representation of a structure that has been used very often in the area of mechanical engineering. It consists of a metallic cylinder that is closed from one side. From the other side, a movable piston is placed into this cylinder, which is filled with a dielectric medium. As an example, a robotic arm can be considered. But also hydraulic systems of a variety of machines use a similar arrangement.

This paper defines a measuring procedure and, according to this technique, describes the design of a sensor that determines the length l_{res} of the resulting cylindrical cavity without disturbing mechanical properties of the system.

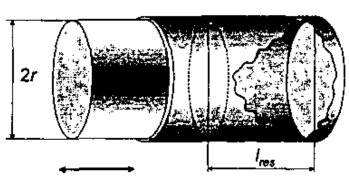

Fig. 1. Schematic description of the measurement problem.

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II. Operation Principles and System Design

A. Measurement Procedure

The principles of the sensor operation is based on the fact that the initial mechanical structure from Fig. 1 can be considered as a cylindrical cavity resonator. The resonance frequencies in a cavity strongly differ from one mode to another. Further, they usually are a function of length for every single mode. Figure 2 demonstrates several resonance frequencies for the first three modes of an ideal cylindrical cavity. In this figure, the resonance-frequency ratio—the normalizing factor is the cut-off frequency $f_{c,H_{11}}$ of the basis cylindrical waveguide mode—is shown as a function of the normalized length l_{res}/r, where r is the resonator radius.

According to Fig. 2, only certain resonance frequencies correspond to a particular resonator-length value (e. g. dashed line). This resonance-frequency sample (taken from a particular frequency range) is unique for every resonator length. Therefore, if a resonance-frequency set is fixed for a particular resonator length, this length value—which is the parameter to be determined—can be unequivocally extracted.

For sensor applications, the resonance mode E_{01n} is of

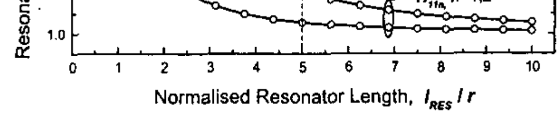

Fig. 2. First three resonance modes within a cylindrical cavity (without coupling). Higher resonance numbers n of a particular mode correspond to the resonances with higher frequencies.

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a special interest. It is the first mode that owns a basis resonance (E_{010}), whose frequency does not depend on the resonator length. Therefore, it can be used as a stable calibrating reference allowing one to take into account only the resonance-frequency **distribution** (or the position of resonances in respect to each other) and not the **absolute value** of resonance frequencies. This calibrating reference can be also used to measure the parameters that exhibit only a weak time dependence (e. g., dielectric permittivity ε_r or the temperature of operation).

The advantage of the distribution technique is the independence of the measurement principle from the absolute values of resonance frequencies, if a particular reference is available. For the sensor system under consideration, this requirement is fulfilled by the resonance modes with a first resonance exhibiting no dependence on the resonator length. Within a circular cylindrical cavity resonator, these modes are: $E_{01n}, E_{11n}, E_{21n}, \ldots$ Furthermore, using the resonance-frequency distribution, the measurement principle ideally becomes independent from the material characteristics of the dielectric medium filling the resonator. This behavior can be used for the mathematical evaluation of the sensor output.

The following procedure can be used to implement the measurement idea described above:

1. Choose a particular frequency range according to the dimensions of the cylinder, whose length has to be measured. The latter choice has to be done also in view of a particular resonance mode to be used (e. g. E_{01n} from Fig. 2). The stimulation of a particular resonance mode allows one easier evaluation of the actual resonator length. Further, the wider the chosen bandwidth range is the lower becomes the minimal resolvable length and the higher is the sensor resolution;
2. Within the chosen frequency range, tune the frequency from one bound to another. In this way, resonances are stimulated within the cavity resonator, which has a particular length value. These resonances appear at a certain value of a particular control variable (e. g. the tuning voltage of a signal source or time). The frequency tuning can be provided by a signal source generating a signal over the chosen frequency band;
3. Detect the appearing resonances as a function of the chosen parameter and calculate the actual resonator length from the output function.

B. Sensor-System Structure

According to the measurement procedure for the length determination of a cylindrical cavity, a sensor concept is proposed whose structure is depicted in Fig. 3.

A sinusoidal signal generated by a voltage-controlled oscillator (VCO) is amplified by a buffer amplifier, and then

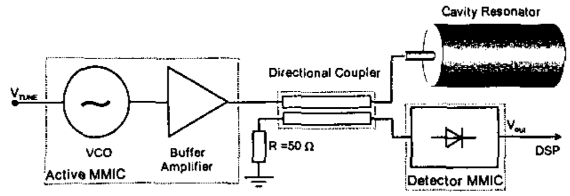


Fig. 3. Block schematic of the sensor system for cylindrical cavity-length measurement.

it is applied to the cavity resonator over a simple directional coupler. The buffer amplifier reduces the influence of the variable resonator-input impedance on the VCO performance. The frequency of the microwave signal can be tuned within the chosen frequency range. In this way, the corresponding resonances of the cavity are stimulated.

At the resonance frequencies of the cavity, the signal power is translated into the resonator. For all other frequency values, the signal is simply reflected back to the coupler. The reflected signal is fed via the coupler to the detector circuit, which detects the power level of the reflected signal. The variation of the power level over frequency results in an alteration of the detector-output voltage. The detector output now contains the information about the distribution of the resonance frequencies within the cavity resonator. Passing this signal to the digital-signal processing unit (DSP), the actual resonator length can be calculated using a mathematical algorithm.

Generally, the derived measurement procedure can be applied to a cylindrical cavity with arbitrary parameters. These variables are the dimensions of the cylinder (its radius and length range) and the art and characteristics of the filling material, which can be any gas or any dielectric liquid. These parameters alter from one application to another. Therefore, the frequency bandwidth of operation and resonator coupling have to be defined for a particular mechanical system.

In this work, a sensor system was designed, manufactured and tested for a cavity, whose parameters are listed in Tab. I. The dielectric medium is the REPSOL vegetable oil that is often used in hydraulic systems. This cavity was chosen to implement a prototype of a sensor system, which should demonstrate the feasibility of the proposed measurement principle, and to investigate its performance.

TABLE I
SUMMARY OF CAVITY PARAMETERS.

Dielectric Constant	ε_r	2.2
Magnetic Constant	μ_r	1.0
Resonator Radius	r/mm	16
Resonator Length	l_{res}/mm	30–200

B.1 Cavity Coupling Issues

Because of the basic idea behind the cavity-length measurement that is described above, solely the E_{01n} resonance mode is taken into account. Moreover, the excitation of other modes such as the H_{11n} complicates the length-evaluating procedure. Therefore, the coupling of these further resonance modes should be made as small as possible. On the other hand, the coupling of the E_{01n} mode has to be strong to allow one a clear detection of single resonances. Due to the radial-symmetrical nature of the E_{01n} mode, the coupling structure has to be chosen to be radial symmetric. It is obvious that radial-symmetric filed probes should stimulate the modes with $\frac{\partial}{\partial\varphi} = 0$ only.

The proposed particular implementation of the field probe is a disc at the end of the coaxial cable that provides coupling between the resonator cavity and the coaxial waveguide. Measurements of a coupled cavity resonator by means of an HP8510 network analyzer showed that the rotation symmetrical modes (E_{01n}, E_{02n}, etc.) are solely excited using this kind of coupling.

B.2 Electronic Part of the Sensor

As shown in Fig. 3, the electronics part of the sensor contains a VCO, a buffer amplifier, and a detector circuit. For the considered frequency range, the circuitry could be realized using either hybrid MIC or MMIC technique. In view of the size reduction and the possible series production, the MMIC technology is a very interesting alternative. Due to the reduced circuitry size, the sensor system can be directly integrated within a cylinder. In the case of mass production, the costs per unit can also be significantly reduced.

On the other hand, the distance between single resonances becomes smaller for longer resonators (Fig. 2), which can lead to a difficult resonance separation and higher measurement error. Hence, higher resonances with n = 4..7 should be taken into account for higher sensor precision. This leads to the requirement that the frequency range covered by the voltage-controlled oscillator should be as wide as possible. This is a very demanding requirement for a fully monolithically integrated VCO.

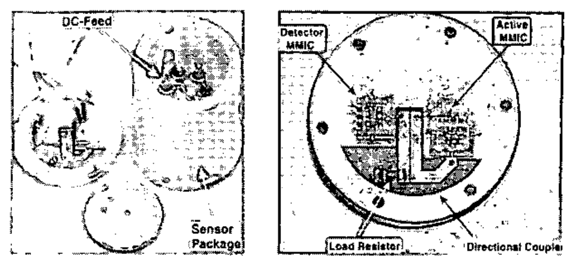
The signal source employed in the current sensor implementation is a feedback MMIC-VCO described in [5]. It offers an excellent combination of bandwidth (4.6 – 7.2 GHz, i. e. 45%), output power ($P_{out} \approx 14.1 \pm 0.7$ dBm), high tuning linearity, and temperature stability. It is manufactured using the PH25 pHEMT process of UMS.

The detector circuit considered here employs a pHEMT in common-source configuration. The RF signal, whose power-level alterations have to be detected, drives the gate-source diode of the transistor while controlling its drain current. Therefore, the DC part of this current is inverted proportional to the level of the input power.

III. Sensor-System Test and Experimental Results

A. Sensor-System Assembly

A sensor prototype was manufactured using the derived measurement procedure and the proposed sensor-system structure (Fig. 3). Figures 4 (a) and (b) show photographs of the packaged sensor system. The packaged MMICs—the active as well as the detector one—together with the directional coupler are glued onto a brass disc that also carries the coupling structure and provides grounding and an excellent heat sink.



(a) (b)

Fig. 4. Photograph of the packaged sensor. (a) The entire system. (b) Close-up view of the active area.

B. Measurement Results

The behavior of the sensor prototype was measured using a testing system employing a step motor, which allows one to drive the piston longitudinally with a minimal step of Δl = 5 µm. The tuning voltage of the VCO was provided by the DC-voltage source HP3631E and was altered in steps of ΔV_{TUNE} = 5 mV. The output detector voltage V_{DET} was measured by the multimeter HP4537. The entire measurement set-up was controlled by the software tool LabVIEW running on a standard PC.

Figure 5 shows the obtained values of the detector output voltages as a function of the tuning voltage and the resonator length $V_{det} = f(V_{TUNE}, l_{res})$. In this 3D plot, one can recognize that the E_{01n} resonance mode of the cylindrical structure was detected only and the distribution of the resonance frequencies corresponds to the theoretical behavior of the E_{01n} mode in a cylindrical resonator cavity.

Furthermore, **all** of these resonances were detected. A comparison with the results of the resonator characterization by means of the network analysis showed that all resonances could be also recognized correctly.

Analyzing Figs. 2 and 5, one can see that the resonance-frequency gradient with respect to the resonator length decreases with increasing values of l_{res}. This behavior im-

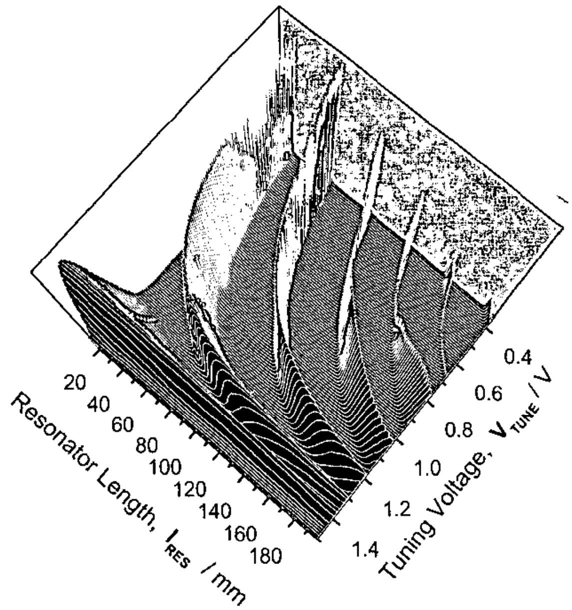


Fig. 5. Detector output voltage as a function of the VCO tuning voltage and the resonator length presented in a 3D plot.

plies that the minimal detectable resonator-length alteration is to look for at higher length values for the case that the next-higher resonance frequency is not detectable yet. For the considered frequency-tuning and resonator-length ranges, this "critical" length was determined to be as high as $l_{res} = 189$ mm. Figure 6 demonstrates the detector output for value of the resonator length of $l_{res} = 189$ and 189.5 mm. The inset within this figure shows that this small length difference is resolvable with the sensor. Assuming that this change is also applicable and detectable by a computer using a certain algorithm, the length resolution of the sensor system would be under $\Delta l = 1$ mm.

Performing dynamic measurements, almost no variations of the detector-output voltage were found up to 100 tuning-voltage sweeps per second. Above this frequency, the position of the resonance peaks as well as their heights start to change.

IV. Conclusion

This paper presents a solution for a classic problem of the length measurement in closed cylindrical structures by means of microwaves. The basic measurement principle is based on the detection of the resonance-frequency distribution within a cylindrical cavity resonator.

Here, the feasibility of the proposed sensor concept has been successfully demonstrated for an example of a particular cylindrical cavity. Table II summarizes the main performance of the integrated sensor for cylindrical cavity-length measurement. In this table, only measured and not absolute characteristics are listed.

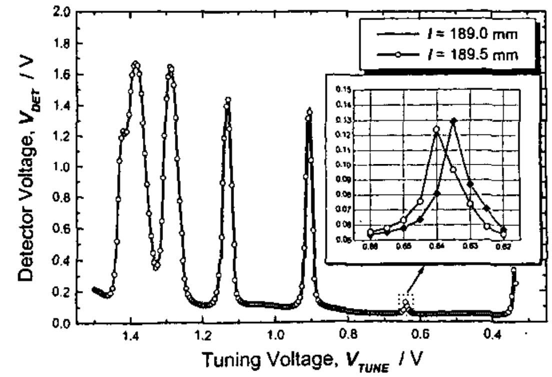


Fig. 6. Detector output voltage as a function of tuning voltage at the resonator-length values of $l_{res} = 189.0$ and 189.5 mm.

The excellent combination of the measurement speed, accuracy, and length resolution of the sensor system designed and manufactured in this work makes it very interesting for various industrial applications, e. g. in automotive shock absorbers (patent [6]).

TABLE II
Measured Performance of the Sensor System Realized

Minimal Length Detectable	$l_{res,\min}$ / mm	30
Length Resolution	Δl / mm	< 1
Dynamics (Hardware Limit)	f_{sweep}/ Hz	100
Max. Operation Temperature	$T_{\max}$/ °C	100

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