

Interface electronics for an RF resonance-based displacement sensor

E Asua¹, V Etxebarria¹, A García-Arribas¹, J Feutchwanger¹, J Portilla¹,
and J Lucas²

¹Departamento de Electricidad y Electrónica. Universidad del País Vasco (UPV/EHU)
Apartado 644, 48080 Bilbao, Spain

²Elytt Energy. 28046 Madrid, Spain

E-mail: estibaliz.asua@ehu.es

Abstract. We propose, design, and test an electronic interface for a new standalone, affordable and compact displacement transducer based on resonant cavities. The operation of the interface establishes a self-resonance in the cavities and detects the resonance frequency (which is directly related to the position to be measured) by analyzing the attenuation produced by a low pass filter. The results obtained in a first prototype of the interface built with discrete elements show that the obtainable positioning accuracy using this cost-effective solution is about 5 micrometers.

1. Introduction

In many micro- and nano-scale technological applications high sensitivity displacement sensors are needed, especially in ultra precision metrology and manufacturing. There is a great technological interest in methods of measuring displacement at very small scales [1, 2]. Different solutions have been studied: laser interferometry [3, 4], capacitive sensors [5, 6], solutions involving the use of new materials (magnetostrictive TbDyFe [7] or carbon nanotubes [8]), or solutions related to radio frequency (RF) [9] and microwave cavity resonators [10, 11].

In our previous works [13, 14] a displacement transducer based on RF resonant cavities was proposed and tested. It was demonstrated that sub-nanometric displacements can easily be detected and measured using standard but high performance laboratory instrumentation. The principle of operation consists in discriminating resonant frequency variations. The measurements were performed using an RF network analyzer (NA), but this approach limits the use of this kind of sensor in applications where the use of that instrumentation is not feasible, especially for its cost.

We present here a cost-effective prototype of electronic interface to be used together with the resonant cavity transducer in order to replace the NA with minimum loss of resolution and accuracy. The cavity equipped with the proposed electronic interface would result in a standalone displacement sensor, giving a measurable output proportional to displacement or position. It has been experimentally shown that accuracies about 5 micrometers can be achieved.

2. Sensor description

Figure 1 shows a general scheme of the laboratory prototype sensor made of copper, comprising two resonant cavities whose dimensions change in opposite directions as a function of the displacement of



a transmission rod. The electromagnetic variations caused by the geometry change of the resonant cavities allow to measure the displacement [13].

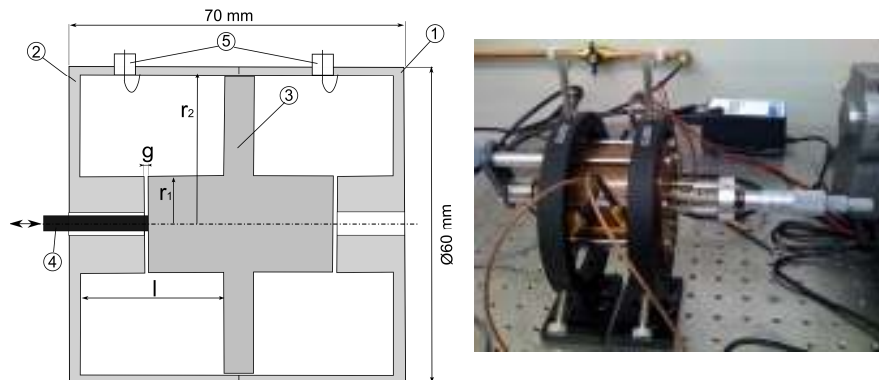


Figure 1. General scheme and photograph of the cylindrical displacement sensor prototype based on resonant cavities. Parts 1 and 2 constitute the body of the sensor. The movement or position to be measured is transmitted to part 3 through the rod 4. Part 5 is an SMA connector for coupling power to the cavity. One resonant cavity is formed on the left side of part 3 and another on the right side. The movement changes the resonant frequency of each cavity in differential form.

A small variation of this gap generates strong variation of the equivalent capacitance, and hence, of the resonant frequency. Let g be the gap, r_1 the radius of the gap region, r_2 the outer radius of the cavity, and l its length. Then, the resonant frequency is:

$$f_0 = \frac{c\sqrt{2g}}{2\pi r_1 \sqrt{l \ln(r_2/r_1)}} \quad (1)$$

where c is the speed of light. The variation of frequency with the displacement may be found by taking a logarithmic derivative of the central frequency expression:

$$\frac{\Delta f_0}{f_0} = \frac{1}{2} \left(\frac{\Delta g}{g} - \frac{\Delta l}{l} \right) \quad (2)$$

In order to maximize the sensitivity, the gap dimension (g) must be much smaller than the total cavity length (l), so the first term inside the parentheses dominates.

Each individual cavity changes its frequency from 280 MHz to 730 MHz approximately (one cavity ascending-wise and the other one descending-wise) along the whole displacement range (400 μm) of the transmission rod. It is remarkable the very high sensitivity of the device, whose response changes as much as 2.25 MHz in frequency for each micrometer of displacement (or 1.125 MHz if we use only one cavity). This result confirmed the usefulness of this new way of sensing displacement for sub-nanometric applications.

3. Signal conditioning design and test

In the previous work [13] the frequency response of both cavities was registered using a radio frequency network analyzer (Agilent model E8358A PNA). In this paper an alternative way to measure the resonant frequency is presented. We divide the proposed electronics interface in two stages: the excitation part and the detection one.

3.1. Excitation stage

The purpose of this part is to excite and induce oscillation in the resonant cavity. We have designed a feedback harmonic oscillator using the resonant cavity itself.

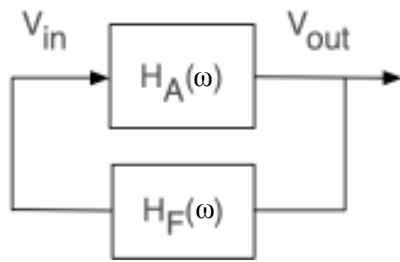


Figure 2. Scheme of the feedback loop to produce the self-oscillation of the resonant cavity. $H_A(\omega)$ is a low noise amplifier. $H_F(\omega)$ comprises the cavity and a phase shifter (see text).

A loop that causes a positive feedback at a selected frequency is the core of any oscillator circuit [15]. The transfer function of the loop shown in figure 2 is described by:

$$\frac{V_{out}}{V_{in}} = \frac{H_A(\omega)}{1 - H_F(\omega)H_A(\omega)} \quad (3)$$

Since there is no input ($V_{in}=0$), to obtain a nonzero output voltage, a Barkhausen criterion has to be satisfied, that is, the denominator in (3) has to be zero. Thus, these two conditions have to be satisfied:

$$\begin{aligned} |H_F(\omega)H_A(\omega)| &= 1 \\ \arg[H_F(\omega)H_A(\omega)] &= 180^\circ \end{aligned} \quad (4)$$

In the proposed prototype, the $H_A(\omega)$ is a low noise amplifier (ZFL-1000LN, MiniCircuits), whereas the feedback system $H_F(\omega)$ is the cavity itself. The amplifier together with the cavity satisfies the first condition, but to meet the second requirement, it is necessary to introduce a phase shifter (JSPH-661) in the feedback in order to add the necessary phase to the system to produce the self-oscillation of the device. The phase shifter is controlled by a voltage that varies between 0 and 10 V in order to shift the phase between 0 and 270 degrees. A filter (VLF-630) is included after the amplifier to clean its output.

For a given position of the resonant cavities (that is, for a given position to be measured), the cavity oscillates for different values of the phase introduced by the phase shifter. However, the power of the obtained signal and even the resonant frequency depend on the actual value of the phase. We decided to select the phase that delivers the maximum power for each position to calibrate the sensor (see figure 3). There are two positions in which the cavity does not oscillate regardless of the value of the phase. These points (empty squares) are presented in the figure for completeness. From now on we will focus in a 200 μm range, where the response is linear.

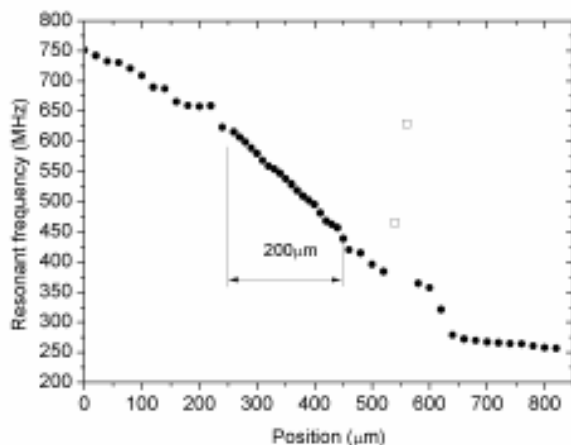


Figure 3. Self-oscillation frequency of the cavity measured using a NA, as a function of position. The phase selected to produce the oscillation is the one that deliver the maximum power.

3.2. Frequency detection

Once the cavity resonates, its output frequency (which is related to the position) has to be measured. To do so, a low pass filter and two RF power detectors are used. A 800 MHz bandwidth low pass filter has been designed to attenuate the signal depending on its frequency. The first RF power (ZX47-50) measures the signal before passing through the low pass filter. The second one (ZX47-50) measures the signal once it has been attenuated. The ratio between those two measurements, that is, the attenuation of the signal, gives us the resonant frequency of the cavity.

Figure 4 shows the elements that constitute the filter, and in figure 5 its performance as measured with a frequency network analyzer. The filter's response is linear in the working frequency of the cavity.

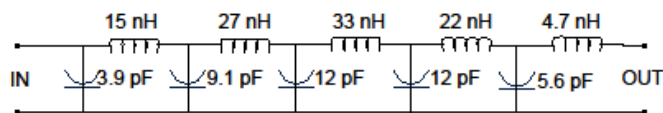


Figure 4. Elements that constitute the low pass filter

The interface used to test the proposed frequency detection procedure have been built using discrete elements. The complete scheme is shown in figure 6. The measurements from power detectors and the voltage to control the phase shifter are managed using a data acquisition board (Model 6011, National Instruments) and LabVIEW software. To determine the accuracy of the electronic interface, the signal produced by the resonant cavity is simultaneously measured by a network analyzer, which is included in the scheme of figure 8. Three ZX30-12-4-S+ couplers have been added when needed to route signals.

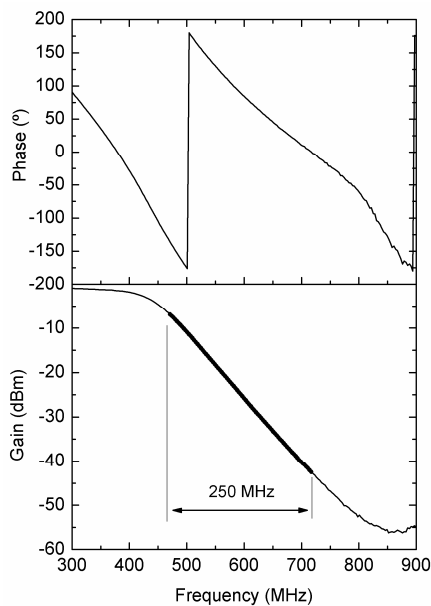


Figure 5. Low pass filter performance. Gain and phase of the transmission parameter S_{21} measured by a network analyzer.

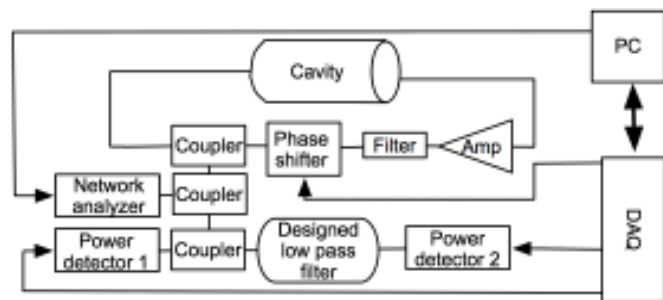


Figure 6. Scheme of the proposed electronic interface. Signals are managed by a data acquisition board connected to a PC. A Network Analyzer is also included to compare the results.

The couplers produce some attenuation, which is independent of the frequency. Thus, the calibration has been done using the ratio between second power detector to the first one when they are connected as the diagram of figure 6 indicates. The results are conveniently fitted to a linear expression:

$$Ratio = 0.00327 fr(MHz) - 0.0858 \quad (r=0.996) \quad (5)$$

It is to be noted again that, in each fixed position, the cavity resonates with different power values depending on the phase shifter. Therefore, the interface is programmed to select the phase shift so the signal power values remain between 0.97 and 0.99 V in the first power detector.

4. Results

Once the cavity oscillates, the resonant frequency has to be measured. As it has been previously mentioned, the method consists of measuring the power of the signal after it passes through the filter. Two nested loops are implemented: the first “coarse” one sweeps the phase shift to achieve oscillation, and the second “fine” one sweeps around this position to reach the correct (0.97-0.99V) power reading. Once this is achieved, the resonant frequency is determined from both power detector readings. In figure 7 the voltages in the first and second power detectors, as well as the calculated frequency based on the ratio between powers and the calibration (equation 5) are shown.

In order to check the performance of the system we compare the frequency as measured with a laboratory calibrated network analyzer and the one given by the proposed electronic interface. As it can be concluded observing figure 8, difference between both readings is about 5 MHz, which corresponds to 5 micrometers according to the transducer intrinsic sensitivity as explained in the introduction section. This error could be improved if we restricted the measurement range of the sensor, or even better if we further constrain the allowable power readings in the first power detector. This latter approach would require a longer time to stabilize the second “fine” loop described above, so there is a clear trade-off between measurement time, precision and range. In any case, from the above experimental results, it can be concluded that the proposed electronics interface is a cost-effective, yet accurate solution for the displacement and position transducer based on resonant cavities.

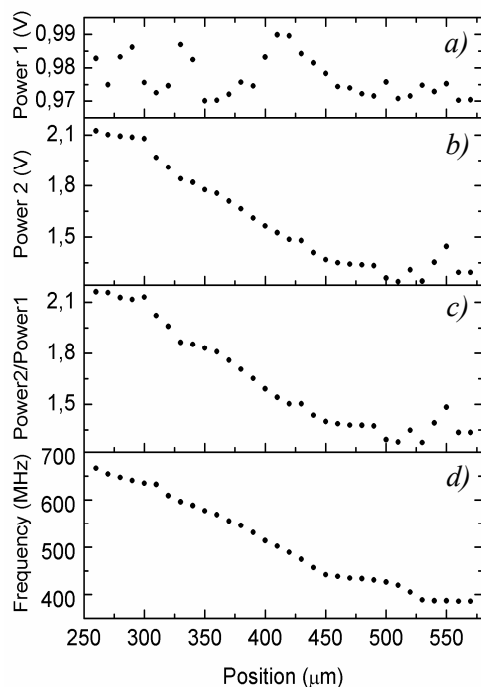


Figure 7. Experimental results. a, b) Voltage measured by power detectors. c) Ratio between both voltages. d) Calculated frequency based on the ratio of powers and calibration (equation 5).

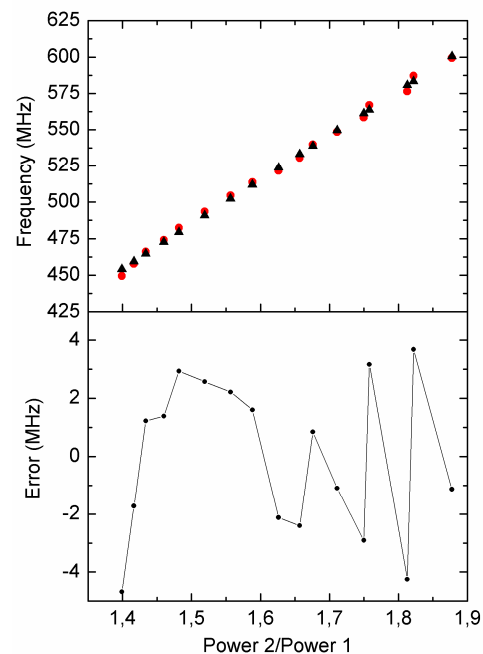


Figure 8. Experimental results. On the top resonant frequency as given by a network analyzer (in black triangles) and as given by the proposed electronic interface (in red points). On the bottom the difference between them.

5. Conclusion and future works

We have designed an electronic interface in order to use it together with a novel position and displacement transducer based on radio frequency resonant cavities, so that it can be used as a standalone positioning sensor. The complete system has been presented and a laboratory prototype has been experimentally tested. It has been shown that the transducer response is linear and exhibits very high sensitivity (1.125 MHz for each micrometer). Besides, it has been experimentally tested that if the proposed electronic interface based on low pass filters, power detectors and low noise amplifier is used, accuracies around 5 MHz in frequency are achieved (corresponding to less than 5 micrometers in displacement). This performance could be further improved restricting the range or increasing the measurement time.

Alternative interface approaches are being considered for testing in order to take better advantage of the sensitivity of the transducer. One of those alternatives implies using the RF cavity to implement a variable low pass filter, so the displacement to be measured produce changes in the attenuation of the filter. Then, a fixed frequency oscillator would be used to supply a fixed amplitude RF signal and the magnitude of the signal after the filter will give the position measurement. This approach has been successfully used in sensors based in self-inductance changes [16].

As a general conclusion, it can be stated that the proposed electronic interface together with the designed displacement transducer based on resonant cavities constitute a cost-effective, yet accurate displacement sensor.

Acknowledgement

The authors are grateful to CICYT and to the Basque Government for partial support of this work through projects DPI2011-24821 and IT-381-10, respectively.

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