Frequency Shift Baseline Removal for Improved Flow Measurement using Microwave Cavity Resonator

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***Abstract*— The flow velocity of the coolant in the high-temperature fluid advanced reactor is an important variable for reactor performance monitoring. However, due to the harsh environment inside the nuclear reactors, there are limited options for measuring flow velocities. A microwave resonant cavity-based flow sensor is a novel sensing approach that measures flow velocity through deflection of the structure due to dynamic pressure. Hollow metallic resonator offers resilience to high temperature and radiation. A key technical challenge of the microwave resonant cavity-based flow sensor is the measurement of the resonant frequency shift due to membrane displacement. This research proposes a baseline removal technique that overcomes the large baseline in the forward gain of the S_{21} parameter frequency sweep introduced by nonideal components in the microwave system. The signal processing technique allows locating the microwave resonances, thus enabling the enhanced measurement of flow velocities. Several smoothing filters that can remove the baseline, while preserving the resonant frequency are implemented and evaluated. This approach is then realized in the LabVIEW for an actual experiment. The experimental results show the measured frequency shifts match with theory, which indicates the proposed method provides a reliable way to measure the frequency shift for flow measurement.**

Keywords—microwave resonators, resonance, filters, smoothing filters, high-temperature fluid flow measurement.

I. INTRODUCTION

In high temperature fluid advanced reactors, such as liquid metal and molten salt cooled reactors, the flow velocity is an important variable for monitoring reactor safety and performance efficiency [1-6]. However, due to the harsh environment of nuclear reactors, there are very limited choices for the measurement of flow velocity. Thermal flow sensor usually functions at room temperature [3], and cannot be used in the high-temperature(>700K) environment of advanced reactors. One option is an ultrasonic flow meter, which relies on ultrasonic transducers, some of which have proven to be suitable for the in-core environment [6]. However, the deployment of the ultrasonic flow meter requires a direct line-of-sight between the transducers, which limits the applicability of this type of flow meter to scenarios with internal structures. In this research, we explore fluid flow measurement using a microwave cavity resonator sensor. This is an immersion flow meter, with a transduction mechanism based on fluid-structure interaction. In the cylindrical metallic resonator shown in Fig. 1, the side of the cavity facing the fluid flow is flexible enough to undergo microscopic deflection due to dynamic fluid pressure. Deformation of the membrane changes the length of the cavity, resulting in a resonant frequency shift. By establishing the correlation between the frequency shift and the flow velocity, we can achieve the measurement of the flow velocity using the microwave cavity. In a practical scenario, detection of frequency shift is challenging due to electronic noise and baseline fluctuation. In this paper, we develop a signal processing method for baseline subtraction that allows measuring resonator frequency in real-time.

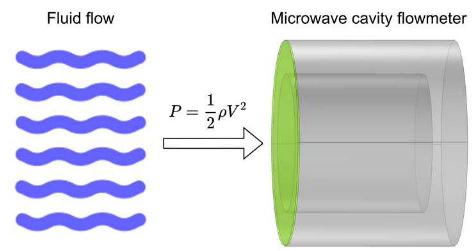

Fig. 1. Microwave cavity flowmeter. The flexible membrane (green) of the cavity faces directly against the flow velocity. The resonator is made transparent to show the interior cavity.

In Section II, we will establish the mathematical relation between the flow velocity and the resonant frequency shift. Then in section III, we explore several smoothing filters [6][7] that have the baseline removal capability. The purpose of using the filters is to accurately measure the resonant frequency, thus measuring the frequency shift when the flow velocity is sensed by the resonant cavity. Finally, section IV shows the results of applying the signal processing method to experimental data.

II. FLOW MEASUREMENT USING MICROWAVE CAVITY RESONATOR

The microwave resonant frequency for a cylindrical cavity excited in TE_{nml} mode has the following closed-form expression [1,2]:

$$f_{nml}^{TE} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{X'_{nm}}{R}\right)^2 + \left(\frac{l\pi}{L}\right)^2} \quad (1)$$

Where f_{nml}^{TE} (Referred to f from now on) is the resonant frequency, c is the speed of light, μ_r is the permeability and ε_r the permittivity of the medium inside the cavity. X'_{nm} is the n^{th} root of the derivative of the m^{th} order Bessel function. Finally, R and L are the radius and height of the cavity. From

Equation 1, for a given TE_{nml} mode and the medium in the cavity, the resonant frequency is determined by cavity radius and length. One side of the cylindrical cavity is a flexible membrane. This membrane should be thin enough that pressure generates by Bernoulli equation [1,2]:

$$P = \frac{1}{2}\rho V^2 \quad (2)$$

Where ρ is fluid density and V is fluid velocity. Dynamic pressure will cause microscopic amplitude displacement of the membrane, such that cavity length change ΔL would result in a measurable frequency shift.

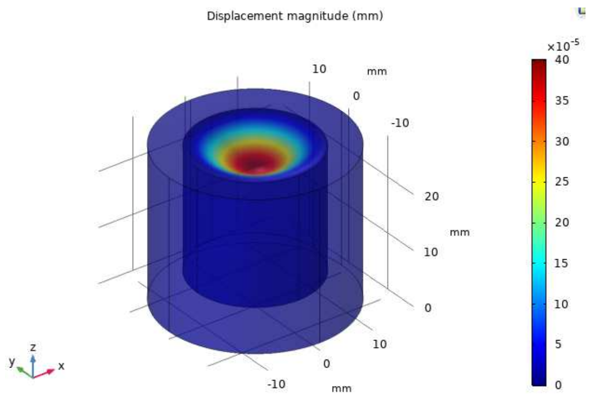

Fig. 2. The microwave cylindrical cavity with one side being a flexible membrane. Deformation of the membrane is magnified by ten thousand times for visualization.

Note that the displacement is not uniform along the radius of the membrane. The displacement along the radius R of the membrane is given by Timoshenko's model for radially constrained circular plate [7]:

$$w(r) = \frac{PR^4}{64D}\left(1 - \frac{r^2}{R^2}\right) \quad (3)$$

Where D is the material flexural rigidity:

$$D = \frac{Ed^3}{12(1 - v^2)} \quad (4)$$

In this equation, E is Young's modulus, v the Poisson ratio, and d the thickness of the membrane. Combining Equations 2, 3, and 4, the displacement becomes:

$$w(r) = \rho V^2 \frac{(1 - v^2)}{10.67E}\frac{R^4}{d^3}\left(1 - \frac{r^2}{R^2}\right) \quad (5)$$

Then the area-average displacement ΔL can be calculated by:

$$\Delta L = -\frac{1}{\pi R^2}\int_0^R w(r) \cdot 2\pi r\, dr = \frac{(1 - v^2)}{32E}\frac{R^4}{d^3}\rho \cdot V^2 \quad (6)$$

Which establishes the relation between the flow velocity V and the displacement of the membrane ΔL.

To establish the relationship between the displacement ΔL and the frequency shift Δf, notice that when $L > 0$, $f(L)$ is smooth, thus we can use Newton's method:

$$\Delta f = \Delta L \cdot f'(L) \quad (7)$$

Before extending this equation, we want to simplify $f'(L)$. For the reason of maximizing the Quality-factor, the dimension of the cavity should follow:

$$L = 2R \quad (8)$$

Also, for a general gas-filled cavity, $\mu_r = \varepsilon_r = 1$. With those constraints, Equation 1 becomes:

$$f = L^{-1} \cdot \frac{c\sqrt{4{X'_{nm}}^2 + (l\pi)^2}}{2\pi} \quad (9)$$

Given the coupling mode, the polynomial in Equation 9 is constant:

$$\frac{c\sqrt{4{X'_{nm}}^2 + (l\pi)^2}}{2\pi} = A \quad (10)$$

$$f = L^{-1} \cdot A$$

Bring this back to equation (6), the frequency shift becomes:

$$\Delta f = \Delta L \cdot f'(L) = C\frac{(1 - v^2)R^2\rho}{Ed^3}V^2 \quad (11)$$

Where C is solely dependent on the mode of the resonance:

$$C = \frac{c\sqrt{4{X'_{nm}}^2 + (l\pi)^2}}{256\pi} \quad (12)$$

Equation 11 indicates that the frequency shift is a second-order function of the flow velocity. Another interesting finding is that the resonant frequency shifts at different scales (with C being the scaling factor) for different coupling modes. With the frequency shift and flow velocity relation established, next we will explore several smoothing techniques that remove the baseline from the frequency sweep so that the resonant frequency shift can be measured efficiently.

III. Baseline Removal Algorithm Design

The need for baseline removal arises from the practical considerations of characteristics of non-ideal microwave electronic components used to measure the frequency spectrum of the microwave cavity. The waveguides, circulator, and RF cables all contribute to the large attenuation and uneven gain of the frequency sweep, as shown in Fig. 3. In order to overcome this challenge, we will explore three smoothing filters that can remove the baseline while preserving the resonant frequency intact.

A. Moving average filter

For a given half-window length N, the moving average filter can be defined as:

$$y[n] = \frac{1}{2N + 1}\sum_{k=-N}^{N} x[n + k] \quad (13)$$

Here y is the output signal, and x is the input signal. The moving average filter is one of the most basic digital filters available and has the advantage of being sensitive to step responses. This is advantageous for the objective of preserving the sharp dip in the resonant frequency sweep.

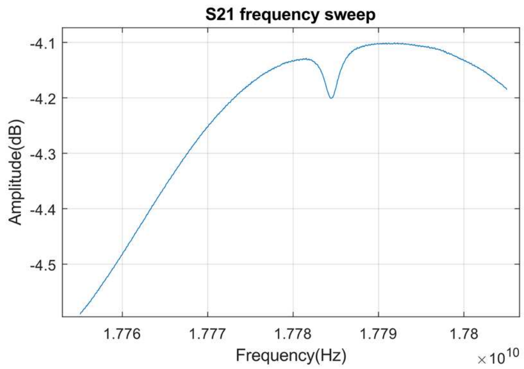

Fig. 3. The uneven baseline is caused by non-ideal microwave components. The sudden dip in the center is the resonance at around f ≈ 17.8GHz. The approximate location of this resonance is found using simulations introduced in the next section.

B. *Gaussian-window filter*

Similar to the moving average filter, the Gaussian-window filter is another windowed filter. However, the difference is that the window is following a Gaussian function:

$$w[k] = \exp\left(\left(-\frac{1}{2}\left(\frac{k}{\sigma N}\right)^2\right)\right), -N \le k \le N \qquad (14)$$

And the filter can be expressed as:

$$y[n] = \frac{1}{2N+1}\sum_{k=-N}^{N} x[n+k]\, w[k] \qquad (15)$$

C. *Savitzky–Golay filter*

Unlike the window filters, Savitzky–Golay filter uses a polynomial function to find the least-squares fit of the target signal. Thus, for a third-order Savitzky–Golay filter we have:

$$y[n] = a_2[n]\cdot n^2 + a_1[n]\cdot n + a_0[n] \qquad (16)$$

Where the polynomial coefficients $a_2[n]$, $a_1[n]$ and $a_0[n]$ minimize the mean squared error at each filter window:

$$MSE = \frac{1}{2N+1}\sum_{k=-N}^{N}(g[k,n] - x[n+k])^2 \qquad (17)$$

$$g[k,n] = a_2[n]\cdot k^2 + a_1[n]\cdot k + a_0[n], -N \le k \le N \qquad (18)$$

Here N is the half-window size of the filter and $g[k,n]$ is the fit polynomial at sample n. In our study, the order of the polynomial and the window size can be adjusted to obtain a good fit at the baseline, while still preserving the fine features around the spectral resonance.

Next, we apply the three smoothing filters to the frequency sweep around a resonant frequency, as shown in the graph in Fig. 3. For the same window size $2N+1 = 101$, the respective filter outputs are shown in Fig. 4. Then, by subtracting the baseline from the original sweep, we can locate the resonance at the trough of the frequency sweep as shown in Fig. 5. Comparing these results, we conclude that using the moving average filter provides the optimal solution for the baseline removal. This is because the moving average filter yields the largest amplitude at the resonance at a given window size, and offers computational simplicity for real-time signal processing.

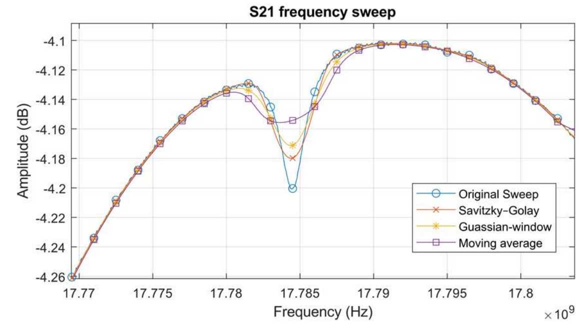

Fig. 4. Smoothing filter outputs for baseline subtraction.

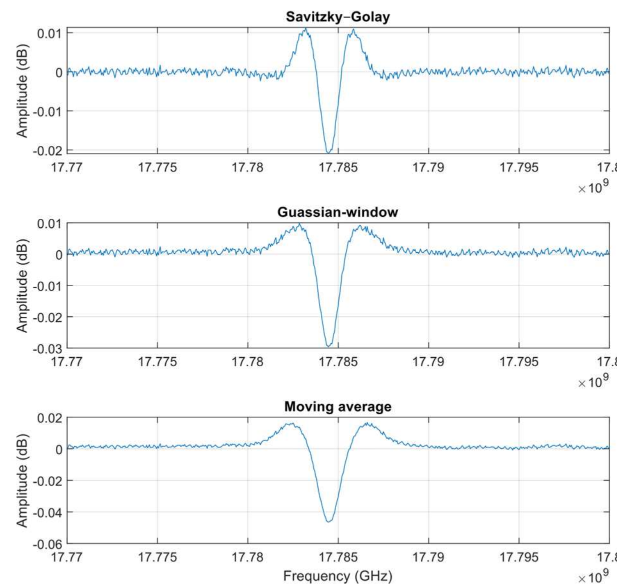

Fig. 5. Frequency sweep after baseline subtraction using the three filters. The resonant frequency locates at the trough of the sweep.

IV. Experimental Results

The first step of measuring the resonant frequency shift is finding the approximate location of the resonant frequency, for the given resonant mode. Due to better Q-factors of low order coupling modes, we choose the TE_{011} mode. To locate the resonant frequency, use the COMSOL Multiphysics® Software to solve the eigenfrequency (resonant frequency) of the microwave cavity. After providing the 3D dimensions of the cavity, the solver gives a series of solutions, from which we can identify the TE_{011} mode using the electric field distribution. Fig. 6 shows the simulation result. The frequency agrees with the value calculated using the expression in Equation (1).

With the knowledge of the approximate location of the resonance, we program a 26.5GHz bandwidth Vector Network Analyzer (VNA) to perform a sweep around the resonance frequency and apply the baseline removal method described in the previous section to accurately locate the spectral resonance. This allows measuring frequency shift, which can be related to the flow velocity according to Equation (11).

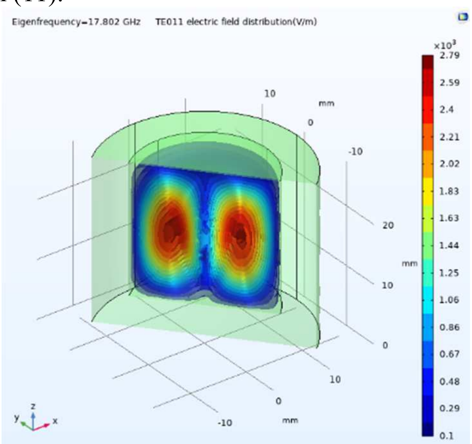

Fig. 6. COMSOL simulation of the microwave cavity resonator. The TE_{011} mode is located at around 17.8GHz frequency

A LabVIEW™ program was designed to control key parameters of the VNA, run the baseline removal algorithm in the back-end, and display the frequency sweep before and after the baseline removal. The user interface of the LabVIEW™ program is shown in Fig. 7. This figure also shows that the actual resonant frequency is 20MHz off from the calculated value, which can be explained by a marginal error of the cavity's dimensions.

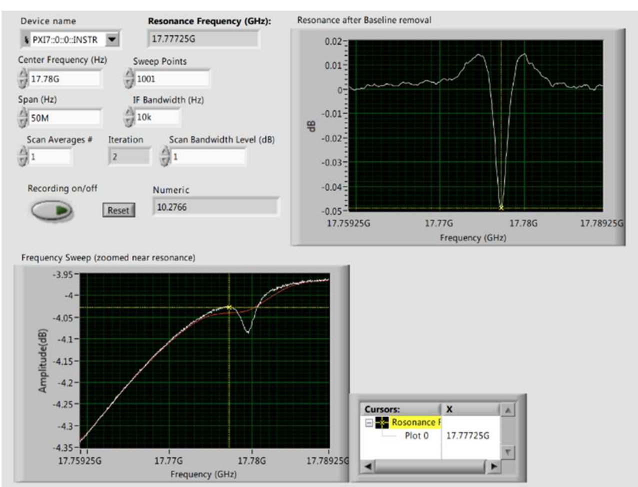

Fig. 7. The LabVIEW user interface. Note that the resonant frequency used here (17.78GHz) is 20MHz off from the simulation result (17.8GHz).

By flowing room temperature water at different velocities, we obtain the plot of frequency shift as a flow velocity, which is shown in Fig. 8. According to this figure, the theory and the experiment result are a close agreement. The standard deviations of Δf vary at different flow velocities because the flow cannot be controlled precisely. On average, we achieved a standard deviation of 0.52MHz. The frequency resolution of measurements in Fig. 7 is 0.5MHz because the frequency sweep of 50MHz bandwidth is sampled with 1001 points. Therefore, we conclude that the standard deviation of measurements is within an acceptable range.

V. Conclusion

In this research, we designed a baseline removal technique for precise measurement of the resonant frequency shift of a microwave cavity flowmeter and improved its flow velocity sensing capability. The experimental results of the graph of frequency shift as a function of flow velocity show a close agreement with the theory, which validates our proposed method. Future work will examine flow sensing at elevated temperatures.

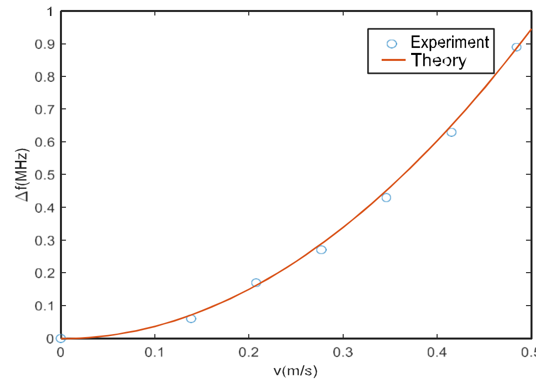

Fig. 8. Flow velocity to frequency shift plots

VI. Acknowledgment

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