Application Note

Characterization Guide of Lens Cover System: LCS-FL-RNG15

ABSTRACT

This document presents the characterization guideline and results for the prototype of a ring piezo-based flat lens cover system (LCS), designated as LCS-FL-RNG15. The LCS, in conjunction with the ULC1001 electrical system, constitutes an ultrasonic lens cleaning (ULC) system.

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Acronyms

- LCS – Lens Cover System
- ULC – Ultrasonic Lens Cleaning
- PZT – Lead Zirconate Titanate

2 Introduction

The Ultrasonic Lens Cleaning (ULC) system is an electro-mechanical design to automatically detect and clean water, ice, or other contaminants from cover lenses in automotive, security, and industrial camera systems. The mechanical portion of the technology is called the Lens Cover System (LCS). Figure 2-1 illustrates the components of a ring piezo-based LCS, which consists of a housing cap, flexible seal, thin film, lens, glue, ring transducer, and housing base. A transducer glued to the lens and the thin film make up the Lens Cover. The Lens Cover is mounted inside a housing (cap + seal + base) to create the LCS.

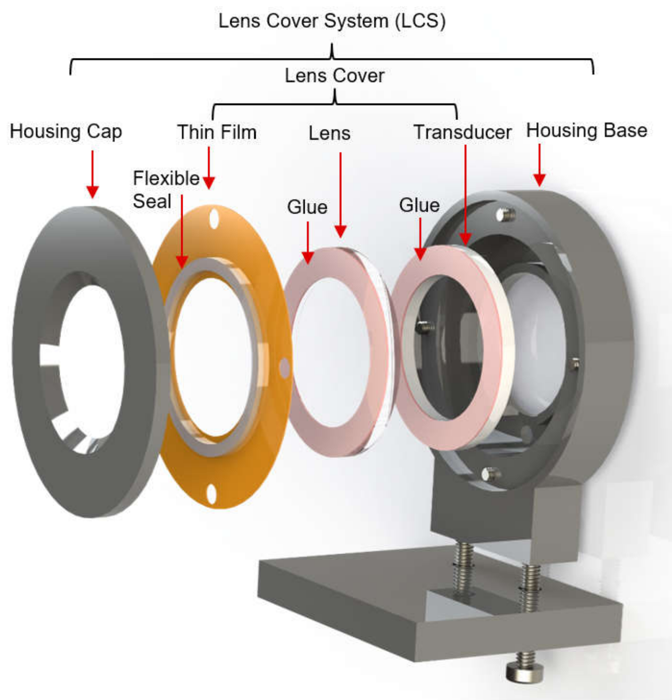

Figure 2-1. Illustration of Flat Lens Cover System (LCS)

TI has designed and prototyped a ring piezo-based LCS: LCS-FL-RNG15. In the document, the tests and characterization results of the prototype are presented to show the performance of the LCS.

> TI has conducted a limited number of characterizations and tests on the LCS-FL-RNG15 prototype. The complete testing and validation requirements must be established by the end customers.

3 Impedance Response

Understanding the impedance response of the piezo component and the associated system is essential for effective utilization of piezo-based loads. It is advisable to measure the impedance response ranging from the individual component to the complete system throughout the critical assembly phases.

The impedance response described in the document is measured by an impedance analyzer (Model: Agilent/HP 4294A). A similar tool can be used.

3.1 Piezo Only

Figure 3-1 plots the impedance response of an individual piezo ring before any gluing. There are two main resonant frequencies within the plotted frequency range. The first one at 59.4kHz is the radial mode of the piezo while the second one at 570kHz is the thickness mode. Mode 59.4kHz is mainly used for water cleaning; the high frequency mode at 570kHz, which has much lower impedance, is favorable for heating and therefore more suitable for de-icing.

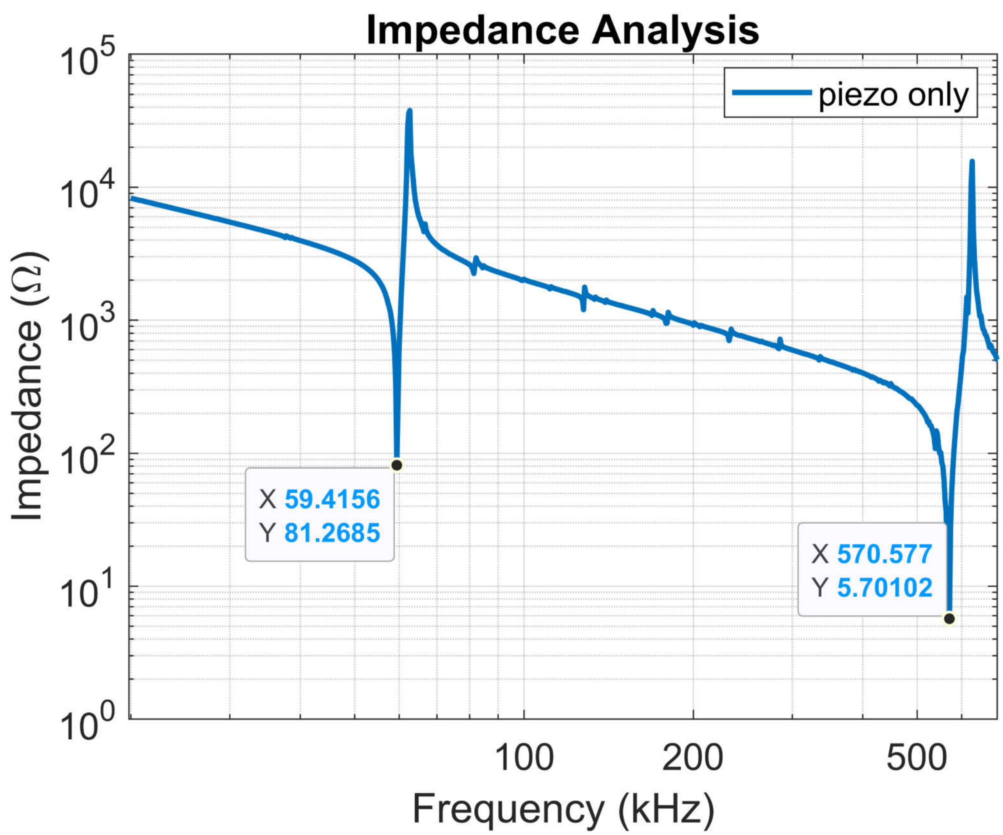

Figure 3-1. Impedance Response of Piezo Only

The rated voltage of the piezo shall be defined by the peizo vendor. Our test shows that the piezo is possibly damaged when the Vp > 20V. When glued to a lens, the piezo can handle much higher voltage (~100V). Figure 3-2 shows the impedance response of a damaged piezo versus a healthy piezo for the radial mode. A damaged piezo shows a much higher impedance with additional noisy resonant peaks.

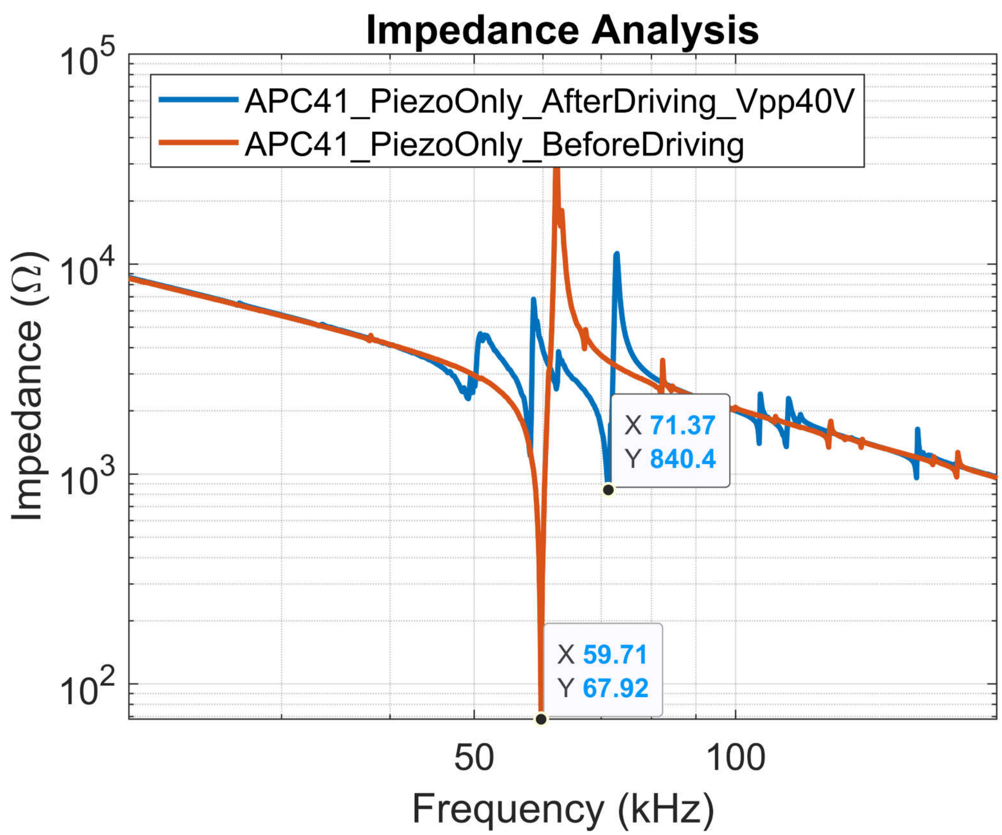

Figure 3-2. Damaged Piezo After Overdrive

3.2 Lens Cover

The main elements of the lens cover include the lens, transducer, and the thin film. This subsystem is vital to the overall functionality of the LCS. Measuring the impedance response of the lens cover represents an important intermediate step between the piezo and the final LCS. This measurement is essential for understanding the variations in resonant frequency and impedance that occur once the piezo is adhered to the lens/film.

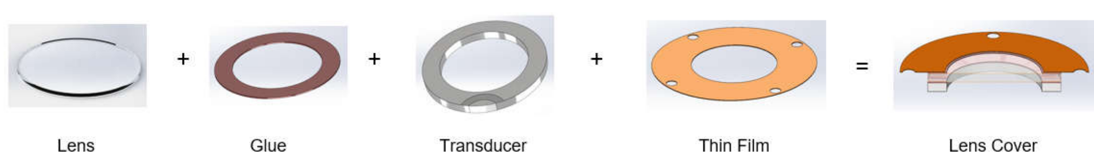

Figure 3-3. Lens Cover = Lens + Glue + Transducer + Thin Film

Figure 3-4 shows the impedance response of the lens cover. Two resonant frequencies are obtained within the 20kHz to 100kHz range. The mode at 65.8kHz has a much lower impedance of 226.7Ω, which can draw higher current for a given voltage compared to the mode at 29.9kHz, and therefore possibly a higher acceleration level to expel water. Note that the frequency of 65.8kHz is a few kHz away from the resonant frequency of the piezo alone. This deviation is reasonable, considering the significant alteration in boundary conditions that occurs once the piezo is adhered to a lens.

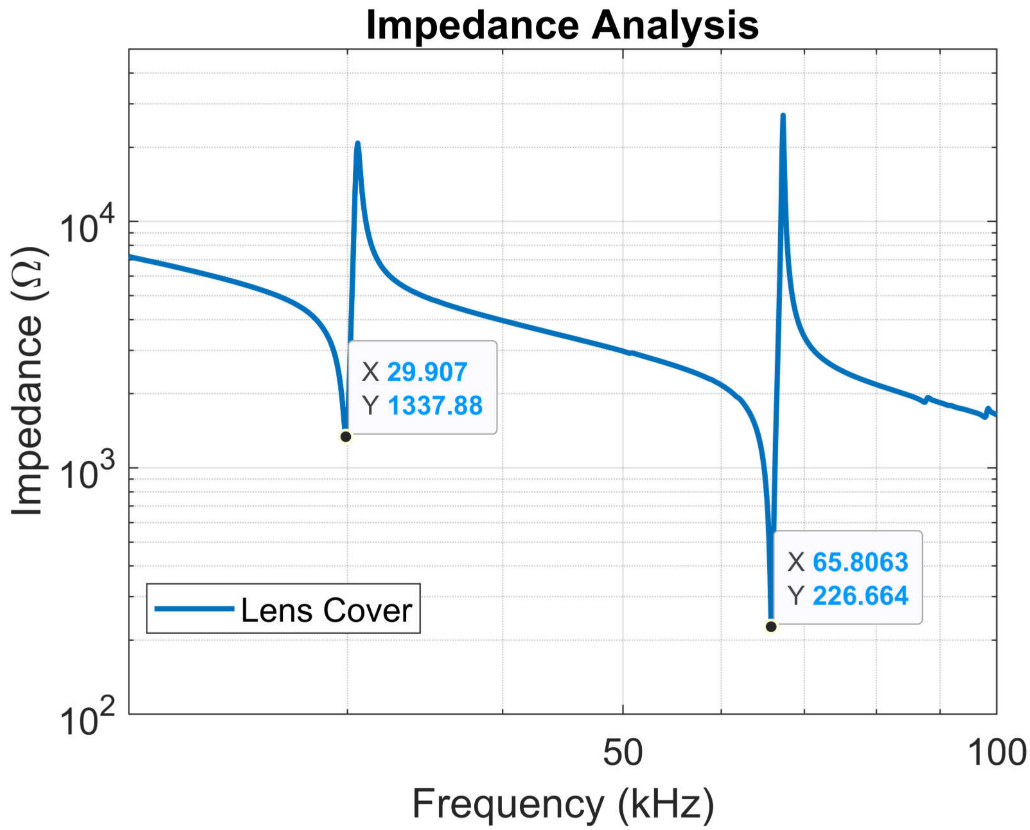

Figure 3-4. Impedance Response of Lens Cover

3.3 Lens Cover System (LCS)

Once the lens cover is properly positioned within the housing, this constitutes the final lens control system (LCS). The housing contributes additional damping, which can result in an increase in the impedance of the lens cover. Make sure to regulate the induced damping from the housing to the smallest extent possible.

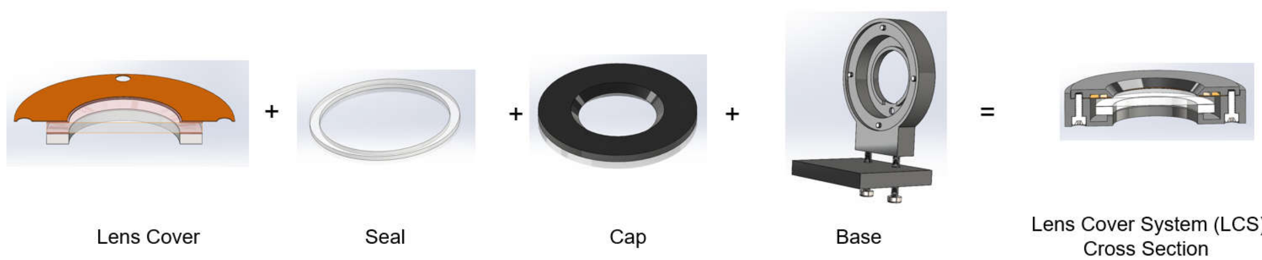

Figure 3-5. Flat Lens LCS (LCS): Lens Cover + Cap + Seal + Base

Figure 3-6 shows the impedance response of the LCS. Compared to the Lens Cover, the resonant frequency of the 65.8kHz changes to 66.2kHz, which is relatively minimal. The impedance increases significantly from 226.7Ω to 337.6Ω.

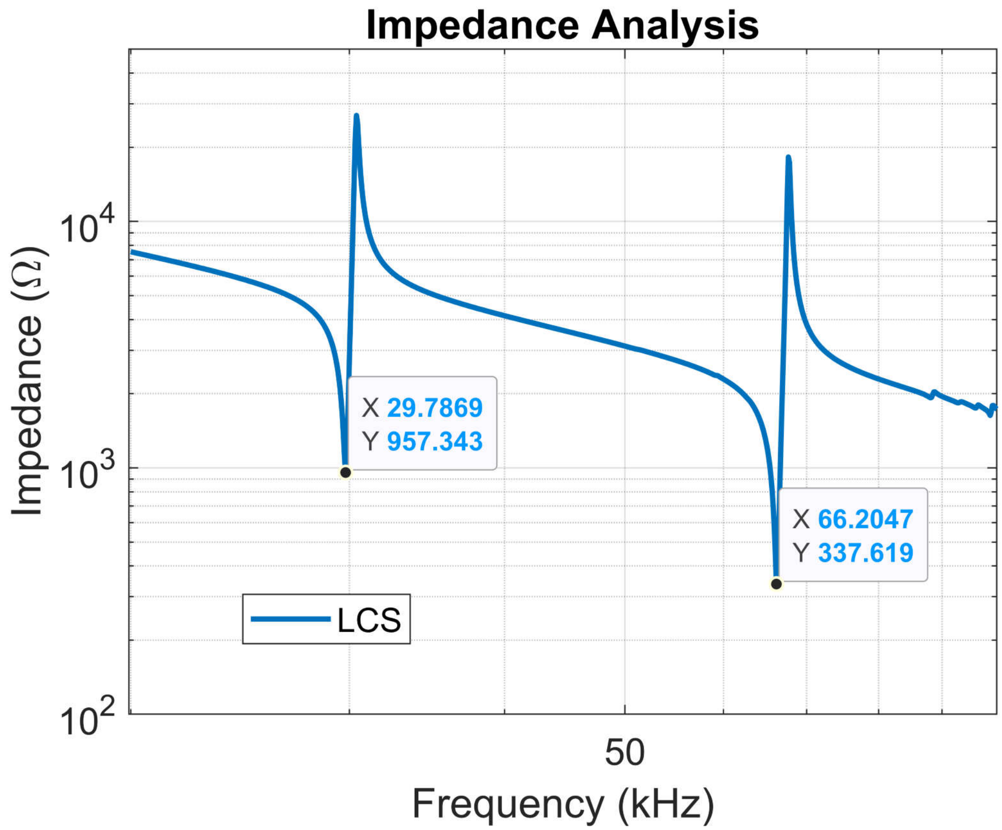

Figure 3-6. Impedance Response of LCS

4 Equivalent Circuit Model of LCS

Understanding a piezoelectric device equivalent circuit is crucial for analyzing and designing systems because this simplifies the complex electromechanical interactions into a manageable electrical model, enabling prediction and optimization of performance. There are multiple models to simulate the behaviors of the piezo and here we provide an example. In the example, the LCS consists of a bulk resistor and a bulk capacitor, along with several LRC networks, all connected in series, as shown in Figure 4-1. Each RLC portion represents the mechanical properties, such as mass (L), compliance (C), and mechanical damping (R), while the serial bulk capacitor and resistor represent the electrical capacitance and resistance of the device electrodes.

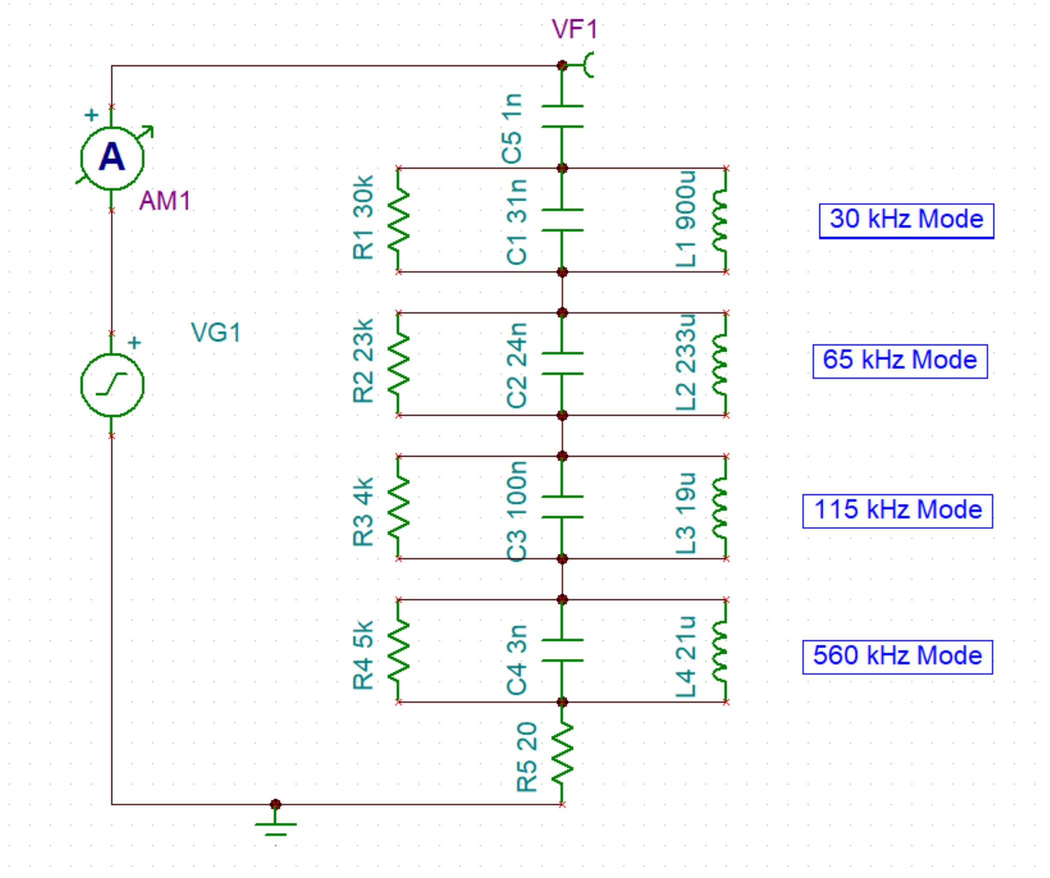

Figure 4-1. Equivalent Circuit Model of LCS

Table 4-1. LCS Electrical Model Parameters

Parameters	Unit	Value	Descriptions
R1	kΩ	30	R component for 30kHz mode
R2	kΩ	23	R component for 65kHz mode
R3	kΩ	4	R component for 115kHz mode
R4	kΩ	5	R component for 560kHz mode
R5	kΩ	20e-3	Bulk resistance
C1	nF	31	C component for 30kHz mode
C2	nF	24	C component for 65kHz mode
C3	nF	100	C component for 115kHz mode
C4	nF	3	C component for 560kHz mode
C5	nF	51	Bulk capacitance
L1	uH	900	L component for 30kHz mode
L2	uH	233	L component for 65kHz mode

Table 4-1. LCS Electrical Model Parameters (continued)

Parameters	Unit	Value	Descriptions
L3	uH	319	L component for 115kHz mode
L4	uH	21	L component for 560kHz mode

Figure 4-2 illustrates the impedance response comparing the lab data with simulation data from the model. The lab results align closely with the simulation model, given the passive component values used in the table.

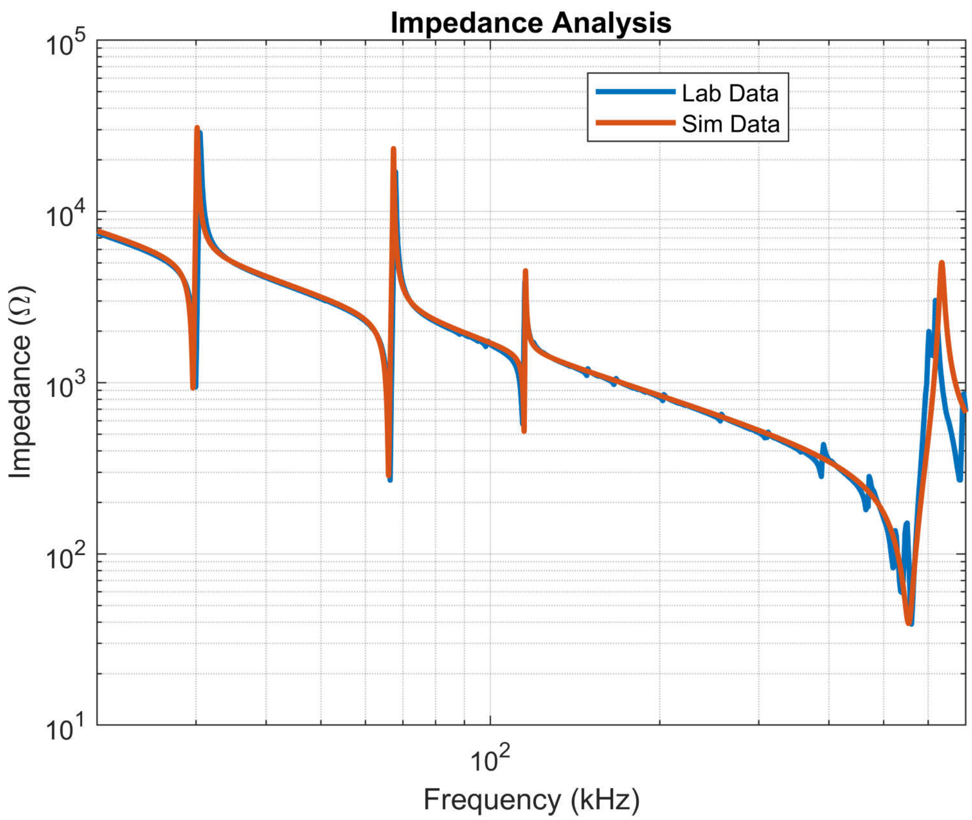

Figure 4-2. Impedance Response of LCS: Lab versus Sim

5 LC Filter for LCS

The LCS-FL-RNG15 requires a voltage as high as 140Vpp to expel water efficiently. However, the maximum voltage output for DRV2911 is limited to 35V, necessitating a voltage gain of 4x to meet the voltage requirement. To achieve this goal, a simple LC filter has been designed and implemented. A passive LC filter can exhibit voltage gain near the resonant frequency, allowing the voltage across the inductor or capacitor to exceed the initial input voltage. This phenomenon is due to the energy stored in the inductor and capacitor oscillates back and forth, causing the voltage across the components to become much larger than the input voltage. Note that, despite this increase in voltage, a power gain cannot be achieved.

The amount of voltage gain at the resonant peak is primarily determined by the quality factor (Q) of the circuit. A higher Q results in a sharper peak and a greater voltage gain. Remember the power output is still limited by the power input. An increase in voltage is accompanied by a decrease in current.

The gain is maximized at the resonant frequency of the LC circuit, which is calculated using the formula:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

For a series RLC circuit,

$$Q = \frac{1}{2\pi f_0 CR} \quad (2)$$

Theoretically, the quality factor can be infinitely high. In reality, parasitic resistances and capacitances limit the maximum achievable Q and thus the maximum voltage gain. To reduce the gain, the resonant frequency of the LC filter can be a certain distance from the resonant frequency of the load. The further of the two resonances, the smaller of voltage gain is applied to the load.

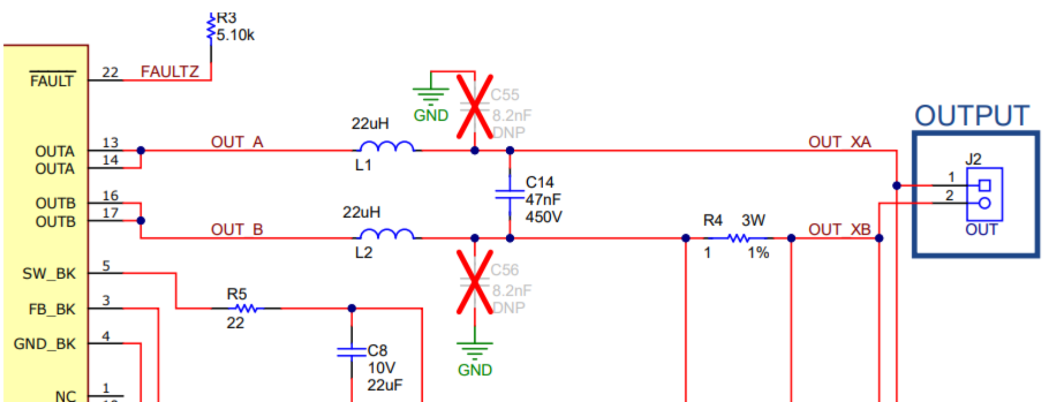

Figure 5-1. The Default LC Filter for LCS-FL-RNG15 in ULC1001-DRV2911EVM

In ULC1001-DRV2911EVM, the LC is set at L= 22uH, and C = 47nF, yielding a calculated cut off resonant frequency of 110 kHz. The resonant frequency of the LCS-FL-RNG15 is 66 kHz. The frequency distance yields a gain of 4.

Figure 5-2 shows the measured impedance response of the LCS with the default LC filter. The measured resonant frequency of the LC filter is 112.7kHz with a low resistance of 0.94Ω. The impedances of the two modes at 30kHz and 66kHz are also significantly lowered when measuring the impedance the LCS and the LC filter as a whole.

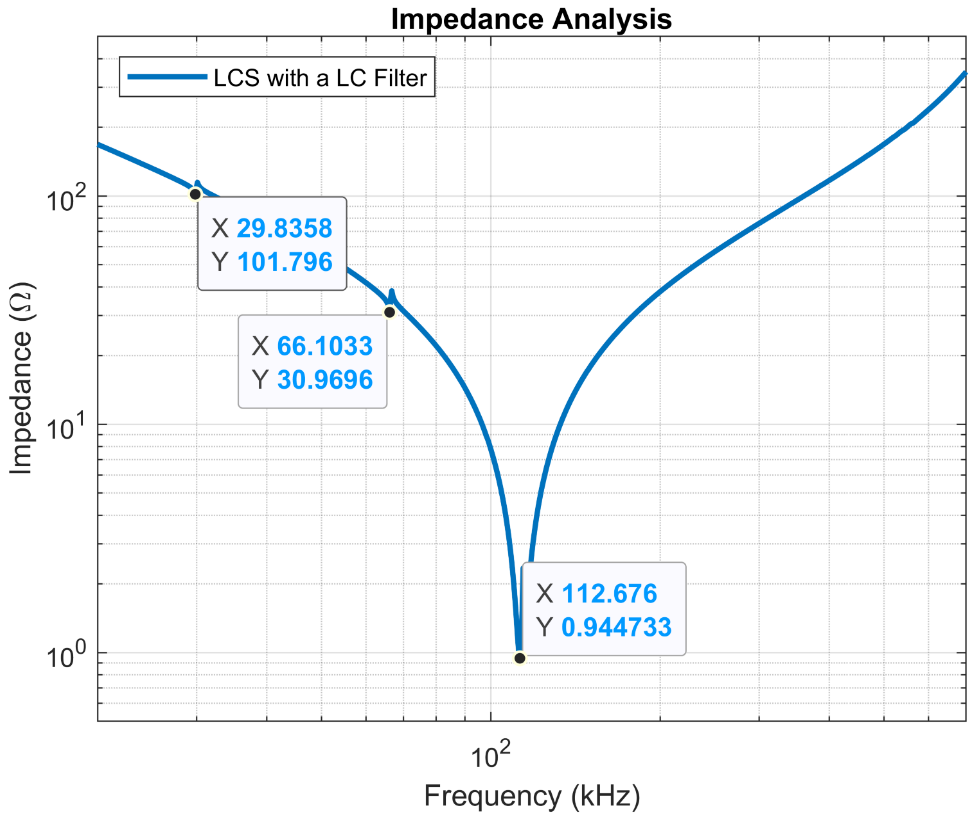

Figure 5-2. Impedance Response of LCS with an LC Filter

6 Water Cleaning

Figure 6-1 shows the GUI setting (GUI version: ULC1001 2.4.10) for the LCS. For more info about the ULC1001 GUI, please refer to the tutorial video on ti.com.

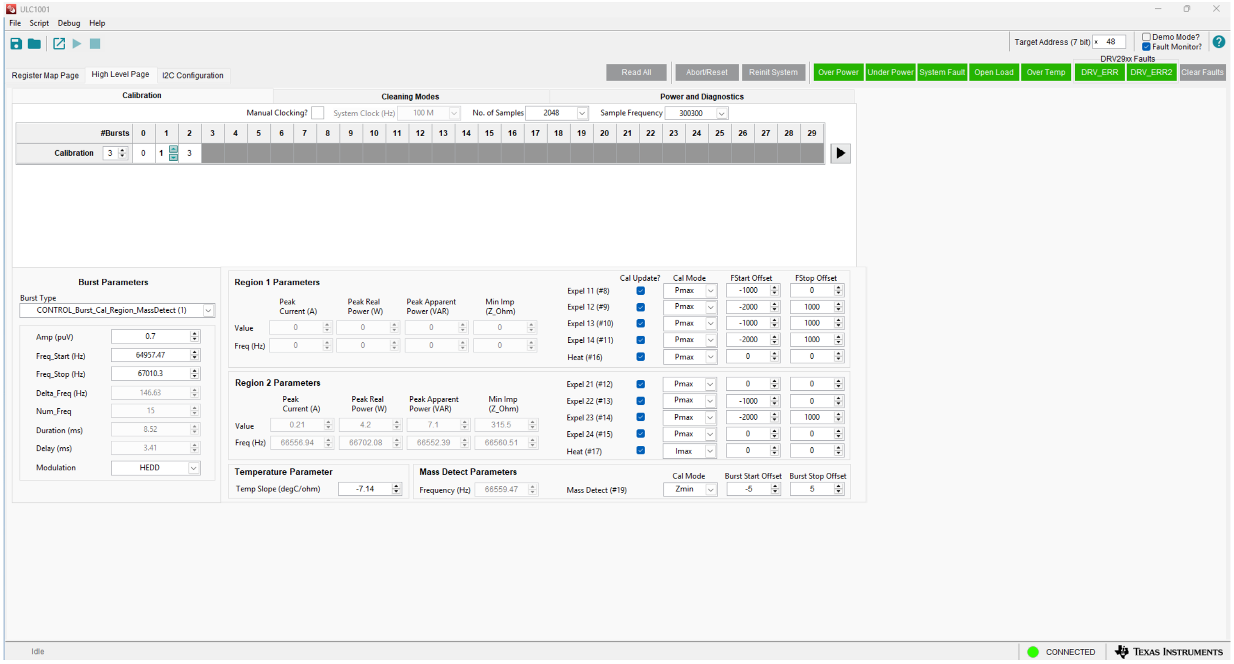

Figure 6-1. GUI Setting: Calibrated Result

Figure 6-2 shows the GUI settings for water mode.

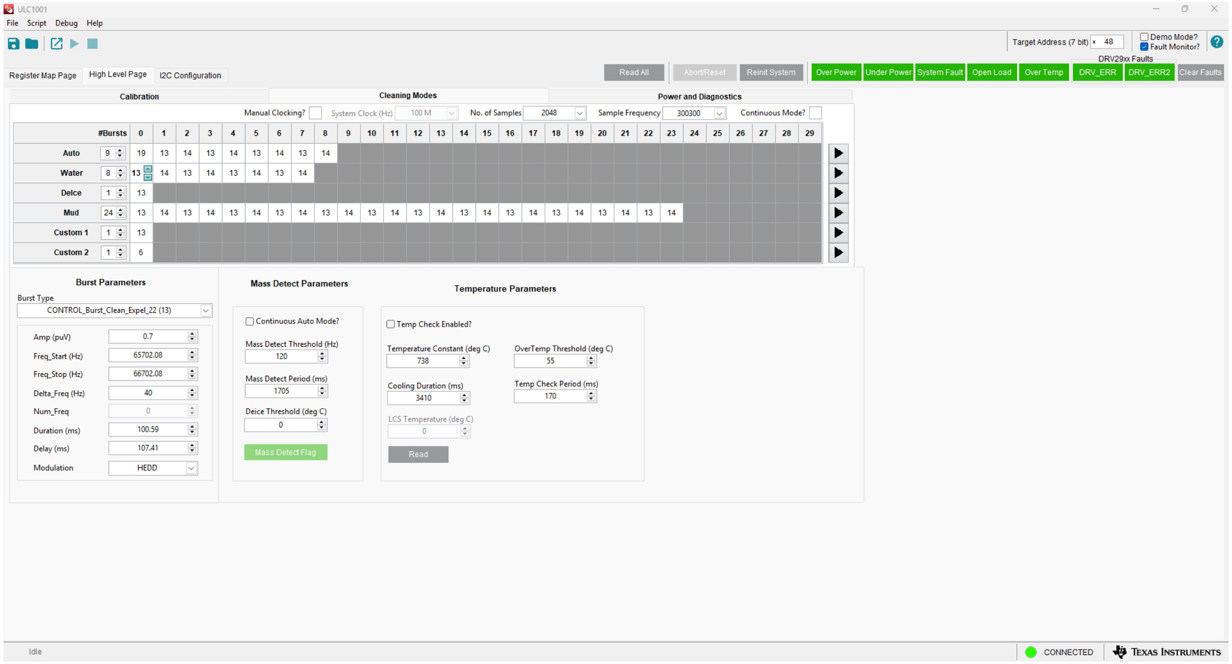

Figure 6-2. GUI Setting: Water Mode for Cleaning

Figure 6-3 illustrates the water cleaning performance observed in the water mode operation. It is evident that the majority of water droplets have been expelled; however, fine mist remain along the edge of the lens (dissipate quickly in typical applications). This phenomenon is typical, as the acceleration is maximized at the center of the lens and diminishes to zero at the outer edges.

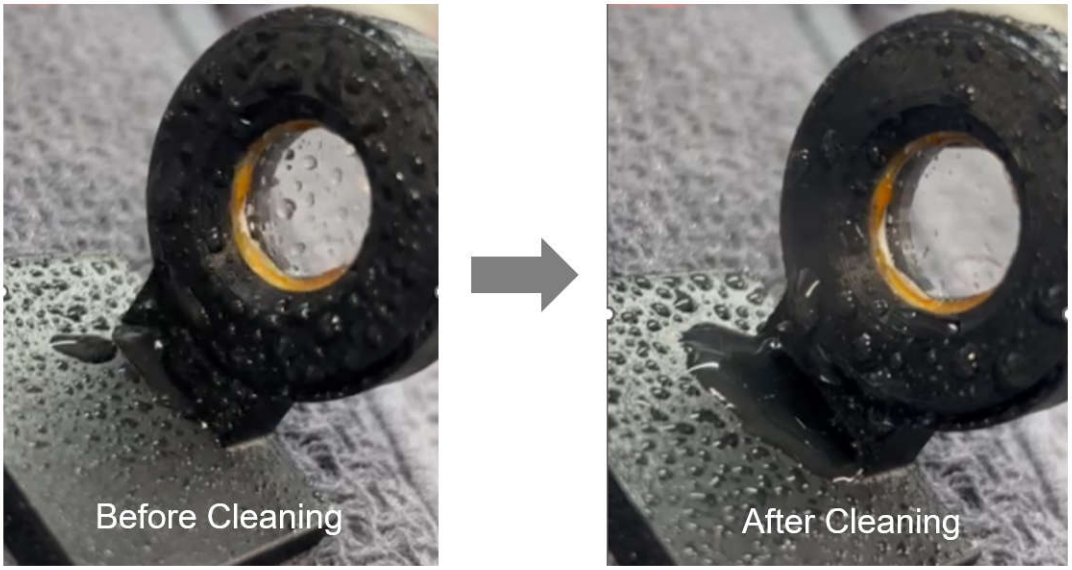

Figure 6-3. Water Cleaning Result: Before Cleaning versus After Cleaning

7 Power Consumption

Figure 7-1 shows the setup with the ULC1001-DRV2911EVM to measure the power consumption. A voltage probe and a current probe are used to measure the voltage and current across the LCS. The current from the power supply is also recorded. For details on how to use ULC1001-DRV2911EVM, please refer to the ULC1001-DRV2911EVM User Guide.

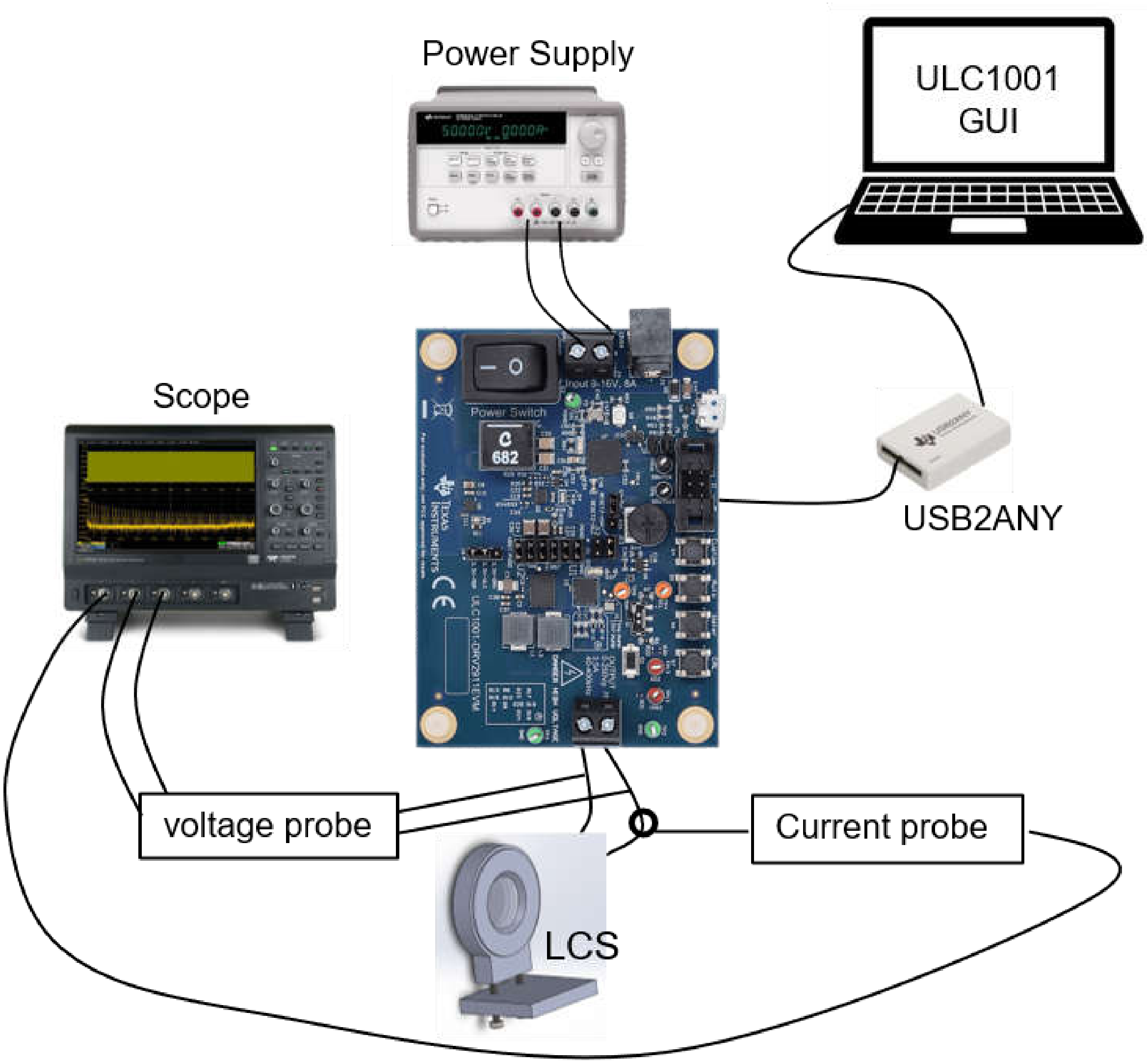

Figure 7-1. The Measurement Setup with ULC1001-DRV2911EVM

Figure 7-2 shows the voltage and current across the LCS near f_1 (30kHz) and f_2 (66 kHz). The peak voltage is 140V and the peak current is 0.4A. Note that the voltage and current across the LCS have a phase difference. The peak power of LCS can be easily estimated by the current from the power supply.

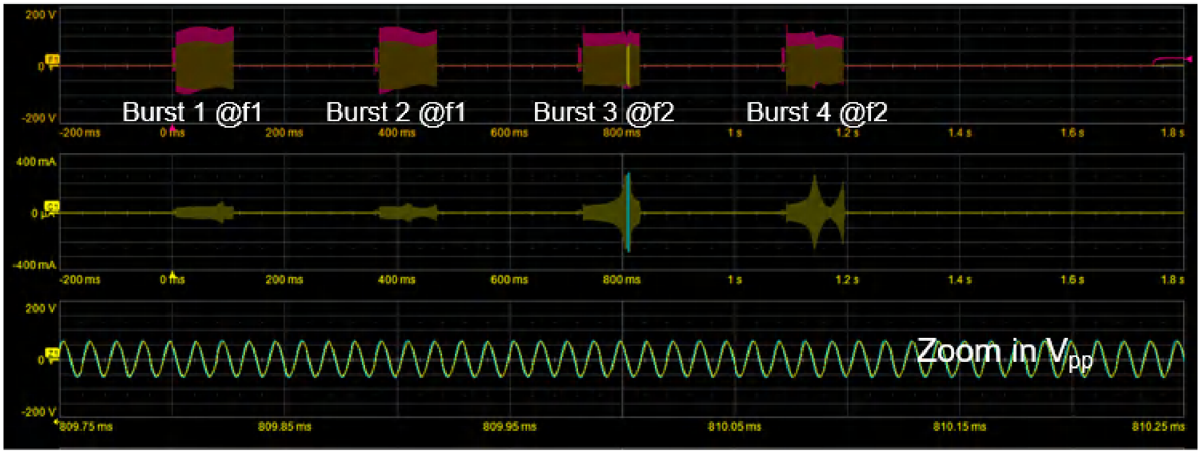

Figure 7-2. Power Consumption of LCS during Water Mode

Table 7-1 shows the electrical characteristics of the LCS.

Table 7-1. Electrical Characteristics of LCS

Parameters	Value	Unit	Description
Vp	70	V	Peak voltage across the LCS
Ip	0.5	A	Peak current across the LCS
Vd	12	V	DC voltage of power supply
Id	0.35	A	DC peak current of power supply
P	4.2	W	Peak power

8 Reliability

High reliability is critical for the vibrating device. We have run a 1 million-cycle test, which can be achieved simply by enabling the Continuous Mode in the ULC1001GUI. Each cycle is defined by running water mode burst 13 and burst 14 once. Each burst consists of a 100ms duration and a 200ms delay (can be adjusted). It takes around 600ms to run a cycle and 6.95 days to run 1 million cycles.

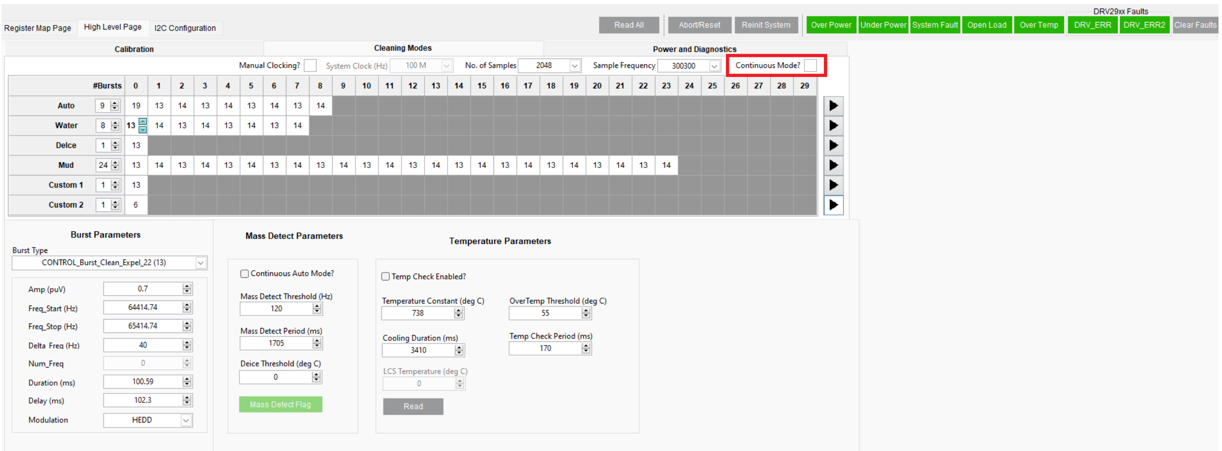

Figure 8-1. GUI Setting: Continuous Mode

Figure 8-2 illustrates the impedance response of the LCS both prior to and following the long-term test. After the completion of the long-term test, the LCS demonstrated minimal changes in impedance, maintaining effective water cleaning capabilities. This outcome underscores the high reliability of the system.

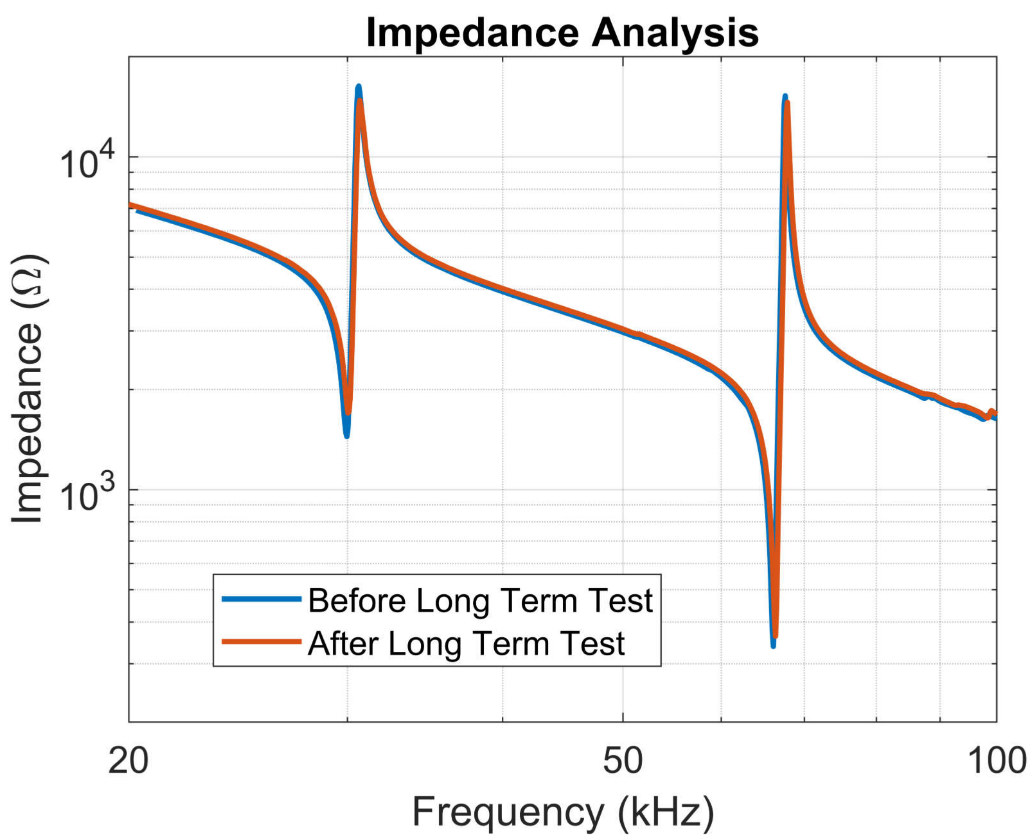

Figure 8-2. The Impedance of LCS before and after Long term test

9 Other Tests

9.1 De-ice

De-icing requires a greater amount of power compared to water cleaning. In the design of the LCS, the mode operating at 560kHz exhibits a significantly lower impedance relative to the mode at 65kHz, making it more advantageous for generating heat and facilitating de-icing. To effectively implement the de-icing mode with the ULC1001-DRV2911EVM, it is necessary to eliminate the LC low-pass filter, as the voltage attenuation is considerably high at 560kHz.

In light of the required de-icing speed, it may be necessary to incorporate a separate heating element to achieve optimal de-icing efficiency. This recommendation arises from the relatively limited heating efficiency of piezo materials compared to other specifically designated heating alternatives.

9.2 Mud Cleaning

The prototype currently has limited capability effectively cleaning mud and dust, particularly when faced with heavy or sticky contaminants. For good results in these conditions, use the water jet alongside the LCS for better mud and dust cleaning performance. Alternatively, collaborating with TI hardware partners can provide more robust LCS designs tailored for tackling mud and dust issues.

9.3 Optical Interference

Our hardware partners have demonstrated that the flat lens cover has a negligible effect on the camera imaging quality. However, note that Texas Instruments has yet to perform any separate tests.

9.4 Waterproof Capability

Texas Instruments has not done any tests on the waterproof capability of the prototype.

10 Resources

1. Texas Instruments, *What Is Ultrasonic Lens Cleaning Technology?*.
2. Texas Instruments, *Ultrasonic Lens Cleaning: a Solid-state Technology You Didn't Know You Needed*.
3. Texas Instruments, *ULC1001-Q1 Configurable Ultrasonic PWM Driver With I/V Sense Amplifiers.*
4. Texas Instruments, *ULC1001-DRV2911EVM User Guide*.