Application Note

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

ABSTRACT

This document presents the simulation guidelines 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

1 Acronyms

- LCS – Lens Cover System
- ULC – Ultrasonic Lens Cleaning
- PZT – Lead Zirconate Titanate
- FEA – Finite Element Analysis

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 the 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 makes up the Lens Cover. The Lens Cover is mounted inside a housing (cap + seal+ base) to create the LCS. Figure 2-2 presents the cross-section view of the LCS.

Simulating the LCS-FL-RNG15, with its various components, can be quite complex. A more manageable approach is to first simulate each individual component, and then bring everything together to model the final system.

For detailed drawing and dimensions of each component, please refer to Design, Fabrication, and Assembly Guide of Lens Cover System: LCS-FL-RNG15.

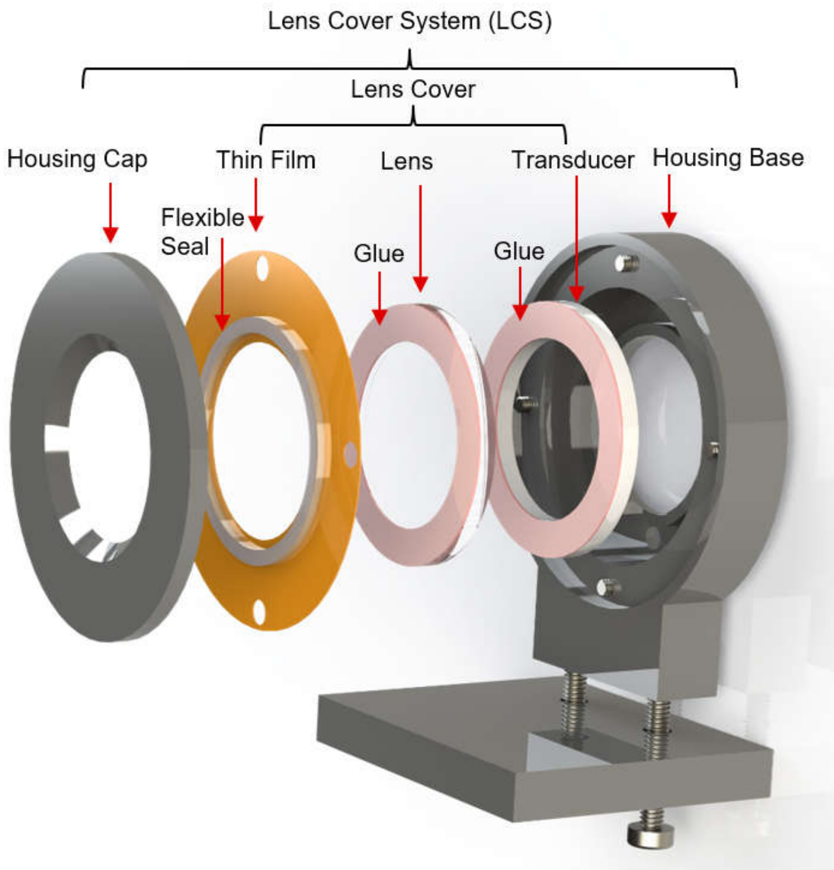

Figure 2-1. Illustration of Flat Lens Cover System (LCS)

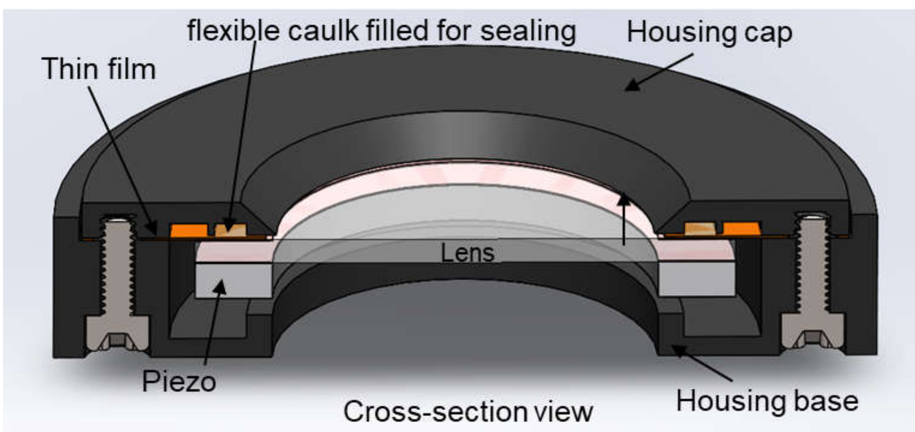

Figure 2-2. The Cross-Section View of the LCS

3 Simulation Environment

TI utilizes COMSOL Multiphysics 6.0 for its simulation processes, but similar tools like Ansys are also effective. Furthermore, TI incorporates COMSOL Livelink for MATLAB to take advantage of MATLAB scripts for performing sweeps and optimizations.

To run simulations for the LCS, the following modules are needed:

- COMSOL Multiphysics
- MEMS Module
- Acoustics Module

2D axisymmetric simulation

In COMSOL Multiphysics, 2D axisymmetric simulations utilize the radial (r) and vertical (z) directions, allowing for the modeling of geometries with rotational symmetry. This approach significantly reduces computational time and resources compared to 3D simulations, as this only requires modeling a cross-section of the geometry.

Given that LCS exhibits axisymmetry, we can take advantage of 2D axisymmetric simulations to optimize our computational resources. To simulate a rectangular lens system for Lidar applications, a 3D simulation must be used due to its non-axisymmetric nature. Figure 3-1 shows all the possible space dimensions. 2D Axisymmetric is selected for each component and the final LCS.

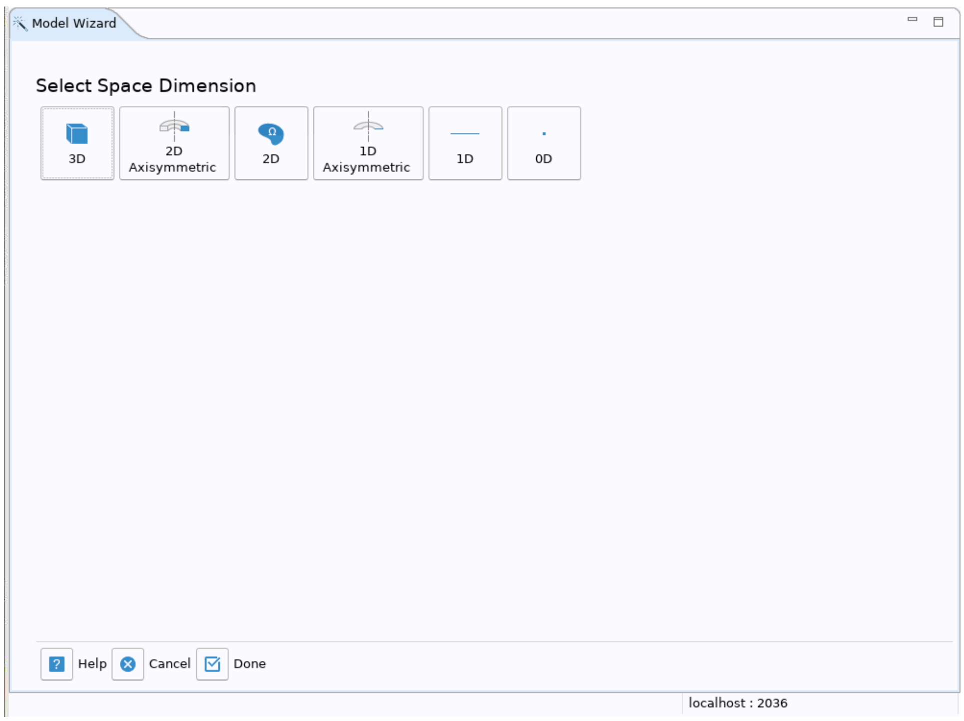

Figure 3-1. All Space Dimensions in COMSOL

Figure 3-2 shows the physics to select for the simulation. Solid Mechanics is required for all components, such as Lens, Piezo, Lens Cover, etc. Piezoelectricity is required when a piezo material is included. The Electrical Circuit is optional for LC filter simulation purposes.

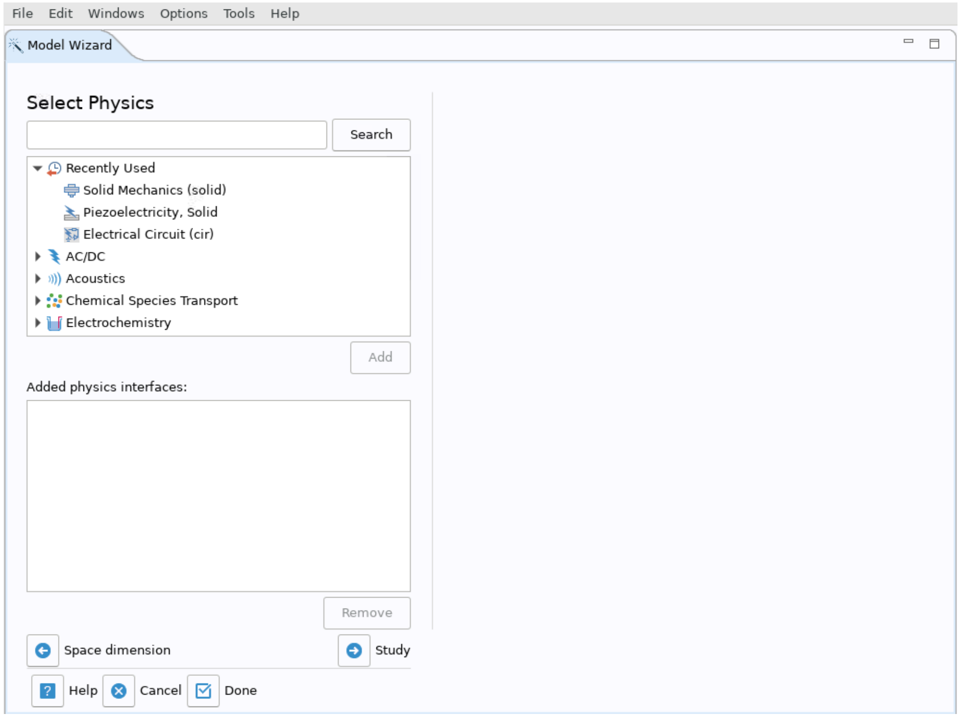

Figure 3-2. Select the Physics

4 Simulation of Lens

Table 4-1 lists the dimensions of lens.

Table 4-1. Lens Dimensions

Parameters	Unit	Value
Diameter	mm	21
Thickness	mm	1

TI uses CDGM HK9LGT® as the lens material in the LCS-FL-RNG15. The material properties can be found in the Table 4-1.

Table 4-2. Mechanical Properties of Lens

Parameter	Unit	Value
Young's Modulus	GPa	79.2
Density	kg/m^3	2520
Poisson's Ratio	1	0.211

Figure 4-1 shows the lens geometry in a 2D axisymmetric view.

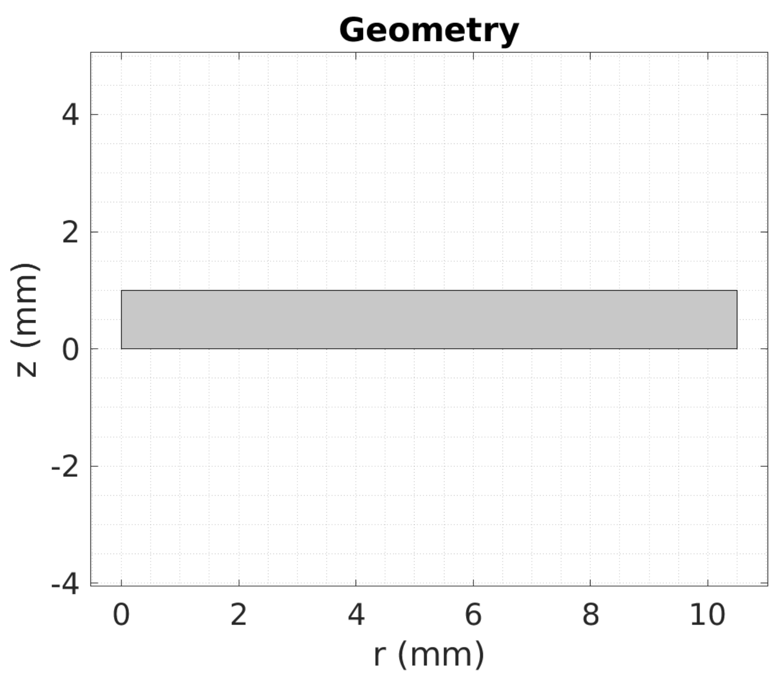

Figure 4-1. Lens Geometry

To simulate a lens, the boundary condition is set as Free. The eigenfrequencies are obtained by running the eigenfrequency study. The result is shown in Table 4-1.

Table 4-3. Eigenfrequencies of Lens

Mode	(0 1)	(0 2)	(0 3)	(0 4)	(0 5)
Frequency (kHz)	20.7	86.7	187.7	312.2	453.9

Figure 4-2 shows the mode shapes of the lens. Red signifies high acceleration while blue indicates low acceleration. In the design, modes (0, 1) and (0, 2) are utilized for effective cleaning since they have fewer nodal circles or dead spots. Also, the modes have lower resonant frequencies and therefore require smaller critical acceleration.

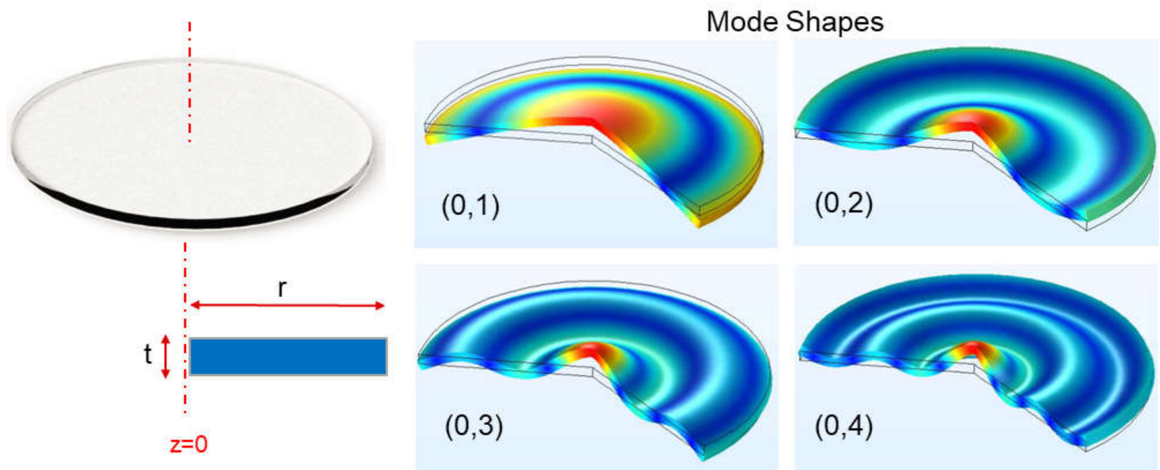

Figure 4-2. Mode Shapes of Lens

5 Simulation of Piezo Transducer

The dimensions of the piezo used in the LCS are listed in Table 5-1.

Table 5-1. Piezo Dimensions

Paramters	Unit	Value
Inner Diameter	mm	15
Outer Diameter	mm	21
Thickness	mm	1.5

PZT8 is used in the LCS and its material properties are listed in Table 5-2. Other common piezo materials and their material properties are also listed in the table.

Table 5-2. Materials Properties of the PZT8 in the Simulation

Symbol	Description	Unit	Navy Type VI (PZT 5H)	Navy type I (PZT 4)	Navy Type II (PZT 5A)	Navy Type III (PZT 8)
$e_{1,}r^{X}$	Relative permittivity	1	3244.97	1193.04	1795.99	1219.69
$e_{3,}r^{X}$	Relative permittivity	1	3984.62	1325.63	1802.77	989.52
tan d (3^{X})	dielectric dissipation factor	1	0.016	0.003	0.017	0.004
d_{31}	piezoelectric charge constant	C/N	-2.59e-10	-1.28e-10	-1.70e-10	-1.14e-10
d_{33}	piezoelectric charge constant	C/N	6.4e-10	3.28e-10	4.25e-10	2.75e-10
d_{15}	piezoelectric charge constant	C/N	6.16e-10	3.27e-10	5.06e-10	4.03e-10
$Q_{m,t}$	mechanical quality factor	1	59	373	74	1088
p	density	kg/m3	7780	7700	7700	7700
s_{11^e}	compliance matrix	m^2/N	1.82e-11	1.30e-11	1.7e-11	1.26e-11
s_{12^e}	compliance matrix	m^2/N	-7.76e-12	-4.35e-12	-6.6e-12	-3.71e-12
s_{13^e}	compliance matrix	m^2/N	-6.85e-12	-7.05e-12	-8.61e-12	-6.6e-12
$s_{33}{}^{e}$	compliance matrix	m^2/N	1.8e-11	1.96e-11	2.32e-11	1.83e-11
$s_{44}{}^{e}, s_{55}{}^{e}$	compliance matrix	m^2/N	3.8e-11	3.32e-11	4.35e-11	3.77e-11
$s_{66}{}^{e}$	compliance matrix	m^2/N	5.2e-11	3.47e-11	4.71e-11	3.26e-11

The transducer is a ring shape and is poled in the top/bottom direction. Figure 5-1 shows the geometry drawing in COMSOL.

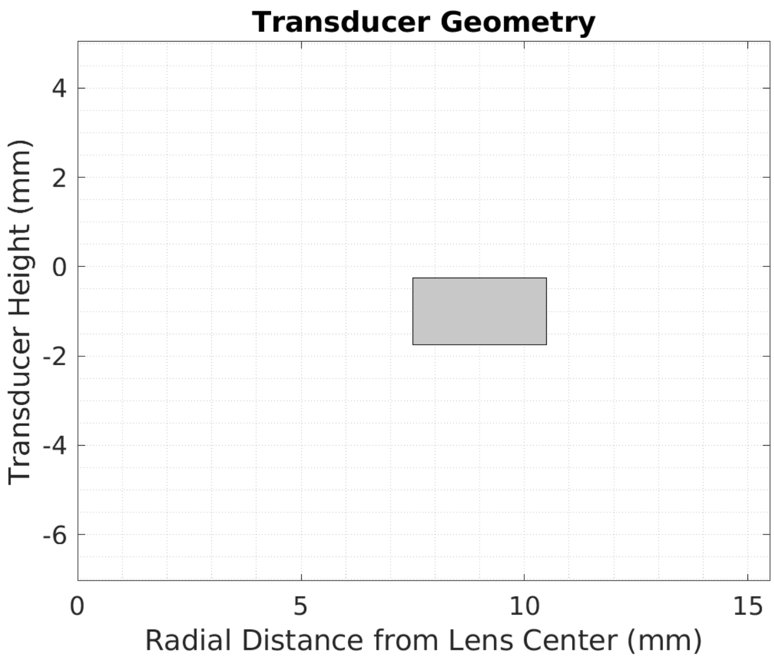

Figure 5-1. Transducer Geometry in COMSOL

Figure 5-2 shows the coordinate system selection, where the Material XZ-plane System is selected.

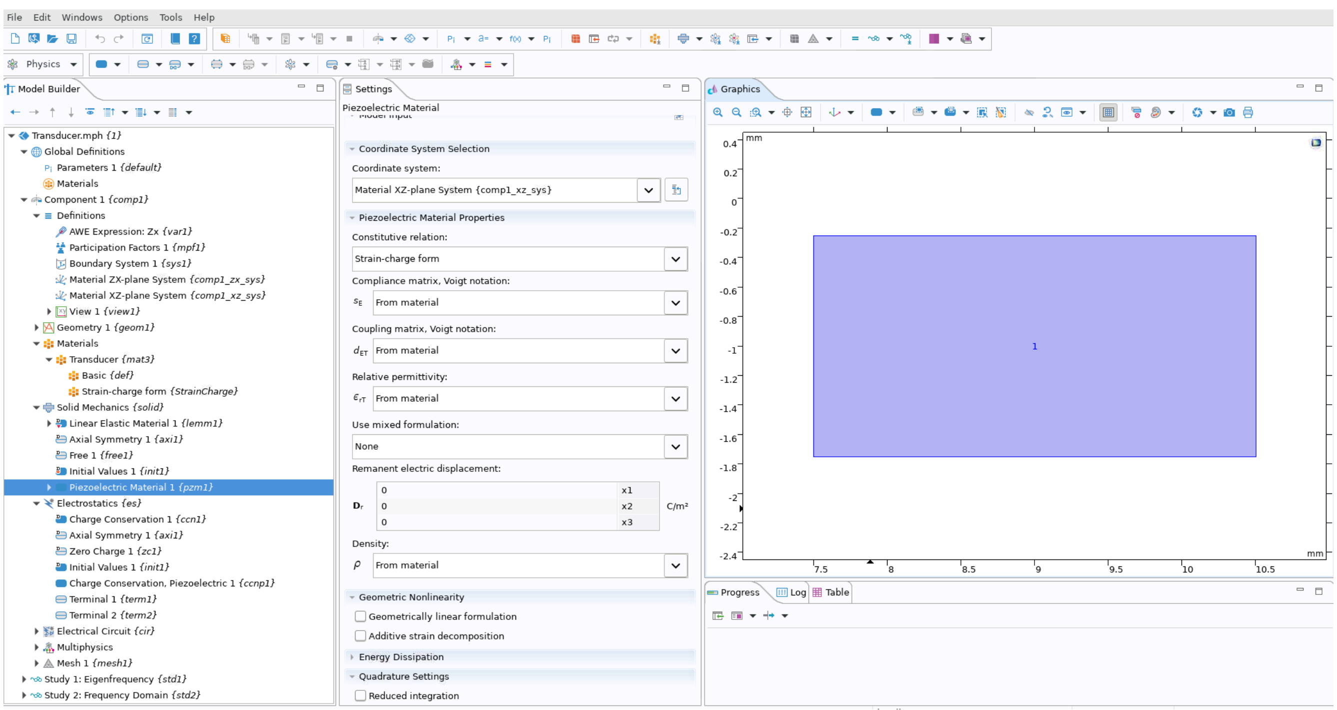

Figure 5-2. Piezo: Coordinate System Selection

Properly setting the damping is crucial in mechanical modeling. Two types of damping are incorporated: mechanical damping and dielectric loss. The damping factor is calculated automatically based on the material properties. Figure 5-3 and Figure 5-4 show the damping settings of the piezo in the COMSOL.

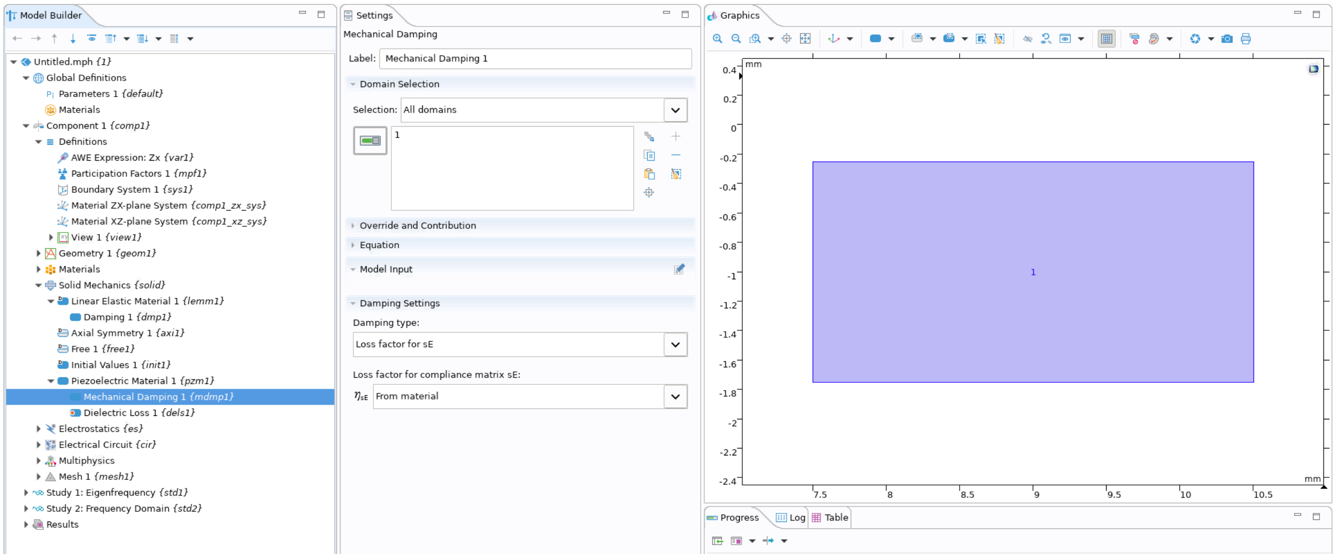

Figure 5-3. Piezo: Mechanical Damping

The loss factor related to electrical permittivity is calculated automatically based on the properties of the piezo material.

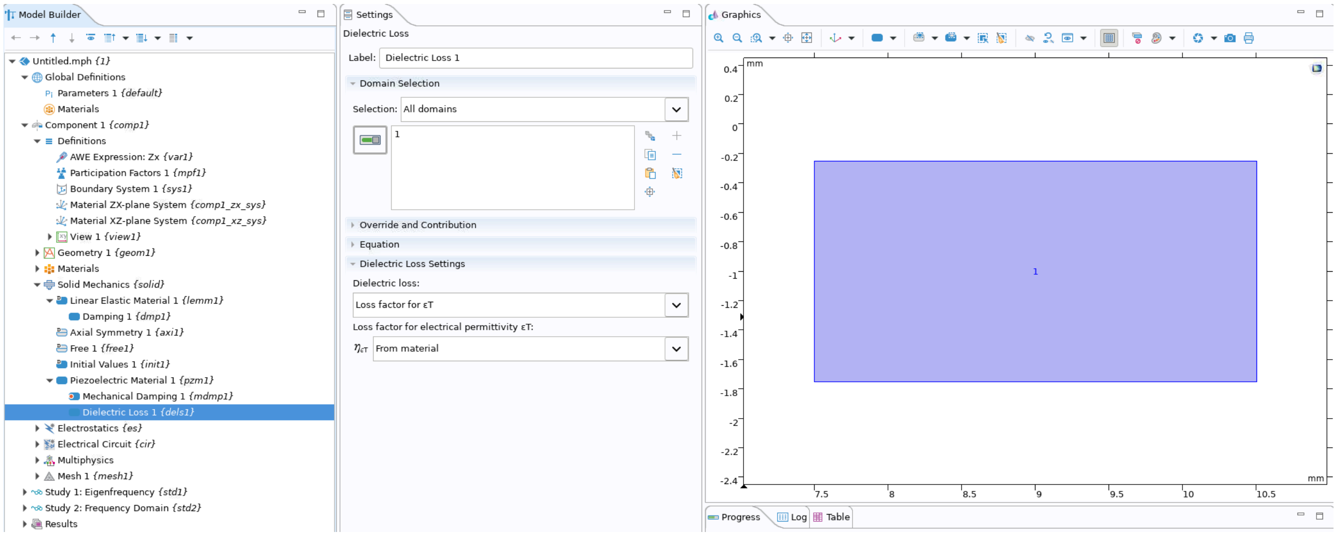

Figure 5-4. Piezo: Dielectric Loss

The piezo electrodes are situated on both the top and bottom surfaces of the piezo component, leading us to designate Terminal 2 and Terminal 3 as the two terminals for the electrostatics. Figure 5-5 shows the screenshot of the terminal selection.

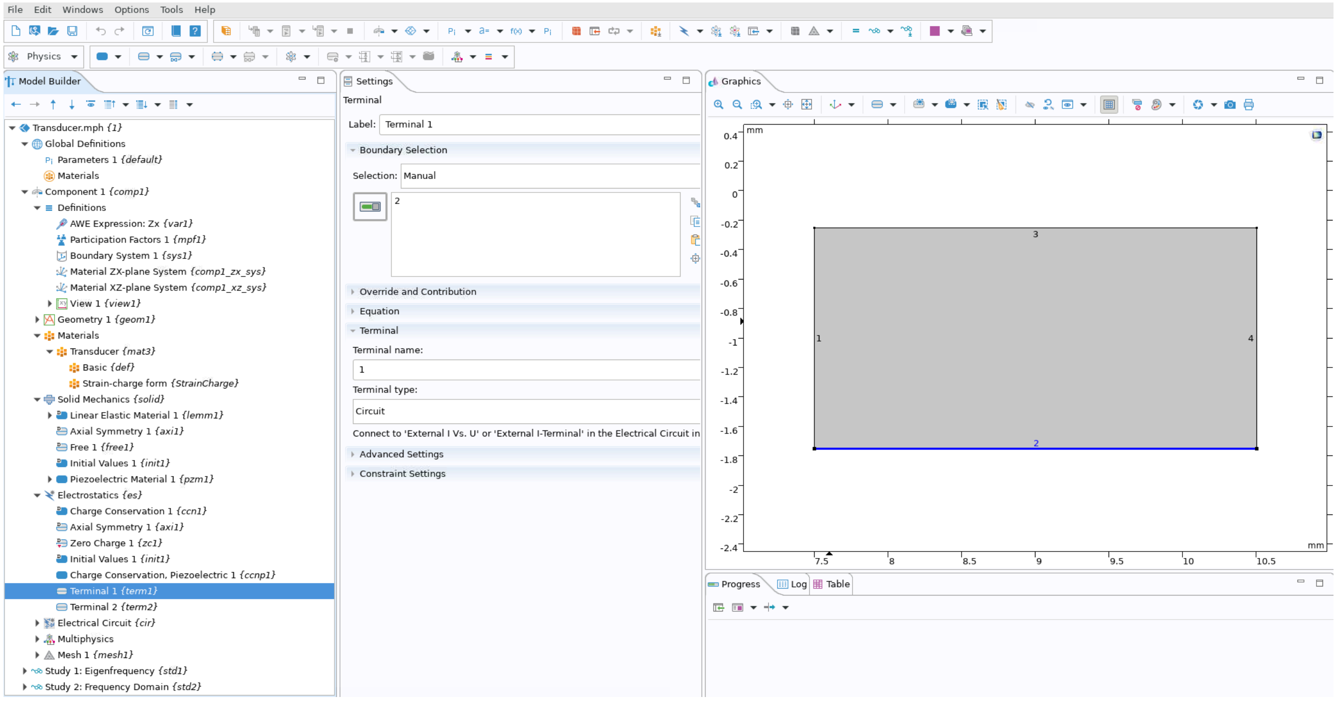

Figure 5-5. Piezo: Terminal Selection

By conducting the Frequency Domain study, we can observe the impedance response ranging from 20 kHz to 700 kHz, as illustrated in Figure 5-6 below. The first mode, occurring at 59 kHz, is identified as a radial mode, where both the inner and outer diameters of the piezo change uniformly while maintaining a constant width. In contrast, the second mode at 525 kHz represents the thickness mode, characterized by variations in both thickness and width.

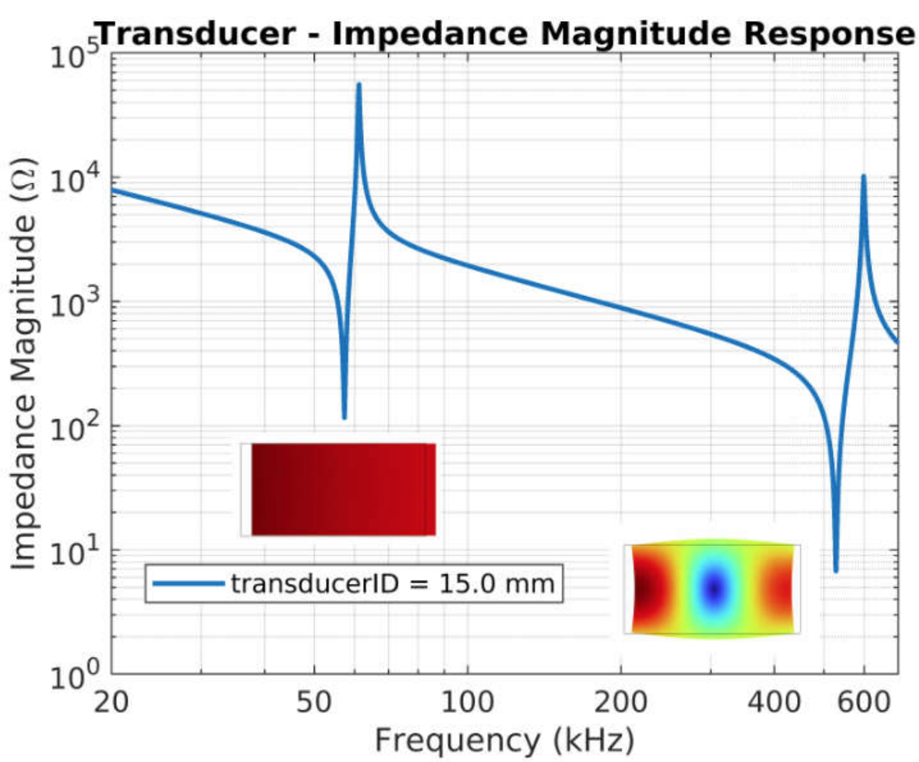

Figure 5-6. Impedance Response of the Piezo Transducer.

6 Simulation of Lens Cover System (LCS)

Figure 6-1 shows the simplified drawing of the LCS geometry. The housing is simplified as a fixed block. The cap is not shown and instead is represented by a damping factor.

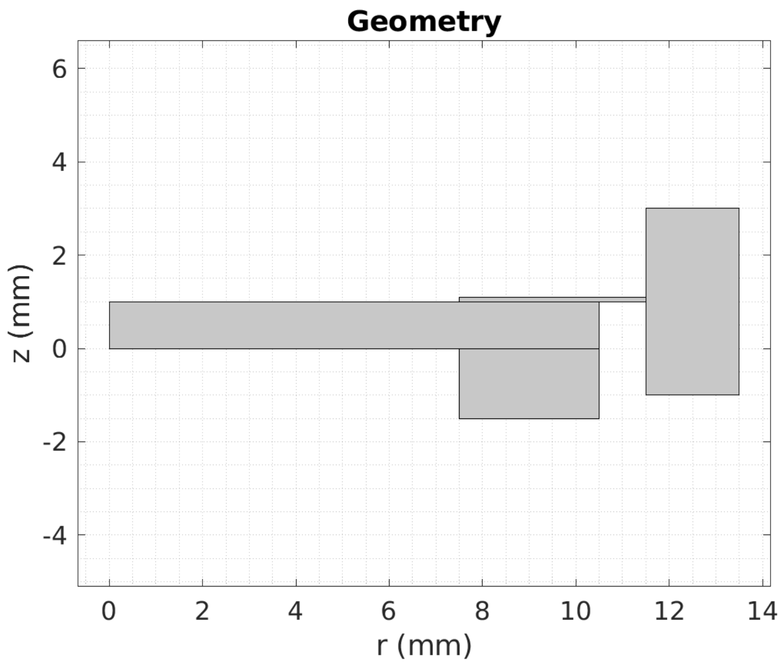

Figure 6-1. LCS: Geometry

6.1 Physics and Boundary Conditions

6.1.1 Glue

TI uses EPO-TEK 323LP-LH as the hard glue material in the LCS-FL-RNG15. The material properties of glue can be found in Table 6-1 below.

Table 6-1. Material Properties of Glue

Parameter	Unit	Value
Young's modulus	GPa	2.67
Density	Kg/m^3	1190
Poisson's ratio	1	0.30

The glue layer is applied to two interfaces. One is the interface between the lens and the piezo, and the other is between the lens and the thin film. The glue is represented by a Thin Elastic Layer, a model advised by COMSOL for accurately simulating the properties of thin adhesives. A damping loss factor of 0.02 has been incorporated into the simulation. The screenshot of the setting is shown in Figure 6-2.

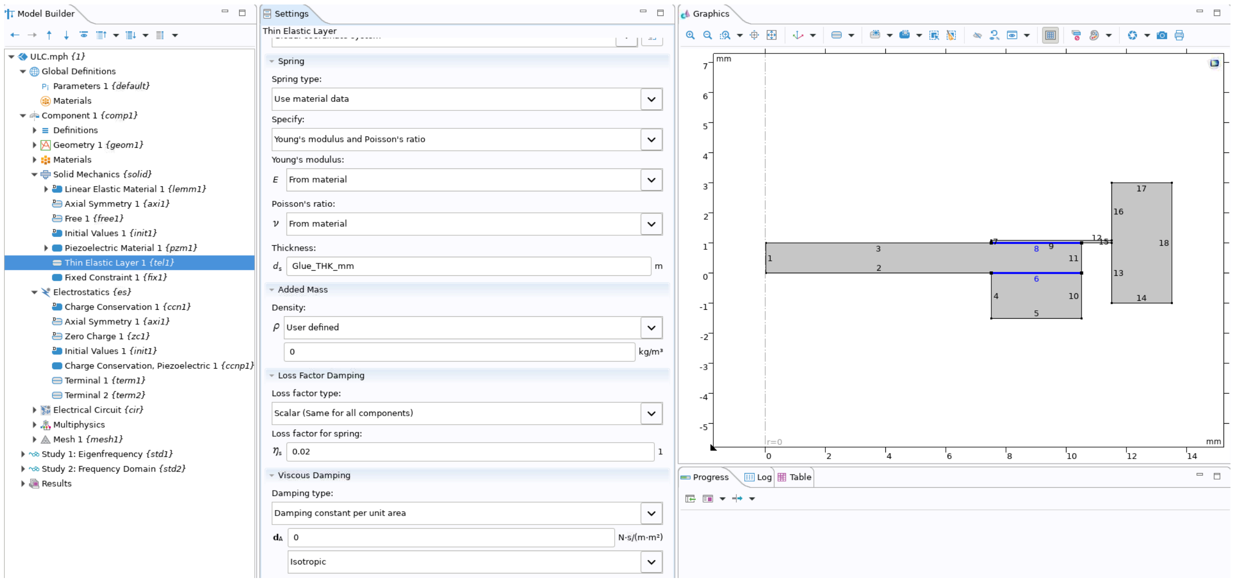

Figure 6-2. Thin Elastic Layer for Glue

6.1.2 Thin Film

TI uses polyamide as the thin film in the LCS-FL-RNG15. The material properties of the thin film are listed in the Table 6-2.

Table 6-2. Material Properties of Thin Film

Parameter	Unit	Value
Young's modulus	GPa	2.5
Density	Kg/m^3	1420
Poisson's ratio	1	0.34

The thin film, together with the housing and the lens, is all modeled by the linear elastic material, with an isotropic damping factor of 0.005. The setting is shown in Figure 6-3.

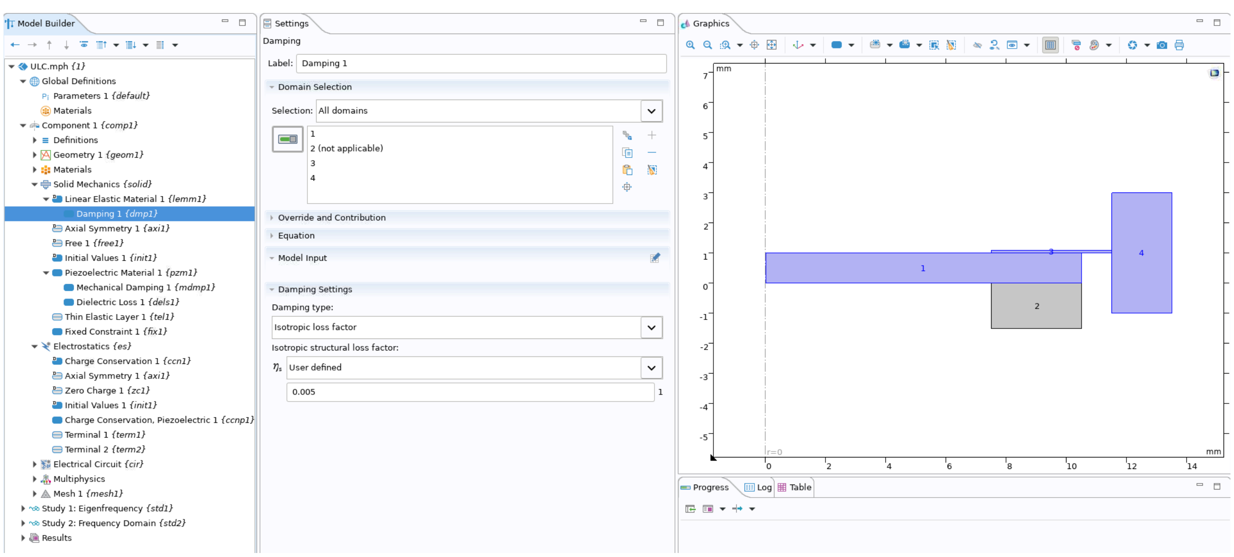

Figure 6-3. Linear Elastic Model for Thin Film

6.1.3 Housing

TI uses Delrin Black as the housing material in the LCS-FL-RNG15. The material properties are listed in the Figure 6-4

Table 6-3. Material Properties of Housing

Parameter	Unit	Value
Young's modulus	GPa	2.0
Density	Kg/m^3	1420
Poisson's ratio	1	0.35

In the model, the housing is modeled by a rectangular block, with a fixed boundary condition, as shown in Figure 6-4. All other domains are set as Free.

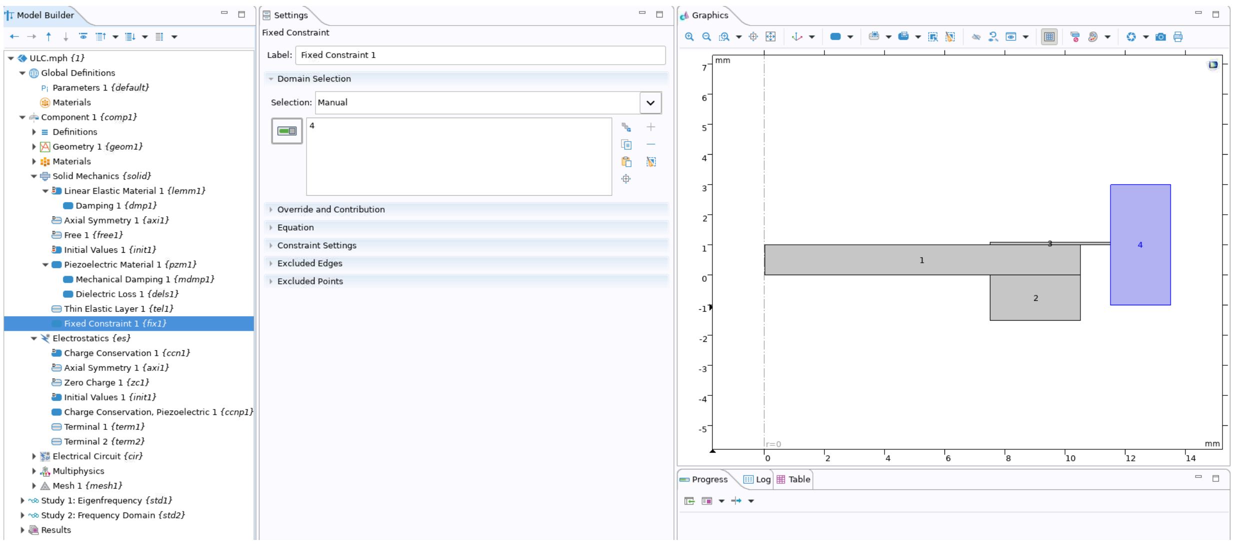

Figure 6-4. Fixed Boundary Condition for Housing

6.2 Results

Figure 6-5 illustrates the lens center's acceleration response and the impedance response from 20 kHz to 100 kHz by running the Frequency study. Within this range, the simulated resonant frequencies are identified at 29.2 kHz and 64.3 kHz. Notably, the accelerations at both peaks exceed the atomization threshold. The key characteristics of the two modes are listed in Table 6-4.

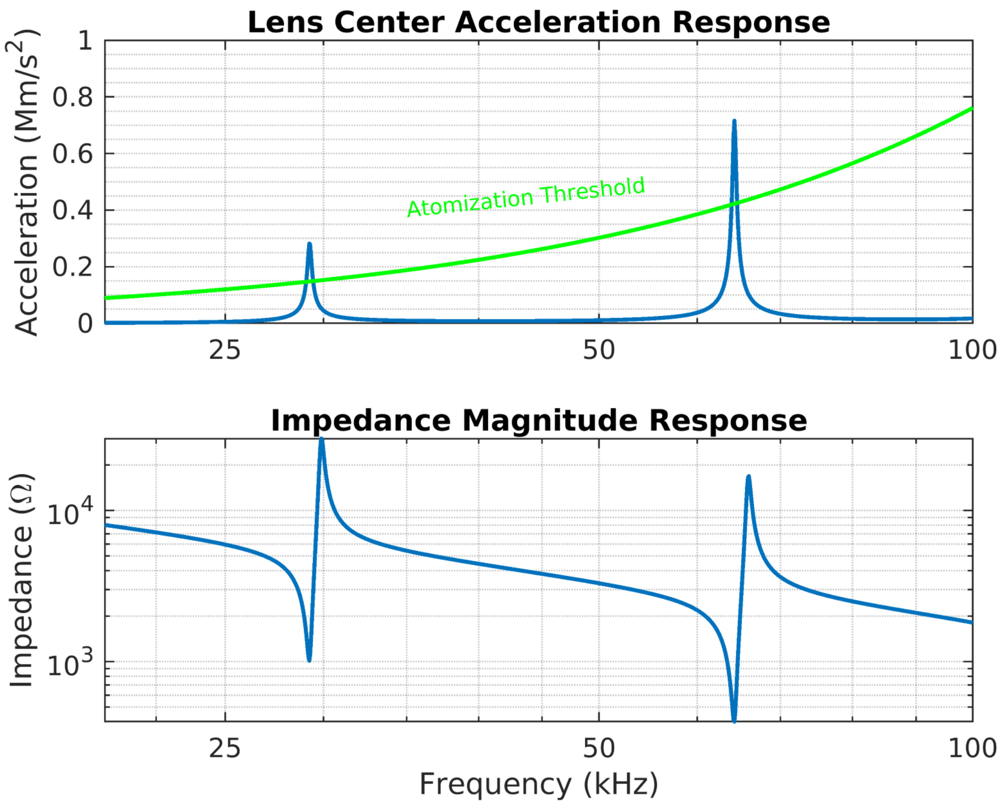

Figure 6-5. LCS: Lens Center Acceleration and Impedance Response

Table 6-4. Key Characteristics of Mode (0 1) and (0 2).

Mode	Resonant Frequency (kHz)	Impedance (Ω)	Acceleration ($10^6 m/s^2$)
(0 1)	29.2	1018	0.28
(0 2)	64.3	403	0.72

Figure 6-6 illustrates the mode shapes of the LCS for the two specific modes. In mode (0 1), you can see that the acceleration diminishes as you move from the center toward the edges, transitioning from red to blue. In mode (0 2), the acceleration similarly decreases from the center to the middle area before increasing again from the middle to the edges.

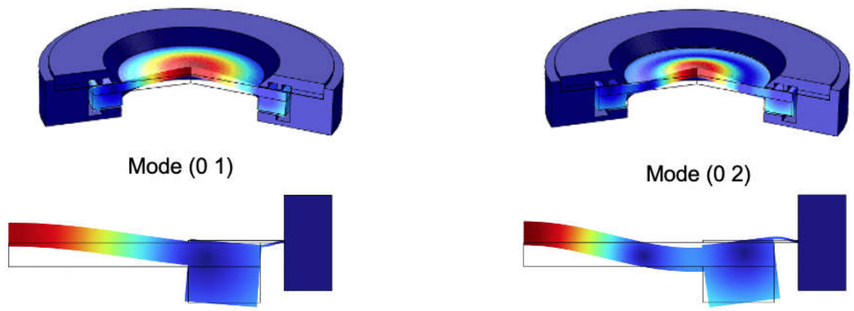

Figure 6-6. LCS: Mode Shapes at Mode (0 1) and Mode (0 2)

Figure 6-7 illustrates the lens surface acceleration of the LCS, highlighting the variation from the center to the edge. Note that only the central region surpasses the atomization threshold, enabling it to effectively expel water, while the edge region does not possess this capability.

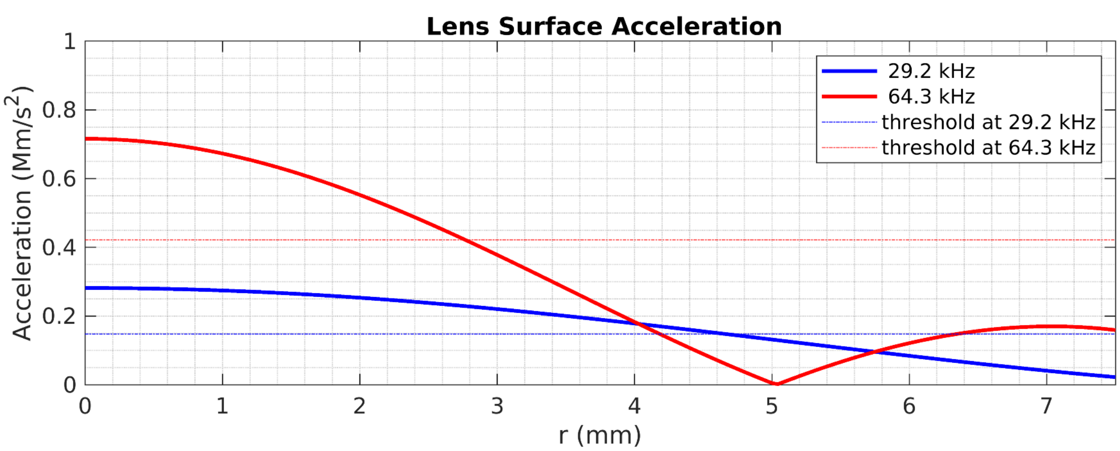

Figure 6-7. LCS: Lens Surface Acceleration

7 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, *Design, Fabrication, and Assembly Guide of Lens Cover System: LCS-FL-RNG15*.