

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



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ABSTRACT

This document describes the design, fabrication and assembly guidelines for a ring piezo based flat Lens Cover System (LCS) for automotive, security, and industrial camera applications. The LCS paired with the ULC1001 electrical system construct a highly-reliable Ultrasonic Lens Cleaning (ULC) system. For more information about the ULC system electronics, see the [ULC1001-DRV290x EVM User Guide](#).

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1 Acronyms

- EPDM – Ethylene Propylene Diene Monomer
- FOV – Field Of View
- 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 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.

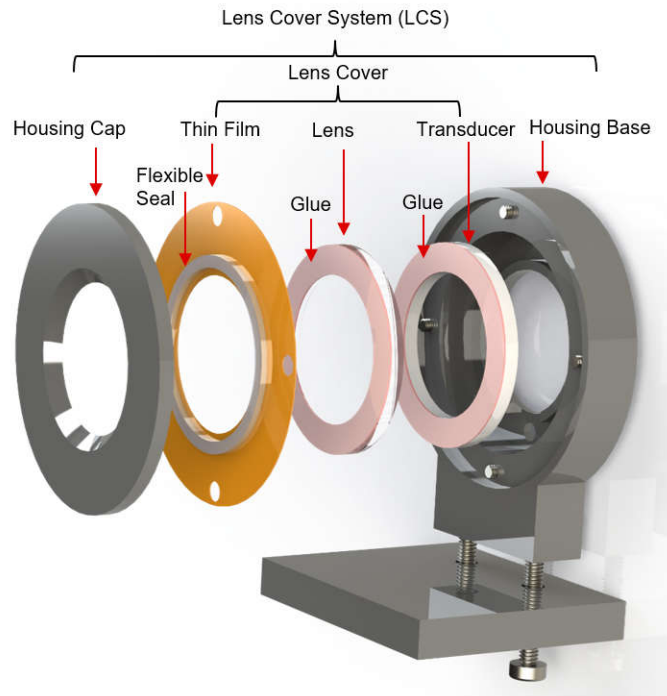


Figure 2-1. Illustration of Flat Lens Cover System (LCS)

Note

The lens mentioned in the document is a component of the LCS system and covers the camera lens and is not part of the conventional camera lens system.

3 Design Principles

3.1 Critical Acceleration

Ultrasonic lens cleaning utilizes the vibration of the lens to expel the water droplets on the lens. To atomize the water droplets, the acceleration needs to be above a threshold. The threshold can be estimated by the following equation:

$$\alpha = 0.34 \left(\frac{\sigma}{\rho} \right)^{\frac{1}{3}} \omega^{\frac{4}{3}} \quad (1)$$

Where α is the critical acceleration —the minimum acceleration at which droplets are ejected from a driven surface, Mm/s^2 or 10^6 m/s^2

$\sigma = 72 \times 10^{-3} \text{ N/m}$, the surface tension of water

$\rho = 1000 \text{ kg/m}^3$, the density of water

ω is the angular frequency, krad/s

Figure 3-1 plots the critical acceleration versus frequency. A low frequency requires a low acceleration to expel the water. Therefore, designing a system that works at a relatively low frequency (20kHz - 100kHz) is preferred. For any LCS design, the goal is to create a design whose lens surface acceleration level is higher than the threshold.

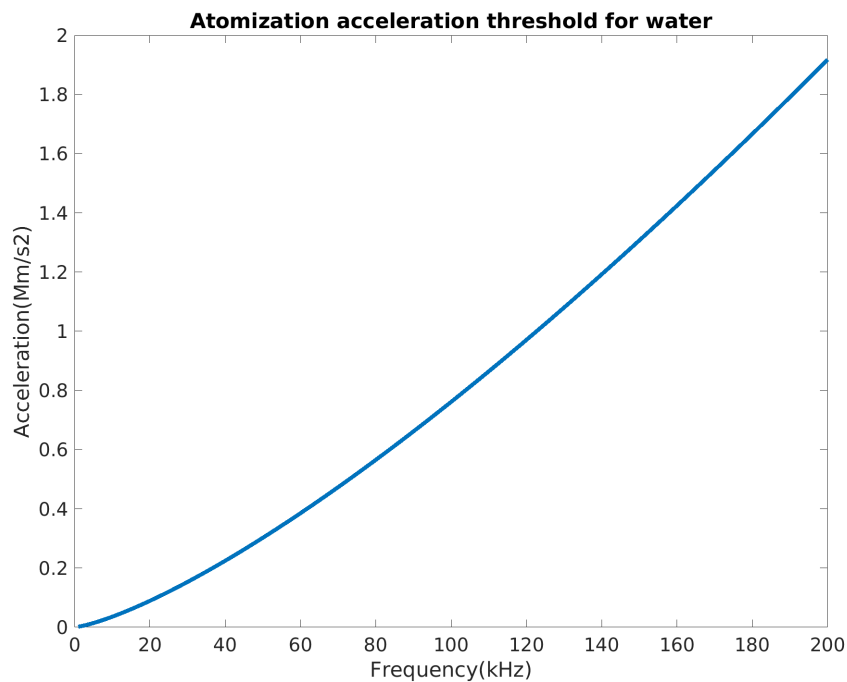


Figure 3-1. The critical acceleration to atomize water versus frequency

Note

The critical acceleration in the equation is only for water. Sticky materials such as oil and mud can have higher critical accelerations.

3.2 LCS Architecture

A good architecture is highly reliable, low power, simple to assemble, and low cost. There can be different LCS architectures that can achieve the goal of cleaning water, and one of them is shown in Figure 3-2. A few key points for the architecture can be summarized as:

- The piezo transducer is concentric and directly coupled to the flat circular lens with glue. The glue must be very strong and own a high modulus so the vibration can be transmitted from the piezo to the lens with high efficiency.
- An annular-shaped film is used to attach the lens with the piezo transducer to the housing. The inner side of the film is bonded or glued to the top of the lens and the outer side is bonded or glued to the housing. The thin film has little impact on the resonant frequencies and mode shape of the piezo transducer and lens subsystem.
- The watertight seal is formed by filling in the flexible glue or caulk in the housing cap trench.
- Piezo is floating, with a small distance from the housing base landing spot, which can help prevent damage to the membrane from large loading on the lens.
- Housing cap and housing base are connected through screws, sandwiching the thin film. Bonding or gluing the cap to base directly without using the screws can be also an option.

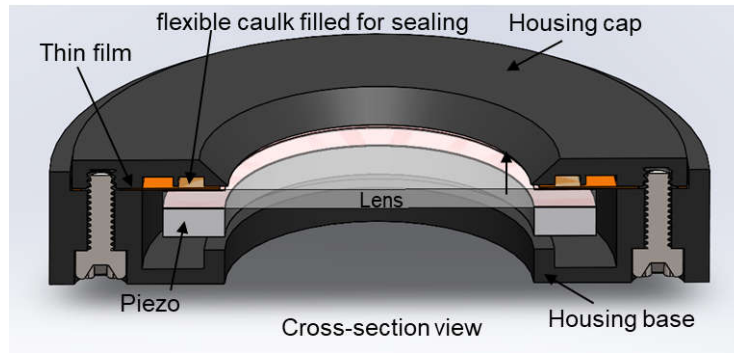


Figure 3-2. The Cross-Section View of the LCS

Note

Improper boundary conditions for the lens cover can induce significant damping to the whole system. The flexible thin film and seal are chosen as the interface between the Lens Cover and Housing to keep a low damping level in the design.

3.3 Design Procedure

The mechanical design procedure involves designing each individual component and assembling the components to build the LCS. In particular, the design procedure (Figure 3-3 and Figure 3-4) can be described by the following steps :

1. Determine the minimum cover lens aperture (that is, transducer inner diameter) based on the camera lens diameter.
2. Design the lens and transducer that is well matched to achieve the best cleaning performance.
3. Design a glue fixture that can help glue Lens Cover components easily.
4. Assemble lens, transducer and thin film by following the proper gluing procedure to create a Lens Cover.
5. Design housing cap and base based on the Lens Cover dimensions.
6. Assemble the Lens Cover and housing to create a Lens Cover System (LCS).

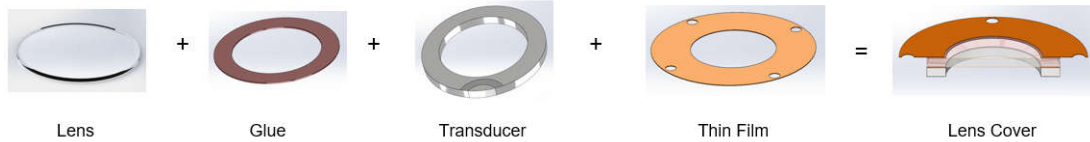


Figure 3-3. Mechanical Design Procedure of Flat Lens LCS: Lens + Glue + Transducer + Thin Film = Lens Cover



Figure 3-4. Mechanical Design Procedure of Flat Lens LCS: Lens Cover + Cap + Seal + Base = Lens Cover System (LCS)

In LCS design, the most critical is to design a Lens Cover where the lens and the transducer is well matched. TI uses a FEA simulation tool- COMSOL Multiphysics to simulate the interactions between the components. Other FEA simulation tools such as Ansys can be used as well.

The goal of the simulation is to obtain the highest lens surface acceleration by sweeping the dimensional parameters of the lens and piezo transducer.

3.4 Design of Components

3.4.1 Lens

In the camera lens cover system, the lens is a transparent piece of material that defines the physical barrier between the environment and the camera lens system. The lens vibrates in the ultrasonic frequency range with enough energy to remove contaminants (for example, rain droplets, snowflakes, mud, or dust) that can be on the lens.

For a thin flat circular lens, the resonant frequency can be estimated by the following equation:

$$f_{ij} = \frac{\lambda_{ij}^2}{2\pi r^2} \sqrt{\frac{Et^2}{12r(1-\nu^2)}} \tag{2}$$

Where f_{ij} is the natural frequency for the i^{th} nodal diameter and j^{th} nodal circle, Hz.

λ_{ij} is the eigenvalue for the i^{th} nodal diameter and j^{th} nodal circle (unitless).

r is the radius of the lens, m.

E is modulus of elasticity for the cover glass material, N/m².

t is the thickness of the cover glass, m.

ρ is the mass per unit area of the cover glass material, kg/m².

ν is Poisson's ratio for the cover glass material (unitless).

Note

Observation: The resonant frequency of the lens increases with the thickness, and decreases with the radius.

Figure 3-5 shows the mode shapes of the lens only. In the design, modes (0 1) and (0 2) are utilized for cleaning with fewer nodal points (little displacement in blue color). Also, the modes have lower resonant frequencies and therefore require smaller critical acceleration.

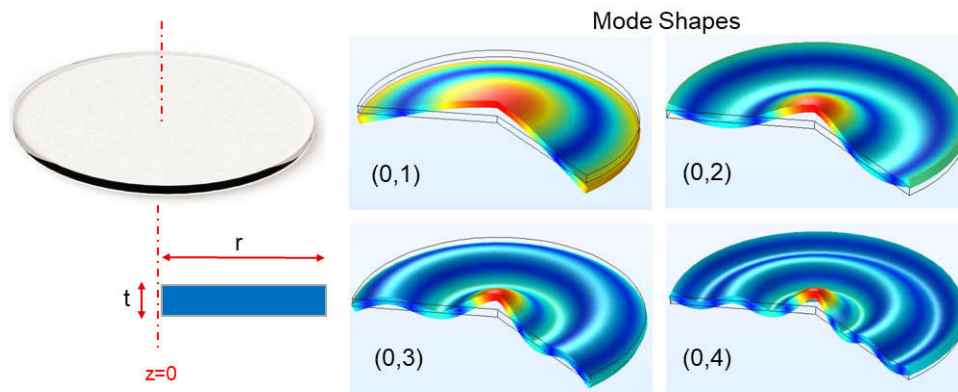


Figure 3-5. Mode Shapes of Lens Only

Material: A desirable lens material must have the following properties in the application:

1. High bending strength. Capable of handling high stress during vibration for cleaning without cracking or breaking.
2. High light transmittance for the wavelength of light used by the camera imaging system. For automotive, the wavelength can be infrared (IR) or visible.

The optional materials include N-BK7®, fused silica glass, Gorilla® Glass 3, polycarbonate, silicon, and so forth, and the key mechanical properties of the materials are listed in Table 3-1. TI recommends CDGM HK9LGT® for general cleaning purposes considering the favorable material properties, mature fabrication feasibility, and relatively low cost. However, a material with comparable properties can also be used.

Table 3-1. Mechanical Properties of Lens Materials

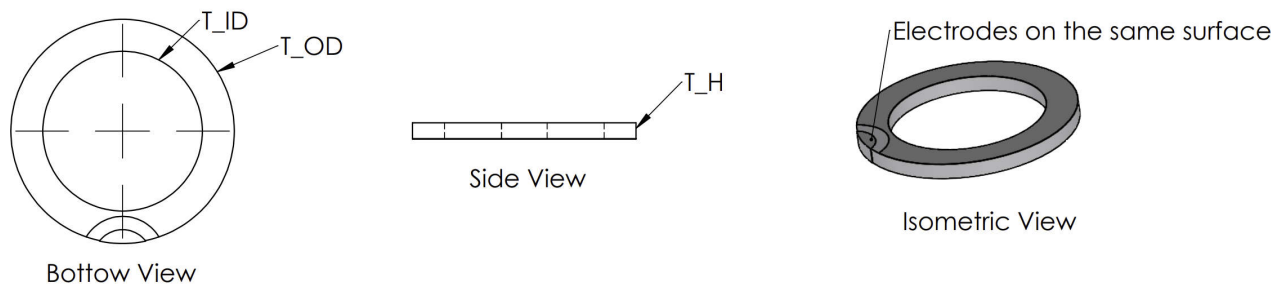
Manufacturer	Material	Young's Modulus (GPa)	Density (kg/m ³)	Poisson's Ratio
Tosoh	Fused Silica Glass N	74	2200	0.17
Corning®	Gorilla® Glass 3	69.3	2390	0.22
Corning	Gorilla® Glass 5	76.7	2430	0.21
Covestro	Polycarbonate	2.34	1200	0.38
Schott	NBK7®	82	2510	0.206
CDGM	HK9LGT®	79.2	2520	0.211

3.4.2 Transducer

The transducer acts as the actuator in the application.

Material: The recommended transducer material is PZT. TI uses PZT 8 in the prototypes considering the high mechanical quality factor. Other PZT materials such as PZT4 or PZT5 can be options as well.

Geometry: The transducer is a ring shape and is poled in the top/bottom direction. Figure 3-6 shows the top view, side view and isometric view of the transducer and also illustrates the dimensions of the transducer. T_ID, T_OD, and T_H represent the inner diameter, outer diameter and the height of the transducer, respectively.


Figure 3-6. Transducer: Top View, Side View and Isometric View

There are multiple resonant modes of the ring piezo. In this application, the radial mode is utilized for the cleaning modes and the resonant frequency can be estimated by the following equation:

$$f_{radial} = \frac{2}{\pi(T_{ID} + T_{OD})\sqrt{\rho s_{11}^E}} \quad (3)$$

where ρ is the density of the material, and s_{11}^E is elastic compliance at constant electric field. This can be further simplified as

$$f_{radial} = \frac{C}{(T_{ID} + T_{OD})} \quad (4)$$

where C is a constant, whose value is estimated to be about $2000 \text{ Hz} \cdot \text{m}$ for PZT 8 material. Piezo suppliers have slightly different C values for the same type of the piezo material due to their recipe variances.

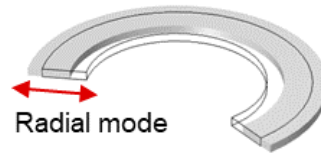


Figure 3-7. Radial Mode of Piezo for Water Cleaning

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- The wall thickness $((T_{OD}-T_{ID})/2)$ between the lens must be at least 3mm to maintain a large gluing area between the piezo and the lens.
 - The wall thickness $((T_{OD}-T_{ID})/2)$ is typically more than 2 times the piezo thickness to be a ring-shaped piezo (thin and wide).
-

3.4.3 Thin Film

As the interface between the Lens Cover and Housing, the flexible polyamide is chosen. The reasons why choosing polyamide film as the interface include the following:

- Very flexible with a flexural modulus of 2.5GPa to reduce damping.
- High tensile strength of up to 340MPa.
- Excellent thermal stability, normal use in -100°C to 260°C .
- Different thicknesses are available with 10um – 1000um.
- Low cost and easy to pattern.
- Other materials (Al, SS, film, nylon, plastic, etc) can be potentially used.

Figure 3-8 shows the top view, side view and isometric view of the thin film in the application. The pattern is so that the inner diameter (F_D2) is identical to the inner diameter of the piezo transducer. Four small holes are designed for screwing purpose.

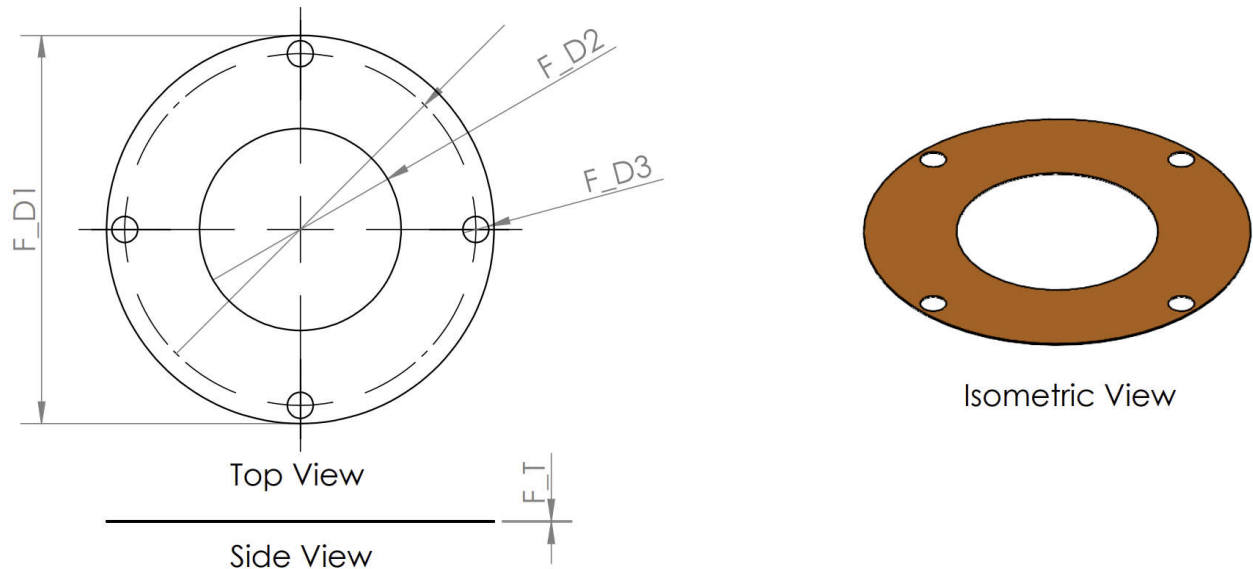


Figure 3-8. Thin Film: Top View, Side View and Isometric View

3.4.4 Glue Fixture

The glue fixture is a mold used to glue the lens and transducer together. A proper glue fixture makes the designed lens and transducer concentric.

Material: The recommended material is Al 6061-T6.

Geometry: Figure 3-9 shows the section view and isometric view of a glue fixture, together with the Lens Cover. The dimensions of a glue fixture are determined based upon the dimensions of the lens and transducer and account for all tolerances. The design of the glue fixture must meet the following guidelines:

1. The inner diameter of the glue fixture cap must be slightly larger than the lens diameter so that the lens can fit inside the glue fixture.
2. Similarly, the corresponding diameter of the glue fixture base must be slightly larger than the transducer diameter ($T_{OD} + \text{tolerance}$) so that the transducer can fit inside the glue fixture.
3. A gap shall be created between the top part of the transducer and the glue fixture to avoid the gluing the lens cover to the fixture.
4. The center of the glue fixture must be hollow so that the lens cover can be easily removed from the glue fixture.

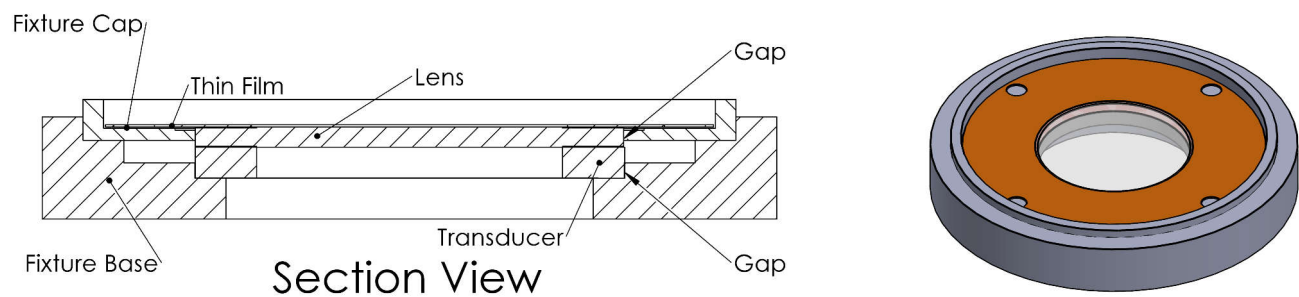


Figure 3-9. Glue Fixture: Section View, and Isometric View

3.4.5 Housing

The housing provides a mechanism to hold the camera and to maintain the relative position between the camera and the Lens Cover. The housing consists of a cap, flexible seal, and a base. A proper housing achieves waterproof capability and help exhibit the cleaning performance to the utmost. On the contrary, a poorly-designed housing design can significantly downgrade the cleaning performance.

3.4.5.1 Housing Cap

The cap contains a trench to hold the seal in place and provides the waterproof. The cap can be designed to have threads and screw onto the housing or a fixed cap and housing assembly can be designed. [Figure 3-10](#) shows the top view and section view of the housing cap. A slope is recommended on the opening of the cap to increase the field of view and also the waterdroplet can roll off along the slope.

Material: The cap material must be strong and durable for the application. TI has used Delrin Acetal Homopolymer Black for prototyping.

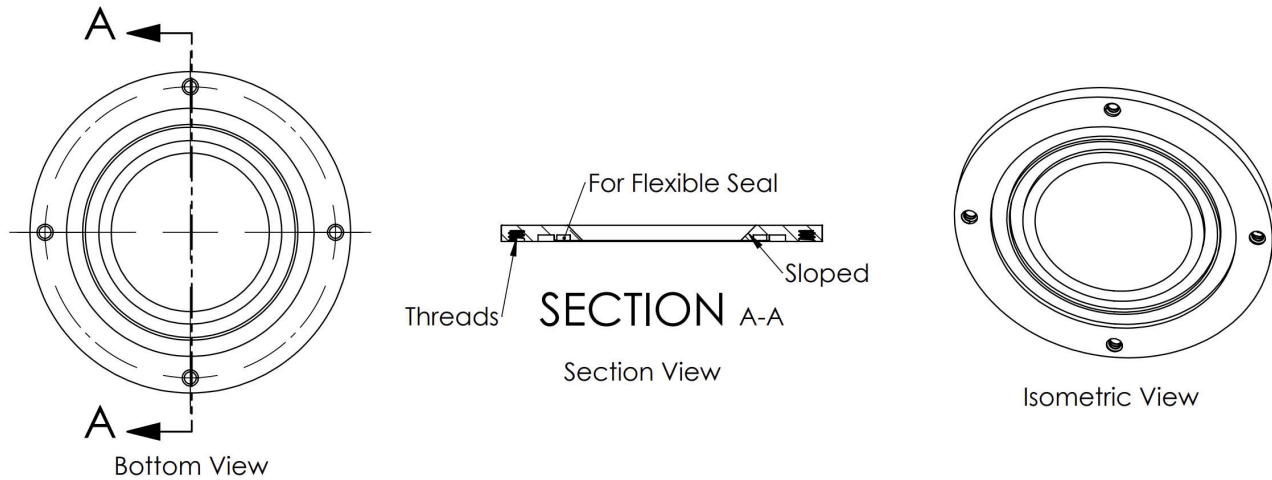


Figure 3-10. Housing Cap: Top View and Section View

3.4.5.2 Flexible Seal

The seal between the cap and the thin film maintains a watertight proof as the lens cover vibrates to expel contaminants. [Figure 3-11](#) illustrates the top view, side view, and isometric view of the seal for housing after hardening.

Material: The recommended seal material is silicone that is soft enough to induce minimal damping during ULC vibration and that can also avoid cracking over weather temperature cycles during the product life cycle. This exhibits excellent resistance to heat, compression set, boiling water, and has excellent low-temperature flexibility.

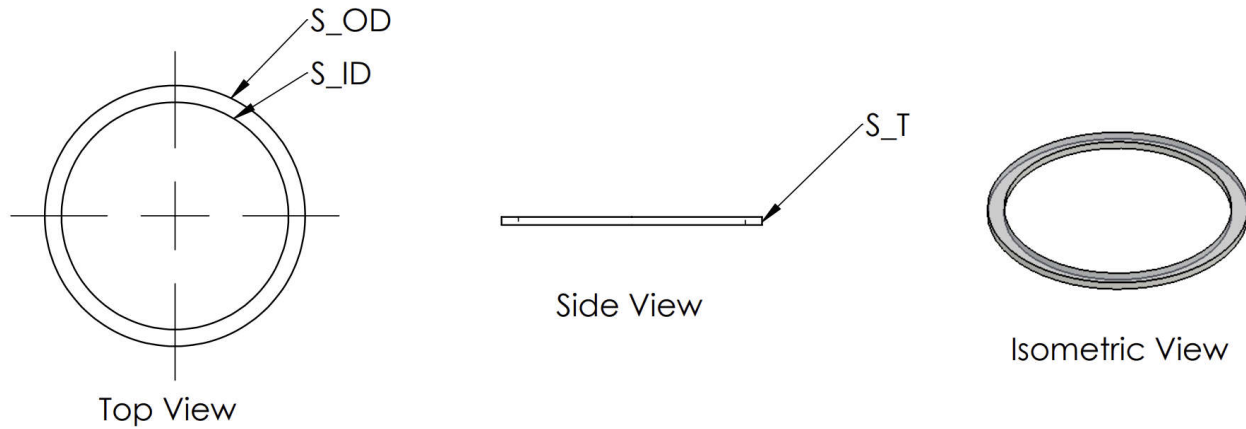


Figure 3-11. Seal: Top View, Side View and Isometric View after Hardening

3.4.5.3 Housing Base

The purpose of the base is to hold the camera and the Lens Cover and to maintain their relative position. The base can keep the Lens Cover concentric with the camera lens and to prevent the Lens Cover from moving radially with respect to the housing. The base also has special accommodations for the wires going to the plates of the transducer. A small lip is designed to keep a small distance from the piezo to withstand in case the piezo faces an extreme large load. The 4x screws can connect the housing base, lens cover and the housing cap. [Figure 3-12](#) show the front view, section view, and isometric view of the housing base.

Material: The cap material must be strong and durable for the application. TI used Delrin Acetal Homopolymer Black for prototyping.

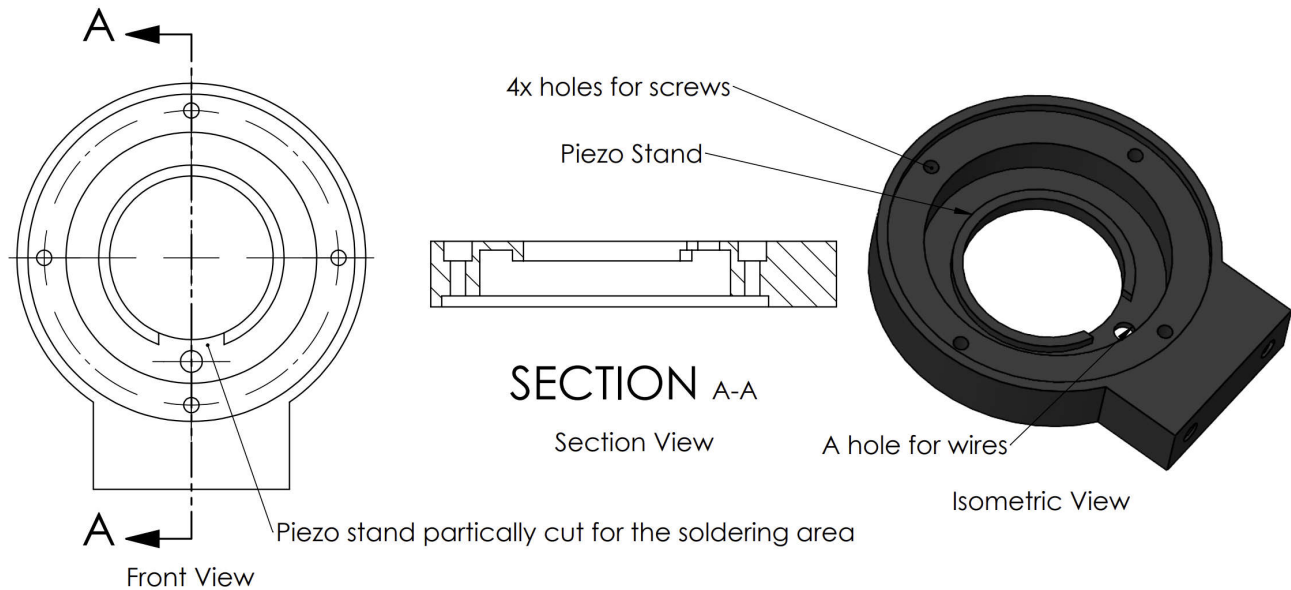


Figure 3-12. Housing Base: Front View, Section View, and Isometric View

4 Fabrication Principles

4.1 Lens

The lens is in the shape of a thin circular disk, as [Figure 4-1](#) shows. There are a few important parameters for the lens: lens diameter (L_D), lens thickness (L_T), surface polishing, the etched outer diameters, and the etched ring surface roughness. The dimensions of the lens must be carefully designed to achieve the best cleaning performance.

Tips:

1. The top and bottom surfaces of the lens must be polished to minimize surface cracks. The recommended polish level is 60/40.
2. The bottom surface of the lens must have an etched area to increase the surface contacting area for gluing. The ring can be etched by several methods, including light sand blasting, chemical etching or laser etching, with an estimated surface roughness of 300 mesh (48um). The recommended method is light sandblasting.
3. The etched ring diameter (R_D) must be slightly smaller than the transducer's inner diameter.
4. The lens edges must also be polished. For additional crack protection, a protective bevel can be added to the lens edges to avoid chipping during fabrication and handling.
5. Chemically strengthened lens is optional. Chemically strengthened lens typically have higher bending strength while other properties (for example, density, Young's modulus and Poisson's ratio) are held almost constant.
6. Hydrophobic and oleophobic coating are recommended to reduce the surface tension of water.

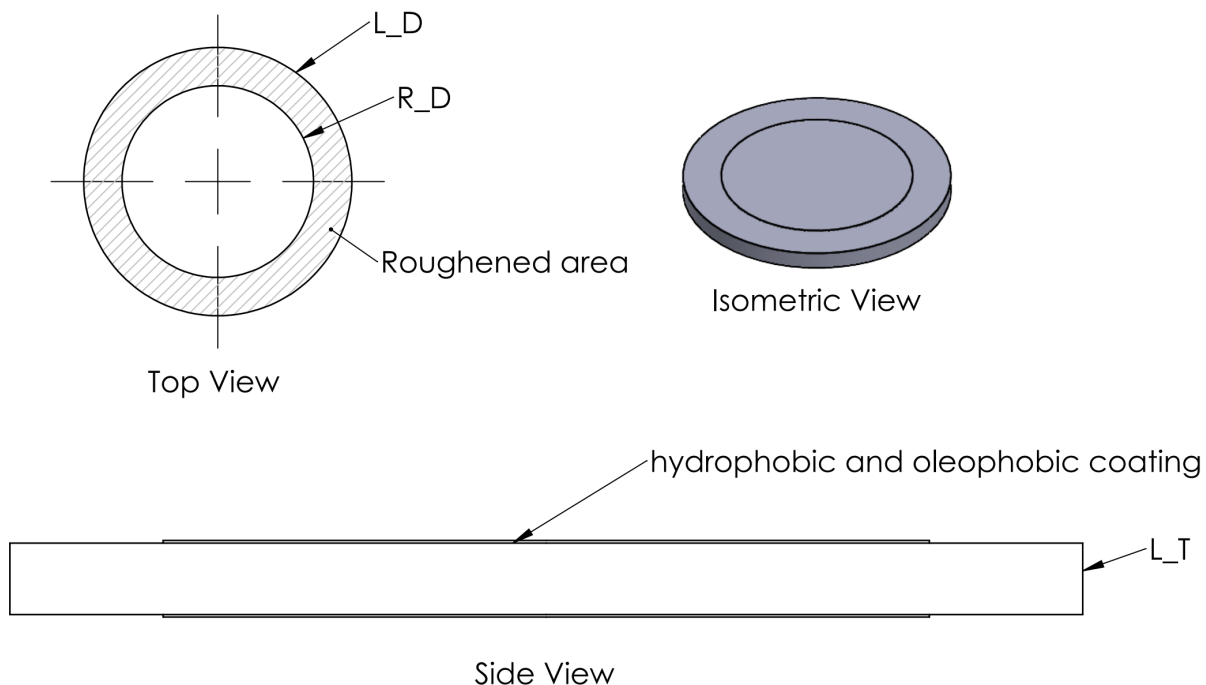


Figure 4-1. Lens: Top View, Side View and Isometric View

4.2 Transducer

Keeping a proper thickness of the conductive silver layer on the electrode is important. The solder joint can come off if the conductive layer is too thin.

In addition, meeting the dimension tolerance requirements is critical for proper lens cover vibration performance. The transducer must meet tolerances for the best performance. Failure to meet the dimensional tolerance requirements can have the following consequences:

1. Significantly increase the impedance magnitude of the desired vibration modes, and raise the power consumption.
2. Reduced vibration level which results in reduced cleaning performance.

4.3 Thin Film

The thin polyamide film can be easily patterned at a low cost. No adhesive is required on the surface of the thin film.

4.4 Glue Fixture

The glue fixture can be fabricated by standard CNC machining tools with standard tolerances (10um). Note to consider the tolerances of the piezo and the lens.

4.5 Housing

The housing cap and base are fabricated by standard CNC machining tools with standard tolerances (10um).

5 Assembly Principles

5.1 Step 1: Gluing Components into Lens Cover

The gluing procedure can be defined by the following steps:

a) Pre-glue Preparation The following items need to be procured before starting the gluing process:

1. Epoxy (TI recommends EPO-TEK 323LP-LH Premium Part A®)
2. Epoxy hardener (TI recommends EPO-TEK 323LP-LH Premium Part B®)
3. Glue fixture
4. Lens
5. Transducer
6. PI film
7. Scale (with 0.1 g of accuracy)
8. Isopropyl alcohol (IPA)
9. Delicate wipes
10. Chemical handling gloves
11. Applicator syringe (TI recommends 16Ga blunt needle in the step)
12. Plastic cup
13. Plastic rod

b) Glue Preparation Procedure

Mix glue per [data sheet](#) specifications.

c) Oven Preparation Procedure

1. The oven for curing the epoxy mixture must be preheated to 85°C.
2. Depending on the thermal mass (physical dimensions inside the oven), the preheating procedure can start earlier than glue preparation procedure.
3. Make sure that the oven is clean and there are no other devices, or any water residual inside.

d) Gluing the Transducer to the Lens Procedure

1. Wear gloves and eye protection for personal protection and to avoid surface contamination.
2. Make sure that the glue fixture, transducer and etched glass are cleaned with isopropyl alcohol.
3. Place the piezo into the glue fixture.
4. Apply a thin amount of glue around the top of the transducer.
5. Place the etched glass into the glue fixture with the etched side towards the glue.
6. Make sure the cover lens is as concentric as possible with the transducer.
7. Make sure that there are not air gaps in the glue by viewing the top of the transducer through a microscope.
8. Make sure that no glue has gone into the gap between the transducer and the glue fixture. By viewing the assembly through a microscope. If that glue is present in this gap, remove the glass and transducer and return to step 1. Make sure the fixture is clean of any glue. Otherwise, the transducer gets glued to the fixture.

e) Glue Curing Procedure

1. Place the glue fixture, which contains the transducer, glue and glass in the oven.
2. Turn the oven temperature up to 150° C per the glue curing specifications. Avoid rapid heating of the cover lens to avoid any possible cracking of the material.
3. Keep the glue fixture, which contains the transducer, glue and glass, inside the oven for 1 hour at 150° C.

f) Glue Cool Down Procedure

1. To remove the glue fixture from the oven, use proper heat-resistant gloves for personal protection.
2. Remove the glue fixture from the oven and allow the glue fixture to reach room temperature.
3. After the glue fixture has reached room temperature, remove the transducer assembly from the glue fixture. If the transducer appears stuck, remove the transducer by pushing against the inside of the glass through the hole of the glue fixture.
4. Discharge the transducer by shorting the two plates of the transducer.

Warning! High voltage, low-power, electrical discharge can occur due to the transducer temperature change.

g) Gluing the Thin Film to the Lens/Transducers Procedure

1. Apply a thin amount of glue on the gluing area of the thin film evenly.
2. Place the thin film on top of the lens.
3. Make sure the thin film is as concentric as possible with the lens.
4. Make sure that no excessive glue has gone into the gap between the thin film and the glue fixture.
5. Put the assembly in the oven and repeat the curing procedure
6. Take the assembly out and repeat the cool down procedure

5.2 Step 2: Soldering of Lens Cover with Wires

Materials and tools for the procedure include:

1. Rosin flux
2. Lead-free solder wire
3. Thin and flexible wire for piezo
4. Hot glue sticks
5. Hot glue gun

Note

TI recommends 30AWG stranded wire with silicone as the insulator. Wires using the PVC insulator can be too stiff and negatively affect the piezo vibration

Below is the soldering procedure:

1. Solder the flexible wire to the two plates of the transducer. Use lead-free solder wire and Rosin flux. The soldering iron tip does not heat the transducer surface. Hence the tip only contacts the transducer for 1-2 seconds.
2. Apply the hot glue on the solder joint to hold the solder on the surface. Without the hot glue, the solder joint can come off during the long-term vibration.
3. Record the impedance response of the transducer using an impedance analyzer. This data can be used to verify the transducer assembly after the gluing process.

Note

The soldering process is quick with a temperature of 650F. A high temperature or long soldering can damage the transducer.

5.3 Step 3: Assemble Lens Cover into Housing

Materials and tools for the procedure include:

1. Flexible silicone seal
2. Applicator syringe (TI recommends 16Ga blunt needle in the step)
3. Screwdriver
4. Screws
5. Housing cap
6. Housing base
7. Housing foundation

The assembly procedure can be described as:

- Apply the silicon seal into the trench of the housing cap
- Leave the seal in the cap for 3 hours at room temperature to get hardened
- Assemble the housing foundation, housing base, lens cover, and the housing cap using the screwdrivers.

6 Example: CAD Drawings for Aperture = 15mm

CAD Drawings for Aperture = 15mm

This section shows an example of the 15mm aperture LCS design. Note that the transducer's inner diameter is the equivalent aperture here. The .STEP files for this example are also available.

The transducer dimensions are shown in [Figure 6-1](#).

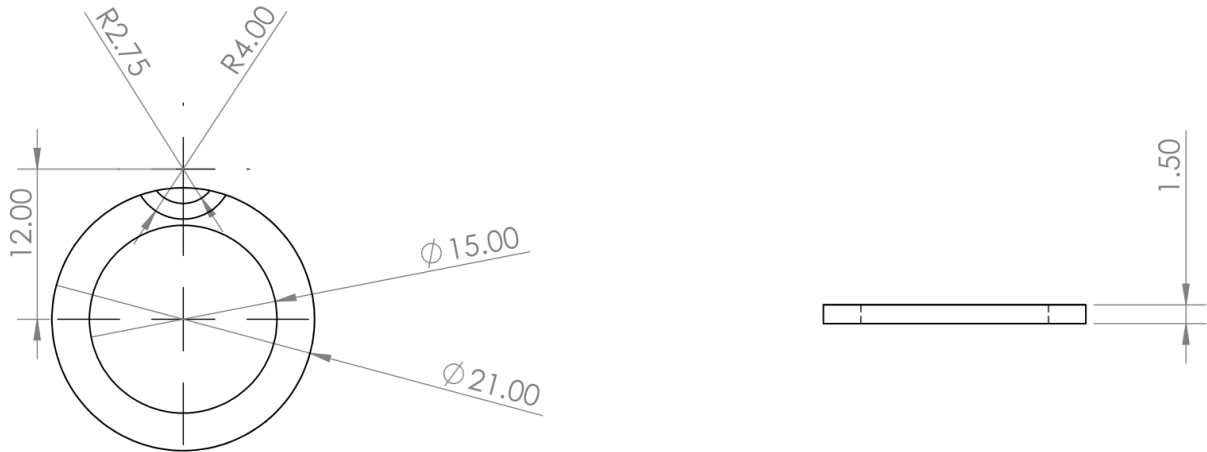


Figure 6-1. Transducer Dimensions

The lens dimensions are shown in [Figure 6-2](#).

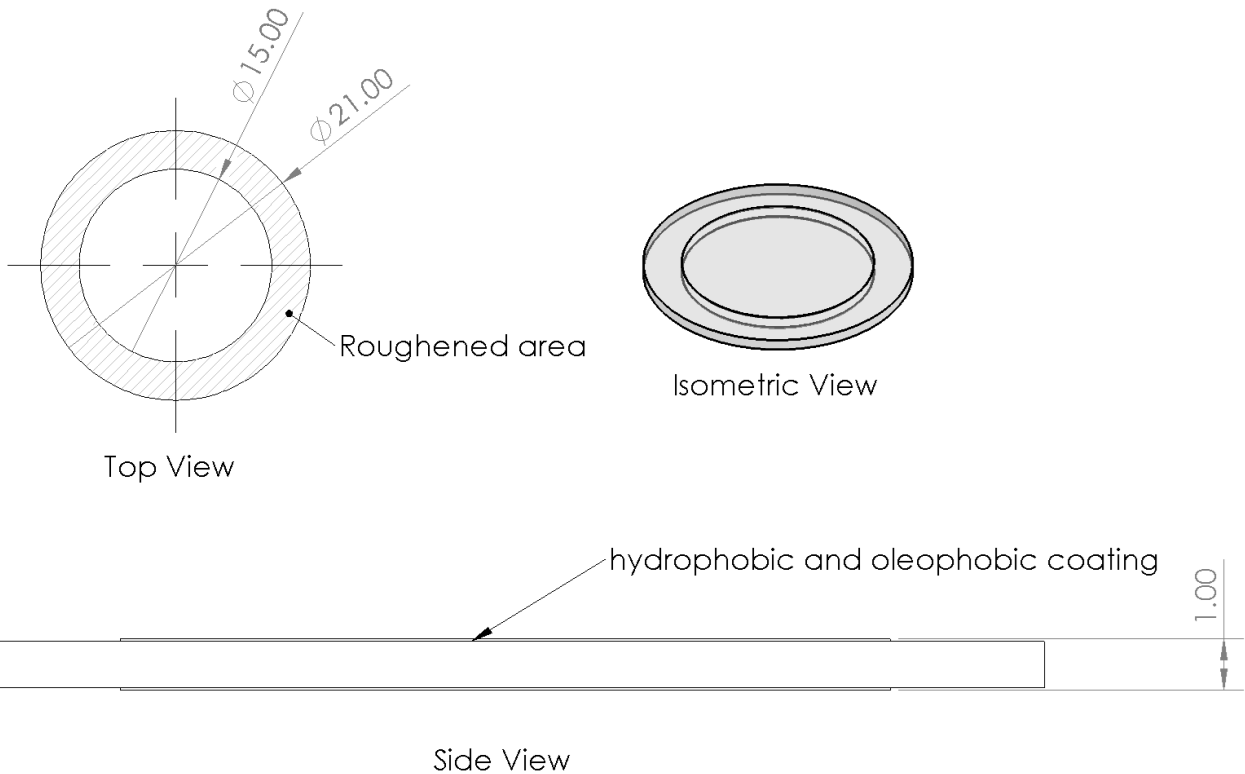


Figure 6-2. Lens Dimensions

The thin film dimensions are shown in [Figure 6-3](#).

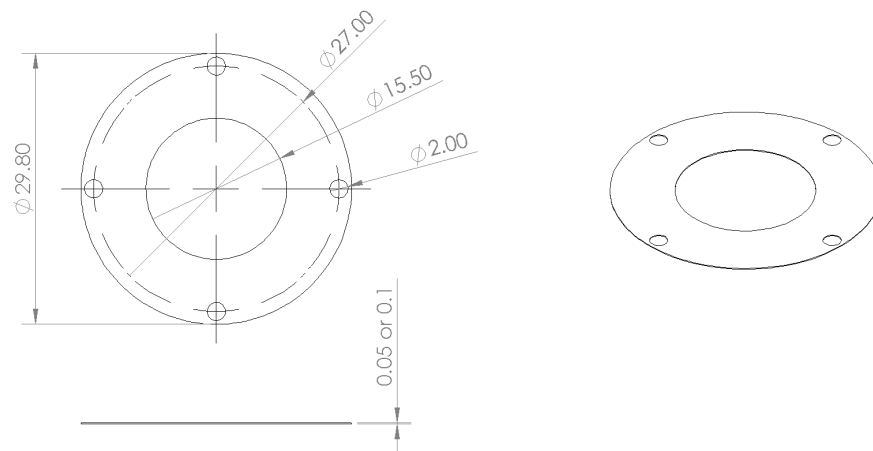


Figure 6-3. Thin Film Dimensions

The glue fixture base dimensions are shown in [Figure 6-4](#).

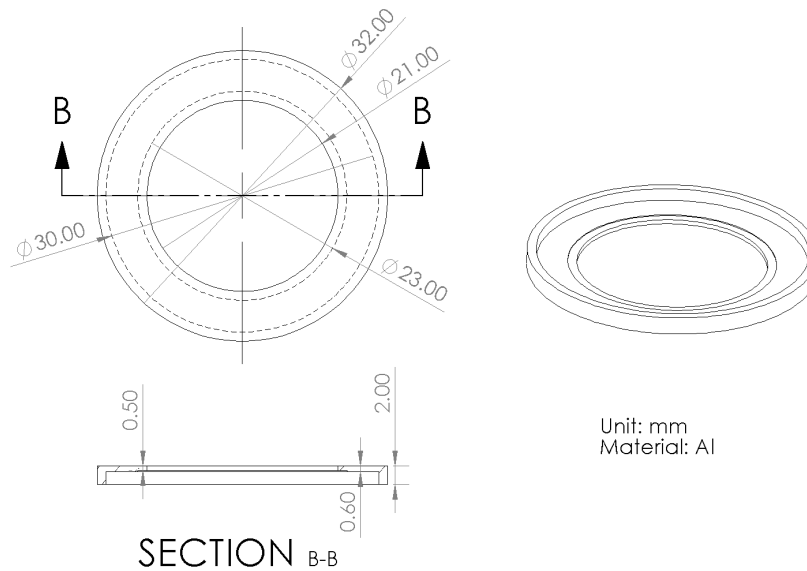


Figure 6-4. Glue Fixture Base Dimensions

The glue fixture cap dimensions are shown in [Figure 6-5](#).

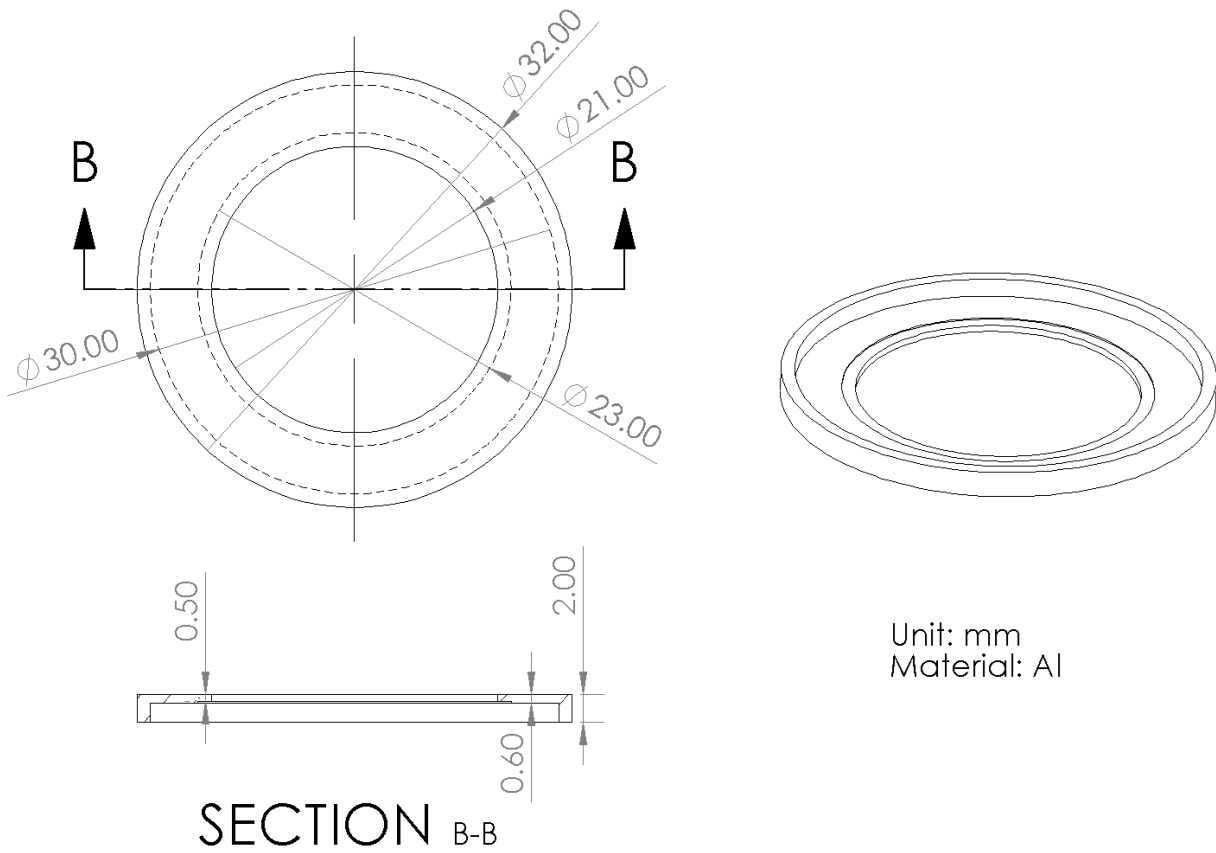


Figure 6-5. Glue Fixture Cap Dimensions

The housing base dimensions are shown in [Figure 6-6](#)

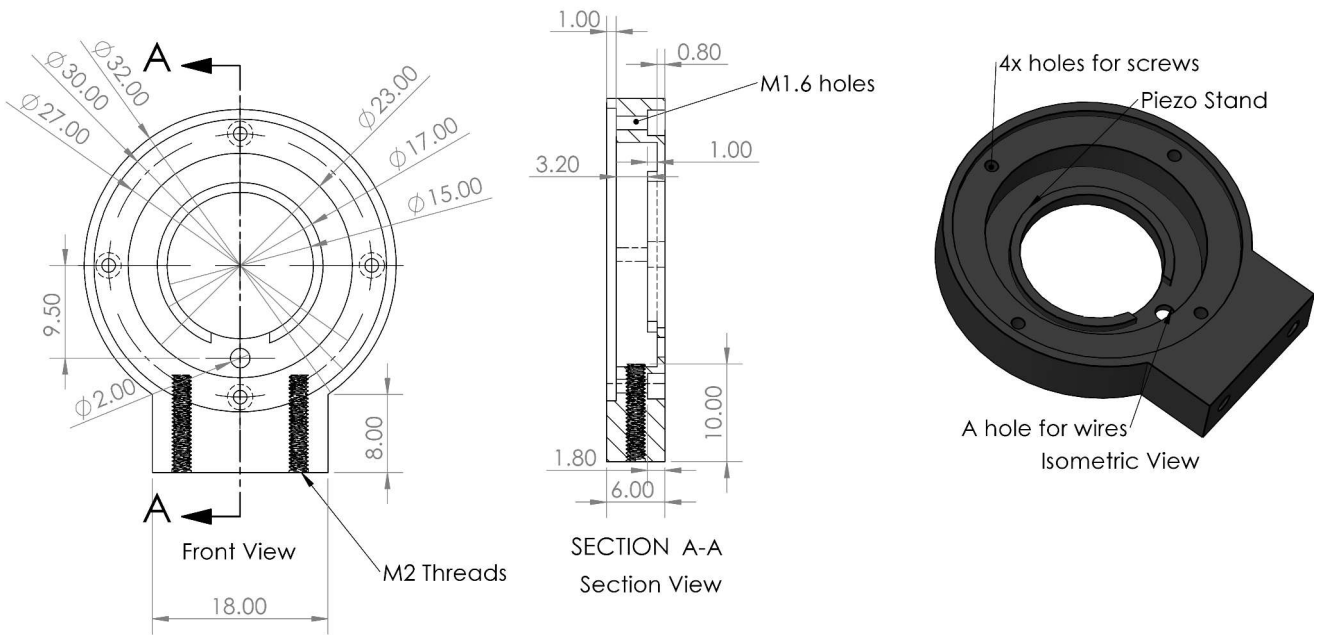


Figure 6-6. Housing Base Dimensions

The housing cap dimensions are shown in [Figure 6-7](#).

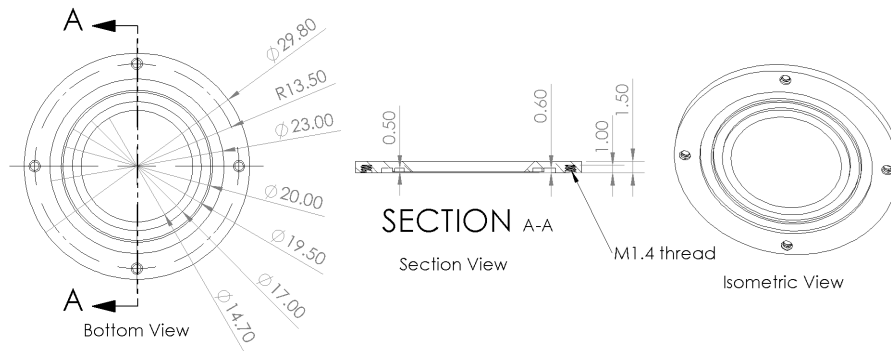


Figure 6-7. Housing Cap Dimensions

The housing foundation dimensions are shown in [Figure 6-8](#).

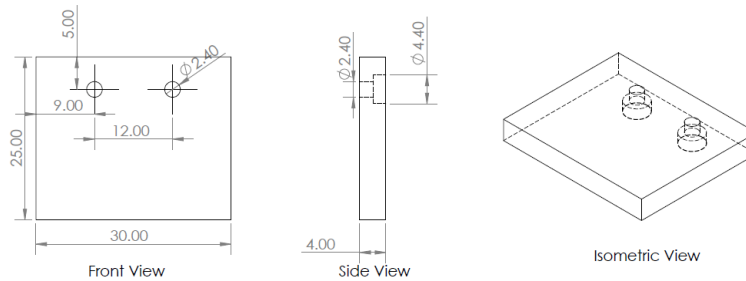


Figure 6-8. Housing Foundation Dimensions

The M2 screw dimensions are shown in [Figure 6-9](#).

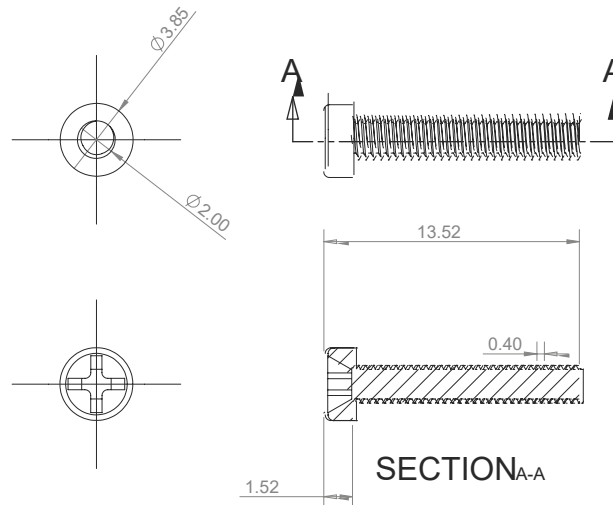


Figure 6-9. M2 Screw Dimensions

The M1.4 screw dimensions are shown in [Figure 6-10](#).

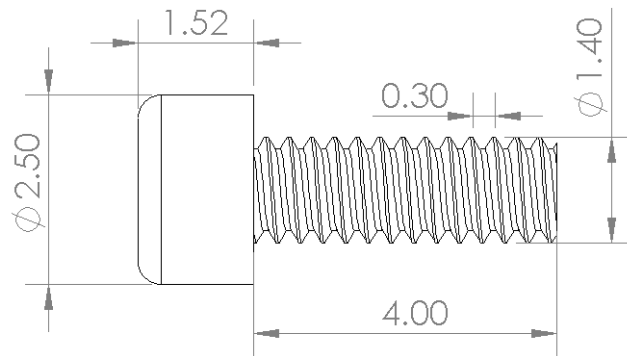


Figure 6-10. M1.4 Screw Dimensions

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, [ULC1001-Q1 Configurable Ultrasonic PWM Driver With I/V Sense Amplifiers](#), data sheet.
4. Texas Instruments, [ULC1001-DRV290XEVM User Guide.](#)

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