Application Note 2019

Ultrasonic Sensor Disks

For Automotive and Industrial Applications

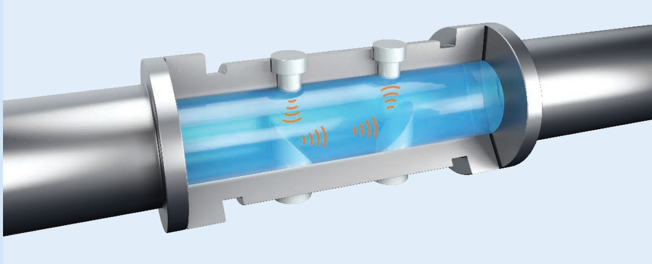
Ultrasonic sensor disks emit and detect inaudible soundwaves. A typical application example is distance measurement using the pulse-echo method.

Working principle

By measuring the time of flight t of an acoustic wave packet and at the known speed of sound in the respective medium c_{medium}, the travelled distance x can be calculated as $x = t/2 \cdot c_{medium}$. This method can be used for obstacle detection or distance measurement, where the wave packet is reflected from an obstacle. The method is also applicable for level measurement where the wave packet is reflected from the surface of a liquid.

By measuring the time of flight across a fixed distance, the speed of sound and related quantities like the density or composition of a medium can be determined.

Ultrasound can be used in air, gas, liquids and solids. With appropriate housing, ultrasonic sensors can be very robust towards dirt, temperature, chemicals and harsh environments. They offer a precise, robust, and contactless option for object detection as well as measurements of level, flow, or distance.



Ultrasonic Sensor Disks

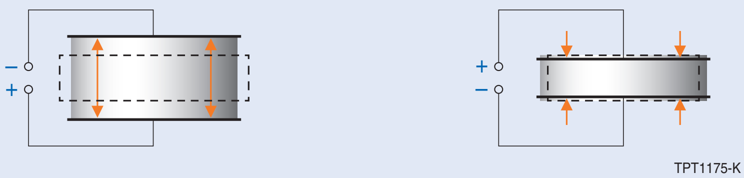
The piezoelectric effect

Ultrasonic sensor disks are based on the piezoelectric effect. Applying pressure to a piezoelectric material leads to the generation of a voltage across the electrode surfaces (*direct piezoelectric effect*). Conversely, when applying an electric field across a piezoelectric material, it will respond with expansion or contraction (*indirect piezoelectric effect)*. Making use of both effects enables the use of just a single ultrasonic sensor disk for both emission and detection of soundwaves.

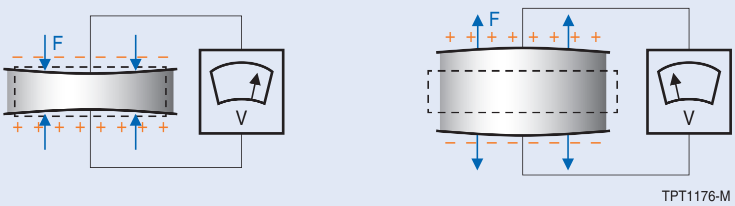
The piezoelectric effect was first observed in 1880 by the brothers Jacques and Pierre Curie in various crystalline materials such as quartz. However, a much stronger piezoelectric effect can be achieved in poly-crystalline ceramic materials such as lead zirconate-titanate (PZT), which is used for TDK's ultrasonic sensor disks. These materials are *ferroelectric* below their characteristic *Curie temperature* T_C. Permanent piezoelectric behavior can be induced in these materials by exposing them to a strong electric field (*poling*) during production.

Poling process

Indirect piezoelectric effect



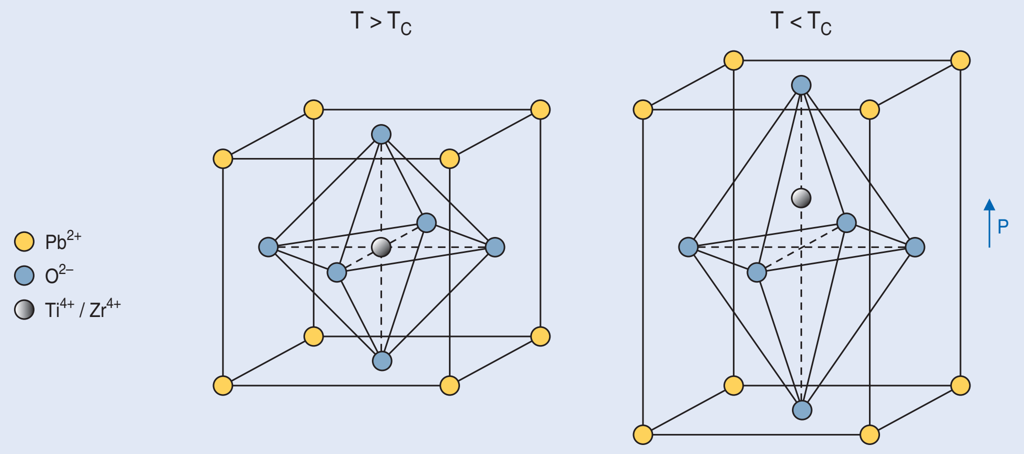
Direct piezoelectric effect



Ultrasonic transducer

Ultrasonic Sensor Disks

The piezoelectric effect – PZT crystal structure



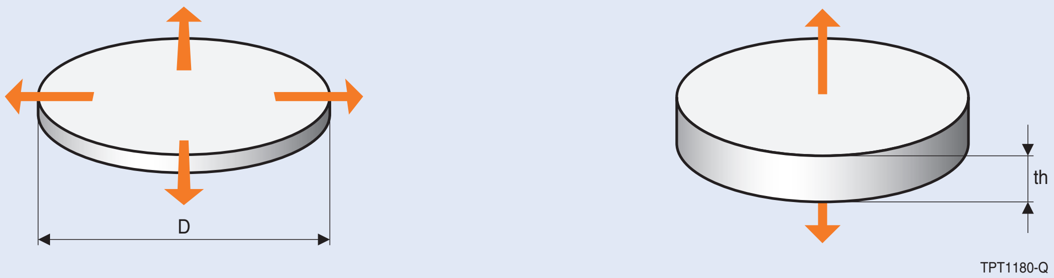
Dynamic behavior of free disks

Resonance modes

When applying an AC signal to the electrodes of a piezoelectric element, the material will respond with periodic expansion and contraction. Due to the material's intrinsic stiffness and mass, mechanical resonances occur at certain frequencies. When the element is operated in resonance, the amplitude of the oscillation – and therefore the sound pressure level and the sensitivity – can be heavily enhanced, an effect that is utilized in ultrasonic transducers.

These resonances can be categorized into different oscillation modes. TDK ultrasonic sensor disks are designed for either radial oscillation or thickness oscillation. The radial mode corresponds to a periodic oscillation of the radial dimension of the disk, while the thickness mode corresponds to a periodic oscillation of the disk's thickness.

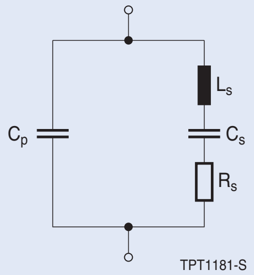
For each basic mode, higher order oscillation modes are possible, but in typical applications only the lowest oscillation mode is used. Any disk will exhibit both radial and thickness mode resonances, but the design is optimized for only one mode.



Radial mode *Thickness mode*

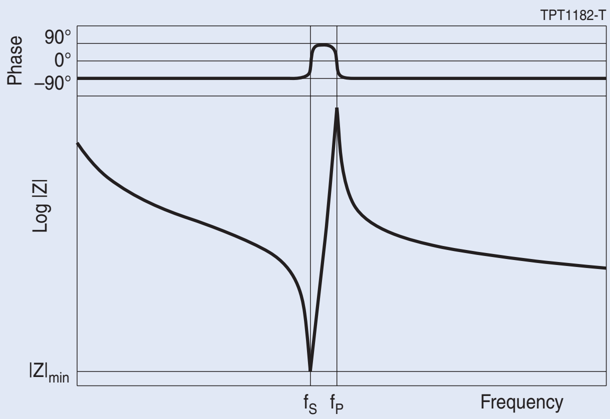
Equivalent electrical circuit

Even though the resonance of the ultrasonic transducer is a mechanical effect, it can be modeled electrically using an equivalent oscillator circuit for frequencies in the vicinity of the resonance.



- C_p represents the electrical capacitance between the electrodes
- C_s, L_s, R_s represent mechanical properties of the ceramic

The relation between electrical impedance and excitation frequency around the resonance can be described by the following diagram.



The resonance has two distinct frequencies, the series resonance f_s with minimal impedance Z_{min} and the *parallel resonance* f_p. Further parameters can be calculated from the electrical impedance measurement.

For example, the coupling factor k_{eff}, a measure for the conversion rate of mechanical and electrical energy, can be calculated as

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2}$$

The calculation of the coupling factor depends on the boundary conditions of the measurement. Slightly different coupling factors k_t and k_p exist for disks oscillating in thickness and radial mode.

After determining the individual components of the equivalent circuit, the mechanical quality factor Q_m of the free disk can be calculated as

$$Q_m = \frac{1}{R_s}\sqrt{\frac{L_s}{C_s}}$$

Note that if the ultrasonic sensor disk is integrated into a module, the disk can no longer resonate freely. The operating frequency, quality factor and other properties of the module will be determined by the entire system that consists of the piezo disk, the membrane and surrounding materials. The controller and excitation signal should be chosen accordingly.

Ultrasonic Sensor Disks

Design guide for ultrasonic sensor disks

General considerations

Beam directivity

Due to the short wavelength in comparison to the area of an ultrasonic sensor disk (or speaker), ultrasound can be emitted in a very directed beam.

In general, the directivity depends on the ratio of the diameter of the oscillating membrane to the wavelength, where a larger membrane diameter leads to a more focused beam. Note that the sensitivity during reception has the same directivity, and a too focused beam may cause issues if the echo is reflected off an irregular object and does not reach the receiver.

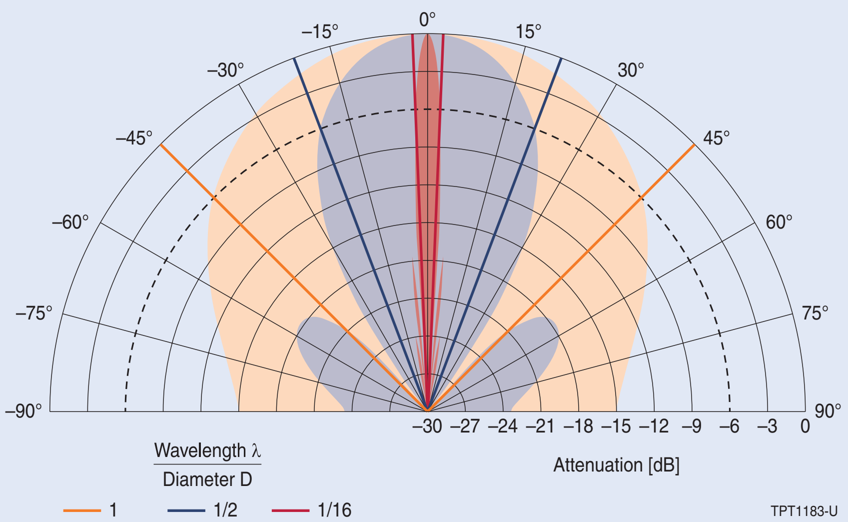
Furthermore, the presence of side lobes leads to reduced power in the main beam and possible interference. The width of the main lobe (6 dB drop of sound pressure level compared to the forward direction) can be estimated using

$$\theta_{-6dB} \approx \arcsin(0.704\,\frac{\lambda}{D})$$

For example, for a transducer with membrane diameter 12 mm, operating at 2 MHz in water:

$$\lambda = \frac{f}{c_{medium}} = \frac{2\text{ MHz}}{1500\,\frac{m}{s}} \approx 750\text{ µm and } \frac{\lambda}{D} \approx \frac{1}{16} \Rightarrow \theta_{-6dB} \approx 5°$$

The following diagram shows the directivity function, calculated for different ratios of membrane diameter to wavelength:



Directivity of sound pressure level calculated for various membrane geometries (unclamped).

In some applications, e.g. sensors mounted close to the ground, a varying directivity is desired in the horizontal versus vertical plane, which can be achieved by using an elliptical membrane shape.

Choice of application frequency

Higher frequencies mean shorter wavelengths, and thus better precision in measurements. This leads, for example to more accurate level measurement or to detection of smaller objects. Furthermore, in pulse-echo measurements, a shorter wavelength leads to spatially shorter pulses, which allows for the measurement of shorter distances. On the other hand, higher frequencies shorten the measurement range of the sensor due to enhanced attenuation.

Liquid transducers

Frequency of transducer disk

Due to the low dissipation of sound in liquids, high frequency transducers (MHz range) can be used for such applications. These transducers make use of the **thickness mode** oscillation. The resonance frequency of the free disk is defined by the thickness of the disk *th* and the frequency constant N_{th}

$$th = \frac{N_{th}}{f_{res,th}}$$

The sensitivity and the directivity of the sensor will depend on the disk diameter D as described above.

Impedance matching

If sound is transmitted from one medium to another, a large portion may be reflected, depending on the acoustic impedance mismatch of the two materials. The acoustic impedance of a material Z_{mat} can be calculated from its density ρ_{mat} and the speed of sound c_{mat}

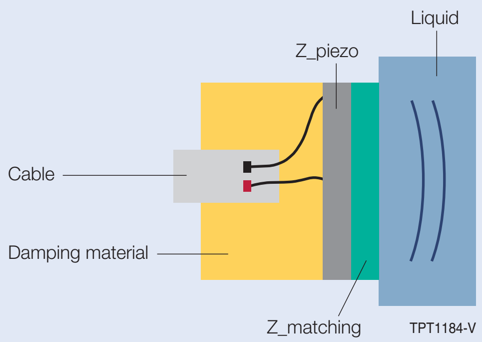
$$Z_{mat} = \rho_{mat} \cdot c_{mat}$$

For example, the acoustic impedance of PZT ceramic is typically 32 MRayl, while the acoustic impedance of water is approximately 1.48 MRayl.

The reflection coefficient for the sound pressure of a wave travelling from medium 1 into medium 2 is given by

$$\Gamma_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

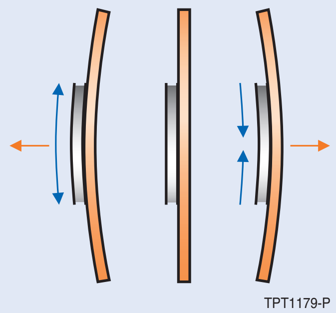
To achieve the best possible signal transfer, impedance matching layers can be used, ideally with a thickness corresponding to $\lambda/4$ and acoustic impedance $Z_M = \sqrt{Z_1 Z_2}$. Impedance mismatch should be considered for all material interfaces, and materials should be chosen accordingly.



Ultrasonic Sensor Disks

Air transducers

Due to the frequency dependent absorption of sound in air, the frequency chosen for air ultrasound applications must be much lower than in liquids.



Membrane bending using radial mode oscillation of piezo disk.

Lower frequency ultrasonic transducers (e.g. air transducers) typically make use of a piezo disk that oscillates in **radial mode** and is attached to a membrane. The radial oscillation of the disk then is transformed into a bending motion of the membrane.

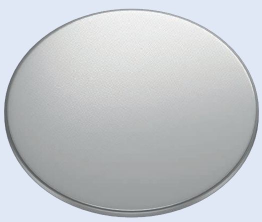
The resonance frequency of a free piezo disk oscillating in radial mode depends on the disk diameter D and can be calculated using the material specific radial frequency constant N_{rad} from

$$f_{res,rad} = \frac{N_{rad}}{D}$$

The characteristics of the transducer module, i.e. operation frequency, Q factor, range, directivity and sensitivity, are determined by the design of the entire module, for example by the thickness and diameter of the membrane and the choice of membrane and absorber materials.

Metallization options

TDK offers both screen printed and sputtered metallization, depending on the desired electrical connection (e.g. bonding or soldering). Metallization wrap around is available, allowing connection of both electrodes to one side of the disk. In general, a possible influence of the wiring on the acoustic properties has to be taken into account.



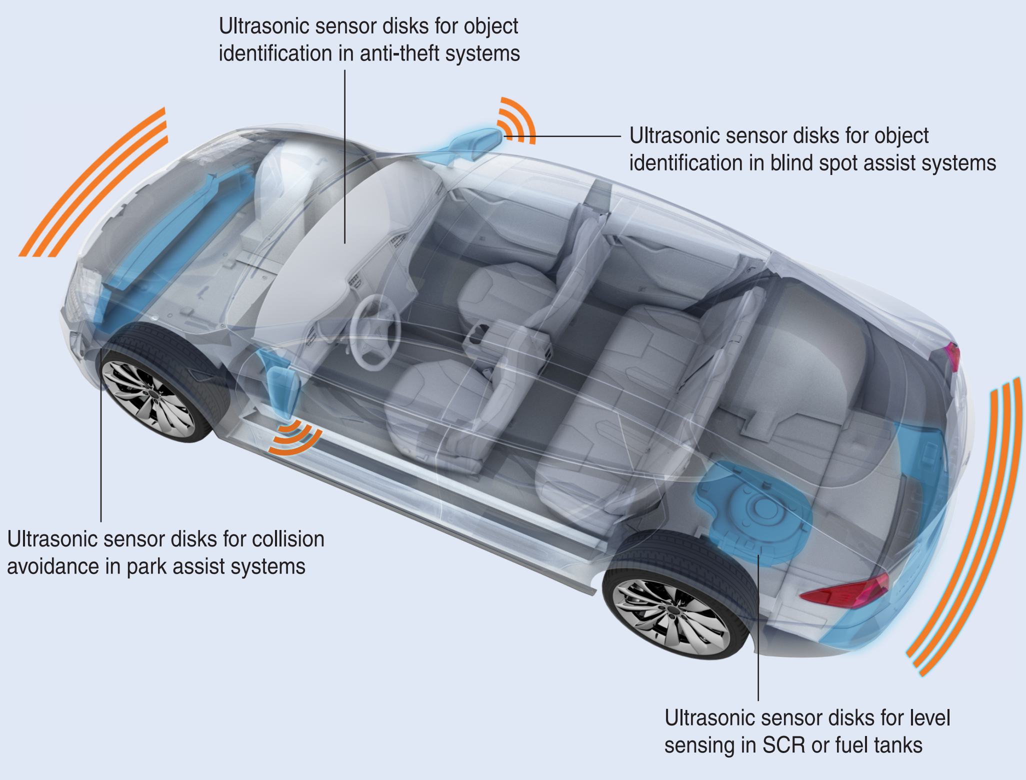
Ultrasonic Sensor Disks

Application examples

Ultrasonic sensor disks can be used for following applications:

Automotive

- Ultrasonic park assist systems
- Blind spot assist systems
- Level sensing for fuel or selective catalytic reduction (SCR) tanks
- Interior monitoring and anti-theft systems



Ultrasonic Sensor Disks

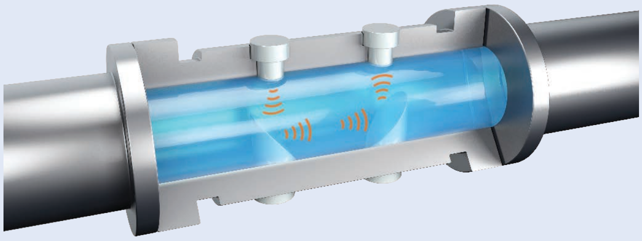
Application examples

Industry

- Flow meters for fluids or gases
- Level sensing for fluids or bulk materials
- Collision avoidance systems
- Concentration measurement systems

Ultrasonic sensor disks for collision avoidance systems in autonomous industrial transport robots

Ultrasonic sensor disks for flow metering systems in gas or fluid tubes



Ultrasonic sensor disks for level sensing systems for fluids or bulk materials in silos

Ultrasonic Sensor Disks

Product range			
Typical material parameters for ultrasonic sensor applications			
Classification (DOD-STD-1376A)	Navy II		
Classification (EN 50324-1)	200		
Dielectric constant (open)	$\varepsilon_{33,r}^{T}$	1800	
Dielectric loss	tan δ	20	10^{-3}
Curie temperature	T_C	340	°C
Density	ρ	7800	kg/m^3
Piezoelectric constant	d_{33}	420	pC/N
Frequency constant	N_{th}	2040	Hz • m
	N_p	1950	Hz • m
Electromechanical coupling factor	k_p	0.65	
	k_t	0.49	
Mechanical quality factor	Q_m	90	
Elastic compliance	s_{33}^{E}	19.6	10^{-12} m^2/N

For further applications or information about handling, mounting and operations, please check our data sheet or contact our sales team and let us know your requirements.

- Frequency
- Diameter
- Wrap-around
- Application
- Gluing, bonding or soldering

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