Introduction to Ultrasonic Drivers

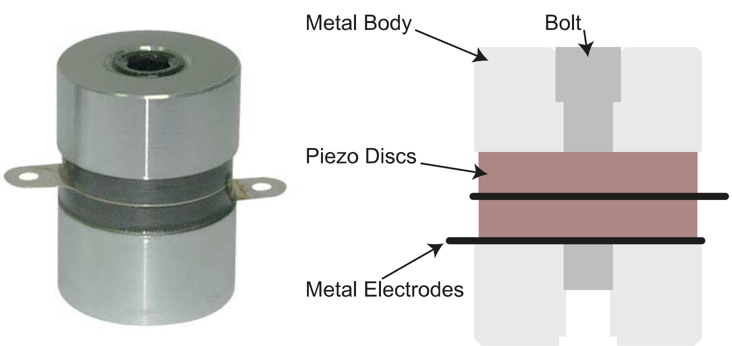
Ultrasonic Applications

Applications of ultrasonic technology can be broadly grouped into two categories: sensing, and actuation. Sensing applications include ultrasonic imaging, sonar, and fluid detection. These applications, which are not addressed in this tutorial, typically require both pulse transmission and reception. In contrast, the topic of this tutorial is actuation applications which require the continuous, or semi-continuous generation of high-power ultrasonic vibration. Applications include:

- Medical devices such as scalpels and dental tools
- Machining, drilling, and cutting tools
- Welding for plastics and metals
- Ultrasonic cleaning
- Sonication for fluid mixing and chemical reactions

Ultrasonic Actuators

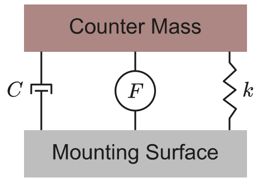
The most common type of ultrasonic actuator is the bolt-clamped Langevin transducer, shown in the image below. These actuators consist of piezoelectric discs sandwiched between metal electrodes. The centre bolt preloads the structure with a compressive force that is sufficient to prevent tensile forces during operation. The threaded centre hole is also used to mount the transducer onto a load, or concentrating horn.



Bolt-clamped Langevin transducer with two piezoelectric layers (www.mmech.com)

When a voltage is applied to the piezoelectric layers, a proportional force is generated in the vertical direction which displaces the two metal ends. When mounted to a surface, the behaviour of the Langevin transducer can be represented by the lumped parameter system shown below. In this model, F represents the piezoelectric force, k is the stiffness of the piezoelectric layers in parallel with the preload bolt, and C is the viscous damping of the system. This system has a resonance frequency:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$



Mechanical model showing the equivalent mass, stiffness k, dissipation C, and force F.

Mechanical Dynamics

In the following figure, the terminal impedance of the transducer is plotted with the mechanical frequency response. The mechanical transfer function is represented by a second order system:

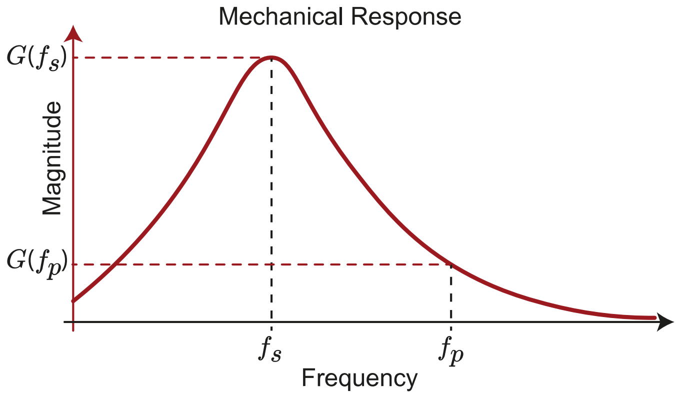
$$G(s) = \frac{x(s)}{V(s)} = \frac{\alpha}{s^2 + \frac{\omega_1 s}{Q} + \omega_1^2}$$

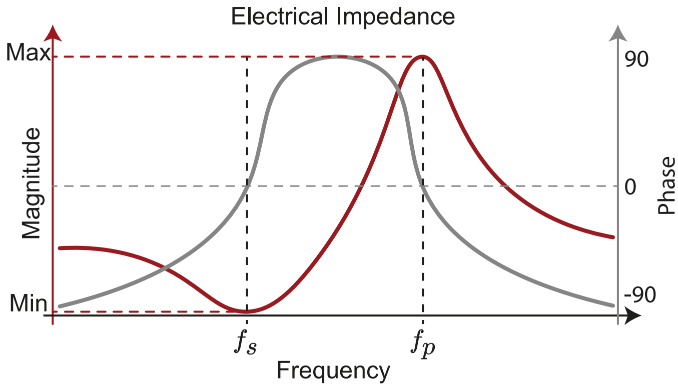
where, x is the displacement, α is the sensitivity of the transducer, Q is the quality factor, and $\omega_1 = 2\pi f_1$ is the resonance frequency. The quality factor Q determines the system bandwidth and the gain at resonance relative to the static displacement. The quality factor is related to the mechanical dissipation C by the equation:

$$Q = \sqrt{Mk}/C$$

The sensitivity at resonance is approximately $G(j\omega_1 = \alpha Q = \alpha\sqrt{Mk}/C)$. That is, higher mechanical loss C, reduces the quality factor and vibration amplitude at resonance.

When the transducer is coupled to a mechanical load, the dissipation C becomes the sum of the internal actuator dissipation and the dissipation of the mechanical load C_{ext} which represents real mechanical power delivered to the load. Most ultrasonic actuators are designed so that dissipation is dominated by external work delivered to the load. Since the displacement at resonance is inversely proportional to the dissipation C, large changes in vibration amplitude can result from variations in load power dissipation.



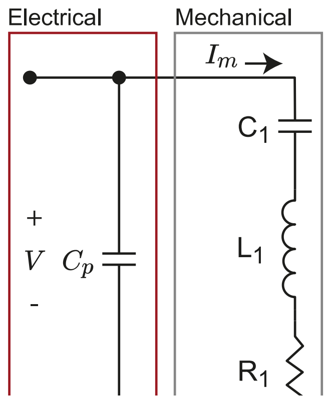


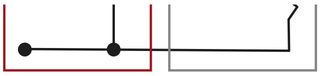
Electrical and mechanical response of an ultrasonic transducer.

Series Resonance Model

The electrical response is dominated by an impedance minima at f_s, known as the series resonance, which is approximately equal to the mechanical resonance frequency $f_1 \approx f_s$. Near the resonance frequency, an ultrasonic actuator can be adequately modelled as the series equivalent circuit shown below, known as the Butterworth Van-Dyke model. This model includes an electrical part which represents the transducer capacitance, and an equivalent circuit which represents the mechanical response of the transducer. The relationship between the electrical and mechanical quantities are:

- Voltage V is proportional to force F
- Current I_m is proportional to velocity $\dot{x}$
- Inductance L_1 is proportional to mass M
- Resistance R_1 is proportional to dissipation C
- Capacitance C_1 is inversely proportional to stiffness k





Series equivalent circuit valid near the series resonance frequency.

At the series resonance frequency, the reactance of C_1 and L_1 sum to zero, leaving only the resistance R_1. Therefore, at resonance, the total power delivered to the transducer is:

$$P = \frac{V_{rms}^2}{R_1} = I_{rms}^2 R_1$$

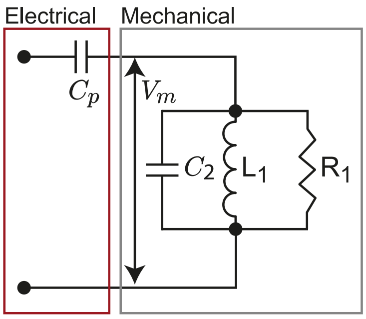
It should be noted that the resistance R_1 is proportional to dissipation which includes the internal and external dissipation. Large variations in amplitude and power can occur with relatively small changes in mechanical dissipation. For example, consider a voltage driven ultrasonic transducer with a loaded resistance of $R_1 = 20\Omega$. If the system is driven at resonance and the load is removed, the equivalent resistance may reduce to 2 Ω which will increase power dissipation by a factor of 10; furthermore, this power dissipation will occur in the actuator as heat.

In series resonance operation, the voltage is proportional to developed force, and current is proportional to velocity. Therefore, constant current excitation provides approximately constant vibration amplitude. In high-power drives, direct implementation of a constant current source is less practical than a voltage source. However, a voltage source can be implemented with feedback regulation of the load current. This topic is discussed further in “Power Control”.

Parallel Resonance Model

In addition to the series resonance, the electrical response also exhibits an impedance maxima, known as the parallel resonance. At the parallel resonance, the equivalent circuit is the dual of the Butterworth Van-Dyke model, as illustrated below. The relationship between the electrical and mechanical quantities are:

- Voltage V_m is proportional to velocity $\dot{x}$
- Current I is proportional to force F
- Inductance L_2 is inversely proportional to stiffness k
- Resistance R_2 is inversely proportional to dissipation C



Parallel equivalent circuit valid near the parallel resonance frequency.

At the parallel resonance frequency, the inductance is at resonance with the transducer capacitance, and the impedance again becomes resistive R_2, however, with a much larger value than R_1. It can be shown that the effective Q factor of the parallel resonance is much lower than the series resonance. The reason can be observed in the mechanical frequency response. The parallel resonance frequency f_p is significantly higher than the mechanical resonance frequency. It can be observed that the slope of $|G(j\omega)|$ is much lower at f_p, therefore, variations in resonance frequency and dissipation have a much smaller effect on the vibration amplitude. Therefore, operation at the parallel resonance is well suited to applications where constant vibration amplitude is desired with reduced sensitivity to changes in resonance frequency and load dissipation.

A disadvantage of the parallel resonance is significantly higher operating impedance which requires higher voltage to achieve an identical vibration amplitude and power. Although efficiency and maximum output power are identical, the higher voltage may require greater safety precautions. A further disadvantage is that pure sine wave drivers are required. Any harmonics in the drive signal will encounter a low impedance resulting in large reactive current flow.

In parallel resonance operation, the voltage is proportional to velocity. Therefore, a constant voltage drive provides approximately constant vibration amplitude.

Comparison of Series and Parallel Operating Frequencies

The operating characteristics of the series and parallel resonance frequencies are compared in the table below. Although both configurations achieve identical power output, the series resonance requires lower voltage but results in higher heat dissipation in the actuator. The parallel resonance provides constant vibration amplitude with voltage excitation and less actuator heating but requires a higher operating voltage and sine-wave driver.

	Series Resonance	Parallel Resonance
Impedance	Low, 20 Ω	High, 400 Ω
Required Voltage	Low, 50 Vrms	High, 224 Vrms

Maximum Power	Identical, 125 W	Identical, 125 W
Driver type	Square, or sine wave	Sine wave
Best suited to applications that require	High-power (>200W)	High precision
Example application	Ultrasonic cleaning	Precision machining
Constant current excitation results in	Constant velocity	Constant force
Constant voltage excitation results in	Constant force	Constant velocity
Higher load dissipation results in	Increased resistance	Decreased resistance

Comparison of the series and parallel resonance conditions, with example quantities.

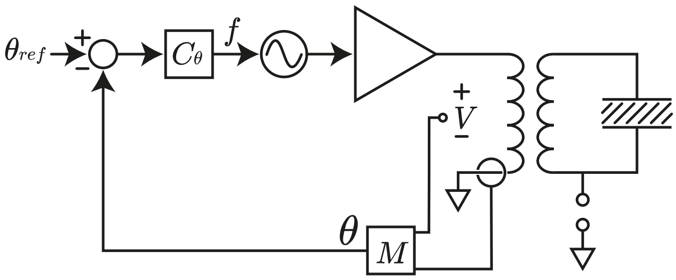
Resonance Tracking

An important function of an ultrasonic driver is to locate and track the desired resonance frequency. A fast transient response is desirable to minimize start up delay and compensate for fast load changes during operation. Since most ultrasonic systems do not have direct access to vibration measurement, resonance tracking is performed using the electrical impedance. Referring to the electrical impedance plot, the resonance frequency can be tracked by simply varying the drive frequency to maximize the current magnitude. Or, if operating at the parallel resonance, by minimizing the current magnitude. A disadvantage of this method is the zero slope of the impedance magnitude at resonance, therefore, the sensitivity is minimum at the desired operating point. As a result, this approach results in large frequency deviations and a slow response. Furthermore, this method is disturbed by changes in load dissipation which naturally vary the current magnitude. Despite the disadvantages, this method is simple to implement and may be suitable for applications with stable load conditions.

Phase tracking is an alternative method where the drive frequency is varied to force the impedance phase to zero, which occurs at both resonance conditions. This method requires a more complex controller but is significantly faster and more accurate than other methods because the slope of the phase curve is maximum at both of the resonance frequencies.

An additional consideration with phase tracking is the choice of phase set point. This can be chosen to operate slightly above or below resonance, which may provide higher immunity to load variations at the expense of electrical efficiency. Furthermore, systems with low quality factor may have phase responses that are non-zero at resonance, particularly for the parallel resonance. In such cases, an impedance response should be performed to identify the desired operating point.

An example implementation of phase control in the PDUS210 driver is described in the diagram below. A phase detector is used to measure the load impedance phase angle from the primary voltage and current. The phase controller $C_\theta(s)$ regulates the load phase to the set point θ_{ref} by driving the frequency of a sine-wave oscillator.

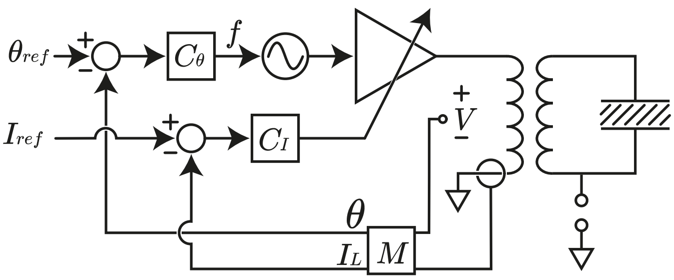


Phase control loop in the PDUS210 driver.

Control of Vibration Amplitude

To achieve constant vibration amplitude, a transducer can be driven with constant voltage at the parallel resonance frequency, or constant current at the series resonance frequency.

In high power applications, constant current is achieved with the feedback loop illustrated below. In this mode, the primary objective is to regulate current, followed by phase tracking.

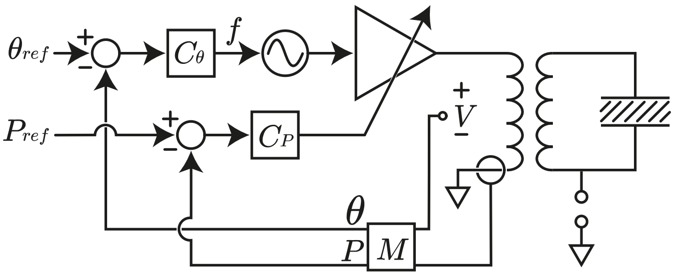


Current control loop in the PDUS210 driver.

Power Control

When operating with constant vibration amplitude, there is no control over how much power is dissipated by the transducer or delivered to the load. However, drivers such as the PDUS210 allow limits to be set on the maximum power regardless of the operating mode.

In many applications it is desirable to directly regulate the load power since this is proportional to considerations such as work-piece heating and cavitation. As shown in the diagram below, the power control loop varies the excitation voltage to maintain a constant load power. In applications such as ultrasonic machining where the tool is intermittently in and out of contact with the work piece, the power control loop is best disabled while the tool is unloaded. Power control is most effectively combined with constant current excitation while operating at series resonance, or constant voltage excitation when operating at parallel resonance.



Phase and power control loop in the PDUS210 driver.

A third option for power control is to regulate the current magnitude to a set point. This is useful in series resonance applications since current is proportional to velocity.

Choosing the Voltage Range

The PDUS210 is available in voltage ranges from 17 Vrms to 282 Vrms, which correspond to impedances ranging from 1.5 Ω to 400 Ω. The optimal choice is determined by the transducer impedance at resonance, and the choice of series or parallel resonance.

The first step is to measure the impedance of the transducer at the series and parallel resonance. This can be performed with an impedance analyser or simply a signal generator and oscilloscope. If possible, these tests should be performed at moderate power with both minimum and maximum load conditions. Fill out the values in the table below:

	Unloaded	Fully Loaded
Series Resonance	$R_{1,min}$:	$R_{1,max}$:
Parallel Resonance	$R_{2,max}$:	$R_{2,min}$:

Table of operating impedance at resonance.

Series Resonance

For operation at the series resonance, the most suitable amplifier has an optimal impedance which is close to, or slightly greater than the fully loaded impedance. Since transducer impedance tends to increase with applied power, an amplifier with a higher optimal impedance is recommended. If the amplifier has a higher optimal impedance than the load, the current limit will be reached before the voltage limit, and the maximum achievable output power is:

$$P = I_{rms}^2 R_{1,max}$$

where I_{rms} is the maximum driver current.

Parallel Resonance

For operation at the parallel resonance, the most suitable amplifier has an optimal impedance which is close to, or slightly less than the fully loaded impedance. Since transducer impedance tends to reduce with applied power, an amplifier with a lower optimal impedance is recommended. If the amplifier has a lower optimal impedance than the load, the voltage limit will be reached before the current limit, and the maximum achievable output power is:

$$P = \frac{V_{rms}^2}{R_{2,min}}$$

where V_{rms} is the maximum driver voltage.

Custom Voltage Range

Custom voltage ranges and optimal impedances are available to provide maximum power for a specific transducers.

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