Rheonics vibrational sensor technology

Vibrational fluid sensors demystified

Fluid properties sensors based on vibrating resonators fall into two categories: density and viscosity measurement.

A resonant structure immersed in a fluid is influenced in two ways:

- Resonant frequency is depressed by mass loading of the resonator by the fluid. Its apparent mass is increased by the fluid it moves due to its own motion. This increased apparent mass decreases the frequency of the resonator.
- Damping is increased by viscous dissipation in the fluid. Friction of the fluid being sheared by its movement carries energy away from the resonator. This energy dissipated by the fluid increases the damping of the resonator

The measurable properties of the resonator – its resonant frequency and damping – are both influenced by the properties of the fluid.

The denser the fluid, the more the mass loading. Therefore, the sensor's resonant frequency is an indication of the fluid's density.

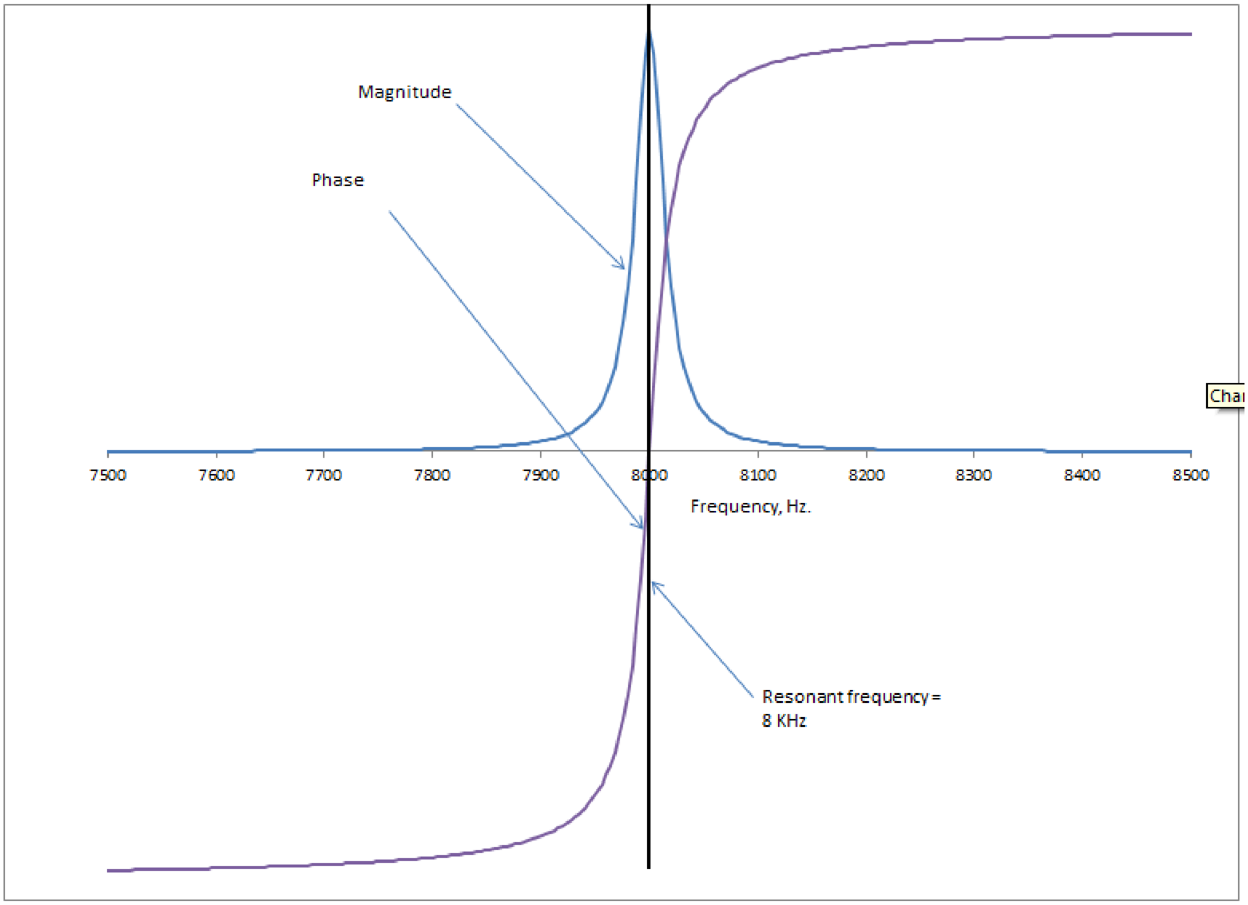
The more viscous the fluid, the more energy is dissipated by the sensor's motion. Therefore, its damping is an indication of the fluid's viscosity.

A sensor's vibrational mode and geometric shape both influence the way in which the sensor will respond to viscosity and density of the fluid. By selecting a mode, and shaping the sensor properly, we can adjust its sensitivity to both mass loading and viscous damping.

A resonator's response to an oscillating driving force depends on three factors:

- its "natural" or resonant frequency – the frequency it would oscillate at if excited by a "kick" or an impulsive force
- the resonator's damping, or energy dissipation per cycle
- the frequency of the driving force.

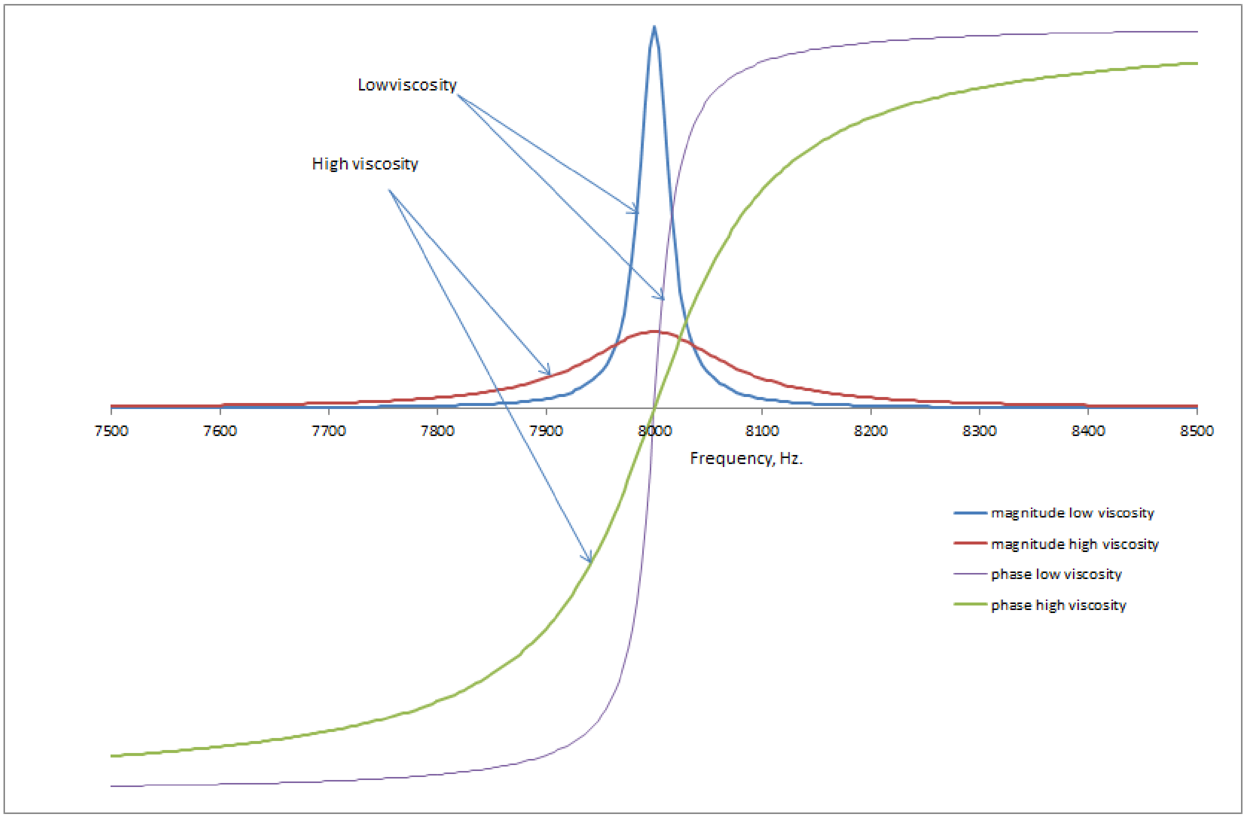
If we plot the response of a typical resonator as a function of the driving frequency, we get two curves:



Amplitude and phase response of a resonator in the neighborhood of its resonant frequency

The “magnitude” curve shows how the amplitude of the resonator’s vibration reaches a maximum when excited at its resonant frequency (in this case, 8 kHz.) and trails off at higher and lower frequencies. Also, the “phase” curve shows the amount by which the response of the resonator trails behind the excitation force. At frequencies far below the resonant frequency, the response is nearly in phase with the excitation. At the resonant frequency, the response trails the excitation by 90° of phase shift. Far above the resonant frequency, the response trails the excitation by nearly 180°.

If the same resonator is immersed in a second fluid with identical density but higher viscosity than the first, its resonant curves are influenced as shown in the next diagram:



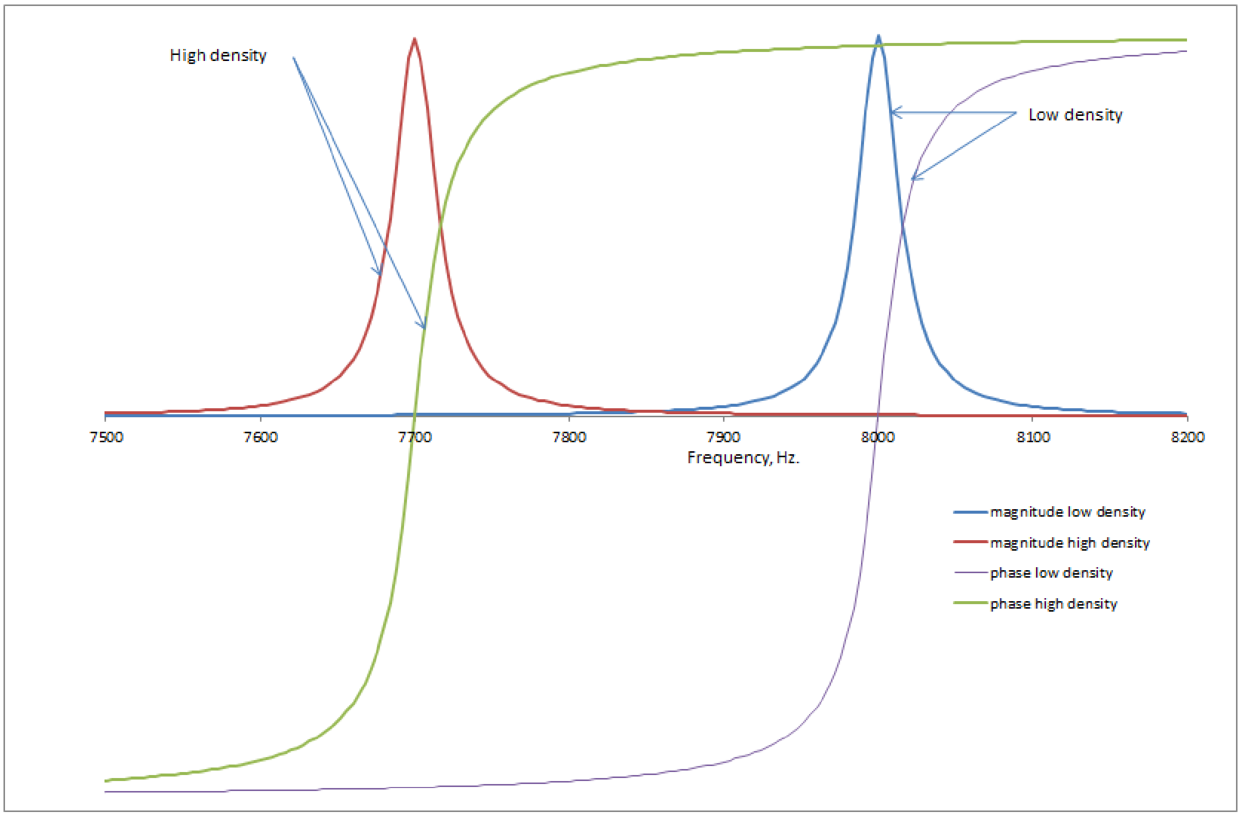
Response of the same resonator immersed in two fluids of different viscosities

The higher-viscosity fluid increases the damping of the resonator without much effect on its resonant frequency. The increased damping has two effects:

- It broadens the curve of the amplitude as a function of frequency while decreasing its peak amplitude
- It makes the slope of the phase curve smaller in the vicinity of the resonant frequency.

It is this second effect, the change in slope of the phase vs. frequency curve, which forms the basis of rheonics' measurement platform.

Now, if the same resonator is immersed in a second fluid with the same viscosity but higher density than the first, the main effect will be a displacement of the resonant peak toward a lower frequency:



Response of the same resonator immersed in two fluids of different densities

The Rheonics advantage

Rheonics currently manufactures fluid properties sensors with two different configurations, the DV family and the SRV.

- DV – Density Viscosity – sensors measure *both* density and viscosity simultaneously. They are the first commercially available family of vibrational sensors to give accurate, repeatable values for both viscosity and density – and to do it at temperatures up to and beyond 200 °C and at pressures in excess of 2000 bars (30,000 PSI).
- SRV – Symmetric Resonator Viscometer – measures the product of density and viscosity, reproducibly with high accuracy up to viscosities in excess of 50,000 cP!

Rheonics sensor systems are the best in their class because of two advantages:

- Ultra-stable resonators, built on a foundation of more than 30 years' experience in materials, vibrational dynamics and fluid-resonator interaction modeling that add up to the industry's most robust, repeatable and well-characterized sensors.

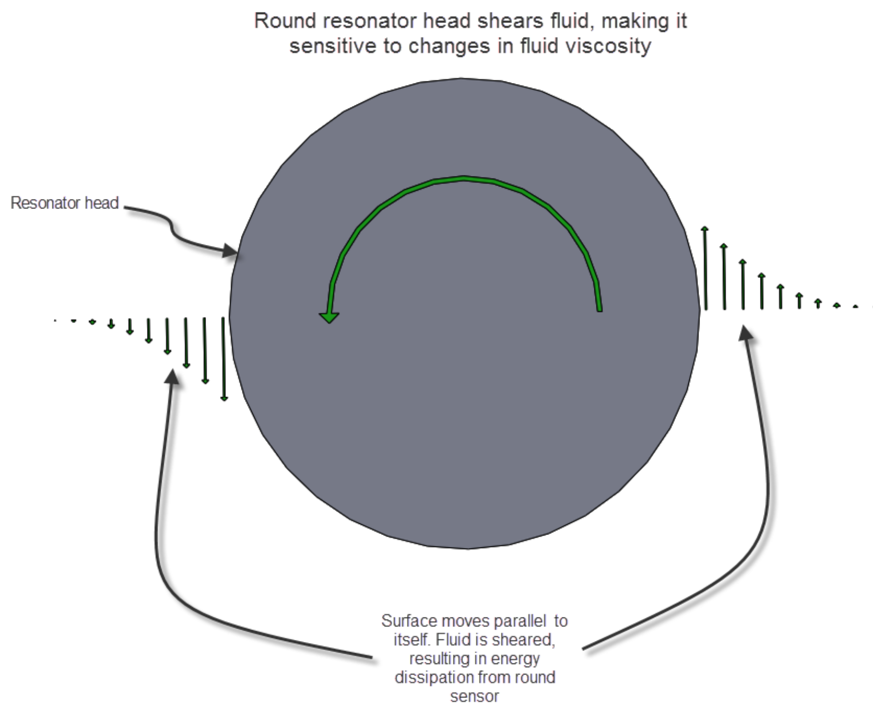
- Sophisticated, patented 3rd generation electronics to drive our sensors and evaluate their response. Great electronics, combined with comprehensive computational models, make our evaluation units the fastest, most accurate in the industry.

Torsional vibrations make accurate sensors.

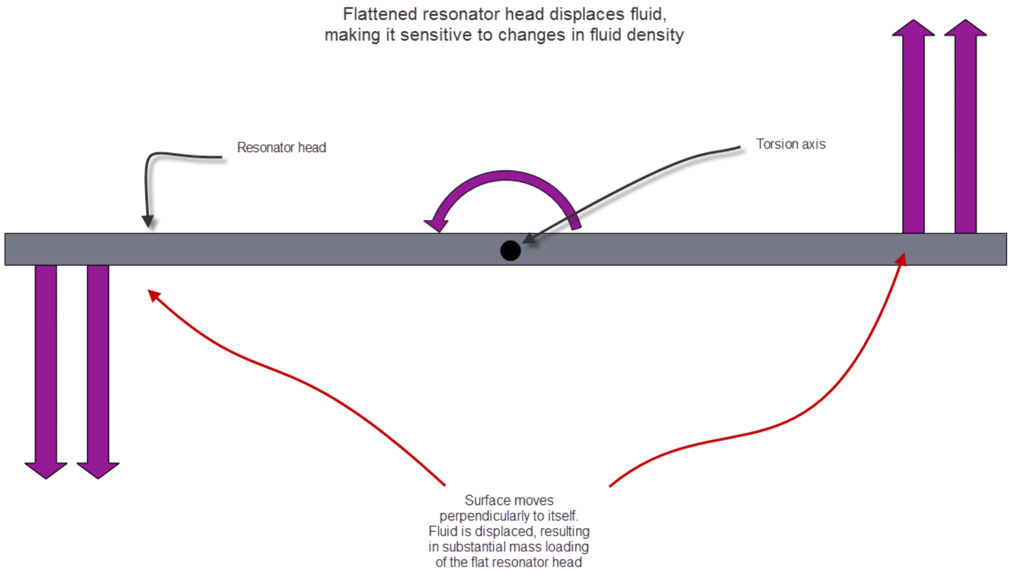
Many types of fluid sensors use lateral vibrations. Vibrating wire viscometers, for instance rely on the displacement of the wire perpendicular to its long axis. Flexural tuning fork resonators have two tines that vibrate as cantilever beams, with motion perpendicular to the plane of symmetry of the tuning fork.

Our sensors vibrate in torsion. Torsional resonators are more stable and better isolated from their mechanical environment than are transverse and longitudinal resonators.

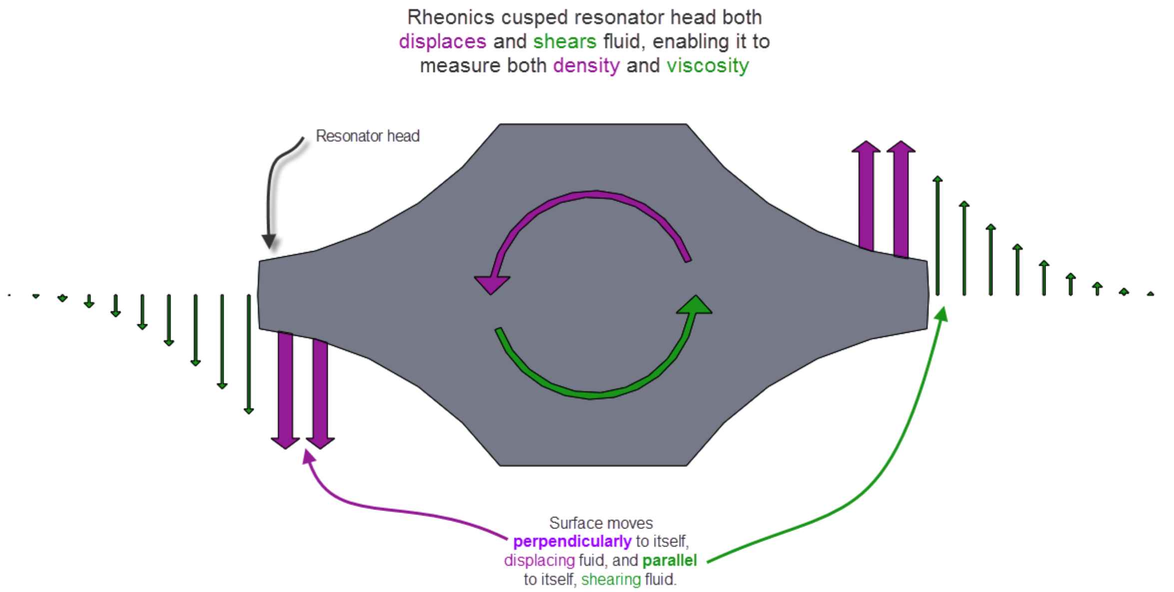
Torsional resonators that are cylindrical vibrate parallel to their own surfaces. They are influenced by shearing forces, and are therefore primarily sensitive to dissipative forces rather than mass loading effects. The following diagram shows the shear gradient around a torsionall vibrating cylinder in a fluid:



Torsional resonators that are flattened move perpendicularly to their own surfaces. They move fluid rather than shearing it. They are primarily sensitive to mass loading, rather than dissipative forces, and are useful for measuring density. A flattened resonator end is shown in the following diagram:



The Rheonics SRV sensor uses a cylindrical resonator head. It is primarily sensitive to fluid viscosity. The Rheonics DV series uses a patented cusped head geometry that both shears and displaces the fluid in which it is immersed. It therefore allows measurement of both density and viscosity with a single resonator:



Resonant sensors fall into two geometric categories – balanced and unbalanced. A tuning fork is a typical balanced resonator. Its two tines vibrate in opposite directions, balancing out bending forces that are otherwise transmitted to the sensor's mounting. A single transversely vibrating beam (a "half tuning fork") by comparison, exerts large reaction forces on its mounting, resulting in large energy loss compared to the balanced tuning fork geometry. A vibrating wire, on the other hand, is an unbalanced resonator, and exerts substantial forces on its mounting structures. In order to reduce the effects of mounting conditions on unbalanced resonators, their anchors must be relative large and massive compared to the size of the actual sensing element.

Rheonics sensors utilize patented balanced resonator configurations to ensure consistent, reproducible measurements no matter how the sensor is mounted.

The DV series uses two cusped resonator heads in a torsional tuning fork cofiguration. The two heads are mounted to stems that function as torsion springs, that are then mounted in a base that both couples the two tines to one another, as well as isolating them from the outside world:

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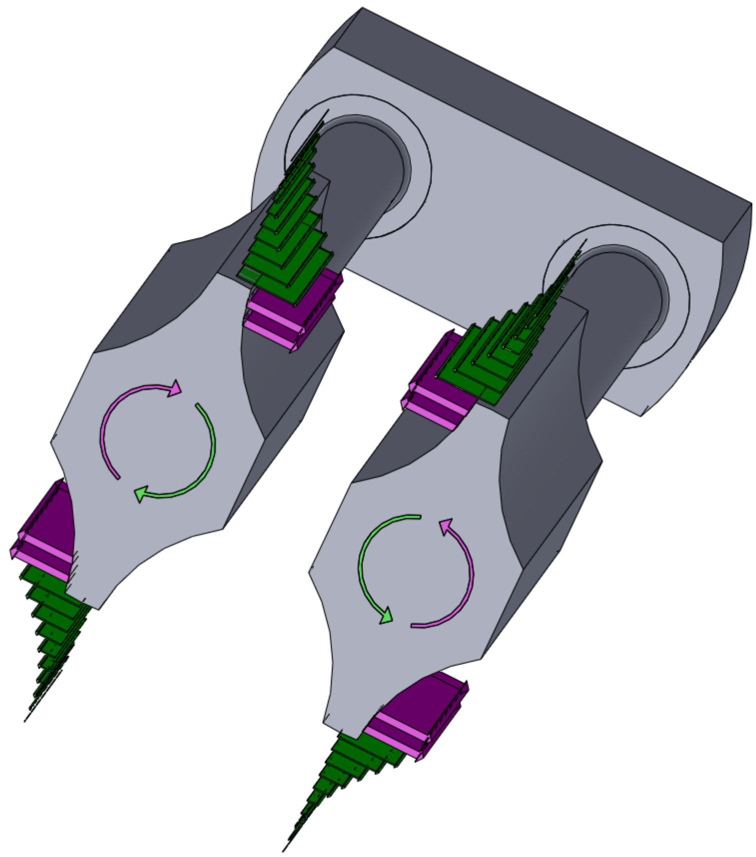
In order to balance the resonator, the excitation system is arranged so as to make the two tines twist in opposite directions, thereby neutralizing each others' reaction torques on the bridge:



Some complications

- Viscous forces influence damping. However, the denser the fluid, the stronger it's damping influence on the resonator. For cylindrical torsional resonators, the damping is generally proportional to the square root of the product of density and viscosity. Therefore, a cylindrical torsional resonator can only measure the density-viscosity product – not the absolute viscosity. In order to measure the absolute viscosity, a separate measurement of density must be made.
- Mass loading of a torsional resonator has two components. If the resonator is flattened, or has surfaces that move perpendicularly to themselves, then they "push" fluid ahead of them, and are directly loaded by the mass of that fluid. However, all objects vibrating in a fluid also *shear* the fluid, resulting in viscous forces that also contribute to mass loading. In order to measure density accurately, it is necessary to take these viscous forces into account. Even the most accurate resonant density sensors, which consist of a "U" shaped tube filled with fluid and vibrating perpendicular to the plane of the "U" are influenced by viscous forces.
- In order for a sensor to accurately measure small changes in fluid properties, its own properties – resonant frequency and damping – must be very predictable despite changes in the sensor's

environment. For instance, the resonant frequency and damping of nearly all resonators are influenced by the temperature of the sensor. As long as the sensor's properties vary with temperature in an absolutely predictable way, their influence can be compensated for when measuring the fluid's influence on the sensor. The degree to which a sensor's frequency and damping are permanently changed by temperature – "hysteresis effects" – limits the ultimate accuracy and repeatability of the sensor's measurements.

Accurate Sensors need Accurate Electronics

Rheonics fluid sensing systems rely on patented technology that allows the use of one electronics platform – the evaluation unit – for all of our sensor products.

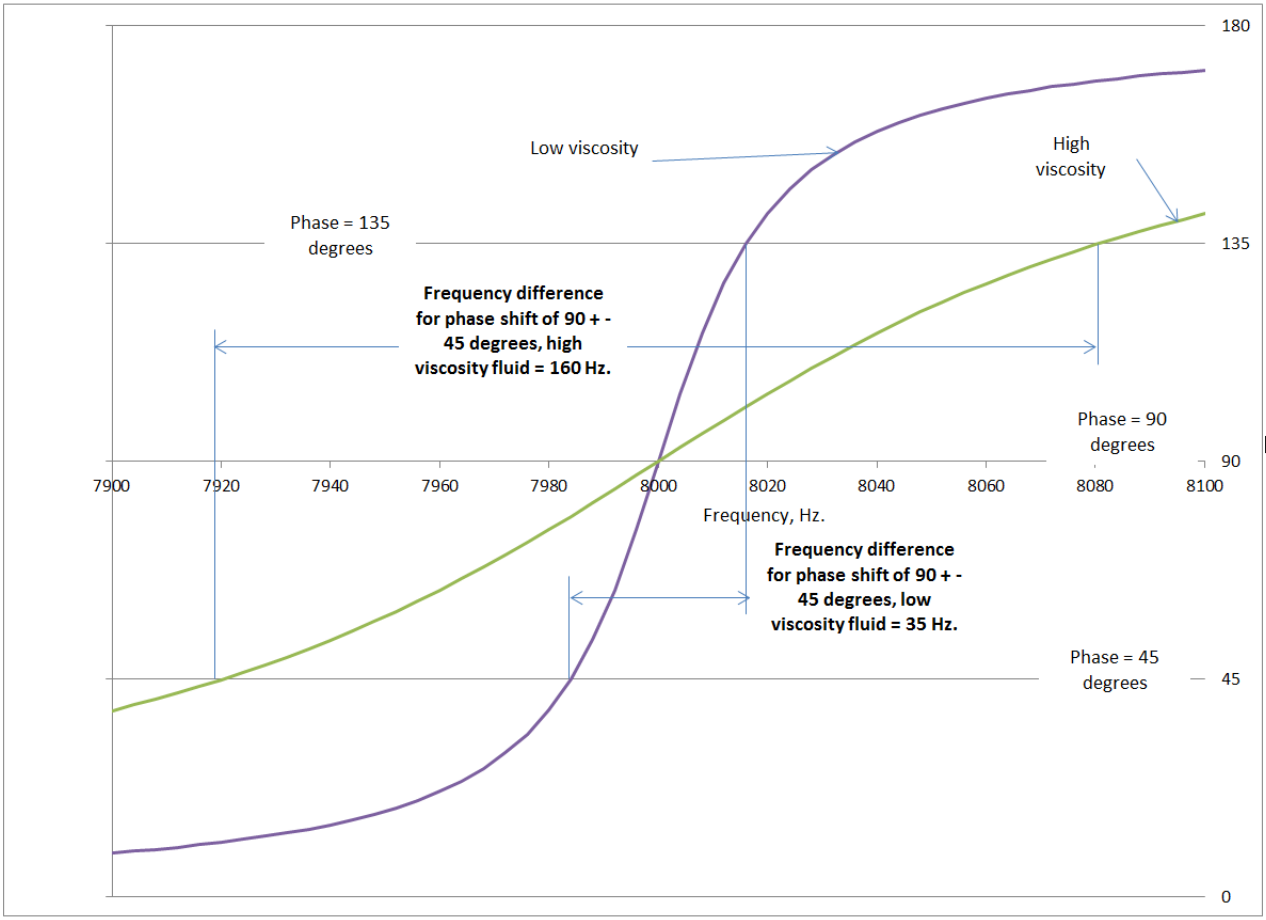
The core task of the evaluation unit is to drive and interrogate the resonant sensor in order to determine its resonant frequency and its damping. Once these two quantities have been determined, it is up to a sophisticated set of algorithms to convert these measurements into values for density and viscosity.

Our electronics platform is based on the *phase shift method* of evaluating the resonant frequency and damping of the resonant sensor.

Many resonant sensors measure the variation of the resonator's amplitude as its driving frequency varies. Although there are many ways to evaluate this variation, it is generally slower and subject to greater variation than the phase shift methods used in Rheonics' evaluation unit.

The phase shift method

The following diagram shows the relationship of a resonator's phase shift with respect to its driving signal over a range of frequencies near its resonance. The relationship is shown for two different fluids of differing viscosity:



Phase response of resonator for two different fluid viscosities

The damping of the resonator – the change of its energy dissipation due to viscous forces – can be inferred from the way its phase changes with excitation frequency. The steeper curve shows the phase behavior for the resonator in a less viscous fluid. The frequencies corresponding to phase differences of 45 and 135 ° differ by about 35 Hz. The shallower curve shows the behavior of the same resonator in a more viscous fluid. For the same phase difference, its frequencies differ by 160 Hz. This frequency difference is a direct measure for the resonator’s damping, and therefore the main factor for determining its viscosity.