Kodai Flow Research Technical Note:

Ultrasonic TOF Flow Meter Theory and Operation

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Disclaimer:
Use of this product is at the users own risk. No liability is implied except for the value of the measurement system. Every effort has been made to insure the equipment is designed to meet required standards in safety, emissions, and susceptibility, however it is left to the user to insure no interference with other equipment exists, and that the installation complies with codes and regulations.

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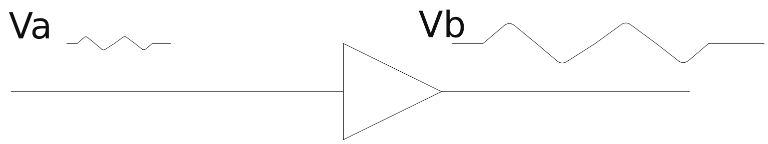
Part 1 - Theory of Time-of-Flight Flow Meters

Terminology

Amplifier – An electrical circuit, usually a network of transistors, that increases the voltage of an alternating electrical signal. The amount the voltage is increased is the *Gain*. The symbol is a sideways triangle.



Attenuation – The process where signals are weakened as they travel through a material or fluid.

Analog to Digital Converter – A circuit that measures the voltage and converts it to a number that can be read by an microcontroller.

Automatic Gain Control (AGC) – A special amplifier circuit that automatically adjusts the gain so the output is always at a constant level. For example, the *AGC* circuit on the CRE adjusts the incoming signal until it is 0.5 volts peak to peak.

Decibel (dB) - A method of expressing gain or loss in a logarithmic format. It is commonly used to express gain or loss of a signal. Amplification and attenuation are usually expressed in dB. A gain is a positive number, loss is a negative number.

$$dB_{ba} = 20 * \log\left|\frac{V_b}{V_a}\right|$$

Frequency – The rate that waves pass a point. It is the inverse of the time *Period* between the peaks of a wave. The unit is *Hertz (Hz)* which is equal to *1/second*.

Incident Angle – The angle a wave front strikes a boundary between different materials.

Multiplexer – A network of relays used switch the paths of electrical circuits.

Noise – Stray electrical patterns introduced to the signal by outside equipment and thermal effects in the amplifier

Refraction – The process where the path of sound waves path is bent when it crosses between materials with a different sound speed.

Sound - An alternating pressure field that travels through a solid liquid or gas.

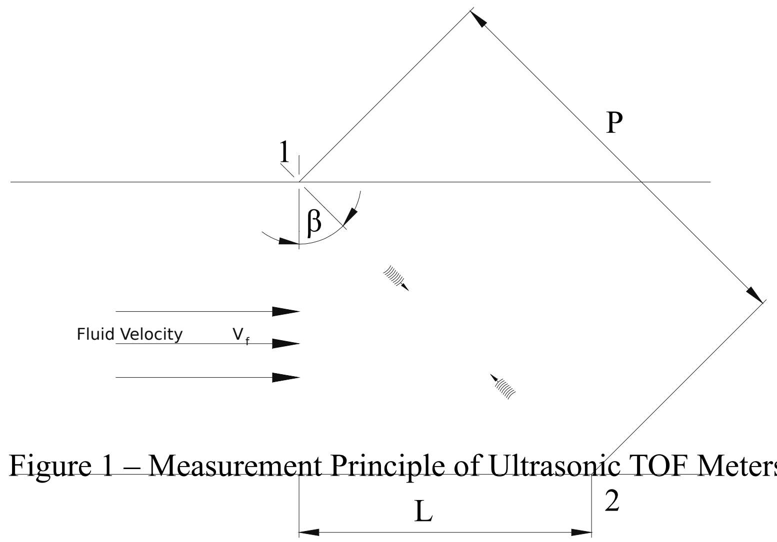
Transducer – A device that can turn an electrical voltage signal into a sound wave, or equally, convert a sound wave into an electrical signal. In a flow meter, a pair of transducers are connected to a transmitter and a receiver through a multiplexer so a sound pulse can be sent through the fluid in each direction.

Ultrasound – Sound that is above the normal hearing range (20 *kHz*). Liquid flow meters usually use frequencies from 0.5 to 5 *MHz*

Velocity of Sound – The rate which a sound wave front travels in a material. Also termed *sound speed.*

Measurement Principle

The velocity of a pulse of ultrasound travels at in a fluid is the sum of the velocity of sound and the velocity of the fluid in the direction of the pulse. See Figure 1. By measuring the time of flight between point 1 and point 2, and comparing it to the time to travel the reverse path, the velocity of the fluid and the velocity of sound for the fluid can be calculated.



$$T_{1\rightarrow 2} = \frac{P}{(VOS + V_f \sin(\beta))}$$

$$T_{2\rightarrow 1} = \frac{P}{(VOS - V_f \sin(\beta))}$$

Figure 1 – Measurement Principle of Ultrasonic TOF Meters

Velocity and Flow Calculation

The distances P and L can be solved using the angle, *β*, and the inside diameter of the tube, *D*. The two equations shown in figure one can then be combined to solve for both the average velocity of the fluid, V_f and the velocity of sound, *VOS*. The flow rate is determined by multiplying V_f times the cross-sectional area of the tube.

$$V_f = \frac{D(T_{2\rightarrow 1} - T_{1\rightarrow 2})}{2\ T_{2\rightarrow 1}\ T_{1\rightarrow 2}\ \sin(\beta)\ \cos(\beta)}$$

$$VOS = \frac{2\ D}{(T_{2\rightarrow 1} + T_{1\rightarrow 2})\ \cos(\beta)}$$

Part 2 - Digitization

Custom Logic Integrated Circuit

To simplify manufacturing, most of the digital functions in timing the transit of an ultrasonic is combined into a specialty integrated circuit. There are several manufactures for this type of chips for low end and consumer devices. These do not have the performance needed for precision measurements so at KFR we develop our own Custom Logic Integrated Circuit, CLIC to handle the synchronized clocking and data acquisition functions. As the volume is small for a custom ASIC, we use an off-the-shelf FPGA with internal RAM blocks and customize it using firmware to handle the digital functions. This CLIC serves as a co-processor and memory buffer to a commercial micro-controller which handles the asynchronous tasks rapidly and efficiently. This chip is essentially a precision function generator and digital oscilloscope combined into a finger nail sized IC.

Analog to Digital Conversion

Modern measurement systems do not time analog signals with complicated analog circuits. Besides being expensive, they require large amounts of power and can can be unpredictable in adverse conditions. To simplify this, the electrical signals from the receive transducers are feed into a special integrated circuit (ADC IC) that converts the voltage level in the line to a binary number. This binary number is connected to the CLIC by 10 logic lines. The CLIC provides a jitter free (5 pico seconds) clock signal synchronized to transmit signal the so the voltage is sampled and latched onto the lines just before the value is stored in memory in the CLIC memory buffer. Now the chip has an array digital values of the signal voltage versus time relative to the transmit.

Digital Signal Synthesis

This is the opposite function to above. This circuit takes logic signals to create high voltage analog voltages time locked to the original logic, but safely isolated from the digital circuitry of the micro controller. Usually capacitive isolation is used, but inductive or optical isolation is possible if the method is time stable in the pico-second range.

Automatic Gain Control

The ADC chip described above has a fixed range. A 10-bit DAC convert the voltage input to a number between 0 and 4096. For example, a DAC may convert -1 V to 0 and 1 V to the integer 4096 (in binary format). The automatic gain control, AGC, is a circuit that continuously adjusts the amplification of the received signal so that the signal may be digitized optimally, but with out the chance of the signal being too large and clipped.

Blanking Delay and Acquisition Window

Because the large transmit signal will couple into the receive circuit, it important that the meter does not start digitizing until some time after the transmit has finished. This amount of time is the blanking delay. After this delay, the CLIC begins reading the signal until the sample buffer is full. The period of time from the end of the delay until the memory buffer is full is termed the ***Acquisition Window***. The exact width of the window depends on the buffer size and the sample rate. If the buffer size is 1000 points and the sampling rate is 20MHz, the window size is 50 microseconds. The window must be wide enough to account for variations in the velocity of sound of the fluids.

Anti-Alias Techniques

To increase accuracy, the meter transmits multiple times in each direction. The final array is the sum of these captures. The time between each of these captures in non-equal and random. This prevents any aliasing of flow dynamics or electrical noise

Part 3 - Signal Processing

Digital Filtering

After the acquisition process described above is completed for both directions, the data is stored in two separate arrays of integer information. From this point, all measurements are made from mathematical calculations performed on these arrays. The first is digital filtering. KFR flow meters do not use standard methods such as FFT, FIR or correlations as these have problems with turbulent flows and highly attenuation fluids. Instead, an optimized form of wavelet transform is used to remove random noise without loss of time resolution.

Direct Timing in Transform

Because the wavelet transform is still time based rather than a spectrum technique, the time measurements can be calculated directly in the wavelet space. This eliminates the need for reverse transform calculations and further time distortion.

Statistical Error Handling and Intelligent Averaging

In operation under adverse conditions, individual transmissions of ultrasound are blocked or scattered, preventing a valid measurement. The algorithms inside the controller use pattern recognition to identify if a valid signal has been received. If the signal is not valid the information is shifted to a statistical process to a momentary interference, or a persistent condition. This algorithm allows the meter to be used in fluids with high percentage of bubbles, but still issue an alarm in seconds to a dry pipe condition.

Another intelligent algorithm is used to average the flow rate. This allows the meter to provide a steady trend to smooth out pulsations from pump or process interactions, but still respond to step changes in flow rate.

Part 4 - Refraction

Snell's Law

While some ultrasonic meter do use transducers mounted directly into the fluid, the TWD semiconductor measurement system clamps to the outside of the users tube. The sound beam is refracted through tube wall. As the ultrasonic pulse enters the pipe, the angle of the beam is bent to a new angle, β_w. The angle changes again, β_f, as the beam enters the fluid as shown in Figure 2.

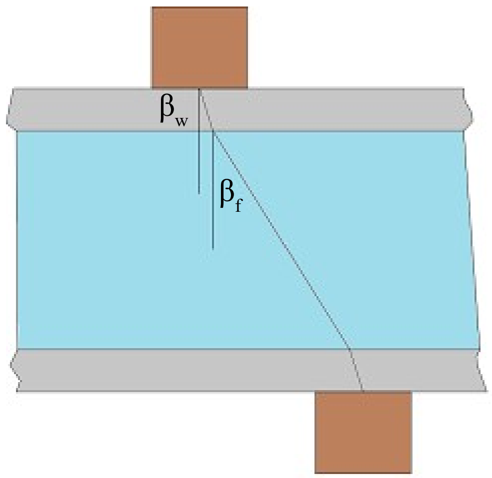


Figure 2 – Bending of sound beam traveling through wall and fluid.

How much the angle changes is determined by the velocity of sound of the wall material and the fluid in the tube. This relationship is called Snell's law. In equation form:

$$\frac{VOS_{wall}}{\sin(\beta_{wall})} = \frac{VOS_{fluid}}{\sin(\beta_{fluid})}$$

For any combination of wall thickness and fluid, there is only one position for the ultrasonic sensors where the beams strike the transducers exactly. This is the ideal spacing.

Non-Ideal Spacing

In actual practice, the acoustic sensors are never at the ideal positions. In older flow meters, the sensor are mounted to an adjustable frame where the end user is expected to adjust the spacing depending on the fluid in the tube and operating temperature.

In semiconductor applications, this is not practical. This requires a high degree of expertise by the installation technician and the tubing is located in a very cramped locations where only a limited number of materials like PTFE are allowed.

To simplify installation, KFR makes a fixed spacing frame for each of the common sizes of PFA tubing. A support frame is required because the PFA tubing becomes very soft as the temperature of the fluid goes above 120º C. Besides positioning the sensors, the frame keeps the tube straight and circular and insulates the tube from heat loss.

For each tube size there is an A-type sensor that can be used for any of the RCA process chemicals. There is also a B-type sensors for concentrated hydroxide etch solutions like KOH etch. APM solution can be used with either type. Figure 3 is the velocity of sound of common fluids.

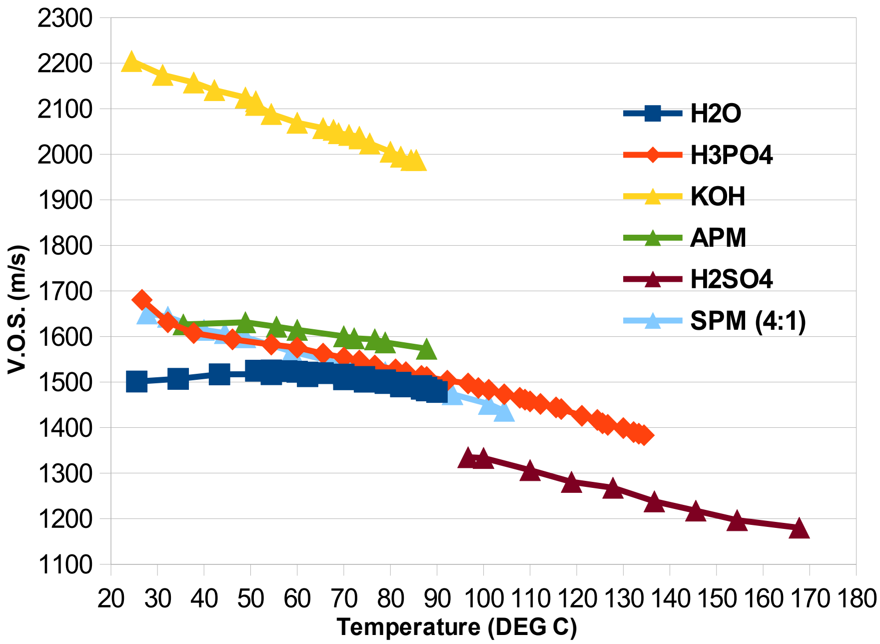


Figure 3 – Velocity of sound for common semiconductor fluids versus temperature.

When the sensors are not at the ideal spacing the signal gets to the receiver by a combination of beam spread and wall travel (Figure 4.) Beam spread happens because the sound is not a ray but actually curved field. The wall run happens because of the wide field generated when the wave front strikes the tube wall. In metal pipes, wall run dominates the acoustics of non ideal spacing, but in the viscoelastic materials like PTFE and PFA the complexities of beam spread must be taken into account. These effects can be corrected for in the timing calculation, but if the sensor is too far from the ideal, the signal can become distorted and weak. Because of this, KFR offers sensors for concentrated acids or bases. Either sensor type can be used for dilute solutions or slurries.

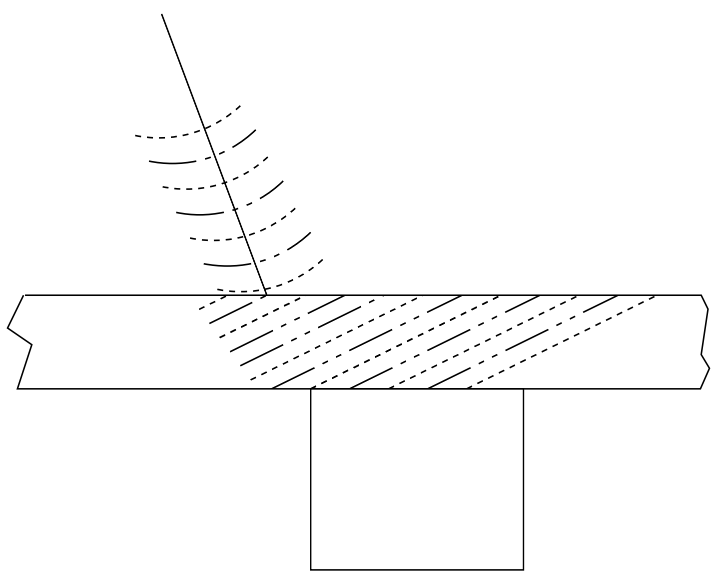


Figure 4 – Beam Spread as Fluid Sound Velocity Changes.

Effect of Tube Curvature

The models presented above treat the pipe wall as if it was a flat plate. This is incorrect. The curvature of the wall acts as a lens with a focusing effect. This effect is larger when using lower frequency sound with smaller tubes. However, like the beam drift above the effect is small. These and other non-linear effects are handled by a perturbation method to the linear, ray acoustic model. This is computationally challenging, but the micro-controller inside the meter has more than enough power to solve it with out any delay to the response time.

Part 5 – Additional Features

Flow Pulsation Statistics

The semiconductor process tools commonly use bellows or diaphragm pumps to move the high purity fluids. These are ideal for low shear and no trapped volumes, but they produce non-steady flow. The KFR flow meter rapidly measures the instantaneous flow through out the stroke of the pump, and calculates the average flow without the need of pulsation dampeners. However, it does not through this information away. Instead, it keeps statistical information about the pulsation of the fluid which can be retrieved via digital communication (Modbus is standard). Like an medical EKG, this information can alert operates to problems with pumps or filters and prevent critical time failures.

Equations Of State

The KFR flow meter systems has other unique features not found on other flow meters of any technology. One of them a set of equations that take the acoustic properties measured by the system and calculate the other properties. These equations that take two key properties and calculate all the other properties are called Equations Of State, or EOS. The internal computer in the flow meter uses these equations (and an assumed pressure of 2 Bar absolute) to estimate the temperature and viscosity of the process fluids. It uses these values to refine the measurement and can also report the values to the user via digital communication.

Bubble or Clump Detection

The flow meter also uses beam scattering data collected along with the transit time data to look for the presence of area of non uniform density. In etching and cleaning processes, these are usually bubbles formed when the water in the solution vaporizes and forms a bubble. This is not normally a good thing as the process is designed for this to happen only when the fluid contacts the wafer to be processed. Excess bubbles in the line leading to the process mean that either the fluid temperature is higher than correct, the pressure is lower than correct, or the concentration of the etching agent is too low.

In CMP processes, this can occur when micro-fine particles clump together. This can be damaging to both the wafer and the tool in general so early detection is an advantage.

In either case the flow meter provides the estimated size and concentration of the density variation as an output via the digital interface