

Field Experience Proving Liquid Ultrasonic Meters Using a Small Volume Prover and Master Meter

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Introduction

The use of liquid ultrasonic meters for liquid petroleum applications such as custody transfer or allocation measurement is gaining worldwide acceptance by the oil industry. Ultrasonic technology is well-established, but the use of this technology for custody transfer and allocation measurement is relatively new, and users often try to employ the same measurement practices that apply to turbine technology. There are some similarities between the two approaches, such as the need for flow conditioning and upstream and downstream piping requirements, but there are also differences, like the proving technique or field validation procedure. This paper will discuss the various *in-situ* proving methods that can be used for successful field calibration of a liquid ultrasonic meter.

How Transit Time Ultrasonic Flow Meters Work

A transit time ultrasonic flow meter uses the transit times of the signal between two transducers to determine fluid velocity. The transducer transmits ultrasonic pulses with the flow and against the flow to a corresponding receiver, as shown in Figure 1. Each transducer alternates as a transmitter and a receiver.

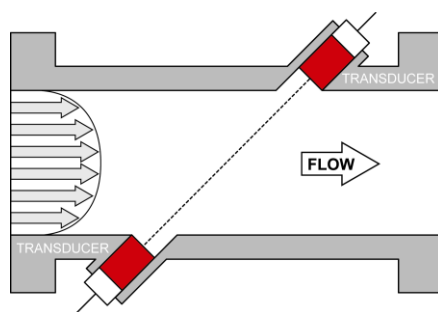


Figure 1: Transit time principle for ultrasonic flow meters

Consider the case of fluid *stationary* in a full meter spool. In theory, it will take precisely the same amount of time for a pulse to travel through the fluid in each direction, since the speed of sound is constant within the fluid. If fluid is *flowing* through the pipe, then a

pulse traveling with the flow traverses the pipe faster than the pulse traveling against the flow. The resulting time difference is proportional to the velocity of the fluid passing through the meter spool. Single and multiple acoustic paths can be used to measure fluid velocity. Multi-path meters tend to be more accurate since they collect velocity information at several points in the flow profile.

The transit time of the ultrasonic signal is measured and used with other variables to calculate flow. Although the ultrasonic signal is traveling in a straight line, it is traveling at an angle, θ , to the pipe axis, as shown in Figure 2.

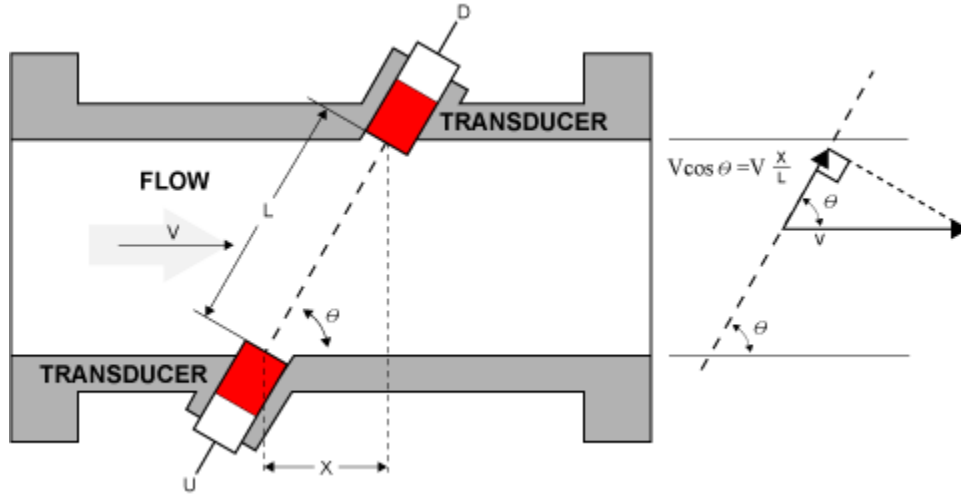


Figure 2: Variables for calculating transit time

Equations 1 and 2 define the flow rate between two transducers located at positions U (upstream) and D (downstream):

$$t_{ud} = \frac{L}{C + V_i \cos \theta} \quad (1)$$

$$t_{du} = \frac{L}{C - V_i \cos \theta} \quad (2)$$

Solving equations 3 and 4 simultaneously yields the following results for V_i and C (notice that Vx/L can be substituted for “ $V \cos \theta$ ” to simplify equation 4):

$$V_i = \frac{L}{2 \cos \theta} \cdot \frac{t_{du} - t_{ud}}{(t_{ud})(t_{du})} = \frac{L^2}{2x} \cdot \frac{t_{du} - t_{ud}}{(t_{ud})(t_{du})} \quad (3)$$

$$C = \frac{L}{2} \cdot \frac{t_{du} + t_{ud}}{(t_{ud})(t_{du})} \quad (4)$$

Where:

- t_{ud} = transit time from transducer U to D
- t_{du} = transit time from transducer D to U
- L = path length between transducer faces U and D
- x = axial length between transducer faces
- C = velocity of sound in the liquid in still condition
- V_i = mean chord velocity of the flowing liquid
- θ = acoustic transmission angle

Since the equations are valid for fluid flowing in either direction, the method is inherently bi-directional in nature. Also, notice that the speed of sound term through the medium drops out of the velocity equation. Consequently, velocity is determined from the transit times through the predetermined distances, and is independent of factors such as temperature, pressure and fluid composition.

Field Proving

In custody transfer or allocation measurement applications, it is common practice to periodically prove liquid meters in the field. This is done to reduce uncertainty and maintain accuracy for fiscal measurement, establish meter factors at working conditions, and determine meter factors for different fluids. The measurement application or the customer contract generally determines the frequency at which it is proved. Meters in a pipeline that transports several liquids may be proved at every product change. The API Manual of Petroleum Measurement Standards, Chapters 4.8, 5.8, and 13.1 provides guidelines and requirements.

There are four basic requirements for successful proving:

1. The meter should be proved under the normal conditions in which it is expected to operate. Flow variables, including flow rate, pressure and temperature must be stable and unchanging.
2. Adequate prover capacity is required to provide proving runs of sufficient duration. Larger volumes and longer run times will improve repeatability. Upstream flow conditions can affect the run time and volume required.
3. A sufficient number of runs are required to establish a valid proving. If the run-to-run variation is small, then an adequate meter factor can be found by averaging a few runs. As the run-to-run variation increases, the average of more runs is required for an adequate meter factor. See API MPMS Ch. 5.8.
4. Results should be traceable to the National Institute of Standards and Technology. The calibration of the meter prover must be traceable to NIST-calibrated test measures.

Proving Principle

Displacement prover systems operate on the displacement principle, which is the repeatable displacement of a known volume of liquid from a calibrated section of pipe between two detectors. (Figure 3)

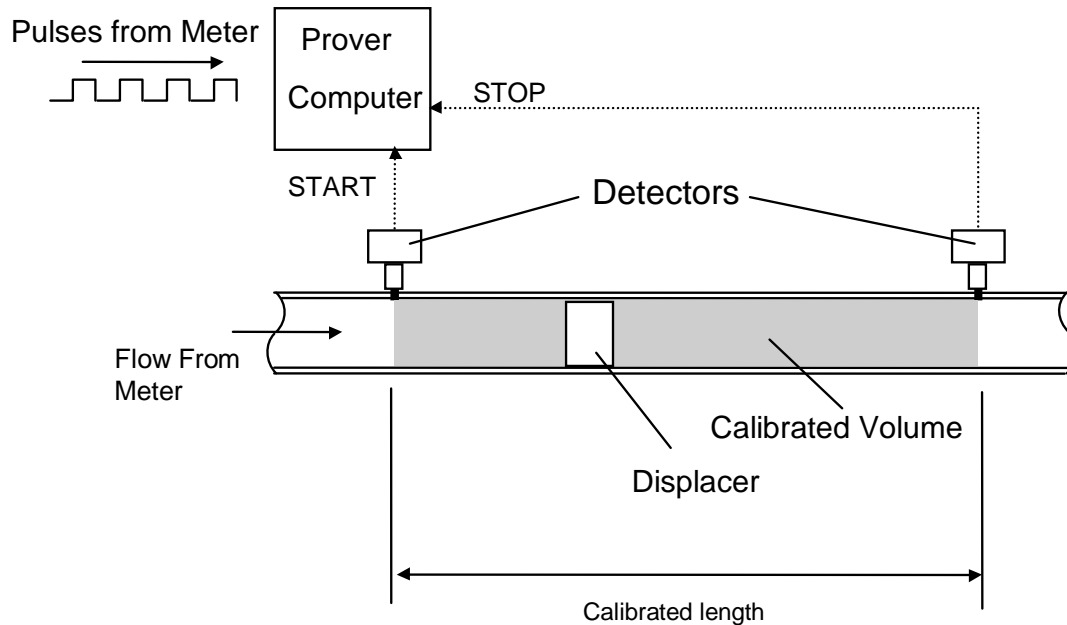


Figure 3: Meter proving by displacement

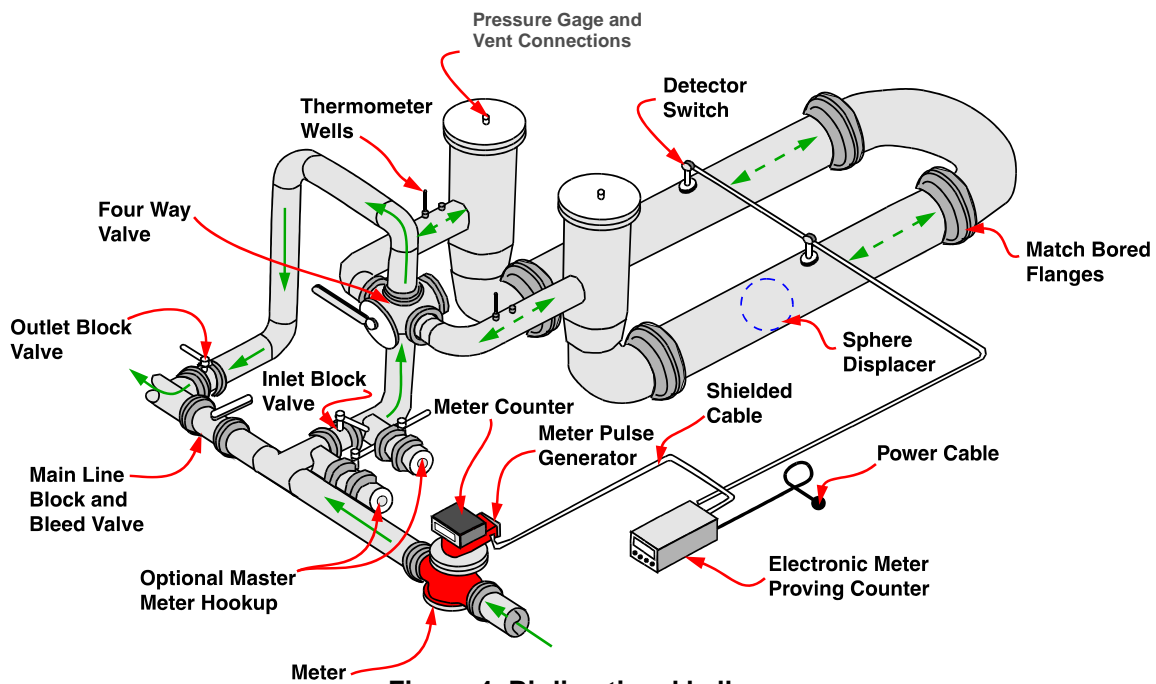
Displacement of the volume of liquid is achieved by a sphere or a piston traveling through the pipe. A corresponding volume of liquid is simultaneously measured by a meter installed in series with the prover. A meter that is being proved on a continuous-flow basis must be connected at the time of proof to a proving counter. The counter is started and stopped when the displacing device actuates the two detectors at either end of the calibrated section of the prover.

A displacement-type prover must be installed so that the full flow of the liquid stream through a meter being proved will pass through the prover. When flow through the meter and prover has stabilized, the proving sequence is initiated. The displacer then travels through the pipe while maintaining a seal between it and the pipe wall. Each of the detector switches is individually actuated upon passage of the displacer. A high-resolution pulse counter connected to the meter output is gated on and off by the detectors. In the event the meter being proved cannot generate a minimum of 10,000 whole meter pulses between detector switches, some form of pulse interpolation must be used to allow discrimination at a rate higher than 1 part in 10,000.

Prover Types

A displacement prover may utilize either a sphere or a piston as a displacer, and may be either unidirectional or bi-directional. Liquid always flows in the same direction through a unidirectional prover, which has a mechanism that returns the displacer to its initial position in the prover pipe. A bi-directional prover utilizes a flow reversal mechanism (such as a four-way valve) that causes the displacer to alternate its direction of passage through the prover pipe.

Unidirectional proving runs consist of single trips of the displacer past the detectors in the same direction. Bi-directional proving runs consist of “round trips” of the displacer (a complete cycle past the detectors in both directions). A typical bi-directional prover is depicted by Figure 4; a typical unidirectional “small-volume” prover is depicted in Figure 5.



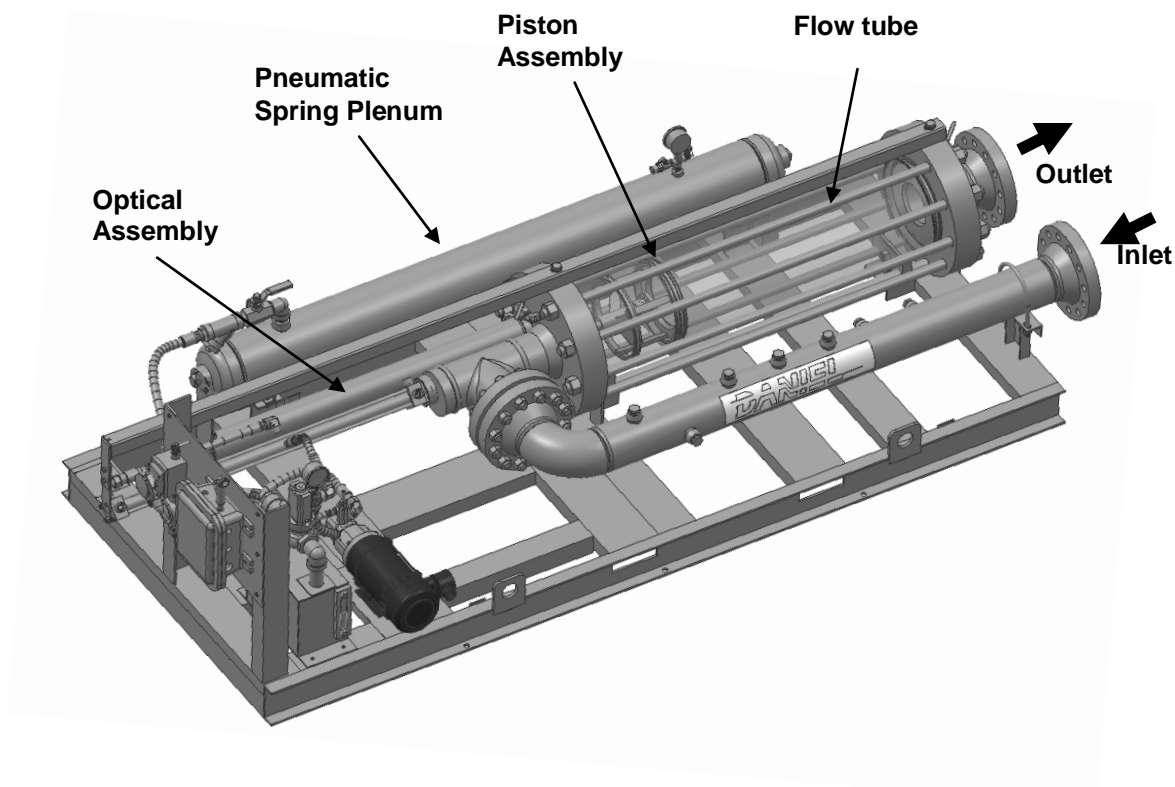


Figure 5: Small-volume prover

Small-volume displacement provers are those with a calibrated volume that permits a minimum of 10,000 pulses collected by the meter under test. Their attributes include smaller size and weight, shorter proving cycles and extremely wide rangeability (in excess of 1,000:1).

Meter Characteristics

The characteristics of a flow meter are important in developing a proving methodology. For example, both positive displacement and turbine meters have mechanical elements that rotate as fluid passes through the meter. It is convenient to use electrical sensors to detect the passing of gear teeth or rotor blades. These pulses are totaled to determine the volume flow through the meter. Since these mechanical elements rotate as a result of the flow passing through them, they tend to average out the eddies associated with turbulent flow. The frequency output, representing pulses per unit of volume, is quite steady and is considered to be a uniform pulse output. These meters exhibit good proving repeatability with fairly short volumes and run times.

An ultrasonic meter has no moving parts. It determines the average velocity over one or more acoustic paths. The actual measurement made is the transit time of an ultrasonic pulse over the path in both the upstream and downstream directions. From this, an average velocity is calculated for each path. The path averages are then combined to

form an average velocity for the whole meter, and the volume flow through the meter can be determined based on the cross-sectional area of the meter.

Since an ultrasonic meter has no moving parts, there is nothing to rotate to provide pulse counts. Pulse generation is done by means of a digital-to-frequency converter. Since the frequency is generated as the result of a measurement, it always lags the flow by the update period.

Also, since the meter is sampling the flow at several locations, turbulence in the flow will be measured. The standard deviation of the path velocity measurements is typically 2 to 5%. This implies a peak-to-peak variance of 12 to 30%. The turbulence is noise in the flow measurement that averages to zero. As a result of this, these meters have varying frequency output and are said to have a non-uniform pulse output. In proving ultrasonic meters, volumes and run times must be sufficient to average the turbulence to an acceptably low value.

Regardless of the method of calibration, repeatability is an important criterion used to determine the acceptability of proving results. Ultrasonic meter performance verification can be ascertained by conventional means and to a level consistent with API MPMS Ch. 4.8, Table A-1 (Figure 6). This table provides guidance in determining the consecutive number of proving runs that may be required to obtain an uncertainty of meter factor of $\pm 0.027\%$ at a 95% confidence level.

Any of the number of runs chosen from the table below will produce results that verify a meter's performance to $\pm 0.027\%$ uncertainty. There is no difference between the traditional 5 consecutive runs that repeat within 0.05% and 10 consecutive runs that repeat within 0.12%; they both demonstrate the exact same uncertainty. The operator in the field will attempt to prove the meter in the smallest number of runs possible, and this table provides a guideline.

Repeatability = ((High Counts – Low Counts) / Low Counts) X 100		
Runs	Repeatability *	Uncertainty
3	0.02%	+/- 0.027%
4	0.03%	+/- 0.027%
5	0.05%	+/- 0.027%
6	0.06%	+/- 0.027%
7	0.08%	+/- 0.027%
8	0.09%	+/- 0.027%
9	0.10%	+/- 0.027%
10	0.12%	+/- 0.027%
11	0.13%	+/- 0.027%
12	0.14%	+/- 0.027%
13	0.15%	+/- 0.027%
14	0.16%	+/- 0.027%
15	0.17%	+/- 0.027%
16	0.18%	+/- 0.027%
17	0.19%	+/- 0.027%
18	0.20%	+/- 0.027%
19	0.21%	+/- 0.027%
20	0.22%	+/- 0.027%
* per API <i>MPMS</i> Ch. 4.8, Table A-1 to achieve +/- 0.027% uncertainty of meter factor.		

Figure 6 : Number of runs and repeatability needed to achieve +/- 0.027% uncertainty in proving an ultrasonic flow meter

Figure 7 shows how proving volume has a direct effect on repeatability. The example shows a turbine and ultrasonic meter being proved simultaneously with a small-volume displacement prover. Each of the three proving cycles shown could be as short as ½ second, depending on flow rate. As a result of the small proving volume, it can be seen that the turbine meter, with its uniform pulse output, displays excellent repeatability (0.011%) over the 3 runs, while the ultrasonic meter does not; it shows a repeatability of 0.23%.

This does not mean that the turbine meter is more accurate or repeatable than the ultrasonic meter, as both meters would provide excellent results over a longer period of time, which effectively results in a larger volume.

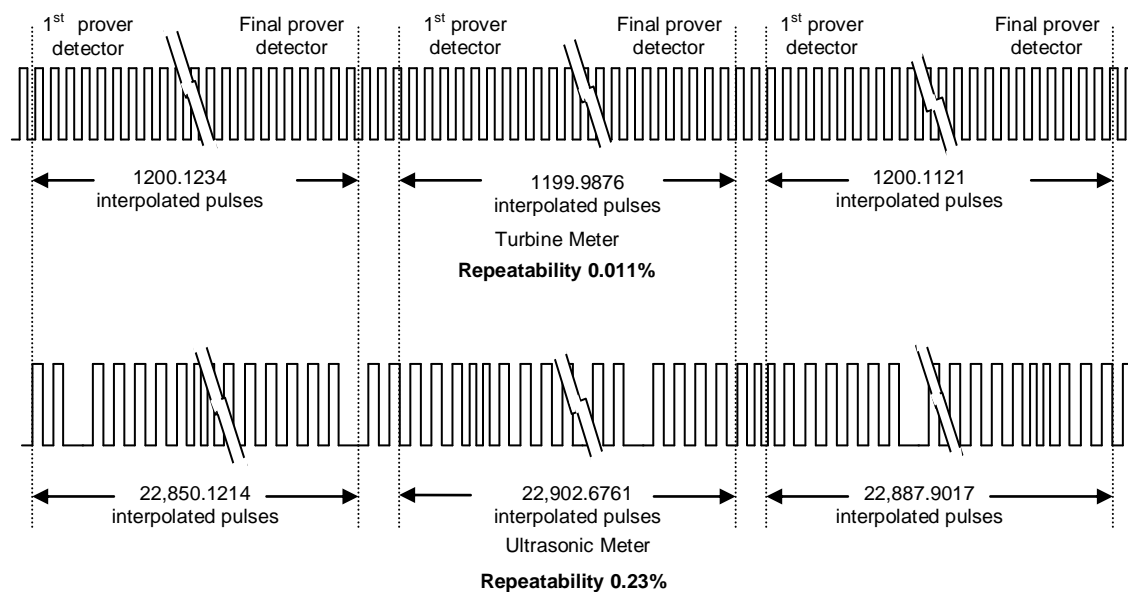


Figure 7 : Typical proving results for turbine and ultrasonic meters using small proving volumes

Figure 8 shows an ultrasonic meter proved using a prover with a larger volume that effectively allows more time for the non-uniform pulse variations to average out. The important point is that increasing proving volumes improves repeatability.

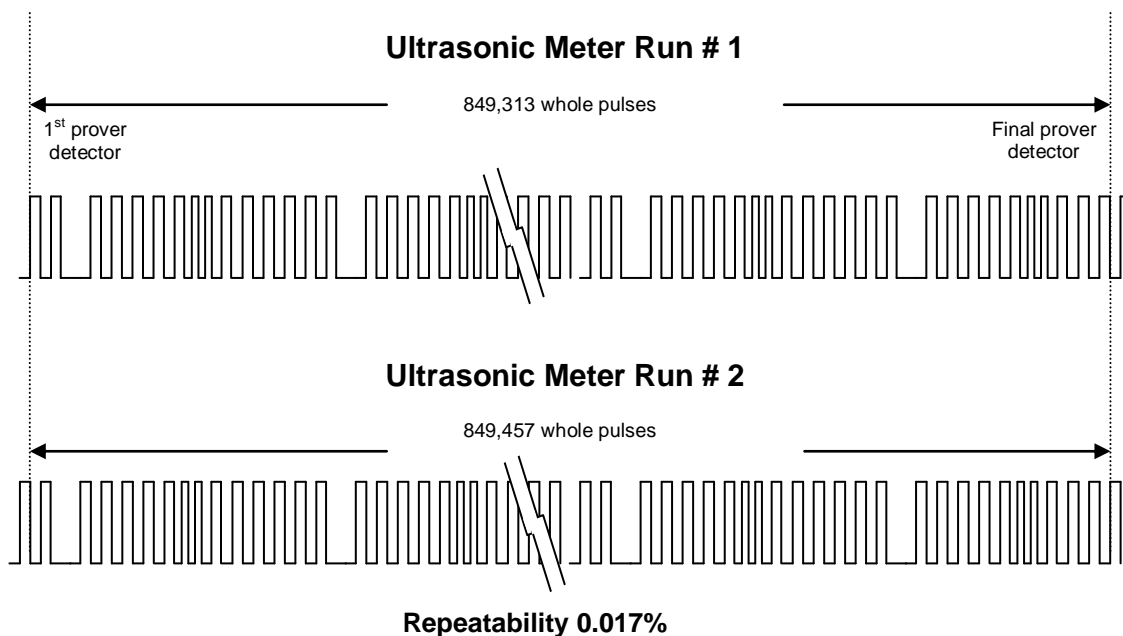


Figure 8 : Typical proving results for ultrasonic meter using larger proving volume

It can be seen that repeatability has improved significantly, from 0.23% in Figure 7 over 3 consecutive runs to 0.017% in figure 8 over two consecutive runs. This is a direct

result of increasing the proving volume, thus allowing additional time for the meter to average the signal output.

Increasing the proving volume can be accomplished by using a larger-volume prover or by using another method that is being adapted by many end users-the prover-master meter method (see Figure 9).

Master meter proving is an accepted and recognized method of proving flow meters. However, master meters must also be calibrated on a regular basis to minimize errors. Calibrating a master meter in any situation other than the actual operating conditions can introduce uncertainties that must be compensated for. Changes in fluid composition, viscosity, density and pressure can affect a meter's performance, as can installation effects.

Using a prover-master meter combination installed in series with the meter under test eliminates all of these uncertainties, since the master meter is first calibrated by the meter prover *in-situ* under the actual operating conditions and using the actual fluid being measured. Once this is accomplished, then the master meter is used to calibrate the ultrasonic meter using the master meter calibration methodology.

The advantage of this method is that it allows for much larger proving volumes, since the volume can be as large as necessary to allow an acceptable level of repeatability.

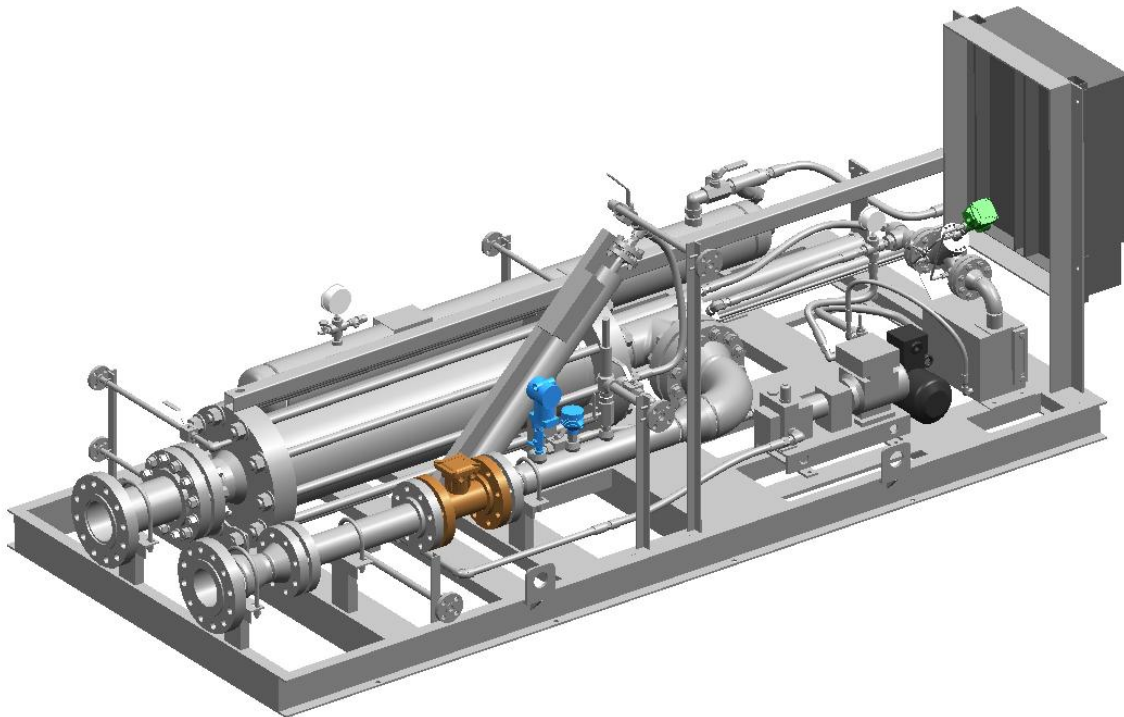
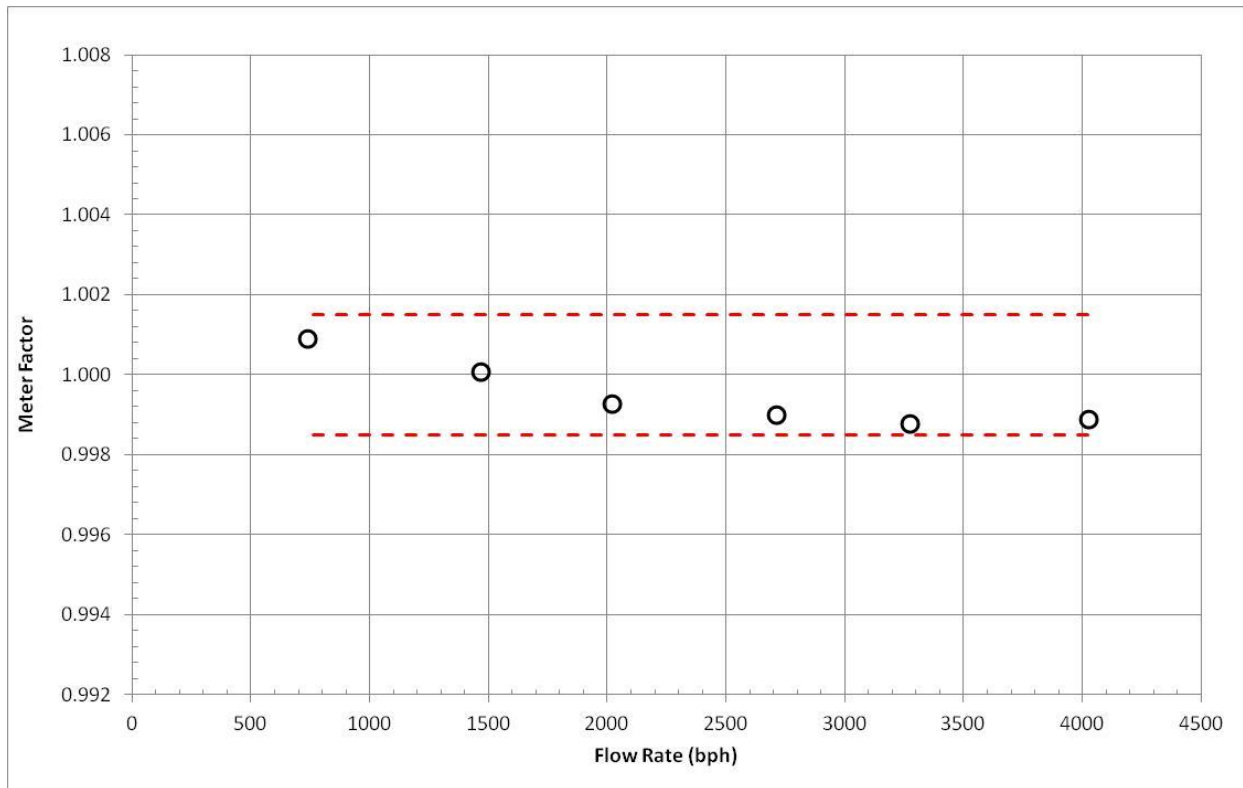


Figure 9 : Small-volume prover with turbine master meter

Existing provers, whether ball-type or small-volume, can be fitted with master meters in the field if it is determined that the existing prover does not have sufficient volume to provide acceptable repeatability.

Figure 10 shows an actual calibration curve on a 6" ultrasonic meter that was calibrated using a bi-directional ball prover with a volume in accordance with the recommendation in API Chapter 5 Section 8.



Linearity = $\pm 0.106\%$

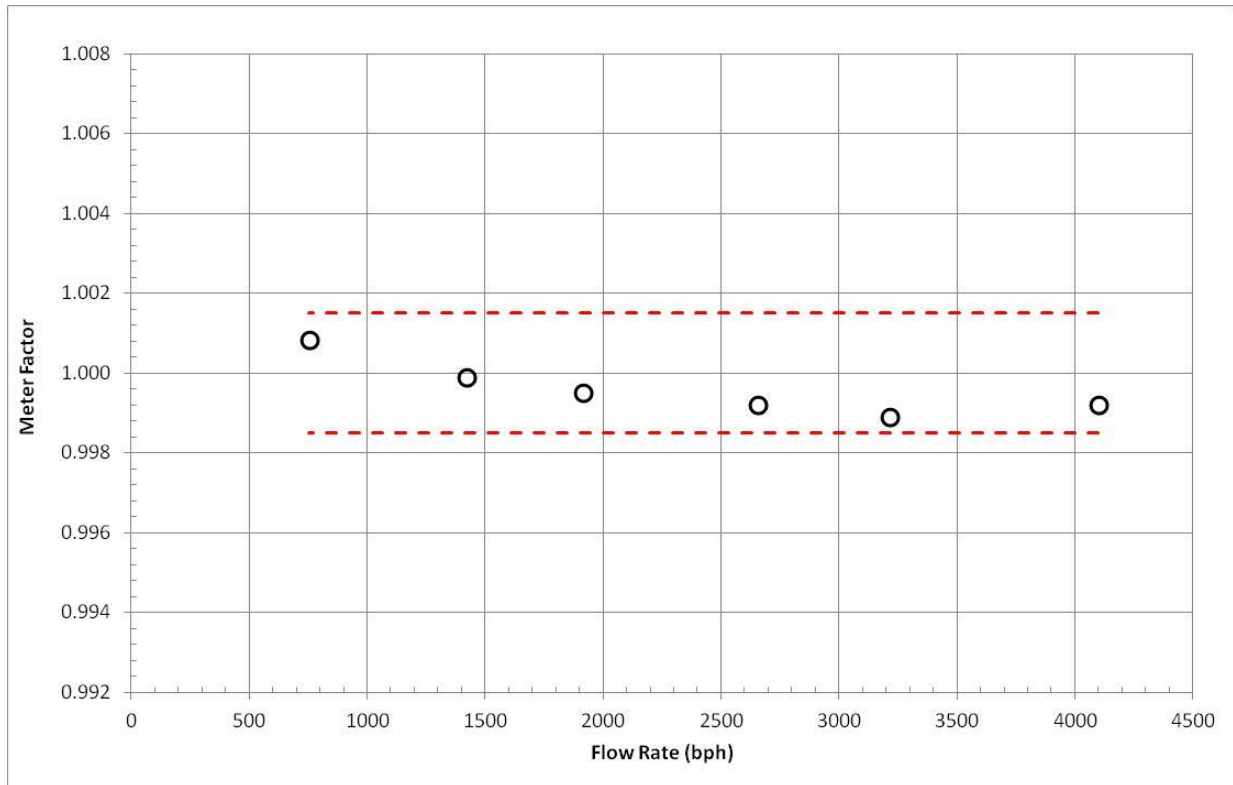
Uncertainty of Meter Factor = $\pm 0.013\%$

Figure 10: Liquid ultrasonic meter 6" calibration chart – using ball prover with ample volume

Figure 11 shows the same 6" meter calibrated using the prover-master meter method described above.

A small-volume prover was used to calibrate an 8" turbine meter, which was then used as the master meter to calibrate the 6" ultrasonic meter.

The results are virtually identical to those above, illustrating the viability of both methods and the reproducibility of the meter itself.



Linearity = $\pm 0.097\%$

Uncertainty of Meter Factor = $\pm 0.015\%$

Figure 11: Liquid ultrasonic meter 6" calibration chart using *in-situ* master-meter/small-volume prover

Below is the recommended sequence for proving a Liquid Ultrasonic Meter using the prover/master meter method;

1. Establish flow through the prover loop and verify the integrity of the double block and bleed valves.
2. Adjust flow rate to that desired for proving and verify temperature stability between meter under test and prover/master meter.
3. Prove the master meter with prover to meet required uncertainty, typically $\pm 0.027\%$ or better.
4. Reconfigure prover electronics for master meter prove operation using new meter factor obtained in step 3 above.
5. Prove Liquid Ultrasonic Meter with master turbine meter to required uncertainty (recommend 2 minutes per run)
6. Re-prove master meter with prover to verify that meter factor has not changed by more than 0.02% from initial prove in step 3 above.

The above sequence is repeated for every flow rate tested or if the repro of the master meter in step 6 above shows a change in meter factor greater than 0.02% of initial value from step 3.

Large Liquid Ultrasonic Meter Proving

Proving larger liquid ultrasonic meters (> 12 inch) to their maximum design flow rate can be a challenge. The limiting factor in being able to do a direct proving of these large meters is the maximum recommended velocity of the sphere or piston in the prover. API recommends the displacer (sphere or piston) velocity to be a criterion in the design of the prover to prevent damage to the displacer and the detectors. Typically, bidirectional displacement provers are designed where the maximum displacer velocity is somewhere around 5 ft/sec (~ 1.5 m/sec.) and unidirectional provers typically permit operation up to a maximum displacer velocity of around 10 ft/sec (~ 3.1 m/sec.).

In order to prove a liquid ultrasonic meter at flow rates higher than the capabilities of a prover, parallel master meters are a viable solution for proving at high velocities. Figure 12 is a basic configuration of a parallel master meter layout that is employed at SPSE in Fos sur Mer, France.

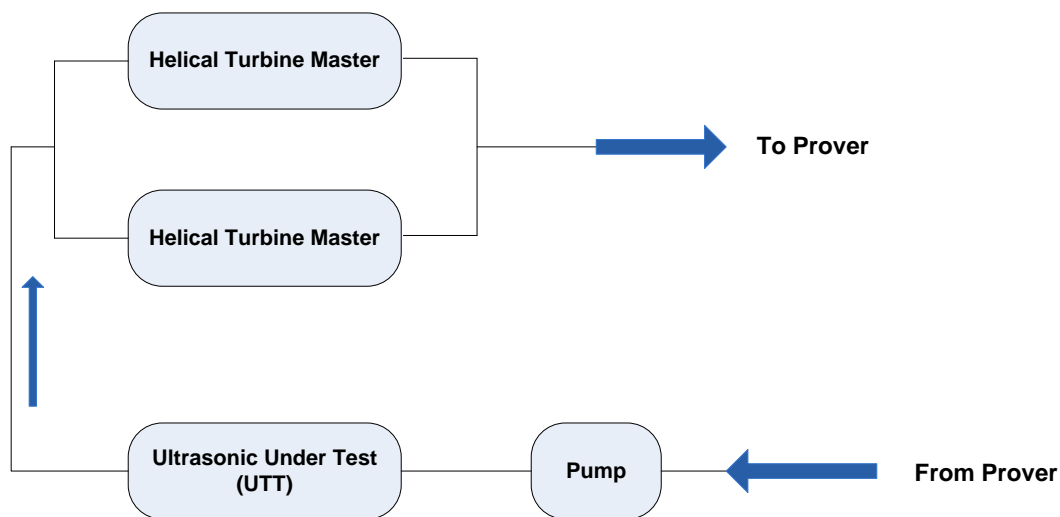


Figure 12: Parallel Helical Turbine Master Meter Layout

In March 2011, a 16" liquid ultrasonic meter run (including upstream meter tube, 19 tube bundle and downstream meter tube) were installed in the SPSE flow loop in the "UTT" position shown above in Figure 12. Calibrations performed by SPSE required use of the (2) Master Meters in parallel flow in order to achieve the maximum calibration

flow rate of 4000 m³/hr for the 16" ultrasonic meter. Figure 13 shows the results of the calibrations. Direct proving of the liquid ultrasonic meter under test (UUT) was not possible due to the flow rate limitation of the prover. It is normal procedure for SPSE to use the parallel flow Master Meter method to achieve flow rates higher than 3000 m³/hr.

The parallel master meter arrangement was used to calibrate the 16" liquid ultrasonic meter on three different viscosity fluids: Naptha, Oural and Arabian Heavy (ARH). Prior to conducting the ultrasonic calibrations, the pair of master meters were calibrated over its flow range by direct proving on the operating fluid prior to calibration of the UUT on the same fluid.

The results of the March 2011 calibration are shown below in Figure 13.

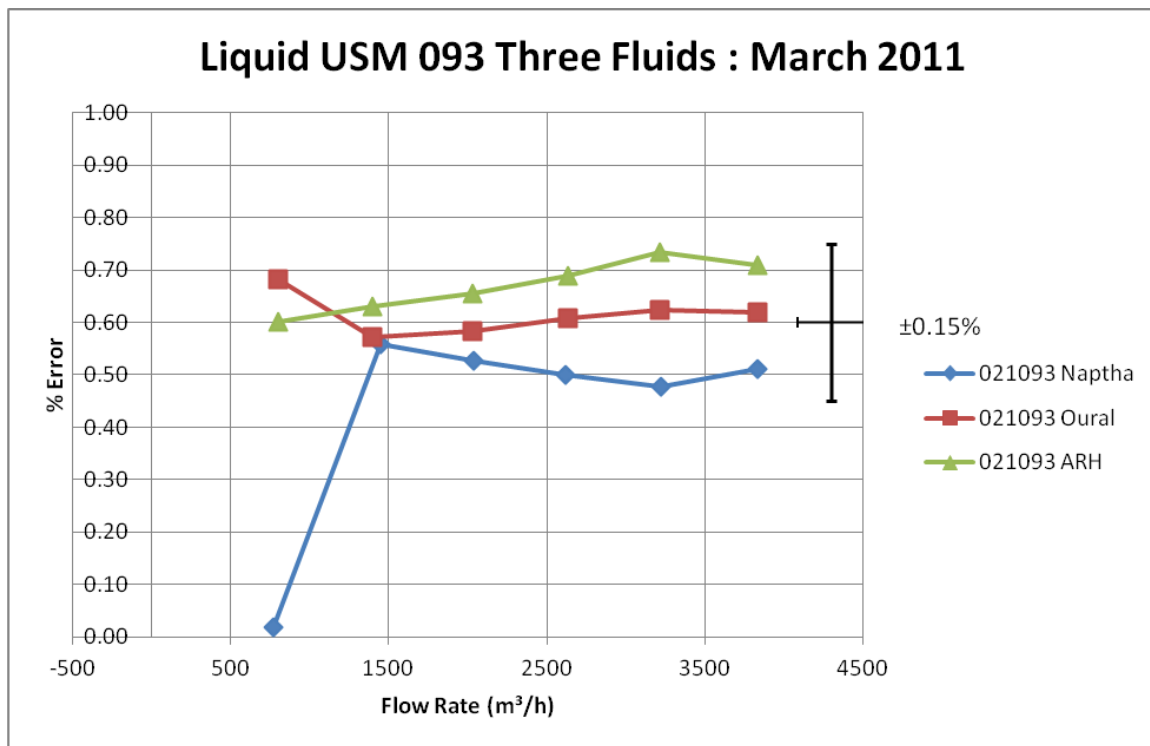


Figure 13: 16 Inch Liquid Ultrasonic March 2011 Calibration

The original factory meter factor and configurations were used for this entire calibration on the three different fluids. The results for the UUT linearity were within the acceptable linearity limits of $\pm 0.15\%$ for the Oural and ARH fluids as indicated below:

ARH linearity: $\pm 0.10075\%$

Oural linearity: $\pm 0.06031\%$

The linearity for the Naptha fluid was outside the acceptable limits and is listed below;

Naptha linearity: $\pm 0.28815\%$

Due to time constraints of the SPSE lab, the Naphtha calibration could not be re-run on this visit, and since another lab date was already planned, it was decided to re-run the calibrations at a later date. The complete meter run was removed as a single piece and the plan was to re-install and re-run the calibrations later. In reviewing the calibration data, it was hypothesized that the calibration methodology or process was suspect and not the liquid ultrasonic meter as the maintenance logs and meter diagnostics indicated the meter was operating correctly.

In June 2011, the complete liquid ultrasonic meter run was re-installed in the SPSE lab in the UUT position. The parallel master turbine meters were once again calibrated over the operating range and operating fluids. This time the calibration results for all three fluids were acceptable. Linearity's were all within the acceptable limits, which are as follows:

ARH linearity: $\pm 0.05388\%$

Oural linearity: $\pm 0.07144\%$

Naphtha linearity: $\pm 0.06508\%$

For the calibration in June, no changes to the installation or to the meter settings that were used during the March 2011 calibration. Previous thinking was the unacceptable linearity on the Naphtha fluid was a result of the calibration methodology or process. During this calibration, only one master meter was utilized at the lowest flow rate calibration point of the UUT for the Oural and Naphtha fluids (March calibration utilized both masters at the low flow rates). After completion of UUT calibration on Naphtha, the UTT was proved at its two lowest flow rate points by the direct proving method (using the ball prover). The direct proving results were found to closely match the linearity of the points that were proved by the master meter.

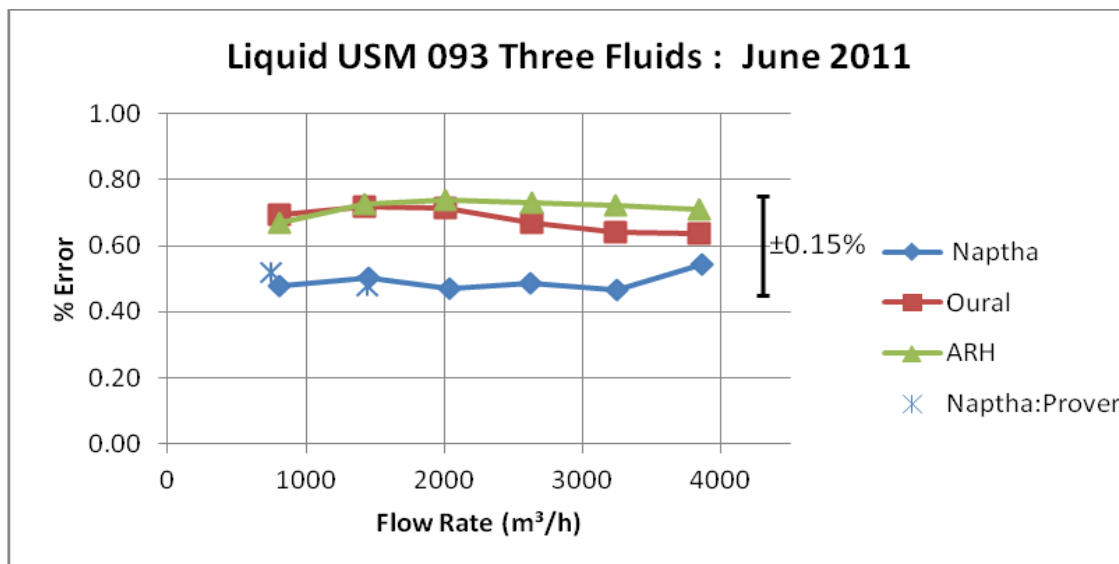


Figure 14: 16 Inch Liquid Ultrasonic June 2011 Calibration

Using two Master turbine meters in parallel at the lowest flow calibration point for the USM resulted in a linearity curve less flat as compared to use of a single Master at the same flow rate. This is because the single Master operated at a higher flow rate compared to the flow rate for each of two Masters. With the lower specific gravity and viscosity of Naphtha compared to the two oils, the driving force on the turbine meter rotor is less and frictional forces of the bearings introduce more non-linearity in the low flow range. It is therefore desirable to operate the turbine meter in a higher flow range if possible. When using the Master for calibration purposes, the lowest flow rate point of the UUT should closely match the flow rate at which the Master was proved in order to minimize any error introduced by non-linearity in the low flow region.

Summary

Liquid ultrasonic meters are continuing to gain acceptance in an ever expanding variety of measurement applications.

The mystery of how to prove ultrasonic meters is diminishing as more users have a better understanding of the technology, the standards, and the issues discussed in this paper. Companies are successfully proving liquid ultrasonic meters in the field on a regular basis.

Proving large ultrasonic meters are not impossible, and utilizing a parallel master meter arrangement works very well. It is important that you understand the performance limitations of the master meter technology with respect to the fluid, its characteristics as well as flow rates.

References

- (1) API Manual of Petroleum Measurement Standards (MPMS), Chapter 5 - Metering, Section 8 – Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters Using Transit Time Technology
- (2) API Manual of Petroleum Measurement Standards (MPMS), Chapter 4 – Proving Systems, Section 2 – Displacement Provers
- (3) API Manual of Petroleum Measurement Standards (MPMS), Chapter 4 – Proving Systems, Section 5 – Master – Meter Prover
- (4) API Manual of Petroleum Measurement Standards (MPMS), Chapter 4 – Proving Systems, Chapter 8 - Operation of Proving Systems