Index

Paper 5.4

API's Microprocessor Based Flowmeter Testing Programme

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1 INTRODUCTION

Modern microprocessor based flowmeter technologies for measuring liquids, such as Coriolis meters, and Ultrasonic flowmeters (UFMs), hold great promise, the technologies offer many advantages including; no rotating parts, and self-diagnostic checks. When correctly interpreted, these diagnostic checks can help anticipate and warn of impending failures before they have a major impact on the measurement. These meters however are substantially different than other primary devices due to their heavy reliance on the accompanying secondary electronics.

They all present the same challenge: How do you prove that they are accurate?

One method would be to prove the flowmeter using a pipe prover or small volume prover (SVP), but these proving methods are designed to count 'real time' pulses from a turbine or PD meter between a known volume, they are not designed to count 'time delayed' 'manufactured pulses' from a microprocessor. To understand the challenges, we need to understand the limitations of the manufactured pulse train, and how it affects the ability of the flowmeter to be proved using current proving technology.

The author of this paper is chairman of an American Petroleum Institute task group that has been charged with investigating how the 'microprocessor generated pulses' produced by these types of flowmeters, interact with the existing measurement technologies in use today. Funded by the API, the task group has been performing controlled flow testing in a laboratory in Pasadena, Texas. The testing programme was initiated in July 2003, the flowmeter testing phase concluded in August 2004.

Several flowmeter technologies utilizing microprocessors have been tested, these include; Ultrasonic, Coriolis, Vortex, and a Helical Turbine with pulse multiplying preamplifier. Wherever possible, flowmeters of various sizes, and from several vendors have been tested. Most industry testing of these flowmeter technologies has focused on accuracy, repeatability, and reproducibility, over a wide range of flowrates. This testing programme has focused solely on the errors and uncertainties introduced by the flowmeter electronics used to calculate flow and generated flow proportional pulses. Because of space limitations it was necessary to limit this technical paper to Coriolis and Ultrasonic flowmeter technologies.

2 THE DELAYED PULSE

When a turbine meter is proved, each pulse counted represents an incremental volume that is passing through the meter at that instant in time, the pulse is effectively occurring in real time. If there were a step change in flowrate, the pulse frequency from the turbine would almost instantly reflect that change. This is not the case with pulses obtained from a flowmeter utilizing a microprocessor. These flowmeters perform many indirect measurements in order to calculate a flowrate, and then must manufacture an output pulse frequency that accurately represents this flowrate. The manufactured flow pulse always lags the actual flow in the pipe by some sampling or calculation time T1 (Fig.1 and 2), and may be further delayed by filtering or damping applied in the pulse output stage of the flowmeter's electronics T2 (Fig.1 and 2). Because of this lag, during a meter proving we are counting pulses representing a volume that has already passed by the detector switches. The pulse lag makes the proving process more sensitive to flowrate changes during the prove process, and causes an incorrect K-Factor (pulses /unit

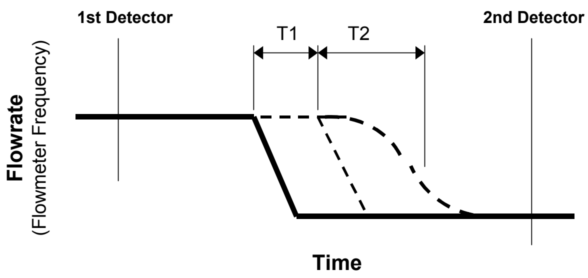

Fig. 1 - Pulse Delay Decreasing Flow

volume) result. With delayed flow pulses, a meter calibration can end up introducing bias errors instead of eliminating them.

2.1 The K-Factor Bias Error

Fig.1 above shows what happens when a decrease in flowrate occurs between the detector switches. Because the flowmeter pulse frequency lags the actual flowrate change, too many flow pulses are registered between the detector switches. The K-Factor shows a positive bias with decreasing flowrate. Likewise, Fig.2 shows the opposite effect, in this case with increasing flowrate, too few pulses are registered between the detector switches, and the K-Factor shows a negative bias. The amount of bias in either direction can be shown to be roughly proportional to the amount of pulse delay and flowrate change, and inversely proportional to the time between the detector switches. In reality it is very difficult to quantify the pulse delay because of the re-shaping of the leading and trailing edge of the flowrate change profile, i.e. a sharp step change in flowrate can become a smooth ramp in flowrate as reported by the test flowmeter if there is heavy filtering of the pulse output.

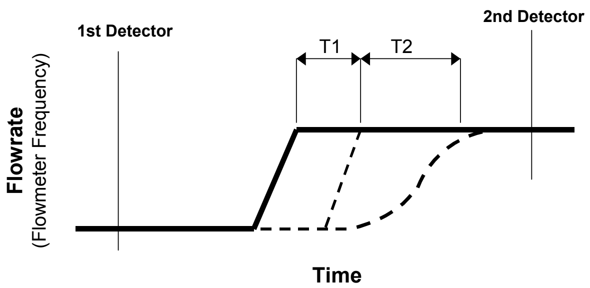

Fig. 2 - Pulse Delay Increasing Flow

2.2 Flow Disturbances During a Prove

Prior field-testing by the API TAG has shown that significant and very repeatable flow disturbances can be generated by the prover mechanism itself. These disturbances were found to occur before the first detector on an SVP, and in similar point on some types of unidirectional pipe provers. A flowmeter with a delayed pulse, responding to such a disturbance, could be outputting pulses representing this disturbance, after the first detector if the disturbance was close enough to the first detector, and the pulse delay was long enough. The pressure disturbance created when the displacer is launched was also seen to interact with other control components in the measurement system, causing repeatable flow changes during the prove passes.

2.3 Asymmetrical Response

Measurement errors can also be introduced if a microprocessor-based flowmeter has an asymmetrical response to flowrate changes, i.e. if the flowmeter's response to negative flowrate changes versus positive flowrate changes are not equal, the resultant flow measurement will be in error in variable flowrate applications. A problem of this kind affects not just the proving process but also normal operation.

3 THE TESTING PROCESS

The focus of API's testing programme was to investigate and test flowmeters currently on the market today, measure the pulse delay, and quantify the impact that this pulse delay has on the proving process. Ultimately, the information arising from this testing process is to be used to estimate measurement uncertainty, and also enable the API TAG to provide practical recommendations and language to be incorporated into future API Standards.

Issues that the API TAG wanted investigated were:

- Are the manufacturers' time constant settings practical? Could they be used as input into an uncertainty calculation?
- Is the K-Factor bias error proportional to the pulse delay?
- Is the bias error the same for ramp or step flowrate changes?
- Is the polarity of the bias error consistent with flowrate changes?
- Do the test flowmeters react in a symmetrical way to flowrate changes?

- Is the bias error affected by flowrate (i.e. because of more or less time between the detectors)
- Does the baseline K-Factor change when the flowmeter time constant settings are changed?
- Do longer time constant settings enable the flowmeter to better handle non-ideal flow profiles?
- Is the run-to-run repeatability dependent on flow stability or prove time?

3.1 Overview of Testing Protocol

At a minimum, each flowmeter was tested with two significantly different time constant settings at two different flowrates, one flowrate being nominally 50% of the other. Extra tests were conducted at additional time constant settings where time and equipment permitted it. All SVP proves consisted of 10 passes without regard to test meter run-to-run repeatability. Poor repeatability was to be expected as the tests involved creating significant flow disturbances during each prove run.

The testing sequence was as follows:

1) Steady flowrate conditions
2) Determine the master turbine meter's K-Factor using an SVP prove.
3) Determine the test meter's baseline K-Factor by a master meter prove.
4) Re-verify the master turbine meter's K-Factor using an SVP prove.

Steps 1) through 4) are referred to in this document as a 'master meter transfer prove'. The criteria used to determine the master meter prove volume was as follows: a) The volume used must allow at least 15,000 pulses from master and test meter to be counted, and b) to minimized any impact due to delayed pulses, prove run time must be in the order of 100 times that of the anticipated pulse delay. All test flowmeters of 3 inches or larger used two 30 barrel prove runs, and the 1 inch Coriolis meter was proved using two 5 barrel prove runs.

5) Determine the test meter K-Factor using an SVP with a nominal 5% step increase in flowrate occurring between the detectors.
6) Determine the test meter K-Factor using an SVP with a nominal 5% step decrease in flowrate occurring between the detectors.
7) Determine the test meter K-Factor using an SVP with a nominal 5% ramp increase in flowrate occurring between the detectors.
8) Determine the test meter K-Factor using an SVP with a nominal 5% ramp decrease in flowrate occurring between the detectors.

3.1.1 Determining the Pulse Delay

The actual pulse delay of the test meter was determined by referring to graphical timing data, and by repeating steps 5) through 8) with the test meter detector switch signals delayed to synchronize the prove volume with the delayed meter pulses. The flowmeter's pulse delay was assumed to be realistically determined when the observed K-Factor deviation from the baseline was improved appreciably. In many cases it was possible to reduce the K-Factor deviation by a factor of 10 by delaying the test meter detector switches.

The test sequence 1) through 8) above was repeated for each time constant setting tested, and at two flowrates. The data collected provided K-Factor bias error versus time constant settings, as well as providing test meter baseline K-Factors for each time constant setting used.

3.1.2 Non-ideal Flow Profile Test

With a non-ideal flow profile presented to the test flowmeter, the K-Factor of the test meter was determined at two significantly different time constant settings using the 'master meter transfer' method described above. This test was performed at the high flowrate condition.

3.2 Satisfying The TAG's Requirements

In order to satisfy the API TAG's requirements it was necessary to perform a large number of 10 pass SVP flowmeter provings, on 13 flowmeters, manipulating the flowrate in a consistent manner during the process. The decision was made to use an SVP for three reasons:

1) While the TAG members were aware that SVP's were not the ideal type of prover to be proving these flowmeter technologies, many users around the world were trying to do just that, especially users of Coriolis meter technology.
2) Because the K-Factor bias error due to the pulse delay is inversely proportional to the prove time between the detectors, proving using an SVP provides shorter prove times and larger more easily seen error values, albeit with more uncertainty.
3) The test protocol required many proves at a number of different timing settings and flowrate conditions. It would not have been practical or economically feasible to use a large pipe prover.

When testing was completed in August 2004, each microprocessor-based test meter had been proved an average of 68 times using the SVP, a total of 952 SVP proves. Each test meter was also proved an average of 7 times using the master meter transfer method a total of 88 master meter proves. Two master turbines meters were used, a 2 inch and a 4 inch. The 2 inch turbine was proved 58 times using the SVP, the 4 inch was proved a total of 970 times using the SVP.

3.3 The Flow Test Loop

A flow test loop was constructed as shown in Fig.3 using water as the circulating fluid. Water from a large supply tank was pumped into the test loop, passing first through the reference or master turbine meter, and then though the microprocessor-based flowmeter being tested. Both flow measurement sections were constructed in compliance with current API standards, with 10D upstream sections, and 5D downstream sections, tube bundles were installed in the upstream sections of both flow metering tubes. A SVP (Small Volume Prover) was located downstream of the meter runs, the outlet of the SVP was connected back to the supply tank via a flow control valve. Temperature and pressure taps were located in a pipe section located between the reference turbine meter and the test meter, and also at the outlet of the SVP.

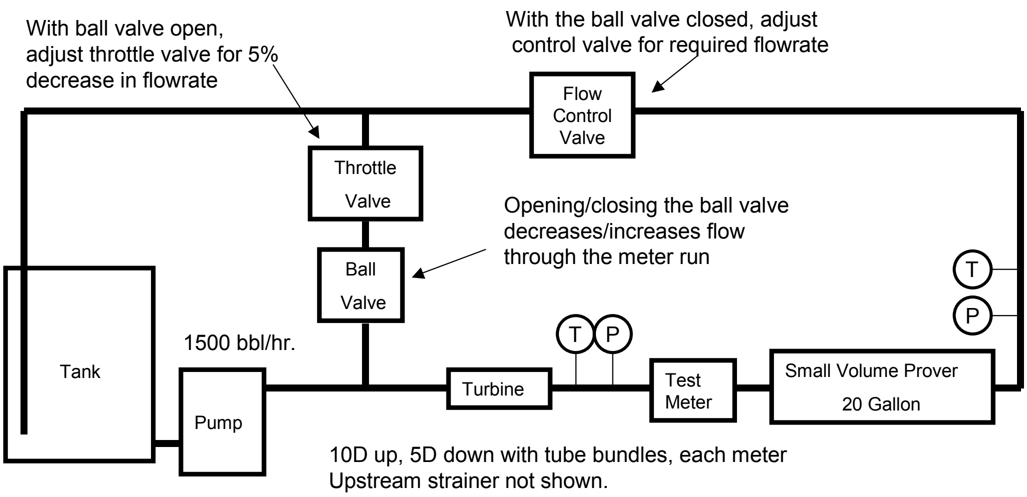

Fig. 3 - Flow Test Loop Details

A bypass ball valve fitted with a fast acting actuator was connected in series with a hand operated throttle valve between the pump outlet and the return line to the tank. The flow through the flow loop was step increased or step decreased during each prove run by quickly opening or closing the bypass ball valve at the appropriate time as controlled by computer. The air operated actuator of the bypass valve was also fitted with solenoid operated needle valves in the air vents, these allowed the ball valve to be opened or closed more slowly to produce a ramp flow increase or decrease during each prove run as required.

3.3.1 Creating a Non-Ideal Flow Profile

During the development of the API's UFM Draft Standard in 2002, the possibility had been raised that, given more measurement samples, a UFM could better predict the flow profile in the measurement section and therefore provide better accuracy. The testing protocol developed by the Manufactured Pulse TAG required a test where the test flowmeter was presented with a non-ideal flow profile to verify this hypothesis.

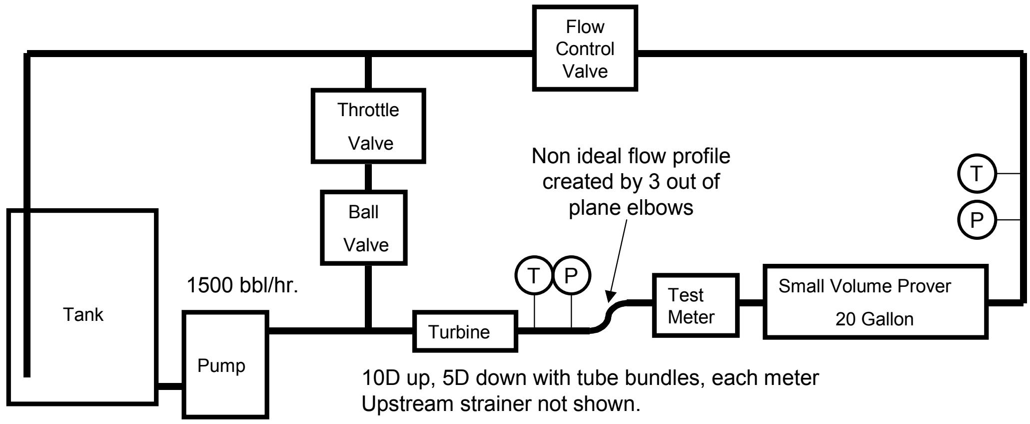

Fig. 4 – Flow Test Loop - non ideal flow profile)

This was achieved on the flow test loop by inserting three out of plane elbows immediately upstream of the test meter flow section as shown in Fig. 4.

3.4 Data Acquisition and Control

To streamline the testing process, proves using the SVP always proved the reference turbine and test flowmeter simultaneously. A custom control panel was constructed which housed two flow computers and various controls and switches. The control switches were connected to the flow computers and were used to select and/or indicate the type of flow disturbance to be applied during an SVP prove. One flow computer was used to prove the reference turbine meter, archive it's prove data, and operate the bypass ball valve. A second flow computer was used to prove the test meter and archive it's prove data. A custom programmed PC based acquisition system was used to monitor the flowmeter pulse signals, the SVP launch control, and detector switch signals. Instantaneous pulse frequency measurements for both the test meter pulses, and the turbine meter pulses, were taken each and every flow pulse using the reciprocal of the measured pulse periodic time. The SVP detectors and launch command signals were sampled for time reference purposes every 1 mS. The control panel also contained a programmable digital delay module which could be used to delay the test meter's detector switches. The delay module reproduced a delayed set of detector switch signals to a resolution of +/- 50 nS. Delay intervals were selectable in 1mS increments.

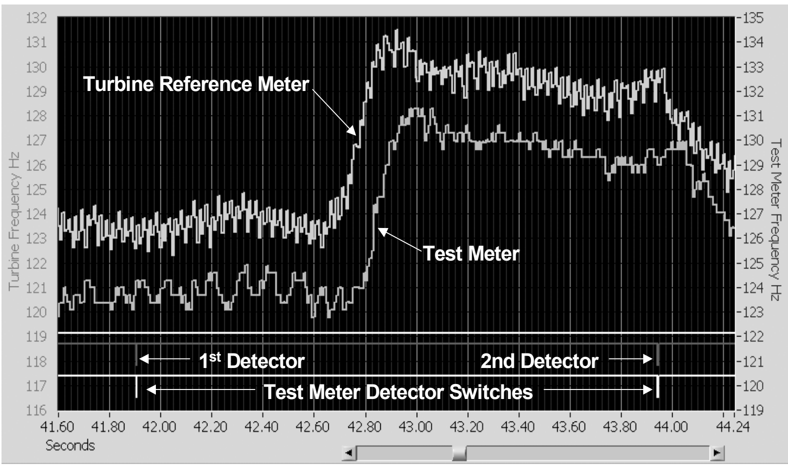

Fig. 5 - Step Increase in Flow – Fast Response Setting

4 Data Analysis

All test data was blinded and preliminary data analysis has taken place, it is summarized in this technical paper. Because there is a large amount of data it is expected that analysis will continue for some time into the future. Analysis work is also continuing into the asymmetrical response aspects of these technologies.

4.1 Manufacture's Time Constant Settings

One of the goals of the API TAG is to develop an equation that will allow uses of the technologies to calculate the uncertainty associated with the delayed pulse. One of the critical variables needed as input to this equation will be the actual value of the flow pulse delay. Currently there is no standard method used by manufacturers that specifies what this delay is. In one case the user selects the flowmeter's time constant as 'Short', 'Medium', or 'Long'. In another case the time constant setting is '0' through '4', and it isn't linear! Clearly the equipment manufacturers need to provide this information in a more scientific manner. Referring to Table 1, it can also be seen that in all cases, the actual observed pulse delay is different from what the manufacturers time constant settings (Tc1 and Tc2) would lead you to believe it is.

Table 1 – Manufacturers Time Constant Settings versus Observed Delay

Test Meter	Fast Response Setting			Slow Response Setting		
	Tc 1 Setting	Tc 2 Setting	Nominal Observed Delay	Tc 1 Setting	Tc 2 Setting	Nominal Observed Delay
A	100mS	na	175mS	na	na	na
B	50mS	na	100mS	100mS	na	175mS
C	100mS	na	125mS	500mS	na	240mS
D	10mS	0mS	50mS	50mS	800mS	950mS
E	na	#0	60mS	na	#2	225mS
F	20mS	0mS	15mS	60mS	50mS	50mS
G	0mS	na	125mS	1000mS	na	600mS
H	na	0mS	125mS	na	250mS	200mS
I	0mS	Short	325mS	1000mS	Long	1700mS
J	na	na	13mS	na	na	na
K	0mS	0mS	200mS	0mS	1000mS	1000mS
L	0mS	na	400mS	1000mS	na	1200mS
M	40mS	10mS	30mS	60mS	50mS	80mS

4.2 Methodology Used to Summarize Results

A method was needed to condense a large amount of data into a form, which would be easy to understand, and where trends could be recognized. Results are presented as follows:

- Data for flowmeters using the same technologies are grouped.
- Data within a technology are grouped according to observed flowmeter response time.
- Individual flowmeters may have multiple sets of data included in a data set according to their time constant settings during the tests i.e. Data from a flowmeter may be include in a data group twice because tests were performed at multiple time constant settings falling within the group criteria.
- K-Factor bias errors are normalized as a percent error per percent change in flowrate, i.e. API standards currently require flowrate to be held within 5% during a prove, in that instance, the bias errors in these tables have to be multiplied by 5 to arrive at the estimated bias error.

The data is presented in 'Min', 'Max', 'Average', form specifically to show trends over a range of flowmeter devices, the author wanted to avoid singling out any individual flowmeter as being better or worse than any other flowmeter.

4.3 Coriolis Flowmeter - K-Factor Bias Versus Pulse Delay and Prove Time

Referring to the data in the 'Avg' columns of Tables 2, 3, and 4, it can be seen that:

- The K-Factor bias error is more or less proportional to the response time of the flow-meter.
- The bias error is approximately the same for ramp or step changes in flowrate.
- The polarity of the bias error is consistent, and in the opposite direction to the flowrate step or ramp change.
- While mostly symmetrical, there is some slight asymmetry in bias error versus direction of flowrate change.
- Longer prove times appear to equate to less bias for the faster response settings (Tables 2 and 3), this was not the case for the slower response settings (Table 4) where the bias error appeared to be unaffected by double the prove time.

The percentage values in these tables are normalized to error percent versus percent flowrate change.

Table 2 – 3 Inch Coriolis Meters – 50mS to 125mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*			420 BBL/Hr.*(~3.8sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.0574%	-0.0309%	-0.0410%	-0.0250%	-0.0076%	-0.0163%
Flow Step Decrease	0.0602%	0.0162%	0.0379%	0.0176%	0.0036%	0.0106%
Flow Ramp Increase	-0.0572%	-0.0298%	-0.0411%	-0.0304%	-0.0133%	-0.0219%
Flow Ramp Decrease	0.0655%	0.0204%	0.0410%	0.0158%	0.0018%	0.0088%

Table 3 – 3 Inch Coriolis Meters – 200mS to 325mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*			420 BBL/Hr.*(~3.8sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.1627%	-0.0885%	-0.1329%	-0.0805%	-0.0400%	-0.0659%
Flow Step Decrease	0.1671%	0.0907%	0.1279%	0.0920%	0.0421%	0.0694%
Flow Ramp Increase	-0.1619%	-0.0949%	-0.1346%	-0.0854%	-0.0405%	-0.0629%
Flow Ramp Decrease	0.1321%	0.0807%	0.1135%	0.0937%	0.0412%	0.0674%

Table 4 - 3 Inch Coriolis Meters - 600mS to 1700mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*			420 BBL/Hr.*(~3.8sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.3845%	-0.3614%	-0.3698%	-0.3439%	-0.4994%	-0.4216%
Flow Step Decrease	0.4601%	0.3517%	0.4122%	0.4157%	0.2181%	0.3169%
Flow Ramp Increase	-0.3753%	-0.2923%	-0.3346%	-0.2966%	-0.2966%	-0.2966%
Flow Ramp Decrease	0.3979%	0.1907%	0.2877%	0.2465%	0.2465%	0.2465%

The lack of a bias error reduction with increased prove time at the slower response settings (Table 4) is not unexpected and is thought to be due to the response time of the flowmeters being a similar magnitude to the prove time. It is expected that significantly larger prove times between the detector switches would provide a reduction in bias error.

4.4 Coriolis Flowmeter - Run-to-run Repeatability

Tables 5, 6, and 7 show typical run-to-run repeatability and also equivalent random uncertainty values calculated per API MPMS Chapter 13 for three groups of test meters with different response characteristics. Taken individually, the results of any one prove may have an uncertainty greater than API currently requires, but when the same trend is observed in over 900 proves, a higher confidence level in the data is appropriate.

Referring to the values in the 'Avg' columns of Tables 5, 6, and 7:

- Notice that the average repeatability for all three flowmeter response settings is only marginally improved when there is no flow disturbance taking place.
- There is a correlation between faster flowmeter responses settings and an improvement in repeatability when prove times are longer. There is little or no improvement in run repeatability when longer response times are selected (Table 7). It should be noted however that while the prove time was approximately double at the lower flowrate, the number of pulses output by the flowmeter during that time remained the same.

Table 5 - 3 Inch Coriolis Meters - 50mS to 125mS Response

SVP Run Repeatability %								
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*				420 BBL/Hr. *(~3.8sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.251	0.052	0.120	0.028	0.043	0.031	0.037	0.009
Flow Step Increase	0.270	0.065	0.150	0.035	0.075	0.048	0.062	0.014
Flow Step Decrease	0.215	0.095	0.148	0.034	0.117	0.050	0.084	0.019
Flow Ramp Increase	0.177	0.091	0.125	0.029	0.039	0.032	0.036	0.008
Flow Ramp Decrease	0.230	0.065	0.142	0.033	0.081	0.031	0.056	0.013

Table 6 - 3 Inch Coriolis Meters - 200mS to 325mS Response

SVP Run Repeatability %								
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*				420 BBL/Hr. *(~3.8sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.212	0.088	0.155	0.036	0.161	0.036	0.102	0.024
Flow Step Increase	0.195	0.169	0.184	0.043	0.191	0.055	0.144	0.033
Flow Step Decrease	0.287	0.115	0.178	0.041	0.252	0.046	0.136	0.032
Flow Ramp Increase	0.376	0.100	0.279	0.065	0.215	0.051	0.133	0.031
Flow Ramp Decrease	0.332	0.215	0.264	0.061	0.251	0.057	0.154	0.036

Table 7 - 3 Inch Coriolis Meters - 600mS to 1700mS Response

SVP Run Repeatability %								
Flow Disturbance Type	850 BBL/Hr *(~2sec Prove)*				420 BBL/Hr. *(~3.8sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.317	0.184	0.261	0.061	0.295	0.295	0.295	0.069
Flow Step Increase	0.375	0.269	0.333	0.077	0.324	0.303	0.313	0.073
Flow Step Decrease	0.395	0.260	0.315	0.073	0.427	0.255	0.341	0.079
Flow Ramp Increase	0.368	0.242	0.303	0.070	0.292	0.292	0.292	0.068
Flow Ramp Decrease	0.465	0.225	0.355	0.082	0.295	0.295	0.295	0.069

4.5 Coriolis Meter - Baseline K-Factor Shift With Disturbed Flow Profile

The focus of this test was to determine if longer sampling times (more input data being available to calculate flowrate) would improve the flowmeters ability to operate with a non-ideal flow profile. Using the master meter transfer method, baseline K-Factors were developed for each flowmeter at two different time constant settings at the higher test flowrate. A flow profile disturbance was then introduced and K-Factors were again developed using the same master meter transfer method. The test was designed with Ultrasonic flowmeters in mind, but for consistency was also performed on the Coriolis flowmeters. The test was initially performed on Meter D with the tube bundles still in place and with inconclusive results. The next meter tested was Meter I where it was decided to perform the test with and without the tube bundles in place. Meters G and H were tested with the tube bundles out. The results in Table 8 for Meter I show that the tube bundles have little or no impact when used with Coriolis flowmeters.

Table 8 - Coriolis Meter – Baseline K-Factor Shift With Disturbed Flow Profile

Disturbed Flow Profile - *(3 Elbows Out of Plane 10 D Upstream of Flow Section)*						
Test Meter	Response Time mS	Tube Bundles		Response Time mS	Tube Bundles	
		In	Out		In	Out
Meter D *(3 Inch)*	325	-0.025%		950	-0.043%	
Meter G *(3 Inch)*	63		-0.154%	600		-0.138%
Meter H *(3 Inch)*	125		0.047%	200		0.034%
Meter I *(3 Inch)*	325	-0.033%	-0.033%	1250/1500	-0.063%	-0.070%

4.6 Coriolis Flowmeter – Baseline K-Factor Versus Time Constant Settings

A baseline K-Factor was developed for each meter using the master meter transfer method, at the higher test flowrate. Flowmeter time constant settings were then changed significantly and a new K-Factor developed. Table 9 below shows very small shifts from the baseline K-Factor (less than 0.01 %) for three of the flowmeters, the fourth meter showing a 0.033% shift for a time constant change of 1:5.

Table 9 – Coriolis - Baseline K-Factor Shift Versus Flowmeter Response Time

Test Meter	Initial MM Baseline K-Factor & Response Time		Observed K-Factor with Response Time Change		Shift
	Pulse/BBL	mS	Pulse/BBL	mS	
Meter C *(1 inch)*	42896.56	125	42896.90	240	0.0008%
Meter D *(3 Inch)*	542.103	50	542.054	325	-0.0090%
Meter G *(3 Inch)*	544.220	63	544.170	600	-0.0092%
Meter H *(3 Inch)*	545.753	125	545.793	200	0.0073%
Meter I *(3 Inch)*	542.185	325	542.365	1700	0.0332%

4.7 Ultrasonic Flowmeter - K-Factor Bias Versus Pulse Delay and Prove Time

Referring to the data in the ‘Avg’ columns of Tables 10, 11, and 12, it can be seen that:

- Like the Coriolis meters, the K-Factor bias error is more or less proportional to the response time of the flowmeter.
- The bias error in most cases is similar for ramp or step changes in flowrate.
- Except for two instances (‘Min values’ of Table 10, 600bbl/hr, step and ramp increases), the polarity of the bias error is consistent, and in the opposite direction to the flowrate step or ramp change. The two non-complying values in Table 10 were rechecked and found to belong to the flowmeter with the fastest response. The pulse signal for this flowmeter appeared to lead the turbine meter’s pulse signal for flow increases only, and only at the lower flowrate.
- Unlike the Coriolis meters that exhibited mostly symmetrical bias errors, the Ultrasonic flowmeter bias errors are more difficult to characterize. ‘Avg’ values in Table 11 representing meters with response time in the range of 80 to 125mS are reasonably symmetrical while values in Tables 10 and 12 are mixed.
- Longer prove times generally produce a smaller bias error.

The percentage values in these tables are normalized to error percent versus percent flowrate change.

Table 10 - 4 & 6 Inch Ultrasonic Meters - 15mS to 60mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*			600 BBL/Hr *(~2.9sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.0385%	-0.0157%	-0.0283%	-0.0117%	0.0073%	-0.0046%
Flow Step Decrease	0.0138%	0.0620%	0.0296%	0.0133%	0.0327%	0.0243%
Flow Ramp Increase	-0.0713%	-0.0286%	-0.0454%	-0.0186%	0.0154%	-0.0051%
Flow Ramp Decrease	0.0074%	0.0603%	0.0273%	0.0140%	0.0352%	0.0244%

Table 11 - 4 & 6 Inch Ultrasonic Meters - 80mS to 125mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*			600 BBL/Hr *(~2.9sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.0889%	-0.0561%	-0.0673%	-0.0330%	-0.0280%	-0.0312%
Flow Step Decrease	0.0477%	0.0814%	0.0652%	0.0225%	0.0400%	0.0291%
Flow Ramp Increase	-0.1190%	-0.0530%	-0.0786%	-0.0407%	-0.0220%	-0.0284%
Flow Ramp Decrease	0.0483%	0.0720%	0.0609%	0.0230%	0.0436%	0.0336%

Table 12 - 4 & 6 Inch Ultrasonic Meters - 175mS to 225mS Response

SVP K-Factor Deviation from Master Meter Transfer Baseline per % Flowrate Change						
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*			600 BBL/Hr *(~2.9sec Prove)*		
	Max	Min	Avg	Max	Min	Avg
Flow Step Increase	-0.1681%	-0.0792%	-0.1144%	-0.0829%	-0.0008%	-0.0466%
Flow Step Decrease	0.0909%	0.1448%	0.1106%	0.0351%	0.1071%	0.0769%
Flow Ramp Increase	-0.1565%	-0.1078%	-0.1268%	-0.0685%	-0.0479%	-0.0574%
Flow Ramp Decrease	-0.1622%	0.1340%	0.0260%	0.0361%	0.0883%	0.0649%

4.8 Ultrasonic Meter - Run-to-run Repeatability

Tables 13, 14, and 15 show typical run-to-run repeatability and the equivalent random uncertainty calculated per API MPMS Chapter 13 for three sets of Ultrasonic flowmeters, data is grouped by response time.

When comparing devices with similar response characteristics, test results show that the Ultrasonic flowmeters tested, exhibited run repeatability values approximately twice that of results obtained when testing the Coriolis meters (see Tables 5, 6, and 7). It should be noted that the Ultrasonic meters were larger in size (4 and 6 inch versus 3 Inch), and tested at a flowrate more than 50% higher than the Coriolis meters. This higher uncertainty may have impacted the values appearing in Tables 10, 11, and 12, providing less predictable trends.

Referring to the values in the ‘Avg’ columns of Tables 13, 14, and 15:

- Like the Coriolis meters tested, the average repeatability for all flowmeter response settings is only marginally improved when there is no flow disturbance taking place.
- There is a slight improvement in repeatability when prove times are longer. Note also that while the prove time was approximately double at the lower flowrate; the number of pulses output by the flowmeter during that time remained the same, there were however twice the number of sonic measurements made.

Table 13 - 4 & 6 Inch Ultrasonic Meters - 15mS to 60mS Response

SVP Run Repeatability %								
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*				600 BBL/Hr *(~2.9sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.338	0.225	0.263	0.061	0.246	0.161	0.246	0.057
Flow Step Increase	0.860	0.147	0.429	0.100	0.367	0.135	0.269	0.063
Flow Step Decrease	1.190	0.157	0.580	0.135	0.162	0.148	0.160	0.037
Flow Ramp Increase	0.606	0.179	0.374	0.087	0.248	0.152	0.193	0.045
Flow Ramp Decrease	0.574	0.264	0.433	0.101	0.270	0.174	0.202	0.047

Table 14 - 4 & 6 Inch Ultrasonic Meters - 80mS to 125mS Response

SVP Run Repeatability %								
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*				600 BBL/Hr *(~2.9sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.621	0.279	0.500	0.116	0.508	0.133	0.337	0.078
Flow Step Increase	0.691	0.231	0.386	0.090	0.488	0.235	0.368	0.086
Flow Step Decrease	0.817	0.183	0.817	0.190	0.615	0.222	0.372	0.086
Flow Ramp Increase	0.555	0.244	0.448	0.104	0.631	0.170	0.246	0.057
Flow Ramp Decrease	0.677	0.265	0.677	0.157	0.544	0.162	0.399	0.093

Table 15 - 4 & 6 Inch Ultrasonic Meters - 175mS to 225mS Response

SVP Run Repeatability %								
Flow Disturbance Type	1200 BBL/Hr *(~1.44sec Prove)*				600 BBL/Hr *(~2.9sec Prove)*			
	Max	Min	Avg	Uncertainty	Max	Min	Avg	Uncertainty
No Flow Disturbance	0.730	0.460	0.460	0.107	0.604	0.398	0.398	0.093
Flow Step Increase	0.645	0.526	0.645	0.150	0.639	0.424	0.424	0.099
Flow Step Decrease	0.807	0.532	0.751	0.174	0.620	0.358	0.451	0.105
Flow Ramp Increase	0.564	0.449	0.449	0.104	0.725	0.301	0.301	0.070
Flow Ramp Decrease	0.692	0.406	0.553	0.129	0.530	0.354	0.354	0.082

4.9 Removing Outliers – Does it Help?

While no data is presented on this subject in this technical paper, attempts were made to improve the repeatability by removing outliers, to better match the K-Factor result to the base-line K-Factor. This was done for a random selection of twelve provings for Coriolis and Ultra-sonic flowmeters, in only one case did the resultant re-calculated K-Factor better match the baseline K-Factor. The run-to-run prove count scatter appears to be truly random and better left as a set.

4.10 Ultrasonic Meter - Baseline K-Factor Shift With Disturbed Flow Profile

The possibility had been raised that, given more measurement samples, an Ultrasonic flow-meter could better predict the flow profile in the measurement section and therefore provide better accuracy. To verify this, baseline K-Factors were developed for each Ultrasonic flow-meter at two different time constant settings at the higher test flowrate, using the master me-ter transfer method. A flow profile disturbance was then introduced and K-Factors were again developed using the master meter transfer method. Referring to Table 16, flowmeter ‘A’ had fixed time constants so it was not possible to complete this test, it did however show a signifi-cant negative shift in K-Factor when the flow profile disturbance was added. Flowmeters ‘B’ and ‘C’ show significant shifts in K-Factor when the flow profile disturbance was introduced and these shifts were not improved by increasing the flowmeter’s time constant settings. Flowmeter ‘F’ was mistakenly tested with the tube bundles out, but interestingly showed a relatively small shift in K-Factor at it’s fast response settings. The shift increased significantly when more sonic samples were added to it’s timing settings. Flowmeter ‘M’ was something of a puzzle, The number of samples used to calculate the flowrate was changed by over 50% but the observed response time did not change to match the adjustments as expected (80mS to 90mS). The K-Factor shift for this flowmeter was relatively small for both time constant settings.

Table 16 - Coriolis Meter – Baseline K-Factor Shift With Disturbed Flow Profile

Disturbed Flow Profile - *(3 Elbows Out of Plane 10 D Upstream of Flow Section)*						
Test Meter	Response Time mS	Tube Bundles		Response Time mS	Tube Bundles	
		In	Out		In	Out
Meter A *(4 Inch)*	175	-2.802%				
Meter B *(6 Inch)*	100	1.171%		175	1.169%	
Meter E *(4 Inch)*	125	-2.044%		225	-1.918%	
Meter F *(4 Inch)*	15		0.066%	50		0.417%
Meter M *(4 Inch)*	80	0.032%		90	0.020%	

4.11 Ultrasonic Flowmeter – Baseline K-Factor Versus Time Constant Settings

A baseline K-Factor was developed for each meter at the higher test flowrate using the master meter transfer method. Flowmeter time constant settings were then changed significantly and a new K-Factor developed. Because time permitted, a third K-Factor versus time constant test was performed on Flowmeters ‘E’ and ‘M’. Table 17 below shows small shifts from the baseline K-Factor (less than 0.1 %) for flowmeters ‘B’ and ‘E’. Flowmeters ‘F’ and ‘M’ showing a significant negative shift -0.26% to –0.36% when the time constants were changed. Flowmeter ‘M’ was tested twice at two different time constant settings, both K-Factor shifts from the baseline are quite similar being –0.3584% versus -.03239%.

Table 17 – Ultrasonic - Baseline K-Factor Shift Versus Flowmeter Response Time

Test Meter	Initial MM Baseline K-Factor & Response Time		Observed K-Factor with Response Time Change		Shift	Observed K-Factor with Response Time Change		Shift
	Pulse/BBL	mS	Pulse/BBL	mS		Pulse/BBL	mS	
Meter A *(4 Inch)*	542.34	175						
Meter B *(6 Inch)*	543.047	100	543.300	175	0.0466%			
Meter E *(4 Inch)*	543.833	60	544.301	125	0.0861%	543.818	225	-0.0028%
Meter F *(4 Inch)*	541.931	15	540.521	50	-0.2602%			
Meter M *(4 Inch)*	550.797	40	548.823	50	-0.3584%	549.013	80	-0.3239%

5 Conclusions

The summarized results do appear to shed some light on many of the API TAG’s questions:

- Are the manufacturers’ time constant settings practical? Could they be used as input into an uncertainty calculation?

The answer to both these questions is no. There is currently no standard way to adjust the responsiveness of these flowmeters. The manufacturers also need to consider why they provide such a wide range of time constants, and should come up with a standard way of informing the user what they mean in real terms. When asked, “why would a user select a 2 second time constant?”, ‘Process Control’ is often the answer. Is it a good idea to filter the input data into a control system, or is that what the PID tuning controls are for? For analogue readout use, many of the flowmeters provided separate time constant adjustments.

- Is the K-Factor bias error proportional to the pulse delay?

Yes, the bias error results for both Coriolis and Ultrasonic flowmeters are broadly proportional to the pulse delay.

- Is the bias error the same for ramp or step flowrate changes?

In most cases yes, the bias error results for both Coriolis and Ultrasonic flowmeters are similar no matter if the flowrate is stepped or ramped. What matters is, “is the flowrate at the first detector the same as the flowrate at the second detector?" If the answer is 'No', then a change took place and a bias error is possible.

- Is the polarity of the bias error consistent with flowrate changes?

In every case (except the two mentioned in 4.7 above), increases in flowrate during a prove caused the resultant K-Factor to drop. Increases in flowrate had the opposite effect, the K-Factor increased.

- Do the test flowmeters react in a symmetrical way to flowrate changes?

The flowmeters were mostly symmetrical with the Coriolis meters configured for fast response being more symmetrical. Dr. Zaki Husain of Chevron/Texaco is currently investigating how the flowmeters react to increasing versus decreasing flowrates, by analyzing 'rate of change' of flowrates, versus 'rate of change' of pulse frequency response. Preliminary analysis on one flowmeter appears to show some asymmetry under some flowrate conditions.

- Is the bias error affected by flowrate (i.e. because of more or less time between the detectors)

The bias error is less when the prove time is longer and when the flowmeter reacts faster.

- Does the baseline K-Factor change when the flowmeter time constant settings are changed?

This was not the case for four out of five Coriolis meters tested, shifts were less than 0.01%. The fifth Coriolis meter shifted only 0.03% with a 1:5 change in time constant. The Ultrasonic flowmeters showed more sensitivity to changes in time constants, shifts ranged from 0.086% to –0.358%.

- Do longer time constant settings enable the flowmeter to better handle non-ideal flow profiles?

No improvement was observed when testing either Coriolis or Ultrasonic flowmeters. Longer time constants, or more sonic samples just seemed to slow responsiveness and increase sensitivity to flowrate changes.

- Is the run-to-run repeatability dependent on flow stability or prove time?

Overall, repeatability for both Coriolis and Ultrasonic technologies seemed relatively unaffected by significant flowrate disturbances. Repeatability at steady flowrate conditions was only marginally better versus when flowrate was unstable during a prove.

5.1 Practical Recommendations

The TAG members are currently studying the results of the testing programme and will in due course draft recommendations and language that will be included in future API standards.

Practical steps that can be taken by users until then are:

- Optimize the responsiveness of the flowmeter by reducing the Tc1 timing component to the minimum recommended by the manufacturer. Make sure that the contact person you are consulting is aware of the issues.
- If a Tc2 timing component is available, set this to zero or minimum. Filtering of the output pulse has been found to degrade performance.
- Minimize flowrate variations during the prove process. API's MPMS Chapter 4 recommendation of 5% allowable variation may not be conservative enough for these technologies.
- When designing a proving system, eliminate or reduce the effect of flow disturbances which occur before the first detector switch, provide sufficient pre-travel volume to

ensure that any delayed pulse response to such a disturbance has occurred before the first detector.

- Use as large a prover as is practical. The bias error introduced by the delayed manufactured pulse is inversely proportional to the prove time between the switches.
- If a large prover is not an option, consider proving the flowmeter using the master meter transfer method described here, using a turbine meter as a master meter.

5.2 Work Remaining

An area that requires more analysis is the ‘Double Chronometry’ component. Double Chronometry assumes that the periodic time of the flow pulse that straddles each detector switch is the same. This is not the case when the flowrate is different at the first versus the second detector switch. A 5% increase in flowrate during a prove means that the periodic time of the pulse train at the end of a prove is 5% shorter than at the beginning. This pulse period change can be shown to produce a K-Factor bias in the opposite direction to that attributed to the delayed manufactured pulse. This means that the actual bias errors due to delayed manufactured pulses are bigger than those reported here.

As is usually the case with a testing programme, the results often raise more questions than answers. There are still more data to analyze, and many questions still remain.