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Coriolis Mass Flow Meter Developments: Increasing The Range of Applications in Oil & Gas Production and Processing

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CORIOLIS MASS FLOW METER DEVELOPMENTS: INCREASING THE RANGE OF APPLICATIONS IN OIL & GAS PRODUCTION AND PROCESSING

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1 INTRODUCTION

Coriolis mass flow meters are highly regarded in the chemical and processing industries for their precision, accuracy and simultaneous measurement of true mass flow, fluid density and temperature. Unfortunately a well-known shortcoming of such meters is traditionally their inability to operate when presented with two-phase (gas/liquid) flow, which is not uncommon in the Oil & Gas industry! Under such conditions it can be difficult for the flowtubes to maintain oscillation, and even at low levels of gas void fraction severe errors may appear on the measurements. It is sometimes possible to engineer the process to exclude gas from the liquid measurement stream, but even when this is economically viable it still leaves the plant vulnerable should disturbances occur. Similarly, in batching and loading applications it is not generally recommended to use a Coriolis meter unless the meter can be kept full at all times. The ability to batch from and/or to empty would greatly extend the applications for Coriolis metering.

These problems has been investigated for over 15 years in the Invensys University Technology Centre at the University of Oxford and a novel all-digital Coriolis mass flow transmitter has been developed which is able to maintain flowtube operation throughout all conditions of two-phase flow. Key to this technology is the transmitter's ability to respond quickly to flow condition changes and this is also reflected in the meter's ability to accurately track changes in flow-rates with a fast dynamic response. This technology has been made commercially available by Invensys Foxboro in the CFT50 product range.

This paper presents recent results from two, and three phase flow experiments at Cranfield University using an Oxford prototype transmitter, which suggest how such a meter may be used as part of a multi-phase metering facility. Comparisons of batching from full and empty are also given. Results from recent API trials on the use of the commercial meter in small volume proving installations are presented, further extending the range of practical applications now addressed by such Coriolis mass flowmeters.

2 CORIOLIS MASS FLOWMETERS

Coriolis mass flow metering is a well-established technique for industrial flow measurement. The basic principle is that a flowtube is caused to vibrate sinusoidally at a resonant frequency by one or more drivers, while two sensors monitor the vibration. The flowtube geometry and sensor placement are arranged so that the frequency of oscillation (varying from 50Hz to 1kHz for different flowtube designs) is used to calculate the density of the process fluid, while the phase difference between the sensor signals provides the mass flow rate. The primary benefit of Coriolis metering is the direct measurement of mass flow, where commodity value, or chemical effect, is related to mass rather than volume, for example in the fine chemical industry. However, Coriolis meters have other advantages, including high accuracy (to 0.1% for static flow rates), and good turndown (100:1 or better), while their limitations include the need for a separate power supply, relative expense and well-known vulnerability to aerated fluids. For a user perspective on Coriolis as an "almost perfect" flowmeter, see [1], [2].

The key problem in using Coriolis mass flow meters to measure process fluids containing bursts or continuous two-phase flow can be summarized very simply: conventional Coriolis meters are not able to reliably maintain flowtube operation and generate accurate measurements; tens of seconds may elapse after the resumption of single phase flow before nominal performance is restored.

The operation of a Coriolis mass flow meter is dependent upon the proper oscillation of the flowtube. This is controlled by the drive signal(s) generated by the transmitter. The oscillation of the flowtube (as indicated by the sensor signals) is typically sinusoidal and hence characterized in terms of frequency, phase and amplitude. The drive signal is also often sinusoidal, or if not at least a regular waveform (e.g. square wave) for which similar attributes can be defined: the frequency, phase (relative to the sensor signal) and amplitude of the drive signal need to be determined and generated for optimal operation of the flowtube. An obvious and commonly-used criterion for flowtube control is that the flowtube should oscillate at its natural frequency of vibration (which will vary with the overall mass of the flowtube and hence the density of the process fluid), at a constant amplitude. Usually measurement algorithms assume constant amplitude of oscillation over the calculation interval, so amplitude stability is relevant for measurement quality.

For oscillation at the natural frequency, the driving force must be 90º out of phase with the motion of vibration. The most commonly-used form of sensor, based on a simple electromagnetic voice-coil, actually measures velocity, and hence the sensor signal is already 90º out of phase with the motion of the flowtube. Thus an optimal drive signal is one which has the same frequency of oscillation and phase as the sensor signal (or more properly the mid-phase – or sum – of the two sensor signals for non-zero phase difference), and with a drive amplitude selected to maintain a constant sensor amplitude.

The most common technique for generating a drive signal has been *positive feedback*, whereby the sensor signal (containing the desired frequency and phase characteristics) is multiplied by a drive gain factor (either by analogue or digital means). The drive gain required to maintain the desired amplitude of oscillation is closely related to the damping on the flowtube, and the two terms are often used interchangeably. Assuming negligible delay in the (analogue) feedback circuit, this ensures phase matching between sensor input and drive output. Positive feedback is relatively easy to implement, but it provides only partial control of the drive waveform, and cannot readily prevent unwanted components in the sensor signal (e.g. other modes of vibration) from being fed back into the drive signal. An alternative approach is *drive waveform synthesis*, whereby the transmitter calculates a drive waveform digitally, for example a pure sine wave or square wave. This has advantages over positive feedback, including full control over the drive waveform, but the challenge is to match the phase of the sensor signal in real time. Suitable techniques are described in [3].

The main effect of two-phase flow is a dramatic rise in the flowtube damping, perhaps by two orders of magnitude which is a significant challenge to the vibration control. Mechanical energy is lost in the interactions between compressible bubbles, fluid and flowtube walls, and the drive energy required to maintain oscillation rises sharply. Not only does the damping rise, but it varies rapidly, due to the chaotic nature of the interactions. Similarly, the frequency and amplitude of oscillation exhibit much greater variation than for single phase. The consequences for drive output are as follows:

- *Drive energy saturation*. For any intrinsically safe flowtube, there is an absolute limit on the energy supplied to the driver(s). The default amplitude of oscillation may not be sustainable. While many in industry appreciate this limitation, it is widely and *wrongly* assumed that this is the main reason why flowtubes stall. As shown below, it is perfectly possible to maintain flowtube oscillation through two-phase flow even with an artificially low limit on (say) drive current. By far the most common cause of flowtube stalling is drive gain saturation.

- *Drive gain saturation*. Some positive feedback drives cannot exceed a maximum drive gain limit e.g. due to amplifier saturation. This means there is a maximum multiplier between the sensor amplitude in and the drive signal out. Suppose this limit is reached, and the flowtube damping rises again due to yet more gas in the two-phase flow mix. A further rise in drive current to compensate for the increased damping is not possible, due to drive saturation. As a consequence, the sensor amplitude starts to reduce, but this in turn leads, again because of drive saturation, to a *drop* in the drive signal output; the end result is a catastrophic collapse in oscillation amplitude.

- *Poor tracking*. The rapid changes in damping, amplitude, frequency and phase on the sensor signal require fast and accurate tracking by the transmitter in order to generate an appropriate drive signal. If the drive control update rate is simply too slow, or there is too much dead-time [4], the flowtube may stall due to inattention. A second, possibly worse, alternative, is where oscillation is maintained, but inaccurate tracking leads to phase shift between input and output leading to forced oscillation, and hence wayward frequency of oscillation and poor repeatability. In the high damping conditions of two-phase flow, this may be difficult to detect and correct.

Two-phase flow provides different challenges to both of the main drive techniques. With positive feedback, the quality of control is limited, as the drive gain is selected based upon previous amplitude information while the drive signal itself is proportional to the sensor signal which is varying rapidly. Conversely with synthesis techniques, the problems of tracking phase to ensure natural vibration becomes more difficult.

3 THE OXFORD TRANSMITTER

Over the last decade the Sensor Validation Research Group at Oxford has developed a new Coriolis meter transmitter to provide improved measurement performance and robustness [5]. Several features provide improved flowtube control in the face of two-phase flow, including:

- Measurement and control updates every half drive cycle (typically every 6ms)
- Rapid dynamic response [4]
- Synthesis of a pure sine wave with the required amplitude, frequency and phase characteristics, providing a highly adaptable and precise drive signal.
- A non-linear amplitude control algorithm providing stable oscillation [6].
- Selection of a sustainable set-point for the amplitude of oscillation during two-phase flow.
- The ability to generate counter-phase signals or so-called negative gain (see below)

Figure 1 demonstrates the precision of the flowtube control system via a sequence of set point changes over 3 orders of magnitude. The default amplitude is 0.3V. This is reduced to 30mV, 3mV, and finally 0.3mV, before these steps are reversed, all within 45s. Note that 0.3V corresponds to a physical oscillation of 0.6 mm. The graph also shows the drive current requirements during these steps, which reduces linearly with amplitude.

The drive gain is defined as the ratio of the drive current to the amplitude of oscillation. Its mean value is approximately constant when the amplitude is steady. During set-point changes it exhibits large swings. Negative gain values are generated by the control algorithm when it is desirable to reduce the amplitude of oscillation rapidly. The transmitter does this by generating drive signals that are 180 degrees out of phase with the sensor signals, thus opposing drive motion. This is useful not only for effecting set-point changes, but also for maintaining flowtube stability at low amplitudes (e.g. t=15-25s) and with high damping (e.g. two-phase flow).

Figure 2 shows in more detail the sensor voltage and drive output when the amplitude of oscillation is 0.3mV. Several features of the drive synthesis algorithm are demonstrated. The drive and sensor signals are substantially in phase with each other. The amplitude of the drive signal is updated every half cycle. Occasionally a negative gain value is used, in which case consecutive half-cycles of the drive output have the same polarity. These techniques are effective: the sensor amplitude stays within 1% of the set-point, despite operating at only 0.1% of the normal amplitude of oscillation.

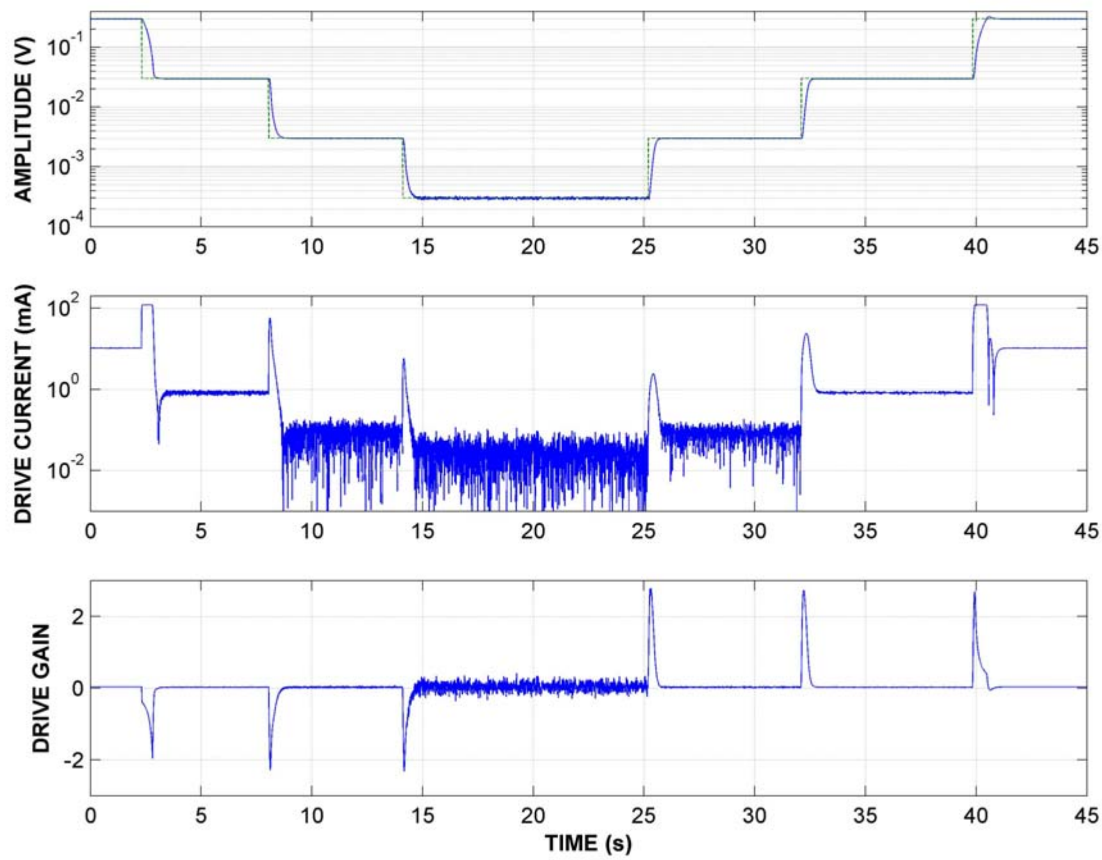

Fig. 1: Amplitude Control Through Setpoint Changes

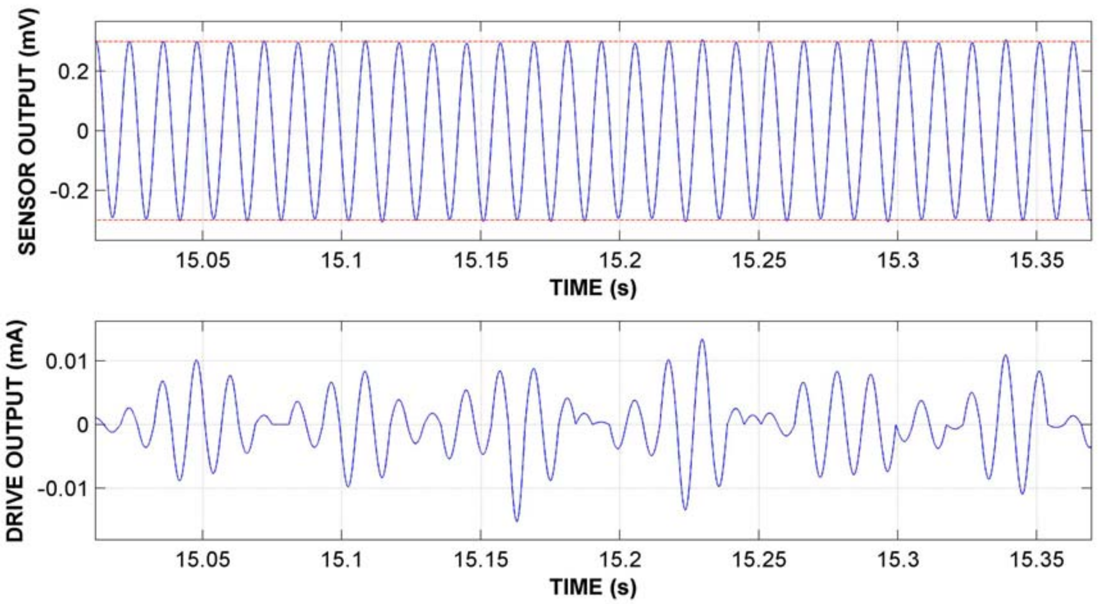

Fig. 2: Amplitude Control At 0.3mv: 0.1% of Normal Setpoint

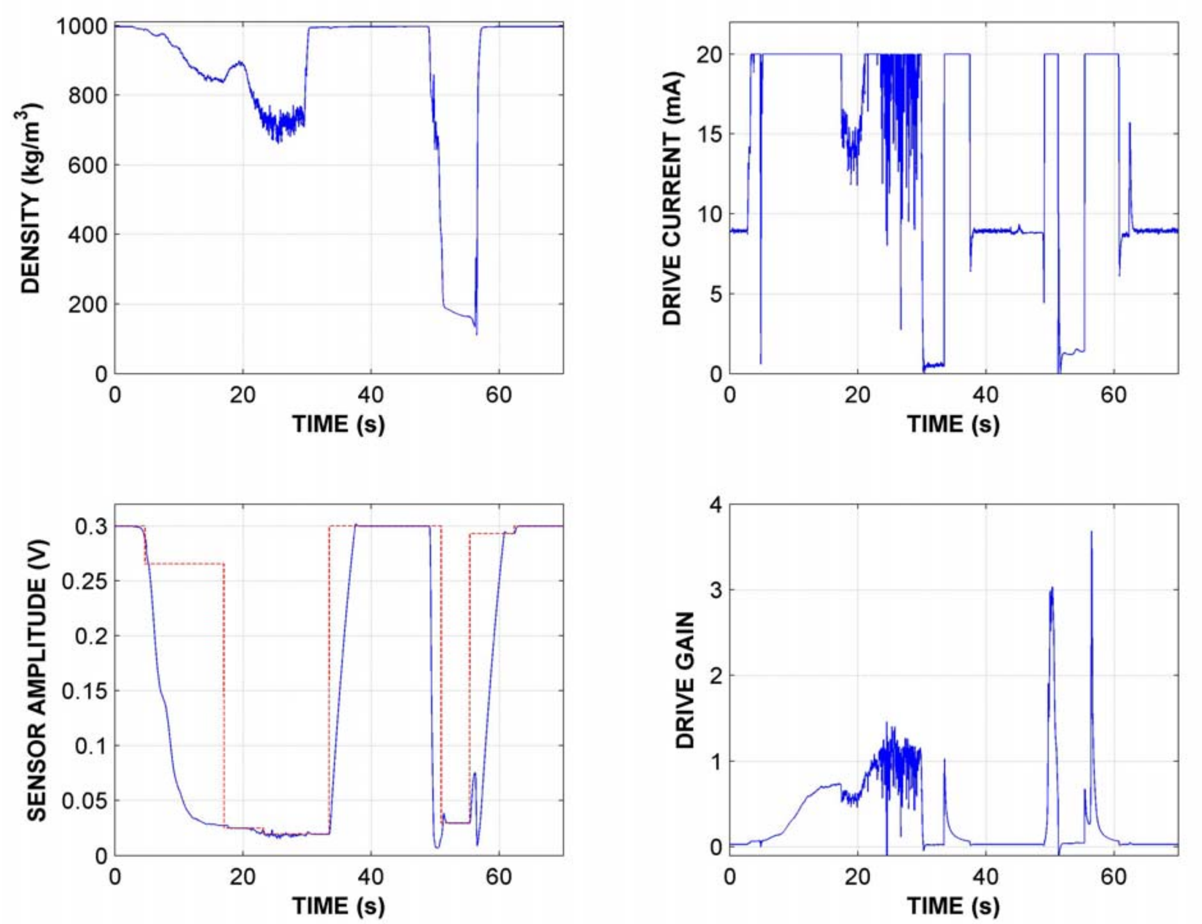

Fig. 3: Two-Phase Flow And Flowtube Draining (Low Power Drive)

Figure 3 illustrates how these features are used to maintain flowtube oscillation during two-phase flow, and when the flowtube is drained and refilled. This is achieved despite an artificially low maximum drive current of only 20mA – a more typical intrinsically safe limit would be 80mA. Initially (t=0s) the process fluid is single phase, and the amplitude of oscillation is the default value of 0.3V, maintained using 9mA per drive. Between t=3s and t=30s, there is a surge of air in the process fluid, as indicated by the density which drops to approximately 700kg/m^3. This causes a rapid rise in flowtube damping and hence the drive current needed to maintain flowtube oscillation. As the drive current limit of 20mA is reached, a new amplitude set-point is selected, and again at 17s, as indicated by the dashed line on the sensor amplitude graph. After t=35s, the process fluid becomes single phase and the drive gain returns to its conventional value. It is thus possible to revert to the default set-point of 0.3V. This is achieved (t=35-38s) using maximum drive current; with a less severe current limit the amplitude rise would occur more rapidly. At t=50s, a new disturbance occurs: the pump is switched off, causing process fluid to drain from the meter. Accordingly the density drops rapidly. The draining process introduces a high degree of damping for several seconds, and so at first a reduced set-point is adopted; however by t=55s draining is completed, and the default set-point is restored. However, at this point the pump is switched on again and the flow meter experiences the hydraulic shock caused by the onset of flow. By t=65s equilibrium has been restored, damping has reduced and the default amplitude of 0.3V has been reinstated. Note that the flowmeter maintains operation and continues to generate measurement data throughout these transients. Note also that this was achieved with only 20mA of drive current: with a more realistic limit of 80mA much tighter amplitude control is achieved.

3 BATCHING FROM EMPTY

There are many processes where the high accuracy and direct mass-flow measurement provided by Coriolis technology would be beneficial in the metering of batches. However, it is not always practical to ensure that the flowmeter remains constantly full of fluid. Large errors may be induced in Coriolis meters when partially filled, or empty with wet flowtube walls. Hydraulic shock from the onset of flow, or a surge of air, may result in large measurement errors and stalling. Most Coriolis manufacturers are thus unable to recommend the use of their products in batch applications unless the flowtube can be kept full. At least one major Coriolis user puts the ability to batch from empty as the most important development required of Coriolis manufacturers [1].

The Oxford transmitter has been designed to be robust to the conditions experienced when batching to/from empty, as illustrated in figure 3. As the flowtube control algorithm ensures that no settling time is needed between batches, it becomes feasible to use Coriolis meters in repeated short batch operations such as filling lines, without excluding entrained air. Industrial applications using the commercial version of transmitter for batching from empty are described in [12] and [13].

Trials have taken place on a small demonstration rig (Figure 4), using a 15mm flowtube, and a flowrate of 0.4 kg/s. For trials with the flowtubes kept full, a diverter system is used. With steady flow established, the diverter under transmitter control switches flow from a recirculation loop to a weigh scale. When the target totalized flow is reached, the diverter is switched back by the transmitter to the recirculation loop, and the finalized weighscale total is noted. This procedure has the advantage of a more or less steady flowrate (compared with say the filling application example described in [4]), but additional system non-repeatability is introduced by any variation between batches in the residual liquid in the pipework leading to the weighscale.

For the batching from empty trials the diverter is permanently switched to feeding the weighscale, and the transmitter controls the flow simply by switching the pump on and off. As the outlet pipe is open to the air, when the pump is switched off the Coriolis meter is drained by gravity, and so starts the next batch empty.

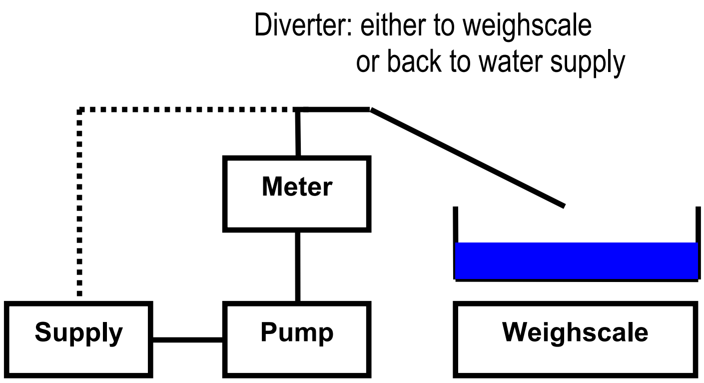

Fig. 4: Small Test Rig With 15mm Flowmeter

At the start of a batch the flow total is zeroed and the pump is switched on. When the totalised flow reaches the specified target weight, the flow meter switches the pump off, and the finalized weighscale total is noted. This procedure has several sources of non-repeatability: most obviously the flowtube filling process itself, but also the diverter performance and fluid retention in the piping.

In each trial, the Coriolis transmitter was given a target weight based upon an approximate batch time at the flow rate of 0.4kg/s. Thus, for the 10s batches the target weight was 4kg, while for 0.25s the target weight was 0.1kg. Of course, for the batching from empty trials, additional time was required to increase flow from zero and indeed to fill the flowtube. Nevertheless the same target was used to allow comparisons. For each target weight, 25 consecutive trials were carried out, and the repeatability recorded, here defined as the maximum difference in total across all 25 trials. The results are shown in Figure 5. The upper graph shows the absolute repeatability in grams, while the lower graph shows the relative repeatability as a percentage of the total batch weight.

For batching from full, the absolute repeatability is approximately constant at 3-4g down to batches as short as 62ms; at 31ms this rises to 7g. As a percentage of batch total, this varies from 0.1% for a 10s batch up to 10% for a 62ms batch. For batching from empty with trials 2s or longer the absolute repeatability remains below 10g; for shorter batches there is poorer performance. From a relative repeatability perspective, these results suggest that 1% repeatability can be obtained batching from empty for batch totals corresponding to 2s or more at the nominal flowrate.

Note that these results are a function of the entire batching system, not merely the flowmeter, and are therefore only indicative of the performance that may be achieved. Nevertheless, for batch times of 10s or longer, it is reasonable to suggest that the slightly poorer repeatability (0.2% instead of 0.1%) is a small price to pay for the engineering convenience of batching from empty.

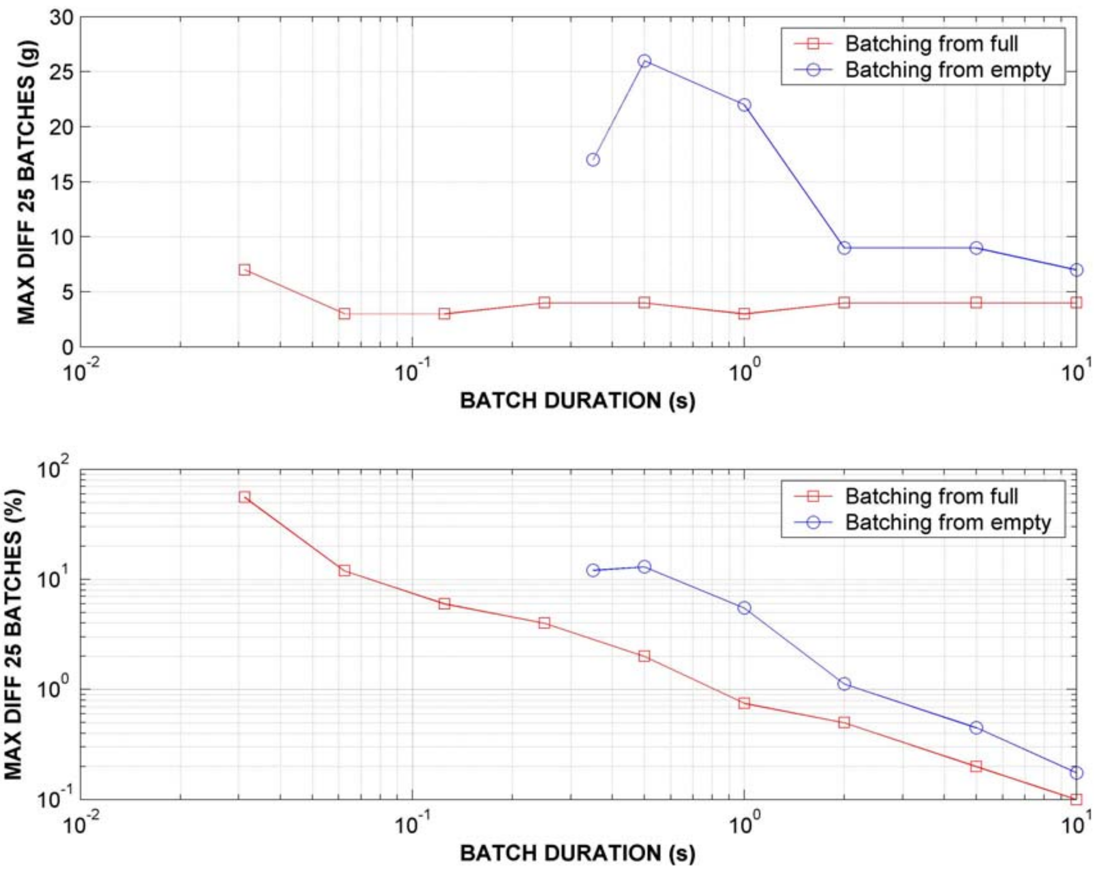

Fig. 5: Short Batch Tests: Full And Empty Flowtube

3 TWO/THREE PHASE FLOW MEASUREMENT

The behaviour of the Oxford Prototype transmitter in two-phase water-air flow has been studied in great detail in the Oxford flow-lab. A fundamental observation is that although the flow-tube oscillation is maintained throughout there is a change in the calibration equations that convert from frequency and phase to density and mass flow. Of great importance is that the behaviour is demonstrated to be repeatable – and on-line 'corrections' have been developed and demonstrated to enable two-phase flow measurement, throughout a wide range of flow [7], [8], [9]. Recent results from a 1" horizontal flowmeter are given in Figures 6 and 7. The density correction is particularly accurate, and provides the density of the water/air mixture mostly to within 1%, for void fractions below 70%. With mass flow, errors are mostly within 2%, except for low flow rates and high pressure drops. Note that at high flow rates, high void fraction results in excessive pressure drop across the meter (>1 bar), and so for each flow line, the void fraction is increased until the pressure drop exceeds 1 bar.

The jump from two-phase to multi-phase flow is large, nevertheless the potential role for Coriolis metering in three-phase flow is evident. A series of trials have been performed at Cranfield University with 1" and 2" meters using the Oxford transmitter on combinations of oil, water and air [10]. Figure 8 shows the flow regime map for the 1" horizontal trials, Figure 9 the raw, uncorrected mass-flow reading for these tests. The results were extremely encouraging, and further trials at Cranfield and elsewhere are ongoing and/or planned.

Post processing the collected data – the following significant observations were made

- Oil/Water behaviour as single phase no significant additional errors.
- Oil/Air behaviour similar calibration curves to water/ air.
- Oil/Water/Air. At low gas-void-fraction (GVF) the mixture often formed a fine emulsion and the meter performed as expected for single phase homogenous flow. At higher (GVF) the performance was similar to two-phase liquid/air where the liquid phase was formed using the oil and water

Further work is being undertaken towards developing a three-phase solution which includes Coriolis metering.

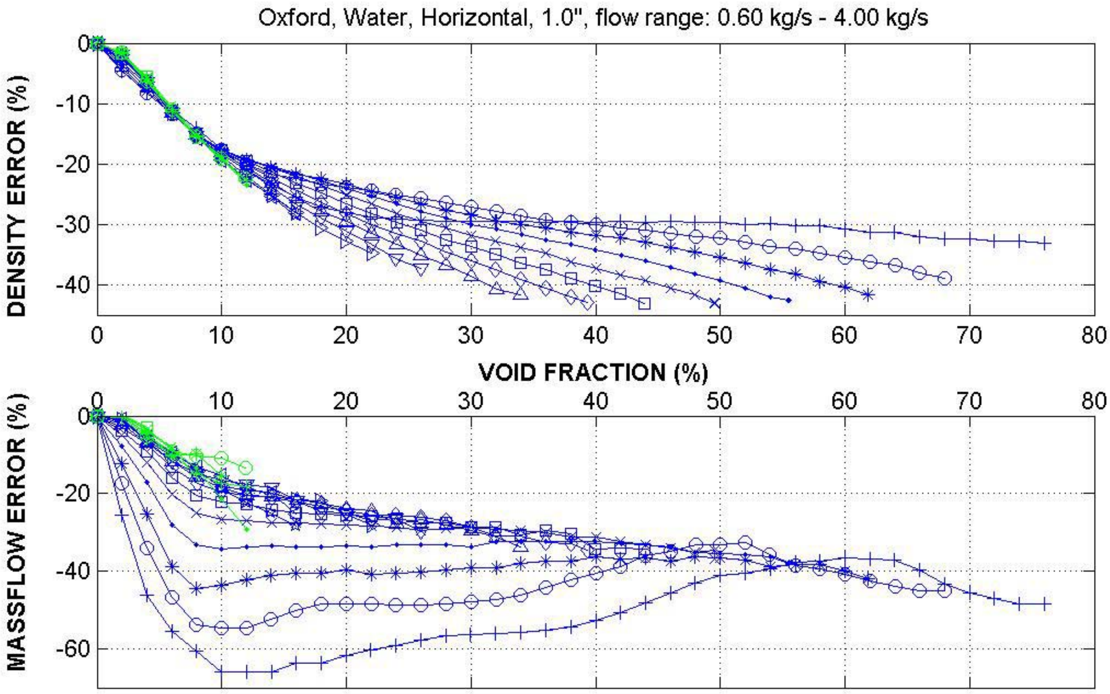

Fig. 6: Raw Massflow And Density Errors With Two-Phase Flow

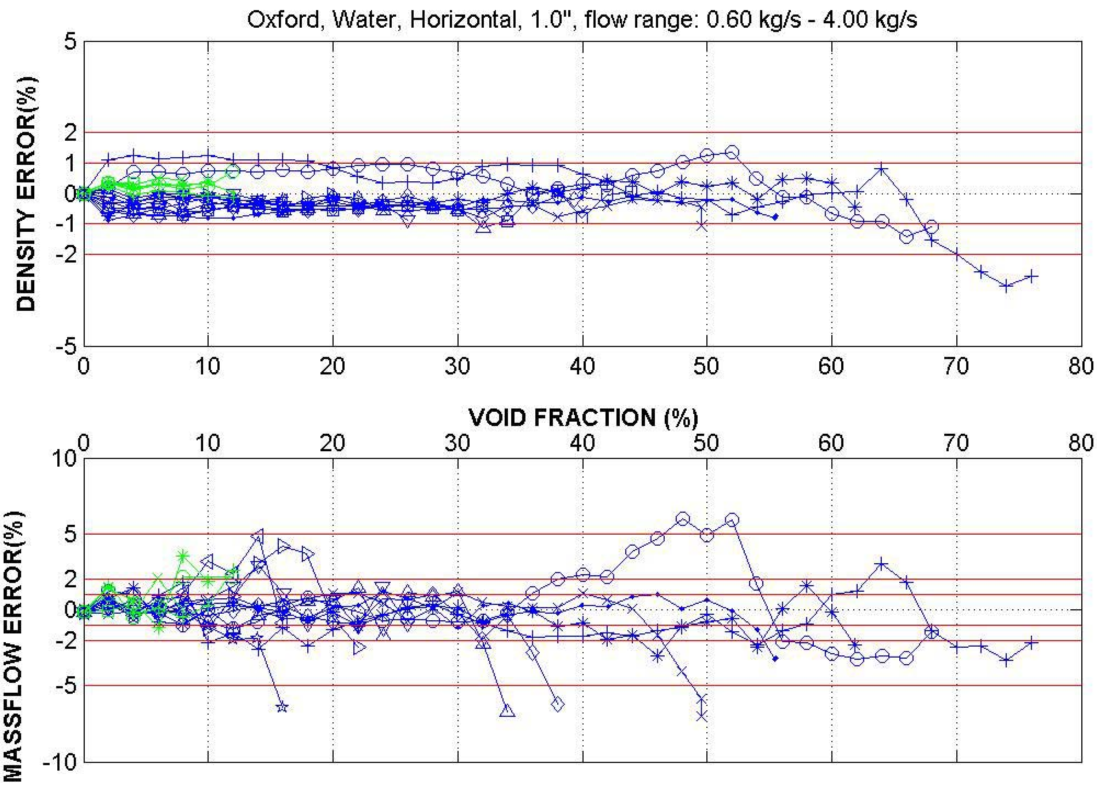

Fig. 7: Corrected Massflow And Density With Two-Phase Flow

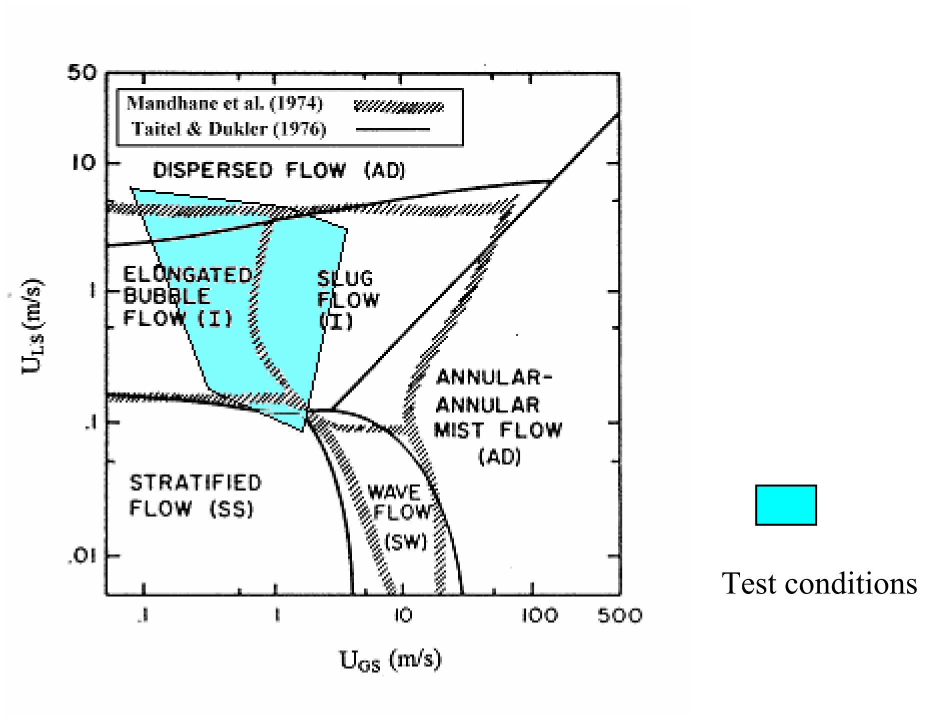

Fig. 8 Two Phase Flow Test Conditions (For Horizontal Arrangement)

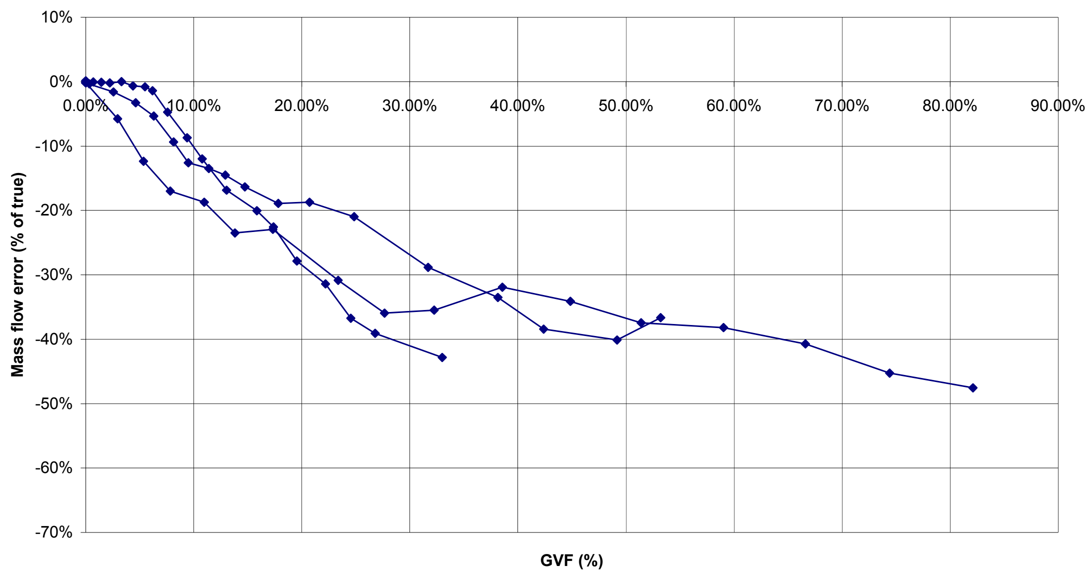

Fig. 9 Uncorrected Mass Flow Error Against GVF (1", Horizontal, Air/Oil)

4 DYNAMIC RESPONSE – SMALL VOLUME PROVING

A consequence of the digital architecture of the Oxford transmitter is its ability to track rapid changes in true flow and a research program in association with Brunel University is currently in progress – some results are presented in [4]. This feature enables very short batches to be metered, for use in small liquid bottle filling lines for example. Of particular interest in the Oil and gas industry is the use of Coriolis meters for calibration proving applications – both in the use of a Small Volume Prover (SVP) to check an installed Coriolis meter or in the future use of a Coriolis meter as a master meter in the test rig.

Historically SVP have been used to check flowmeters whose output is a simple pulse, such as a turbine flowmeter with output rate proportional to turbine rotation speed. Coriolis meters can output a derived pulse-rate proportional to mass-flow which can be termed Microprocessor Generated Flow Pulses (MGFP). A feature of MGFP is that the transmitter processing has a finite delay time, and together with measurement and output signal filtering, the reported mass flow may lag the true measurement. It was reported in [11] that a certain Coriolis meter under test exhibited poor repeatability and that the SVP electronics did not permit compensation for transmitter delay.

In 2001 API formed an ad hoc task group to investigate what impact (if any), MGFP had on the measurement process, especially when the flowmeters were being proved. Preliminary testing on a number of microprocessor based flowmeters (Coriolis and Ultrasonic) showed that the flow pulse output by the flowmeters did in fact lag the flow measurement, and that under certain circumstances this could cause additional uncertainty to be introduced during the proving operation. API subsequently formed the 'Microprocessor Based Pulse' TAG, and funded flow lab research to investigate the issue more fully. The TAG contracted Coastal Flow's flow lab in Houston to perform testing under the supervision of the TAG. At least eight different flowmeters with pulse multiplying electronics were used, including Coriolis, ultrasonic, and helical turbines, from a number of flowmeter vendors. The results reported here are for the Invensys Foxboro Coriolis mass flow meter.

Figure 8 shows actual test data collected by Coastal Flow Measurement, Houston on a commercial Foxboro 3” flowtube with a production CFT50 transmitter at a nominal flowrate of 800 BBR/HR (35l/s). In these trials the output from the CFT50 is filtered/ monitored with a 100ms update rate. While the response to step and ramp changes is good, further improvements in the dynamic response are possible by removing all filtering from the measurement signal and the monitoring system, as discussed in [4].

Flow disturbances were deliberately introduced during the proving cycle, each trial was repeated 10 times and repeatability assessed. The SVP electronics used had the ability to add a delay to the gating signal used to count pulses for the response test meter, it was found possible to tune this delay for each filter setting so that the resulting prove result correlated well with that observed by the reference master turbine meter as shown in Table 1., which is the full record summary for this flowtube at this flowrate. The rightmost column compares the master meter and test meter results. With a suitable selection of the detector delay parameter, excellent agreement is achieved for all test conditions.

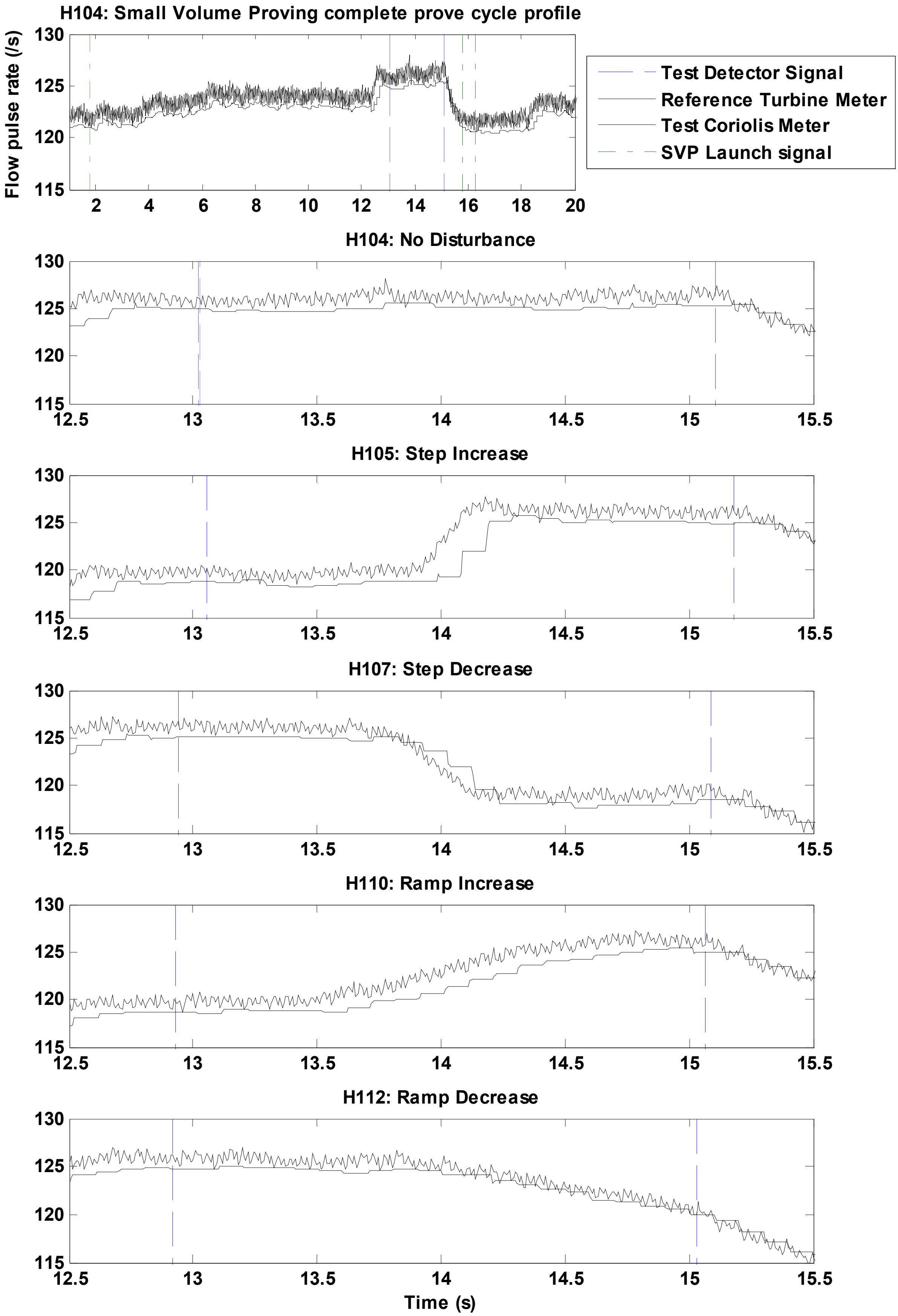

Fig. 8: SVP flow profiles used in API test by Coastal Flow, Houston

API - Microprocessor Based Pulse TAG										
Test Record for Test Meter H - 3 Inch Coriolis										
Data		Reference Meter		Test Coriolis Meter				Comparison	
File Name	Flow Disturbance Applied	Mean observed K-Factor	Spread (max-min) /mean %	Mean observed K-Factor	Spread (max-min) /mean %	Timing/ Damping Setting TC2	Detector Delay mS	Test Meter Change	Master Meter Change
H104	None	550.45	0.021%	545.85	0.100%	minimum	0ms	0.018%	0.002%
H105	Step Increase	550.50	0.041%	543.97	0.077%	minimum	0ms	-0.327%	0.011%
H106	Step Increase	550.52	0.030%	544.04	0.054%	minimum	0ms	-0.314%	0.015%
H107	Step Decrease	550.57	0.393%	547.50	0.099%	minimum	0ms	0.320%	0.024%
H108	Step Decrease	550.34	0.022%	547.40	0.091%	minimum	0ms	0.302%	-0.018%
H109	Ramp Increase	550.45	0.022%	544.00	0.087%	minimum	0ms	-0.321%	0.002%
H110	Ramp Increase	550.48	0.027%	544.17	0.094%	minimum	0ms	-0.290%	0.007%
H111	Ramp Decrease	550.40	0.032%	547.10	0.144%	minimum	0ms	0.247%	-0.007%
H112	Ramp Decrease	550.37	0.017%	547.02	0.121%	minimum	0ms	0.232%	-0.013%
H115	Step Increase	550.51	0.030%	545.65	0.040%	minimum	125mS	**-0.019%**	**0.013%**
H116	Step Decrease	550.37	0.024%	545.74	0.065%	minimum	125mS	**-0.002%**	**-0.013%**
H117	Step Increase	550.48	0.021%	545.72	0.083%	minimum	125mS	**-0.006%**	**0.007%**
H118	Step Decrease	550.36	0.034%	545.67	0.059%	minimum	125mS	**-0.015%**	**-0.015%**
H119	Ramp Increase	550.47	0.026%	545.79	0.073%	minimum	125mS	**0.007%**	**0.005%**
H120	Ramp Increase	550.55	0.019%	545.79	0.062%	minimum	125mS	**0.007%**	**0.020%**
H121	Ramp Decrease	550.38	0.022%	545.68	0.083%	minimum	125mS	**-0.013%**	**-0.011%**
H122	Ramp Decrease	550.41	0.020%	545.75	0.050%	minimum	125mS	**-0.001%**	**-0.005%**
H123	None	550.46	0.017%	545.86	0.046%	minimum	125mS	**0.020%**	**0.004%**
H124	None	550.46	0.040%	545.85	0.069%	minimum	125mS	**0.018%**	**0.004%**
H125	Step Increase	550.51	0.028%	543.11	0.200%	250mS	0ms	-0.484%	0.013%
H126	None	550.45	0.016%	545.80	0.084%	250mS	0ms	0.009%	0.002%
H127	None	550.46	0.019%	545.85	0.092%	250mS	0ms	0.018%	0.004%
H129	None	550.44	0.022%	545.83	0.113%	250mS	0ms	0.007%	-0.003%
H130	Step Increase	550.51	0.024%	543.11	0.136%	250mS	0ms	-0.492%	0.010%
H131	Step Increase	550.50	0.035%	543.09	0.203%	250mS	0ms	-0.495%	0.008%
H132	Step Decrease	550.38	0.021%	548.40	0.152%	250mS	0ms	0.478%	-0.014%
H133	Step Decrease	550.36	0.035%	548.35	0.115%	250mS	0ms	0.468%	-0.017%
H134	Ramp Increase	550.51	0.014%	542.99	0.109%	250mS	0ms	-0.514%	0.010%
H135	Ramp Increase	550.51	0.033%	543.08	0.092%	250mS	0ms	-0.497%	0.010%
H136	Ramp Decrease	550.43	0.023%	547.77	0.234%	250mS	0ms	0.362%	-0.005%
H137	Ramp Decrease	550.38	0.037%	548.02	0.196%	250mS	0ms	0.408%	-0.014%
H138	Step Increase	550.54	0.035%	546.40	0.211%	250mS	250mS	0.111%	0.015%
H139	Step Decrease	550.39	0.017%	544.92	0.111%	250mS	250mS	-0.160%	-0.012%
H140	Step Increase	550.55	0.035%	545.73	0.202%	250mS	200mS	**-0.012%**	**0.017%**
H141	Step Decrease	550.59	0.388%	545.69	0.128%	250mS	200mS	**-0.019%**	**0.025%**
H142	Step Increase	550.53	0.026%	545.74	0.178%	250mS	200mS	**-0.010%**	**0.014%**
H143	Step Decrease	550.37	0.025%	545.78	0.171%	250mS	200mS	**-0.002%**	**-0.015%**
H144	Ramp Increase	550.52	0.015%	545.77	0.085%	250mS	200mS	**-0.004%**	**0.012%**
H145	Ramp Increase	550.52	0.021%	545.66	0.068%	250mS	200mS	**-0.024%**	**0.012%**
H146	Ramp Decrease	550.38	0.027%	545.71	0.067%	250mS	200mS	**-0.015%**	**-0.014%**
H147	Ramp Decrease	550.37	0.026%	545.63	0.081%	250mS	200mS	**-0.030%**	**-0.015%**
H148	None	550.48	0.026%	545.85	0.073%	250mS	200mS	**0.010%**	**0.005%**
H149	None	550.46	0.027%	545.83	0.052%	250mS	200mS	**0.007%**	**0.001%**

Table 1. Results from API test on Foxboro 3” flowtube with CFT50 transmitter

5 CONCLUSIONS

This paper provides an overview of research and development related to Coriolis mass flowmeters activities in progress at Oxford and elsewhere.

Improved Coriolis transmitter design using all-digital architecture permits operation of the flow-tube in applications not previously possible such as those where the flow-tube is required to start or stop empty, or where intermittent bursts of gas shutdown conventional transmitters.

The measurement performance of the meter in multi-phase flow situations is very encouraging and, combined with additional instrumentation has the potential to form part of a multiphase measurement system.

The fast dynamic response of the improved transmitter permits its use in short-batch applications, such as those experienced in small volume proving.

The Coriolis flow-meter is considered by some to be a mature technology; this paper demonstrates, by example that significant developments are in progress. These have the potential to increase the application of Coriolis mass flowmeters in Oil and Gas Production and Processing.

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