Pushing Coriolis Mass flowmeters to the limit

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Flow measurement pervades many areas of mechanised activity. Examples include fuel flow into engines, cooling flows in power stations, and an enormous range of liquid, gas and slurry flows within the food & beverage, chemical and petro-chemical industries. There are also many flow measurement techniques; some are long established e.g. the orifice plate, used on the natural gas national grid, while new technologies are emerging e.g. ultrasound, now being used in the water industry.

The Coriolis mass flow meter has become increasingly important since its introduction in the 1980s; the market has grown substantially. According to the ARC marketing research company it is estimated to be $400M per annum, growing to $520M in the next few years.

The basic sensing element of a Coriolis meter is a vibrating tube; the moving mass of flow passing through the tube produces an asymmetrical distortion of the tube, due to the associated Coriolis forces. The distortion is proportional to the mass flow rate. The Coriolis meter *flowtube* (Fig. 1) has one or more vibration drivers and two motion sensors positioned to detect the tube distortion, while the electronic *transmitter* provides the drive signal to maintain oscillation and calculates the phase difference (due to the distortion) between the two sensor signals to obtain the flow measurement.

The primary benefit of Coriolis metering is the direct measurement of mass flow, which is important where commodity value is related to mass rather than volume, for example in the petrochemical industry. However, Coriolis meters have other advantages, including high accuracy (to 0.1%), and turndown (100:1 or better), while their limitations include the need for a separate power supply and relatively high cost.

TOWARDS SHORT BATCHES

As industry moves towards more flexible manufacturing, interest is growing in short, batch-oriented processes as opposed to continuous operation. Short duration batching is now used extensively with flow times of 1 s or less, e.g. 90 ms for perfume bottling. To reduce start-up times there is a need for flow meters capable of measuring dynamic flows accurately. A recent report by ARC suggests that response times as fast as 1ms will be required in the consumer goods and food & beverage industries. ARC predicts that a new generation of meters will be required for use as process optimization tools, providing real-time operational data to better calculate operating cost and to measure plant performance.

What about the performance of today’s technology? There has been surprisingly little published on the dynamic response of flow meters. However, a recent paper by Wilkund and Peluso [Quantifying and specifying the dynamic response of flowmeters. ISA 2002 Technical Conference, Chicago] compares a variety of commercial flow meters (11 differential pressure (DP) sensors + orifice plate, 3 electromagnetic flow meters, 6 vortex flow meters, and one coriolis meter). They modelled and identified the response of each meter as either first or second order.

Figure 2 shows the resulting step response for the *fastest* flowmeter of each class. As can be seen, the DP + orifice plate is faster than the vortex, followed by the magnetic flowmeter, and finally the conventional coriolis meter. The implication is that despite the excellent static accuracy of coriolis meters, they cannot today match the dynamic response of DP. However, the fastest step response of all in Fig. 2 (superimposed upon the data from Wilkund and Peluso) is from a new type of coriolis meter, developed jointly by Oxford University and Invensys Foxboro.

The Digital Coriolis Transmitter

The Sensor Validation Research Group at the University of Oxford has, in partnership with Invensys Foxboro, been investigating the concept of the Self-Validating (SEVA) sensor for the last 15 years. SEVA now forms the basis of a British Standard for reporting measurement quality in industrial applications. Prototype sensors have been developed to demonstrate the feasibility of SEVA, of which the Coriolis meter is the most advanced. Understanding the limitations of previous coriolis transmitters has led to the development of a new, all-digital, design which eliminates certain classes of fault and which offers a much improved dynamic response. The transmitter is described as ‘digital’ in that all components, other than elementary barrier and gain circuitry, are digital devices. Specifically the drive waveform used to initiate and maintain flowtube oscillation is synthesised digitally, while current market offerings commonly implement a signal path which is partly or wholly analog. Foxboro have now released a commercial product, the CFT50, based on this work.

Its architecture is inherently simple, as outlined in fig. 3. The codec is a combined ADC and DAC chip, typically used in audio applications, providing two input and two output channels, all operating continuously at 40kHz with 24 bit data. Each flowtube sensor is read by one ADC channel and each drive is generated by one DAC channel. Sensor data is passed to the FPGA (Field Programmable Gate Array, a programmable logic chip). After processing and buffering, the data is passed to the processor for detailed analysis. The processor calculates the flow rate along with parameter values for maintaining flowtube oscillation. These are passed to the FPGA, which synthesises the required drive output signals and passes them to the output channels of the codec. Flowtube temperature data is acquired using a conventional ΣΔ ADC, which includes the driver circuitry to drive a 4-wire RTD (temperature sensor) interface.

The FPGA, which provides 300,000 gates of programmable logic, is important in ensuring the rapid dynamic response of the meter. It is used to perform critical real-time tasks, including filtering, waveform synthesis, buffering and peripheral control, under the direction of the processor. These tasks are more effectively executed in true parallel on dedicated hardware rather than by time-slicing on a single processor. The FPGA computational load is equivalent to 4MFLOPS.

The two principle tasks of the Coriolis transmitter are the maintenance of flowtube oscillation and the extraction of measurement data. Novel algorithms have been developed to provide rapid dynamic responses for both control and measurement. In fact, there is strong co-dependence between the measurement and control responses of the meter, particularly when dealing with the rigours of industrial applications, as illustrated in the next section.

Maintaining Flowtube Oscillation

The greatest weakness of coriolis meters is their inability to deal with entrained gas, whether due to unfilled pipes, cavitation, vortices, or an inherently mixed-phase process fluids (e.g. in oil and gas or beverage applications). For example, if an empty coriolis meter suffers the onset of fluid (say during a batch) the meter will typically take 10-20 seconds to recover flowtube control; meanwhile the process is not being metered. The major challenge is the damping on the flowtube, which may vary by two orders of magnitude in the transitions between single phase and two-phase fluids.

The validation research carried out by Oxford suggested an all-digital design with a very rapid control system would be able to maintain flowtube operation, and hence measurement function, through two-phase flows and transients.

Figure 4 illustrates how the transmitter maintains flowtube oscillation during a burst of two-phase flow, and when the flowtube is drained and refilled. Initially flow is single phase, the amplitude of oscillation is the default value of 0.3V, and the required drive current is 10mA. Between t=5s and t=12s, the process fluid becomes highly aerated, as indicated by the drop in the reported density from 1000 kg/m^3 to 300kg/m^3. Two phase flow is associated with high flowtube damping and the drive current rises rapidly. As it approaches the maximum permitted value, a new amplitude set-point is selected, as indicated by the dashed line. After t=12s, the process fluid becomes single phase and the required drive current returns to its conventional value of 10mA. It is thus possible to revert to the default set-point of 0.3V. After t=25s, a new disturbance occurs: the pump is switched off, causing process fluid to drain from the meter. Accordingly the density drops towards zero. 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=30s draining is completed, and the default set-point is restored. Finally at t=45s the pump is switched on again and the flow meter experiences the hydraulic shock caused by the onset of flow. This results in the lowest set-point for amplitude of oscillation. By t=50s equilibrium has been restored, damping has reduced and the default set-point of 0.3V has been reinstated. Note that the flowmeter maintains operation and continues to generate measurement data throughout these transients. The drive gain, defined as the ratio of the drive current to the amplitude of oscillation, is proportional to the damping on the flowtube. In normal operation it has a typical value of 0.03; peak values as high as 5 are observed during two-phase transients.

This laboratory performance is reflected in customer applications. For example, at Great Lakes Chemicals in Manchester, a CFT50 was placed in series with a conventional Coriolis meter on a batching application, which required the meters to start and stop empty. A chart recorder has recorded the time histories of the two meters, together with the density measurement from the CFT50 to show the level of air entrainment. Fig 5a shows the start of a typical batch. Before the onset of flow both meters are partially filled, as indicated by the density reading. When flow begins, the CFT50 registers the increase in flow, while the second meter responds only some 16 seconds later. Towards the end of the batch (fig 5b), as the meters drain (130min), the second meter goes offline and remains so for nearly six minutes, entirely missing the final blow-through of product.

These examples demonstrate that in real industrial applications, rapid and precise flowtube control is a pre-requisite to a robust and rapid dynamic measurement response, and shows that the digital transmitter can be used in novel application areas such as batching to/from empty and dealing with continuous two-phase flow. Quantification of the dynamic measurement response of the digital transmitter, and pointers towards very short batch times, have emerged as a result of a research partnership between Oxford and Brunel University.

Dynamic Response Research at Brunel

The Flow Measurement Research Group at Brunel University is completing a research program investigating the dynamic response of Coriolis flowmeters. The three stages of work are:

(i) Theoretical analysis of the response of a straight tube meter;

(ii) Simulation, by finite element analysis, of the dynamic response of more complex geometry meters; and

(iii) Experimental investigation of the response of commercially available flowmeters to both step changes in flow rate and low frequency (relative to the meter drive frequency) pulsations.

A key basic finding is that the fundamental limit on the response time of a Coriolis meter is its drive frequency. For example, a meter driven at 100 Hz should be able to resolve a change in flow rate of a duration down to 10 ms. This is illustrated in fig. 6, which shows data collected and processed offline by Brunel from a high frequency (800Hz) flowtube, responding to a short (5ms) step change in flow. The offline calculations demonstrate that it is possible to track the step flow with updates once per drive cycle (every 1.2ms). The fluctuations in phase difference immediately following the step are due to Coriolis frequency components in the sensor signals (expected to be present in all meters). These are not apparent in the normal meter output because of the introduction of filtering and damping in the signal processing.

~~Thus~~ Fig 6 shows that in the behaviour of the flow tube, there is the *potential* for very rapid response flowmetering ~~in the behaviour of the flowtube.~~ However, most of today's commercial Coriolis meters fall well short of this capability, due primarily to limitations in transmitter technology. Trials on Oxford's digital transmitter show a performance much closer to the theoretical limit.

In the experimental work, step changes in flow rate have been generated in a flow rig by moving a variable-area orifice plate at high speed across the flow. Relatively large step changes in flow, e.g. from 0.2 to 0.8 kg/s, can be created, with step changes as rapid as 4ms. A modified electromagnetic flowmeter has been used to provide a clear indication of the time-course of the flow step. Instead of the usual ac excitation, continuous dc excitation of the meter is used, which generates an extremely good dynamic response, but at the expense of a poor steady-state flow accuracy.

Figure 7 illustrates the response of the digital transmitter to a step change in flow carried out in the Brunel laboratory. The response is characterised by a transmitter delay time of approximately 20ms. While theoretically the meter should be able to respond within 12ms (given a drive frequency of 80Hz), this nevertheless represents a considerable improvement on the only published data on another commercial flowmeter (fig 2). Unpublished data exists on the dynamic characteristics of other commercial meters, which show a performance that exceeds that implied by fig. 2. It is hoped that the current interest in dynamic response issues will encourage all manufacturers to provided performance data on their meters.

Future Developments

The complementary skill of Oxford (validation, transmitter technology) and Brunel (theory, modelling, experiment) has led to a successful joint EPSRC grant proposal to push Coriolis metering to its dynamic limit. Can advanced transmitter technology deliver the theoretical response times of high frequency straight tubes (to 1kHz) or even the new micro-machined silicon coriolis transducers, resonating at up to 10kHz? How should flow tubes be designed to deliver an optimal dynamic response?

The demand for fast response flow metering extends beyond the traditional coriolis application areas identified by ARC. Manufacturers of gas turbine engines wish to monitor fuel supply with high speed and accuracy. Typically, meter response times of 10ms are required. A more adventurous application area is the measurement of fuel injection flow pulse time histories for automotive engine applications. In the short term, such meters might be used in diesel engine research to measure the time history of the injection to monitor its influence on the combustion process. In the longer term, such a meter might have the potential to be fitted within the engine management system for all motor vehicles with fuel injection.

A user group is being formed around the Brunel/Oxford project, drawing from a mixture of traditional and potential Coriolis application areas. Further expressions of interest from users are welcome.

The IEE Control and Automation Professional Network is organising a seminar on Advanced Coriolis Mass Flow Metering, to be held at Oxford on Tuesday 8th July. Academic and industrial speakers will discuss the state of the art, including the issues of dynamic response and two-phase flow performance. For further details see the event website http://www.iee.org/events/coriolis.cfm.

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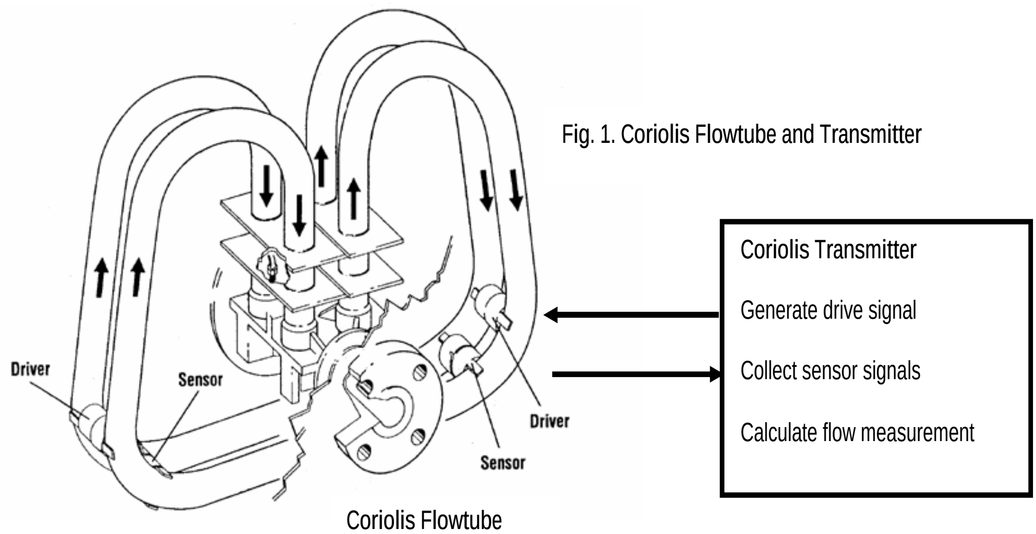

Fig. 1. Coriolis Flowtube and Transmitter

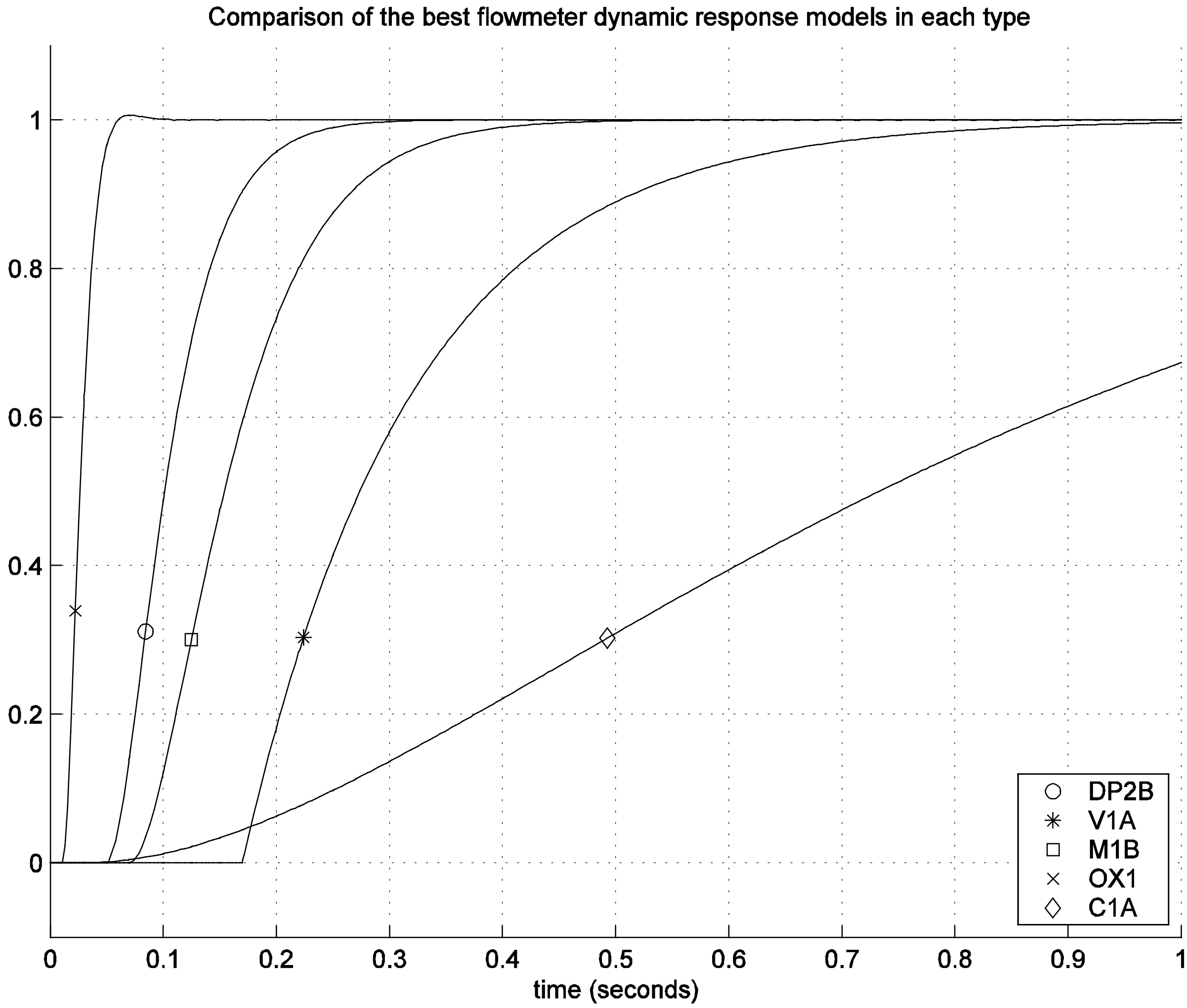

Figure 2. Fastest dynamic response of each type of flowmeter reported by Wilkund and Peluso (2002), together with Oxford prototype response (OX1), on a nominal 0..1 scale. DP = Differential Pressure, V = Vortex Flow, M = Magnetic Flow, C = commercial coriolis massflow meter.

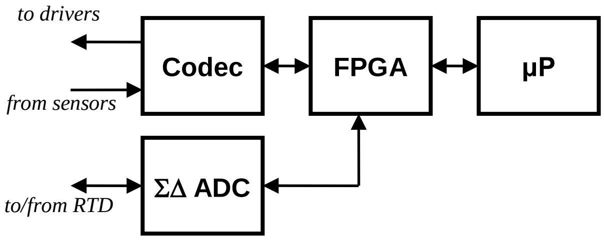

Fig. 3. Outline Architecture of CFT50

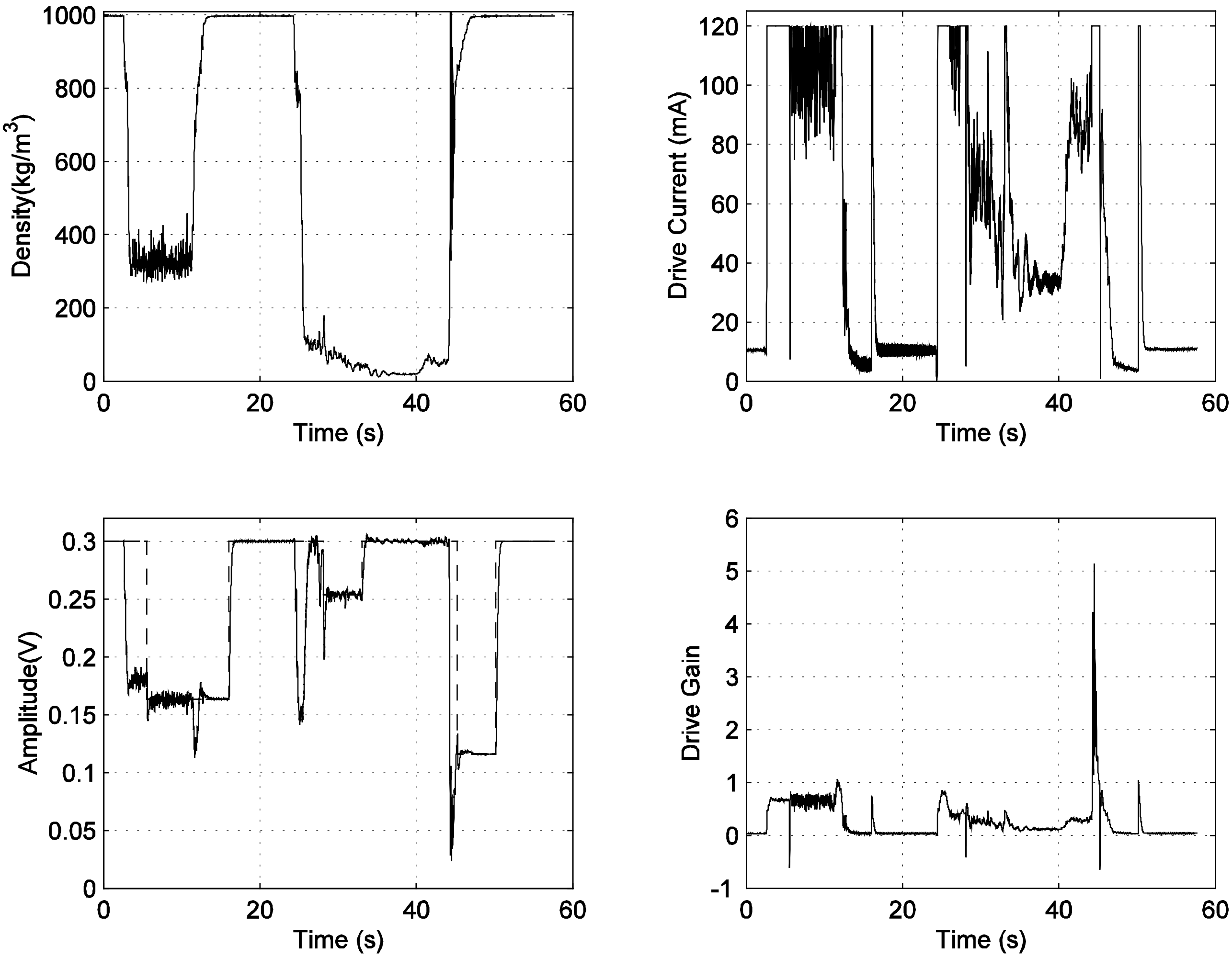

Fig 4. Control performance of digital transmitter responding to two-phase flow and flowtube draining. Top left – fluid density. Bottom left – amplitude of flowtube oscillation. Top right – drive current. Bottom right – drive gain (proportional to flowtube damping).

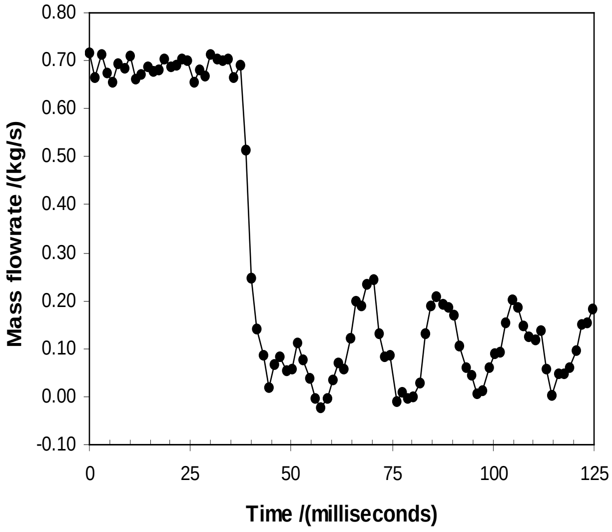

Fig. 6. Response of a high drive frequency Coriolis flowtube to a 5ms step change in flow. Measurement updates have been calculated offline for each drive cycle (i.e. every 1.2ms). The step change in flow is tracked over several measurement points.

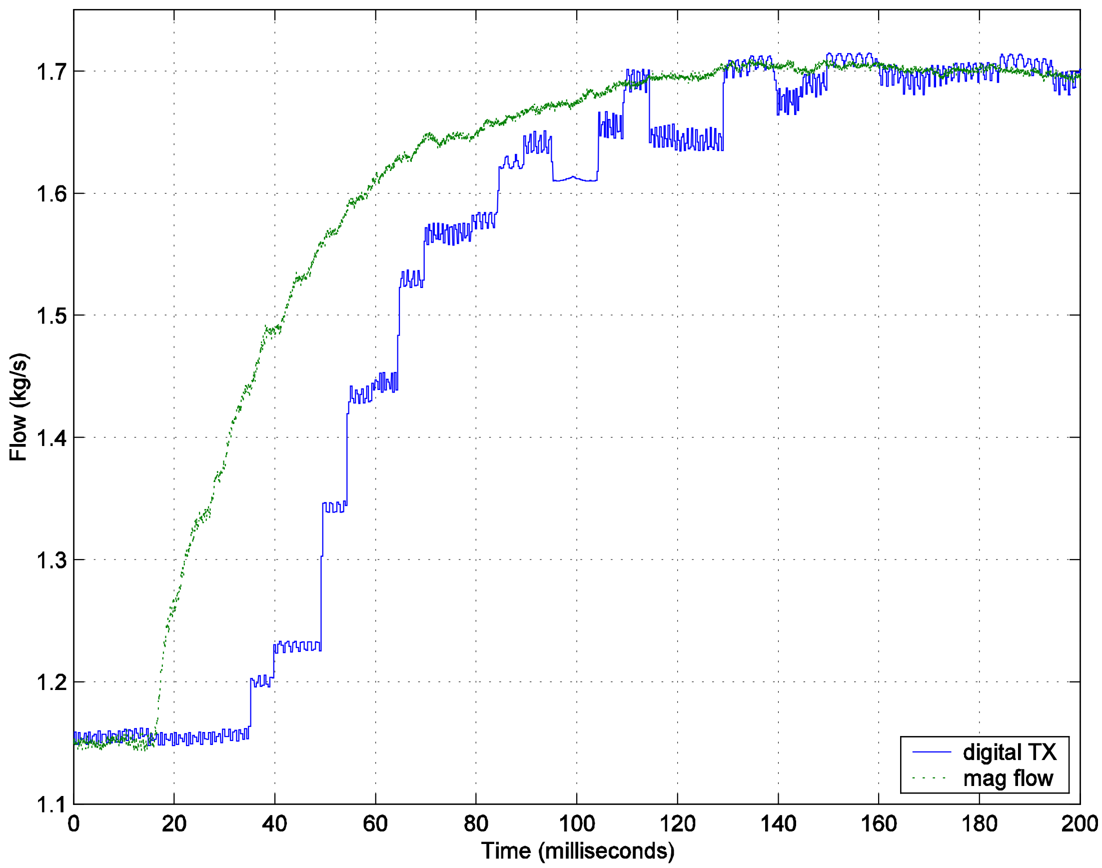

Figure 7. Rapid step change experiment from Brunel. The dotted line is output from the modified magnetic flow meter, showing true flow step. The continuous line is the pulse output from the digital transmitter. It responds within 20ms after the start of the step change observed by the magnetic flowmeter. The staircase form of the pulse output is due to the 6ms update rate, and the dithering of the signal leads to a frequency precision of 1 part in 10 million averaged over 1 second.