Coriolis Transmitter Technology and Dynamic Response Performance

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Summary
Recent research at Brunel University has demonstrated the fundamental limits on the dynamic response of Coriolis meter flowtubes. Commercial meters typically exhibit much poorer dynamic response times, due to transmitter delays. Research at Oxford University into Coriolis transmitter technology has resulted in a prototype with an improved dynamic response, with a typical delay time of only 16ms. The Oxford technology is incorporated in a commercially-available transmitter.

Introduction

Coriolis mass flow metering is a well-established method of industrial flow measurement, with a market projected to grow from $400M currently to $520M in 2007. The basic measurement 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 (which may vary from 80Hz to 800Hz for different flowtubes) can be used to calculate the density of the process fluid, while the phase difference between the two sensor signals provides the mass flow rate. 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, relative expense and vulnerability to aerated fluids.

The University of Oxford, as part of its research program into self-validating sensors, has developed a novel mass flowmeter transmitter based entirely on digital technology, capable of driving several different commercial flowtubes. Perhaps the most significant advantage of the Oxford transmitter is an ability to maintain operation in two-phase or aerated flow, with on-line correction for mass flow errors (this issue is addressed in several of the papers in [1]). However, to achieve good two-phase flow performance, the dynamic response of the transmitter needs to be rapid, in terms of both measurement and (flowtube) control. Trials have been carried out on the Oxford prototype meter to measure its dynamic response to flow step changes and pulsating flow using the test facility at Brunel University. The Oxford technology is available commercially through the CFT-50 Coriolis Massflow transmitter from Invensys/Foxboro.

Transmitter Delays

The static repeatability and accuracy of mass flowmeters have been established for many years. However, as industry moves towards more flexible manufacturing processes, with short batch times and rapid turnaround, the question of the dynamic response of flowmeters becomes more important. Specifically, given the excellent steady-state flow performance of Coriolis meters, is this matched by the dynamic response to flow changes?

Research at Brunel University has established that the response of the flowtube to a step change in flow rate cannot be obtained over a period of less than one complete cycle of the driven motion. Thus a flowtube oscillating at 100Hz cannot respond more rapidly than 10ms, while a 1kHz tube might respond in a millisecond. In practice, however, the response time of commercial flowmeters has been shown to be much slower: Wiklund and Peluso [2] found delays in excess of 1s for one mass flowmeter.

An analysis of the additional stages of processing taking place within the Coriolis transmitter [3] points to sources of delay beyond the response of the flowtube itself:

- The sensor signals from the flowtube are sampled via analog-to-digital (ADC) converters in the transmitter. In some cases additional filtering is applied. Each of these steps introduces delay.

- The transmitter processor may introduce significant delay, as typically measurement and flowtube control calculations are not carried out continuously, but typically once every one or more drive cycles. It is possible to identify two stages within this delay. Firstly, sufficient measurement data must be accumulated to perform the calculation (say during one complete cycle), then the calculation itself takes place. Where intensive calculations are used, it is computationally optimal for such calculations to take as long as the data collection period, and for the two operations to carry on in parallel. Thus, one drive cycle may be required to collect data, then a further drive cycle to process it, leading to an overall delay of 2 drive cycles between the first data of a step change being read by the ADC and the corresponding change appearing in the measurement data calculated by the processor.

- In many industrial applications, the most important yardstick of dynamic response is the time taken for a change in flow to be communicated via the transmitter outputs (e.g. via 4-20mA, pulse or fieldbus output). Again, a measurement update is not always provided to the transmitter output circuitry every time a new measurement value is calculated. Given the conventional scanning rates of industrial control systems, it is more typical for updates to be provided at a rate of 10Hz or slower. Given this update rate, the most accurate representation of the measurement data over the last (say) 100ms would be to provide its average as the measurement update value. This introduces on average (say) 50ms delay in the response of the flowmeter. Furthermore, it is common to introduce additional filtering at this stage, in order to smooth the reported measurement value. With time constants of typically 100-1000 ms, such filtering can be the most significant influence in the dynamic response of commercial meters.

- Finally, the communication mechanism may iself introduce additional delays. Presently there are three classes of commonly-used industrial communication protocols:

  - 4-20mA. Here the flow rate is mapped onto an analog current signal between 4 and 20mA. Being continuous, there is no delay in propagating the signal to the monitoring system, but there can be delay and filtering in the analog current circuitry. Furthermore, in the monitoring system, the signal is sampled using an ADC, which in the process control industry typically operates at 10Hz or slower, leading to a further 50ms or more average delay before the measurement is received by the monitoring processor.
  - Pulse (frequency) output. This consists of a square wave signal in which the frequency of the pulse stream gives an indication of the instantaneous flowrate. This has some of the advantages of 4-20mA, being simple, unidirectional and continuous, while the discrete signal edges give some benefits of digital transmission, including higher precision. There are delays inherent in this technique, however. Typically the upper limit on the output is about 10kHz. Also zero flow is often mapped onto zero Hz, so that at low flowrates there can be non-trivial delays in propagation due to the timing between edges – for example at 200Hz there is a 5ms period between rising edges. If the pulse output frequency is only updated after each rising edge (say), then this can lead to several milliseconds delay in propagating a step change from a low to a high flow value.
  - Fieldbus communications (including HART). Various digital communication protocols allow the transmission of measurement data in floating point format, with no loss of precision. Again, typically in the process industries, measurement data is transmitted no more frequently than every 100ms, which places a lower limit on the overall dynamic response of the meters. In the future, higher-speed digital communication protocols, such as industrial ethernet, will permit the transmission of the measurement data as seen by the transmitter processor directly to the monitoring processor with no loss of precision and with minimal delay (e.g. < 1ms). From the perspective of dynamic response, this is clearly to be welcomed.

Given the current state of communication technology, for dynamic response trials at Brunel the preferred output mechanism has been via the pulse output. This provides a continuous measurement signal, with higher precision than 4-20mA and without the inherent delays of fieldbus.

It is clear that the transmitter is responsible for most of the delays in the Coriolis mass flow meter dynamic response. Given, however, the rapid developments in digital technology that can be applied to transmitters, and increasing interest in faster dynamic responses, it should be possible for manufacturers to improve flowmeter performance.

The Oxford Prototype transmitter

The Sensor Validation Research Group at the University of Oxford has been investigating the concept of the Self-Validating (SEVA) sensor for the last 15 years. A number of 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.

As is well known, the price/performance of digital components continues to improve, and it is now commercially viable to embed a powerful microprocessor in the transmitter. This facilitates high speed, high precision measurement and control calculations. When driving a B-shaped Coriolis flowtube, which typically oscillates at around 80Hz, measurement and control updates are provided every half-cycle (i.e. at 160Hz). However, the transmitter has successfully been used to operate other flowtube designs, including straight tube geometries, with drive frequencies of up to 1kHz. The transmitter also incorporates a Field Programmable Gate Array (FPGA) – a programmable logic chip responsible for all real-time aspects of flowtube control, for example drive waveform synthesis. A third useful digital technology used in the transmitter is an audio codec (combined stereo ADC and DAC) providing 24bit data at 40kHz. In each case, these technologies have been drawn from mainstream consumer markets (e.g. mobile phones) and so offer excellent price/performance.

It is possible to estimate the delays built into the prototype transmitter in the terms of the last section:

- Although the codec samples at about 40kHz, there is a 61 sample 'group delay' i.e. there are 61 samples delay between input and output. This corresponds to approximately 1.5ms delay for ADC sampling.
- Further pre-filtering takes place within the FPGA, creating a 1ms delay.
- The drive frequency of a 25mm flowtube filled with water is typically 82.4 Hz. This corresponds to a delay of approximately 12ms for data acquisition. The processor required a further 1.5ms to perform the measurement calculation.
- The pulse output is updated immediately after the measurement calculation has been completed, and there are negligible delays (<1ms) in propagating a step change in flowrate through to the pulse output, even for low flowrates. The high precision of the measurement calculation and frequency generation means that no averaging or filtering is required to provide a smooth measurement output, which results in a much improved dynamic response.

This analysis suggests a total delay of approximately 16ms from sensor signal input through to pulse output, which is matched in experimental results.

Brunel Test Results

The experimental water flow test rig at Brunel can generate fast steps in flow e.g. from 0.2 to 0.8 kg/s within 4ms. A commercial electromagnetic flowmeter provides a clear indication of the time-course of step. This is achieved by the use of continuous dc excitation of the meter which allows an extremely good dynamic response, but at the expense of a poor steady-state response. The system is described in more detail in [4]. Simultaneous recordings are made of the transmitter pulse output, the electromagnetic flowmeter, and the flow value calculated within the transmitter processor.

Figure 1 shows the observed pulse output after a rapid (4ms) step change in massflow. The pulse output has a staircase form as updates are provided every 6ms. The electromagnetic flowmeter signal provides the reference time-history for the massflow step, which begins at approx t = 5ms. The transmitter is able to estimate its own delay by time-stamping ADC data as it is collected, and calculating the delay between real time and the timestamp of the ADC data when it has been processed to generate a flow measurement. A typical on-line estimate of this delay is about 16ms. The vertical dashed line on the graph is at t = 21ms, demonstrating that the pulse output responds, as predicted, some 16ms after the step change begins. Figure 2 shows typical results from a pulsating flow trial. An 8Hz flow pulsation is generated by the flow rig and tracked by both the magnetic flowmeter and the Coriolis transmitter. Again, the delay is approximately 16ms.

Finally, a comparison is given between the results for the prototype meter and those reported by Wilkund and Peluso [2], who carried out step response tests on a variety of flow meter technologies (differential pressure sensor + orifice plate, electromagnetic flowmeter, vortex flowmeter, and one example of a Coriolis meter). They modeled each flowmeter performance as either a first or second order response and quantified the response parameters for several meters of each type. Figure 3 shows the resulting step response for the *fastest* flowmeter of each class reported in [1], together with that of the prototype meter described herein. Figure 3 suggests the prototype provides improved step response compared with current commercial meters.

Difficult Industrial Applications

The rapid dynamic response of both the control and measurement functions of the digital transmitter has led to improved performance in difficult industrial conditions. The classic Coriolis weaknesses are dealing with aerated or two-phase flow, and batching to/from an empty flowtube. However, recent industrial applications of the commercial transmitter have included the following:

- At Great Lakes Chemicals in Manchester, in a batching to/from empty application, the digital transmitter was able to started metering the batch immediately after the onset of fluid, and successfully metered the aerated product at the end of the batch. Another Coriolis meter had experienced difficulty in the same application [5].
- An application in the US entails unloading glacial acrylic acid from rail wagons into trucks. A typical batch size is 15000kg, and the batch duration is 23 minutes. In first 150 seconds air entrainment of typically 10% gas void fraction (GVF) takes place. Weighed trials found batch accuracy to be with 0.1%.
- Ethylene Oxide is notoriously difficult to meter due to its tendency to boil. A US plant has recently installed digital transmitters which have operated successfully despite GVFs in excess of 10% for 20% of the time, and occasionally in excess of 80%GVF.

New Applications

While improved dynamic response offers improved performance in traditional Coriolis application areas such as process control and custody transfer, it also suggests the possibility of entirely new applications requiring more responsive flow monitoring. Examples might include very fast batching for consumer goods (<1s fill time), or the monitoring of fuel injection for turbine engines. An EPSRC research grant recently awarded to Brunel and Oxford Universities will be used to investigate the improvement of Coriolis dynamic response to meet the needs of such applications.

References

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[3] Henry, M. P. et al., *Flow Measurement and Instrumentation,* **14**, 109-118, 2003.

[4] Cheesewright, R. et al., J Fluids and Structures, 2003 (in press)

[5] *Control Engineering Europe*, **4**, 2, 29-31, 2003.

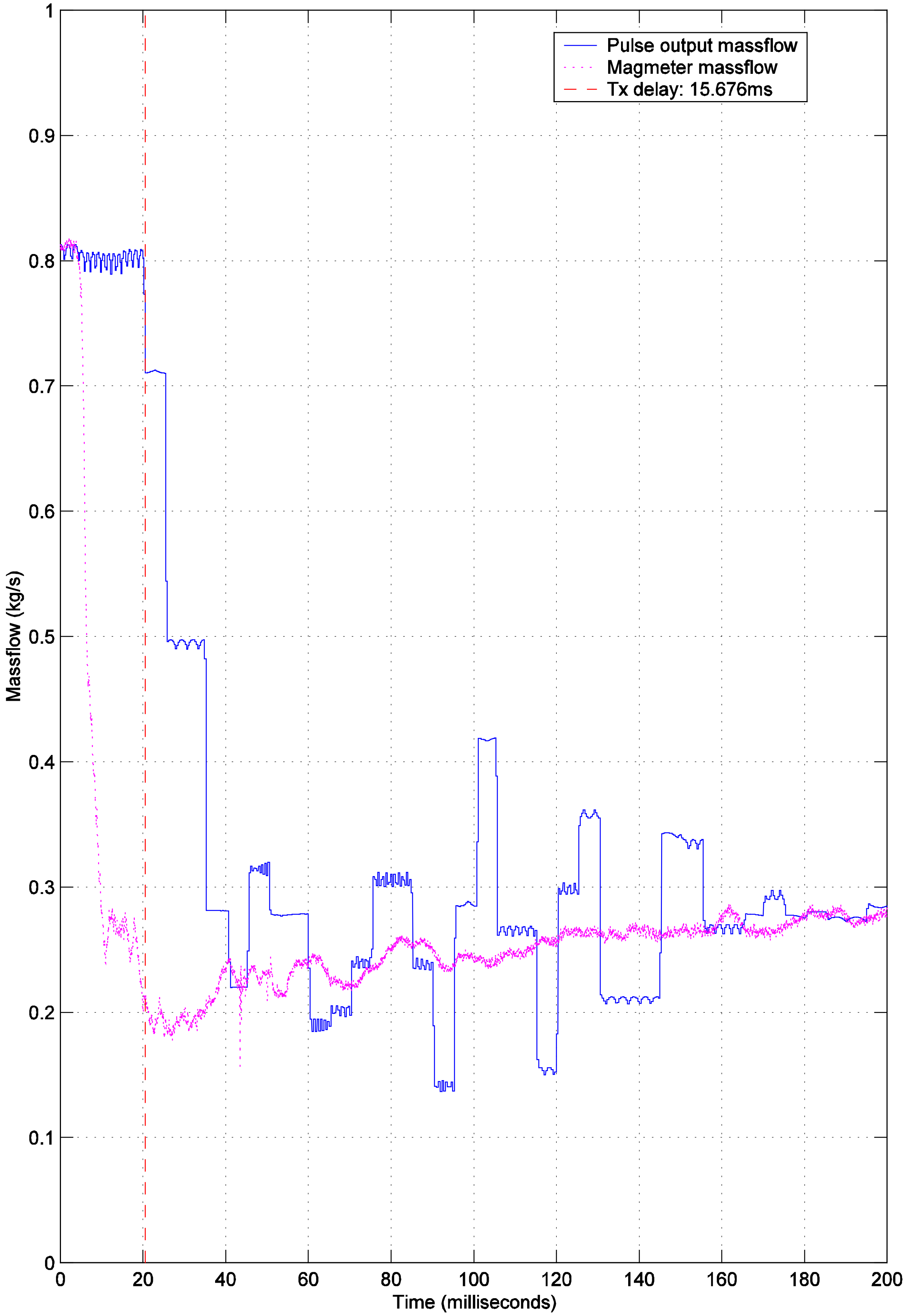

Figure 1. Pulse output after a rapid drop in massflow, with the magnetic flowmeter signal.

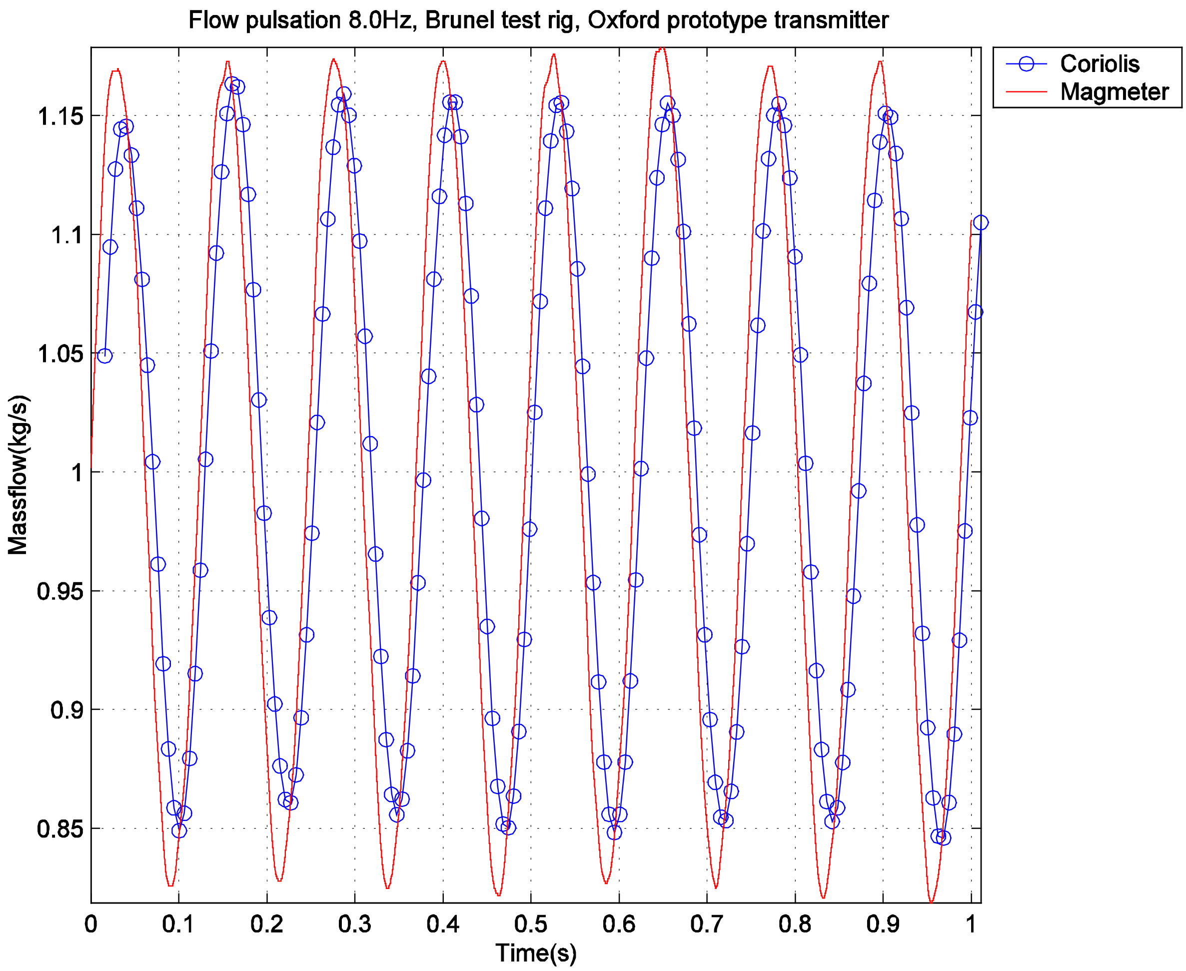

Figure 2. Mass flow values calculated by prototype Coriolis transmitter processor during pulsating flow, together with magnetic flowmeter estimate of true flow value.

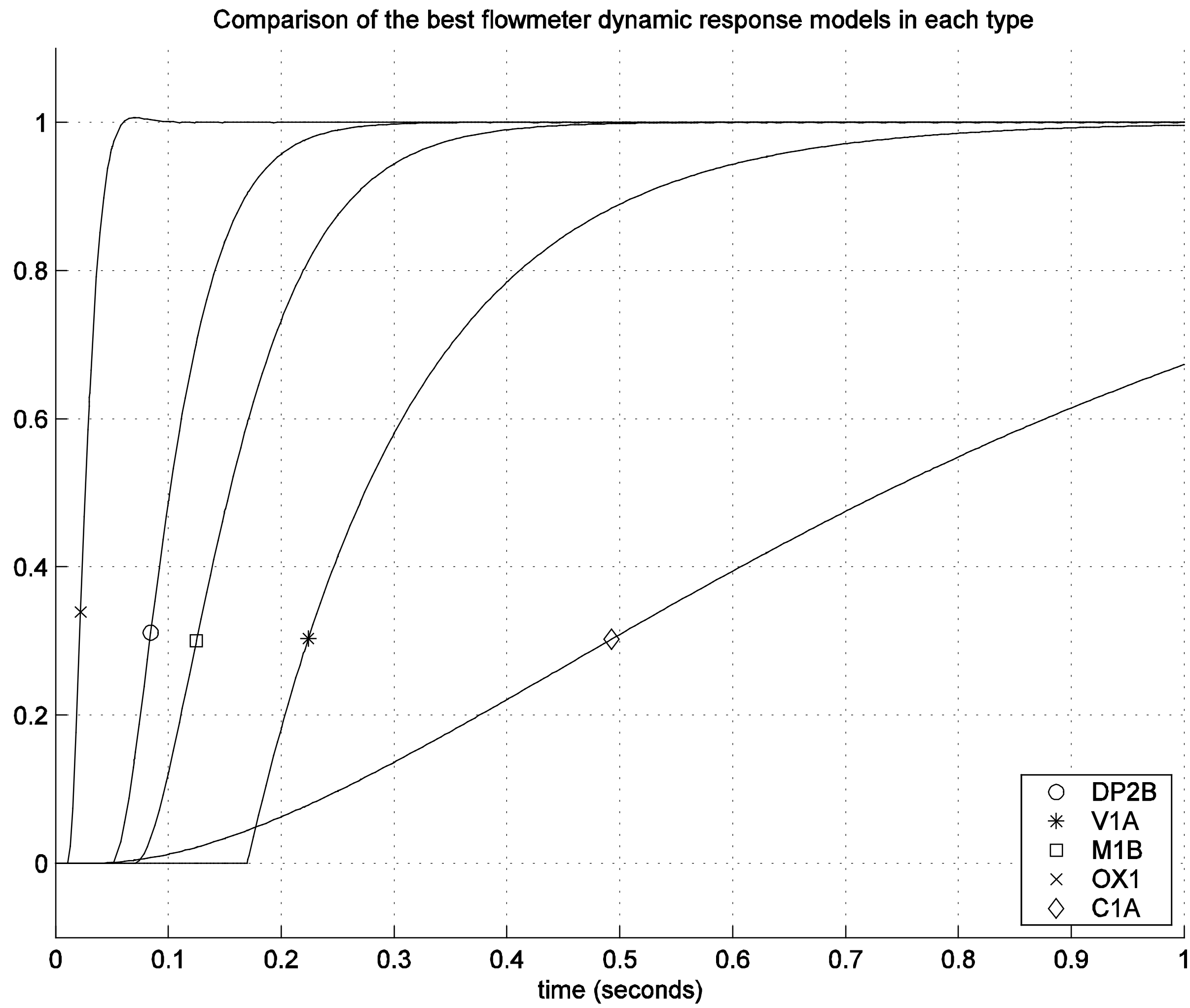

Figure 3. Fastest dynamic response of each type of flowmeter reported by Wilkund and Peluso (2002), together with Oxford prototype response (OX1), on a nominal 0..1 scale. DP = Differential Pressure, V = Vortex Flow, M = Magnetic Flow, C = commercial Coriolis massflow meter.