

# The Dynamic Performance of a Micro-machined Coriolis Flow Meter

C. Clark, S. Wang and R. Cheesewright

School of Engineering and Design, Brunel University, Uxbridge, UB8 3PH, UK

## ABSTRACT

The performance of a prototype micro-Coriolis flow meter, developed by ISSYS, was investigated by simulation, using the Brunel University Virtual Coriolis Meter facility. The flow meter comprises a vacuum sealed vibrating flow-tube, driven at its fundamental resonant frequency, and associated electronics for the tube drive and processing of signals from the two internal sensor. The meter measures flow rates of order 0.1 to 10 mg/s and has potential applications in medicine (e.g. drug infusion) and, in smaller versions, the area of micro-fluidic devices. The simulation facility comprises finite element modelling of the motions of the vibrating tube, with a 1-dimensional frictionless flow through it, thus allowing the generation of pseudo-data at points on the tube corresponding to the internal sensor locations. Signal processing algorithms then enable representation of an indicated meter flow-time history (output), in response to a prescribed flow input. Results have shown that the device is linear and that its sensitivity is uninfluenced by fluid density, but is very strongly dependent upon the location of the internal sensors. The dynamic response time (= reciprocal of the drive frequency) is of order 0.1 ms, and the device step response shows noise due to signal components at a higher resonant mode frequency.

**Keywords:** micro-Coriolis, dynamic response, simulation, Coriolis meter.

## 1 INTRODUCTION

Use of the Coriolis flow meter has increased progressively, as has its market share, since it was first introduced some three decades ago. The principal advantages of this technique include: being a true mass flow rate device, low measurement errors (0.1% in single phase liquid flows) over a relatively high turndown ratio, and its potential, yet to be fully realised, for a very fast dynamic response. The basic sensing element of the Coriolis meter is a vibrating flow-tube; the moving mass of flow passing through it produces an asymmetrical tube distortion due to the associated Coriolis forces. In macro-Coriolis meters this tube distortion is proportional to the mass flow rate and is detected by the use of motion sensors. A flow-transmitter provides the drive power and control and the signal processing required to extract the distortion-induced phase-difference between the two sensors signals.

There is now a growing need for the capability to measure very low flows (say, 0.1 to 500 g/h) and ultra-low flows (say, 0.1 to 100 mg/h). Application areas include medicine (e.g.

drug infusions to patients) and a wide range of micro-fluidic devices. The potential for the Coriolis meter to meet this need was recognised in Sweden about a decade ago by Enoksson and co-workers [1]. These authors claimed to be the first to produce a micro-machined mass-flow sensor based upon the Coriolis principle. More recent work by ISSYS in the USA [2], [3] has also yielded prototype versions of a micro-machined Coriolis flow meter. The ISSYS tube has a rectangular shape, as indicated in Fig.1, with overall dimensions 3.5 mm (nodes 14 to 24) by 3mm (nodes 6 to 14). The tube cross-section is also rectangular and a typical flow cross-section is 0.5 mm × 0.1 mm. The reported flow rate range tested [3] for these devices is 0.6 g/h to 2.4 g/h for gas (nitrogen, argon) flows and for liquid (water methanol) flows 0.5 g/h to 110 g/h (but the last figure is for a larger device than detailed above).

In physical operation, the ISSYS device is forced into a sustained constant amplitude vibration at its fundamental resonant mode by use of an electrostatic driver. Distortion of the flow tube produced by the flow-rate dependent Coriolis forces is detected by two displacement sensors (capacitive devices), each of which extends over the full length of the two parallel side arms of the flow tube (Fig. 1). A particular feature of these very small flow tubes is, as expected, the relatively high drive frequencies required to match the first mode resonant frequency, typically 10 kHz and above.

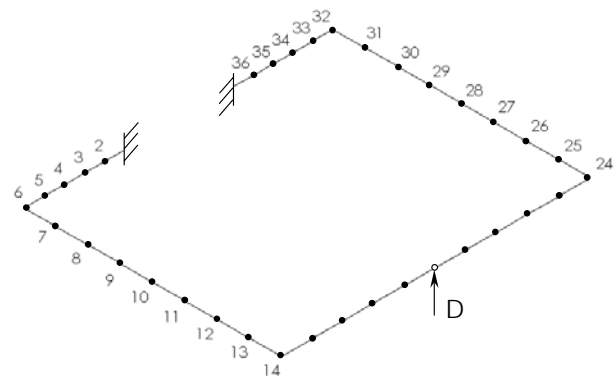


Figure 1: Finite element mesh for micro-Coriolis meter

The purpose of this current paper is to report on the performance characteristics of the ISSYS micro-machined devices, as evaluated through finite element simulation using the Brunel University virtual Coriolis meter facility [4]. Essentially, the work focuses on the flow-tube performance and specifically does not include any representation of the

physical flow-transmitter. This separation allows the full potential of the flow-tube to be evaluated, and is facilitated by use of the force-driver and off-line signal-processing features of the virtual Coriolis meter [4]. Particular issues addressed through the simulation work were: (a) the influence of flow-tube wall-thickness upon both meter sensitivity and dynamic response time (these properties are coupled [4]); (b) the consequences of having “distributed” (rather than “point”) displacement sensors; (c) the influence of small physical scale upon dynamic response of the flow-tube.

It should be noted that within this work, sensitivity,  $K$ , is defined as the time-delay,  $\delta t$ , ( $\mu s$ ) between the two internal sensor signals, per unit mass flow rate. Theoretical results for a simple straight-tube meter indicate that  $K$  is independent of the meter drive frequency ( $\gamma_1$ ) and, hence, is independent of the fluid density, [4].

## 2 MODELLING OF METER PERFORMANCE

The Brunel virtual Coriolis meter is based upon a finite element (FE) representation of the flow tube, which, in general, can be of any shape. Simulation of the flow tube in motion, either through free (damped) oscillation or in driven mode, allows the generation of a stream of pseudo-data at points on the tube selected to represent displacement (or velocity) sensor locations. As with a physical meter, signal processing algorithms are then applied to these data streams, in order to extract the phase-difference estimates. A suite of such algorithms has been developed for the off-line analysis of sensor signal data [4]. In practice, for a physical device, the meter phase-difference output is calibrated against known mass flow rates. In this study, the phase-difference results yielded by processing the pseudo-data are given directly as time-delay values ( $\mu s$ ) for which one estimate is obtained per meter drive cycle.

The FE model is described in [4] and is based upon earlier work presented in [5] and [6]. The FE mesh used to represent the ISSYS rectangular flow-tube is shown in Fig.1. The model tube was based on the dimensions given above, and two values of (uniform) tube wall-thickness,  $t$ , were investigated, ( $t = 10 \mu m, 25 \mu m$ ). The required physical properties of silicon were taken from [7] and the material critical-damping ratios used were calculated from measured Quality factor ( $Q$ ) values, assuming the high-vacuum packaging of the flow-tube prevented any external damping. Representative mass flow rates for both water and low-pressure air were selected for the simulation cases. No attempt was made to model the effects of fluid viscosity, the flow was considered to be 1-dimensional and frictionless.

## 3 SIMULATION RESULTS

Mode shapes for the first two resonant frequencies producing out-of-plane motions, (respectively, “flapping” and “twisting” modes) are shown in Fig. 2. The meter is driven at

the first mode frequency. In pure steady flow, the Coriolis forces produce a twisting motion very similar to the second mode shape, but it occurs at the **first mode frequency**. The second mode frequency **may** be excited by a variety of factors, including flow noise, external vibrations and dynamic events. Resonant mode frequency values are given in Table 1, for the flow-tube water-filled and then filled with low pressure air, with zero flow in all cases.

Fluid	$t = 10 \mu m$		$t = 25 \mu m$	
	$\gamma_1$	$\gamma_2$	$\gamma_1$	$\gamma_2$
Water	8,644	18,628	12,922	27,951
L P air	14,212	30,619	16,618	35,936

Table 1: Frequencies (Hz) for first ( $\gamma_1$ ) and second ( $\gamma_2$ ) resonant modes.

Table 1 also gives mode frequencies for both values of tube wall-thickness ( $t = 10 \mu m, 25 \mu m$ ). It can be shown that the effect of increasing tube wall thickness is to increase the stiffness at a greater rate than the associated increase in tube mass. It is this feature which explains the larger wall-thickness producing higher frequency values for each resonant mode.

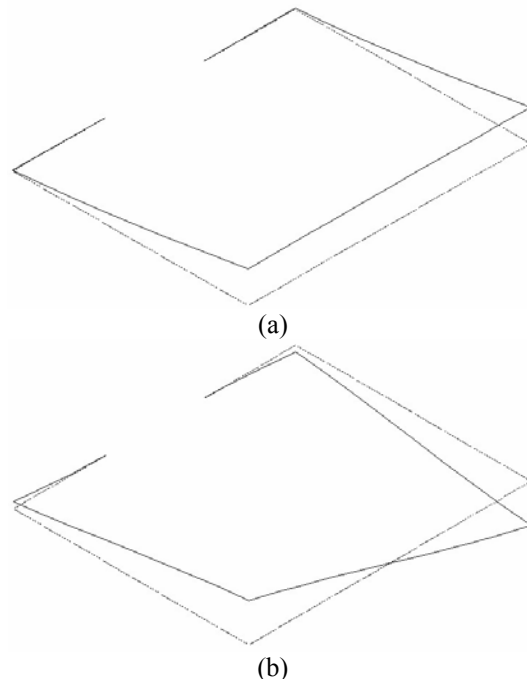


Figure 2: Micro-Coriolis meter resonant mode shapes (a) first (driven) mode, (b) second (Coriolis) mode.

For simulation of the meter with flow, the flow-tube was driven by a force driver (see [4]), at a constant amplitude of vibration ( $= 3 \mu\text{m}$ ) at point D, as shown in Fig.1. The results for device sensitivity (phase time-delay per mass flow rate) are given in Fig. 3.

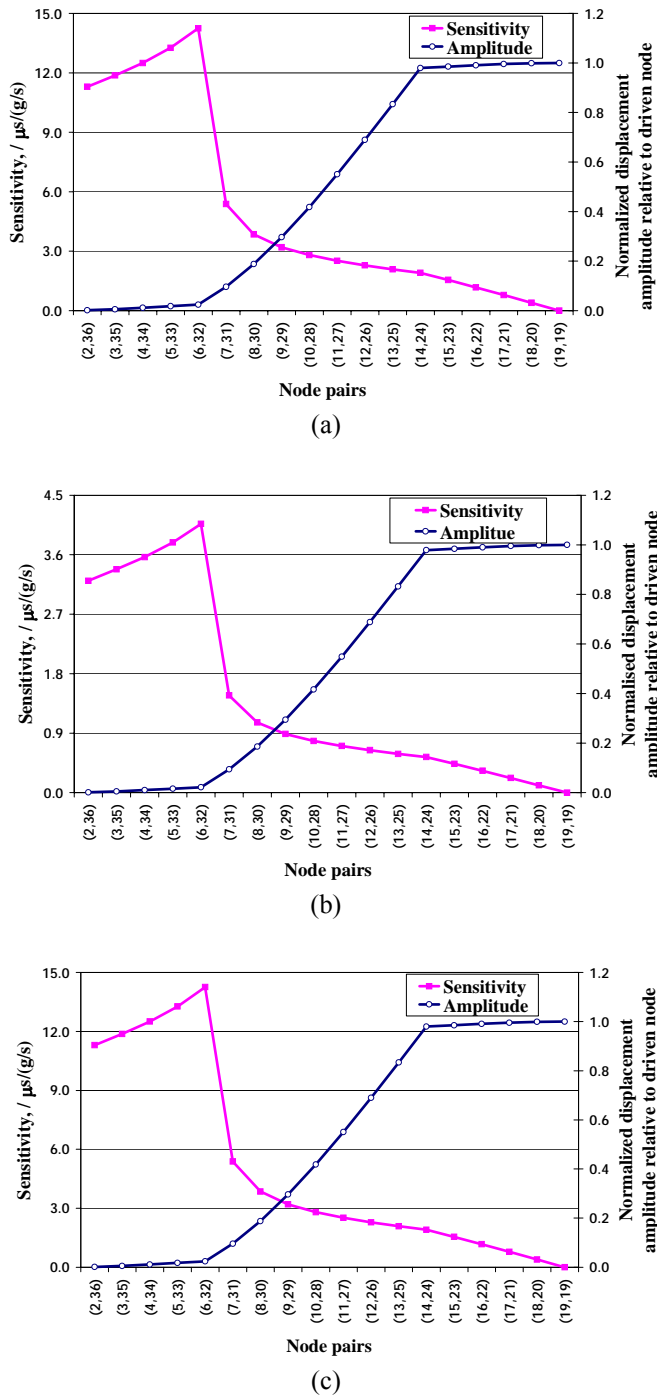


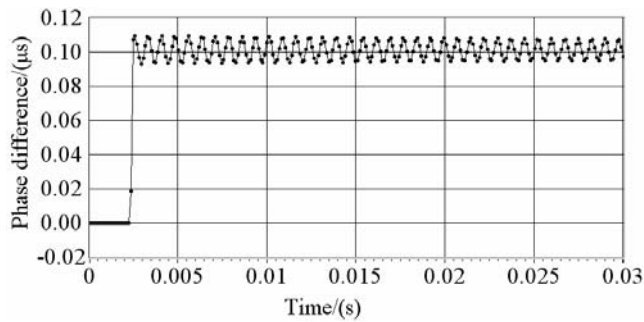
Figure 3: Meter sensitivity and flow-tube displacement amplitude,  
 (a) water ( $t = 10 \mu\text{m}$ ), (b) water ( $t = 25 \mu\text{m}$ ), (c) air ( $t = 10 \mu\text{m}$ )

For each identified node pair in the finite element mesh (Fig. 1), Fig. 3 shows (i) the meter sensitivity ( $\mu\text{s}/(\text{g/s})$ ) that would be obtained if point sensors were to be mounted at the identified node pair positions and (ii) the corresponding “sensor signal” (= displacement amplitude) relative to the forced displacement produced at the driven position (‘D’ in Fig.1). Comparison of results between Figs. 3 (a) and (b) show the effects of increasing wall thickness; the higher value ( $t = 25 \mu\text{m}$ ) results in substantially reduced sensitivity values, associated with the increased tube stiffness. Fig. 3(c) shows the results obtained with a low-pressure air flow through the meter, at a mass flow rate equal to one fifth of the water flow rate which yielded the results given in Fig. 3(a) and both are for  $t = 10 \mu\text{m}$ . An important observation is that the sensitivity values with the air flow are precisely the same as those derived for the water flow case, i.e. independent of fluid density. This result is consistent with the theoretical predictions for a straight tube meter, as described in Section 1 above. Simulations for different flow rates also showed the device to be highly linear.

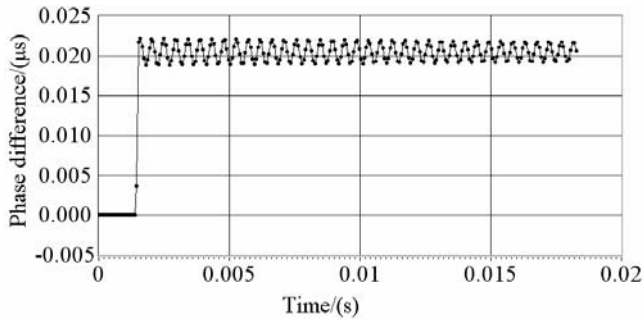
In practice, it may be very difficult to achieve suitably robust “point” sensors by micro-machining. The current fabrication of the rectangular-tube Coriolis meter provides long sensors, each of which extends the full length of the side arms, i.e. from nodes 6 to 14 and nodes 32 to 24 (Fig. 1). Thus, these are essentially “distributed” sensors, and if a simple arithmetic averaging of sensitivities of the “point” sensors (nine on each side arm) is assumed to give a representative value, then for example, from the results shown in Fig. 3(a), the “distributed” sensors give a mean sensitivity of  $4.25 \mu\text{s}/(\text{g/s})$ , which is to be compared with a maximum sensitivity (node pair 6,32) of  $14.25 \mu\text{s}/(\text{g/s})$ . However, achievement of the maximum sensitivity would not be practicable, because of the relatively poor signal-to-noise ratio associated with the extremely small amplitude signals at node pair 6,32.

The dynamic response of the thin-walled flow-tube was investigated by imposing a step change in flow rate, starting from zero flow, and is shown in Fig 4.

The flow step occurs within one computational time step (typically of duration 0.5% of one drive cycle). The response shown in Fig. 4(a) is for water flow with a step amplitude of  $53.2 \text{ mg/s}$  ( $= 192 \text{ g/h}$ ), and the material critical-damping ratio is  $10^{-5}$ . The response to a step change in air flow rate ( $0$  to  $10.8 \text{ mg/s}$  ( $= 39 \text{ g/h}$ )) is shown in Fig. 4(b), and a higher value of damping ( $5 \times 10^{-5}$ ) was used for this case. The step response characteristics presented are qualitatively the same as were found for macro-Coriolis meters. In particular, the step is apparent within the duration of one drive cycle, which is the shortest period within which the signal processing can extract a single phase difference value [8]. In addition, the ratio of step noise (peak-to-peak) amplitude to step height is a constant for steps of different size, and the value of this constant is about 7% greater for the thicker walled rectangular-tube (not shown). The step noise derives mainly from excitation of the second (Coriolis) resonant mode of the flow tube.



(a)



(b)

Figure 4: Response to step change in flow  
(a) water flow ( $t = 10 \mu\text{m}$ ), (b) air flow ( $t = 10 \mu\text{m}$ )

## 4 CONCLUSIONS

The performance characteristics of a micro-Coriolis meter are qualitatively similar to those of macro-Coriolis meters. However, the high drive frequencies of micro-meters offer the capability for an extremely fast (sub-millisecond) dynamic response. These small devices have potential for the measurement of very low and ultra low flow rates, but pose a considerable challenge for the development of flow transmitters that will fully exploit the mechanical performance capability.

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