Early Detection of the Wear of Coriolis Flowmeters through In-Situ Stiffness Diagnosis

Jingqiong Zhang, Yong Yan, *Fellow, IEEE*, Jinyu Liu, and Edward Jukes

***Abstract*—Coriolis flowmeters have been widely employed in a variety of industrial applications. There is a potential that the measuring tube of a Coriolis flowmeter may be eroded when it is used to measure abrasive fluid such as slurry flow. However, it is challenging to verify the structural health of the flowmeter without process interruptions or using on-site calibration devices such as meter provers. This paper presents an in-situ structural health monitoring technique through stiffness diagnosis to identify the potential wear occurring on the measuring tube. To measure the frequency response of a Coriolis flowmeter which strongly depends on the structural characteristics of the tube, the tube is not only excited at a resonant frequency but also at two additional off-resonant frequencies. Through digital processing of the drive and sensor signals, the frequency response is obtained and a stiffness related diagnostic parameter (SRDP) is extracted from a Coriolis flowmeter. The proposed stiffness diagnosis technique was experimentally evaluated on a commercial bent-tube Coriolis flowmeter with dilute sand-water slurry flow. The results illustrate that the slight tube erosion is successfully identified when a relative change in SRDP reaches −1%, showing a good capability for an early detection of tube wear. In addition, the outcomes from recalibration with water suggest that, after the erosion occurs, the flowmeter overestimates the mass flowrate and underestimates the flow density.**

***Index Terms*—Coriolis mass flowmeter; erosion; frequency response; slurry flow; tube stiffness; wear detection.**

I. Introduction

ABRASIVE or corrosive flow media are widely encountered in chemical (e.g. hydrochloric acid), pharmaceutical (e.g. passivation process), petroleum (e.g. hydraulic fracturing), mining (e.g. drilling mud, clays and fine limestone) as well as manufacturing (e.g. production of cement, brick, mortar, concrete or glass) industries. Owing to the abrasive or corrosive nature of the flow media, one key issue in flow measurement in a harsh industrial environment is the potential wear problem of the measuring devices. Coriolis flowmeters are capable of providing stable and highly accurate single-phase mass flowrate (typically 0.1% uncertainty for liquids) and simultaneous density measurement. However, when a Coriolis flowmeter measures abrasive or corrosive fluid, its measuring tube can be potentially eroded or corroded. For instance, during the transportation of slurry flow in an industrial process, frequent collisions between the passing solid particles and the measuring tube would inevitably lead to erosion on the tube. An example of corrosive fluid is hydrochloric acid of which the fluoride and chloride impurities commonly result in stress corrosion cracking of the tube material and hence unexpected failure of the flowmeter [1].

A typical service life of a Coriolis flowmeter is over 10 years, whereas its lifespan might be reduced to 1 to 2 years in an abrasive or corrosive environment because of tube wear [2]. Early detection of tube wear will facilitate a cost-efficient maintenance and extend the service lifespan of a Coriolis flowmeter and prevent unexpected process downtimes. In addition, the wear problem can adversely affect the measurement accuracy of a Coriolis flowmeter and excessive structural damage can even lead to the unexpected facility failure [2]. In highly demanding applications such as custody transfer in the oil and gas industry, a small measurement error of 0.1% would lead to a financial exposure of $78.8 billion in a year for a single pump station [3], [4]. If an early warning of tube wear is given to the operator, the flowmeter in use can be cleaned or recalibrated or replaced promptly, ensuring an accurate flow quantification as well as safe process operation [5]. Hence, it is essential to monitor the structural conditions of the flowmeter for detecting tube wear, including the abrasive or erosive or corrosive wear. It should be noted that the scenarios of possible structural damage generally include tube wear, coating, and overpressure on the tube in various industrial processes. This study focuses on the problem of tube wear.

To lower the chance of tube wear, several suggestions have been supplied by the user instructions [1], including the recommendations on optional wear-resistant material of the tube, flow profile conditioning, preventing solid-liquid separation as well as the consideration on straight-tube over bent-tube configurations. With the removal of material, the early signs of tube wear generally include the wear scars or the ripples on the inner surfaces of the tube or the welds [6]. Nevertheless, regular off-line examination of the tube, such as image inspection or meter calibration, is impractical to implement, always requiring the operator to stop the ongoing industrial process. If the structural conditions of the meter can

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be examined in situ at the measuring point, there is no need to interrupt the process so as to enhance the operational safety, reliability and efficiency.

Wear problems of Coriolis flowmeters are receiving an increasing attention in the last decade. Bell *et al.* [7] undertook numerical simulation work to investigate the erosion phenomenon due to the interactions between the measuring tube and solid particles entrained in the liquid medium. The simulation results indicated that the tube wall became thinner and the tube stiffness decreased as a result of tube erosion. Boussouara *et al.* [6] conducted experiments to intentionally erode two Coriolis flowmeters from different manufacturers and assessed the influence of the tube erosion on Coriolis flow metering. Their experimental findings demonstrated the large errors up to 18.3% and –17% in mass flowrate and density measurements, respectively, resulting from the severe tube erosion. However, the major focus of their study was the impact of the tube erosion on the measurement accuracy of Coriolis flowmeters. Although their study reported some structural condition related information available from one manufacturer, the relevant technical details were not provided.

Due to the importance of the structural integrity of Coriolis flowmeters, several manufactures have proposed patented techniques to allow the end user to monitor the structural health of the flowmeters for enhancing the confidence in the measurements [8]–[10]. For example, one manufacturer has developed a diagnostic tool "SMV (Smart Meter Verification)" with a claimed alarm limit of 4% for structural diagnosis, which means the tool can warn the structural changes of the tube exceeding ±4% [2]. Another manufacturer has released a new tool called "Heartbeat Technology" to assess the performance of their flowmeters and alert the user for possible structural damage of the measuring tube in challenging applications such as corrosive or abrasive environments [5].

After the investigations into the recent advances in the structural verification of Coriolis flowmeters contributed from the manufacturers [2], [8]–[10], we find that the crucial parameter related to the structural conditions is the stiffness of the measuring tube, whereas the relevant technical details of stiffness determination have not been fully disclosed. Moreover, very little research has been undertaken to date to examine the structural health of Coriolis flowmeters under abrasive flow conditions. Besides, the existing experimental studies [2], [6] created greatly accelerated erosive or corrosive processes with thick slurry flows or acids, making it difficult to see whether the presented techniques can offer a prompt response to tube wear at an early stage.

This paper presents an in-situ stiffness diagnostic method in order to detect the tube wear of a Coriolis flowmeter. The procedure for the extraction of a stiffness related diagnostic parameter (SRDP) from the drive and sensor signals in a commercial Coriolis flowmeter is explained in detail. Through erosive tests with dilute slurry flow, the inner surfaces of the tube of a bent-tube Coriolis flowmeter (KROHNE OPTIMASS 6400 S50) are subject to wear in an accelerated, controlled manner. The wear behaviour of the tube is closely monitored by tracking the changes in SRDP on a real-time basis. The use of dilute slurry flow helps identify the reasonable alarm threshold for offering an early warning of tube wear when the stiffness diagnostic method presented in this study is adopted. Furthermore, by correlating the changes in SRDP with the measurement errors, this paper provides quantitative analysis of the measurement errors resulting from the tube erosion, theoretically and experimentally.

II. Stiffness in Relation to Coriolis Flow Measurement

A modern commercial Coriolis flowmeter is composed of a flow sensor (or called a flow transducer) together with a flow converter (or called a flow transmitter) [11]. As a mechanical assembly, the flow sensor consists of several essential components, including the measuring tube, the actuation system, the motion sensors, and other supplementary sensors such as temperature sensors, along with the structural support, as illustrated by Fig. 1. A driver is typically located at the centre to excite the oscillation of the measuring tube whilst a pair of pick-off sensors are symmetrically arranged on the inlet and outlet sides of the tube to characterize the motion of the tube [12]. The flowmeter works by vibrating its tube at a resonant frequency (commonly the first vibration mode) so as to consume minimum energy for keeping a constant oscillation [13].

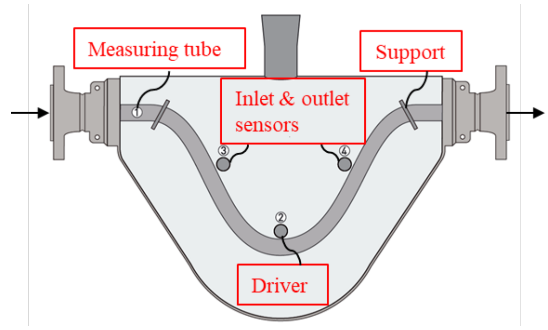

Fig. 1. A typical industrial bent-tube flow sensor with a deeper V-shaped tube configuration [12].

When there is fluid passing through the tube, the fluid-tube interaction creates a Coriolis force and this force indicates the mass of the passing fluid. Consequently, a time delay is generated between the motions of the inlet and outlet sides under the Coriolis force, yielding the measurement of mass flowrate,

$$\dot{m} = C_F \Delta t \tag{1}$$

where $\dot{m}$ is the mass flowrate, Δt the time delay and C_F the flow calibration factor.

C_F is typically determined by the manufacturer under a reference condition and then stored in the flow transmitter. The recorded information about the reference condition generally includes the fluid temperature as well as the pressure, for the purpose of compensating the influence of fluctuations in the temperature and pressure on Coriolis flow metering. Regarding the fluid viscosity, C_F in theory is not a function of the viscoelastic properties of the fluid being metered, while the viscosity can affect the measurement results under practical flow conditions, probably due to the effect of a secondary flow [14].

The interaction between the fluid and the measuring tube of a Coriolis flowmeter can be characterized by the modal matrices, consisting of the mass, the stiffness together with the damping matrices [13]. Here the stiffness of tube is a parameter closely related to its structural characteristics, including the tube geometry, the physical dimensions as well as the type of material [2]. The physical meaning of the stiffness is illustrated by,

$$k = \frac{F}{\Delta x} \tag{2}$$

where k denotes the stiffness of the tube, F the actuation force on the tube and Δx the resulting displacement of the tube.

Meanwhile, as explained in an earlier report [15], the unit of C_F is consistent with that of the stiffness. The dimensional analysis below well demonstrates that the stiffness is the essence of C_F,

$$[C_F] = \left[\frac{\dot{m}}{\Delta t}\right] = \left[\frac{mass}{(time)^2}\right] = \left[\frac{\left(\frac{force}{acceleration}\right)}{(time)^2}\right] = \left[\frac{force}{displacement}\right] = [k]$$

where the square bracket is used to indicate the unit of a physical quantity.

The relationship between the resonant frequency and the effective mass provides the basis for density measurement,

$$\omega_r = \sqrt{\frac{k}{m}} = \sqrt{\frac{k}{m_t + \rho_f V_t}} \tag{3}$$

where ω_r is the resonant angular frequency of the first vibration mode and m the effective mass. For simplification, the lumped mass (m) is simply expressed as the sum of the mass of the empty tube (m_t) together with that of the conveying fluid which is calculated from the fluid density (ρ_f) and internal volume of the tube (V_t).

Accordingly, fluid density is derived from (3),

$$\rho_f = \frac{k}{\omega_r^2 V_t} - \frac{m_t}{V_t} \tag{4}$$

Equation (4) suggests the stiffness of the tube is also related to the density measurement. To summarize, the analysis above clearly explains the direct link between the stiffness and the mass flowrate as well as density measurements of a Coriolis flowmeter. It further implies that the unchanging stiffness is extremely important for delivering accurate flow measurement from factory calibration to the real-world applications. Nevertheless, the stiffness may suffer irreversible shift over the service life of a Coriolis flowmeter, for instance, in abrasive or corrosive processes. If tube wear occurs, the structural properties of the tube would change, consequently giving rise to an incorrect C_F and hence errors in both mass flowrate and density measurements.

III. Methodology for Stiffness Diagnosis

According to the working principle of a Coriolis flowmeter, its oscillation is usually characterized by using a spring-mass-damper model wherein its vibrating tube (namely the measuring tube) acts as the spring in the model [13], [16]. The oscillation of a Coriolis flowmeter can be represented analytically in terms of a basic SDOF spring-mass-damper model [17], [18], in order to demonstrate the physical significance of the modal parameters, as shown in Fig. 2. The assumption here is that all elements in the oscillating system are tightly coupled together, which means the vibrating tube as well as the fluid medium are following exactly the same motions under the excitation exerted by the drive signal. The SDOF model is defined by three modal parameters, the lumped mass (m) which is composed of the effective mass of the tube along with that of the fluid medium, the spring stiffness (k), and the viscous damping (c). The stiffness (k) is closely related to the structural characteristics of the tube whilst the damping (c) quantifies the energy loss due to the interactions between the tube and the surrounding environment.

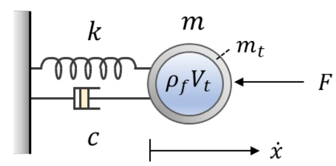

Fig. 2. SDOF spring-mass-damper model of a Coriolis flowmeter.

The frequency response of the tube is derived from the velocity resulting from the actuation force,

$$H(\omega) = \frac{\dot{x}(\omega)}{F(\omega)} = \frac{j\omega}{-m\omega^2 + jc\omega + k} \tag{5}$$

where $H(\omega)$ is the physical frequency response function, $\dot{x}$ the velocity of the tube, and c the viscous damping.

Equation (5) illustrates that the frequency response contains the useful information about the stiffness (k) which is the key parameter for examining the structural integrity of the tube. For a Coriolis flowmeter, it is not convenient to measure the physical parameters (force and velocity) directly, while the drive and sensor signals are closely related to these physical parameters. The current added to the driver is directly proportional to the actuation force on the tube whilst the sensed voltage is proportional to the velocity of the tube. Thus, the frequency response measured from the electrical signals (drive and sensor signals) are proportional to the real physical frequency response via a scale factor,

$$H_C(\omega) = C_{SF} H(\omega) = \frac{jC_{SF}\omega}{-m\omega^2 + jc\omega + k} \tag{6}$$

where $H_C(\omega)$ is the measured frequency response function and C_{SF} the scale factor.

The drive and sensor signals, which are related to the force applied to the tube and the velocity of the tube, respectively, are not necessarily in phase. Hence, the measured frequency response function is written in the complex form,

$$\begin{cases} Re\{H_C(\omega)\} = \frac{C_{SF}\, c\, \omega^2}{(k - m\omega^2)^2 + (c\omega)^2} \\ Im\{H_C(\omega)\} = \frac{C_{SF}\,(k - m\omega^2)\,\omega}{(k - m\omega^2)^2 + (c\omega)^2} \end{cases} \tag{7}$$

where Re and Im represent, respectively, the real and imaginary parts of the frequency response function. At the resonant frequency ω_r shown in (3), the response shown in (7) only has the real part whilst the imaginary part equals to zero.

As illustrated in (3), the drive frequency of a Coriolis flowmeter is actually the undamped resonant frequency [13]. In order to characterize the frequency response, besides the resonant frequency, at least one additional off-resonant frequency is required to be fed into the drive signal so as to yield a second equation. Consequently, with the complementary response excited by the off-resonant frequency (or frequencies), a stiffness related diagnostic parameter (abbreviated as SRDP), is derived from (3) and (7),

$$k_C = \frac{k}{c_{SF}} = \frac{\omega_r^2\, \omega_{or}\, Im\{\dot{H}_C(\omega_{or})\}}{(\omega_r^2 - \omega_{or}^2)\, |\dot{H}_C(\omega_{or})|^2} \quad (8)$$

where k_C represents the measured SRDP value and ω_{or} the off-resonant frequency.

As illustrated in (8), SRDP (k_c) is determined from the responses of the resonant and off-resonant frequencies. Instead of directly measuring the tube stiffness (k), the extraction of SRDP (k_c) is practically beneficial since it utilizes the onboard electronics of a modern Coriolis flowmeter, without adding any extra sensors into the measuring system.

When the user performs the stiffness diagnosis in situ, the relative change in SRDP contains the important information about the structural change, which is more useful than the absolute value of SRDP. The relative change in SRDP is closely tracked on a real-time basis with respect to the factory baseline,

$$\Delta k_C = (\frac{k_C}{k_R} - 1)\ 100\% \quad (9)$$

where Δk_C refers to the relative change in SRDP and k_R the factory baseline of SRDP which is typically obtained under a reference condition. The reference condition here is the related process condition such as the fluid temperature as well as pressure, when the baseline is established. The information of fluid temperature and pressure can be helpful, in consideration of the potential need for the compensation of variations in the practical process condition.

The relative change in SRDP (Δk_C) can be positive or negative. For instance, as reported in [2], [6], [7], when there was an erosion or corrosion occurring on the tube, the tube stiffness shifted negatively, resulting from the thinning of the tube wall. To judge whether there is structural change of the tube, a limit of permissible change (k_{lim}), for instance 1%, is preset by the manufacturer. This limit (k_{lim}) is the alarm threshold for warning the structural damage of the tube. The proper setting of k_{lim} is dependant on the performances of the stiffness determination method and the signal processing unit of the flow converter. If $|\Delta k_C| > k_{lim}$, it implies the underlying structural damage of the tube, suggesting the flowmeter may not function as well as it is specified in the datasheet.

In this research the stiffness diagnosis method is implemented digitally in the on-board microprocessor, without adding any analogue circuits into the flow converter. Fig. 3 depicts the digital signal processing procedure for the stiffness diagnosis (blue colour) whilst the blocks in black illustrate the basic working principle of a Coriolis flowmeter. The resonant frequency (f_r) is usually determined by phase-locking closed-loop control. To perform the stiffness diagnosis, firstly, apart from f_r, at least one off-resonant frequency (f_{or}) is fed into the synthesised drive signal which is digitally generated. For instance, the frequency offset ($\Delta f = f_{or} - f_r$) can be set at 20 Hz. Secondly, the sensor signals, containing the components of f_r and f_{or}, are collected for obtaining the frequency response. Thirdly, by means of quadrature demodulation, the sensor signals are decomposed into the individual components in terms of their frequencies. The separated components are picked out for calculating SRDP (k_c) according to (8). Finally, in comparison with the factory baseline (k_R), the relative change in SRDP (Δk_C) is determined. According to the preset limit (k_{lim}), the diagnostic outcomes are provided to the user regarding the current structural conditions of the flowmeter in use. As shown in Fig. 3, the stiffness diagnostic procedure will not disturb the flow measurement process, which implies the flow measurement results are also available during the stiffness diagnosis.

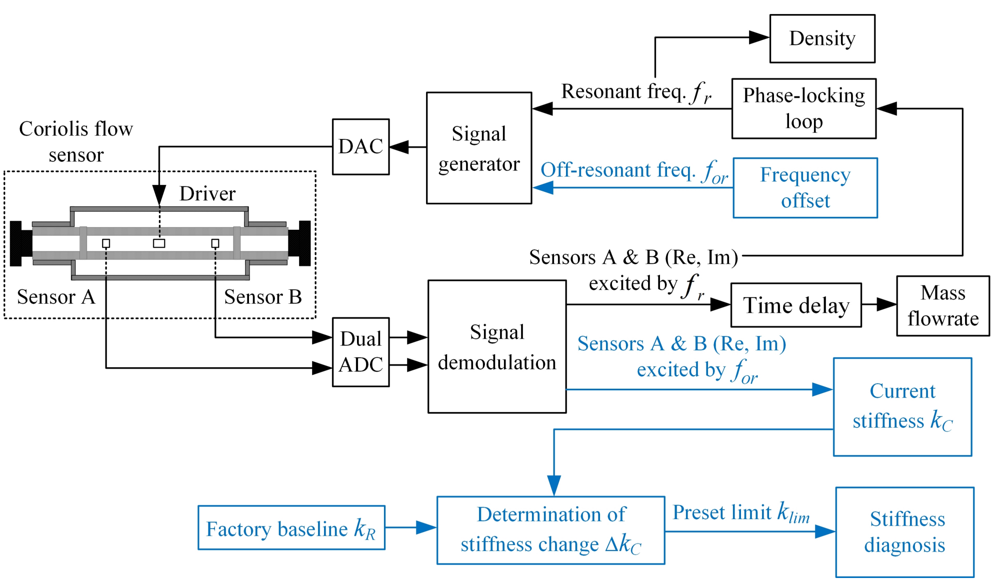

Fig. 3. Block diagram of the digital signal processing in the stiffness diagnosis method.

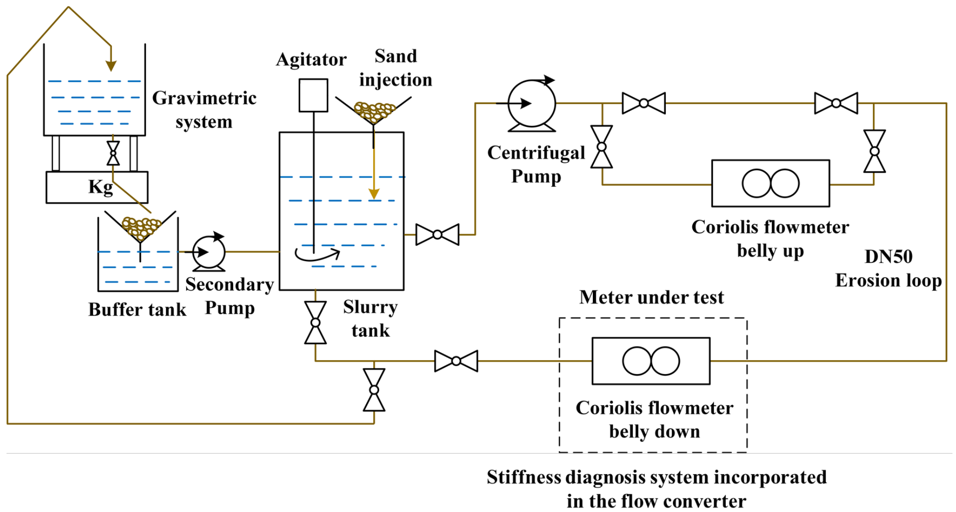

Fig. 4. Schematic of the test rig.

IV. Experimental Validation

A. Experimental Conditions

In order to validate the feasibility and evaluate the performance of the stiffness diagnostic method presented for an early detection of the wear, experiments were conducted on a 50 mm bore erosive test rig (Fig. 4) with dilute sand-water flow. The impacts between sand particles and the measuring tube can cause the degradation or removal of the material of the tube, and this process is called erosion. Erosion rate is defined by the ratio of the weight loss of the material of the tube to the weight of sand consumed [19]. Factors that influence the erosion rate include the properties of sand particles, the characteristics of the material, flow conditions such as flowrate and viscosity of the liquid, sand concentration, impact angle as well as impact velocity of sand particles [20], [21]. Among them, the impact velocity of sand particles (U_s) has been identified as the most important factor, as the erosion rate is proportional to U_s^n wherein the index (n) is typically above 2 [19]. For non-settling slurry flow, U_s is closely related to the flowrate. Hence, in the erosive tests, effective control should be given on the sand concentration and, more importantly, the flowrate.

As illustrated by Fig. 5, slurry flow is circulated throughout the horizontal closed loop for erosion purpose. To create sand-water mixtures, a certain amount of sand is injected into the slurry tank and an agitator is deployed to distribute solids in the liquid medium. The mass flowrate is controlled by adjusting the variable-speed centrifugal pump. The solid concentration is varied by changing the amount of sand being injected as well as the rotation speed of the agitator. The meter under test is the downstream Coriolis flowmeter (KROHNE OPTIMASS 6400 S50) which is designed with a deeper V-shaped tube configuration. A bent-tube Coriolis flowmeter is employed for creating tube erosion as it would be less wear-resistant than a straight-tube meter. The meter under test was horizontally mounted with its belly, namely the measuring tube, facing downwards.

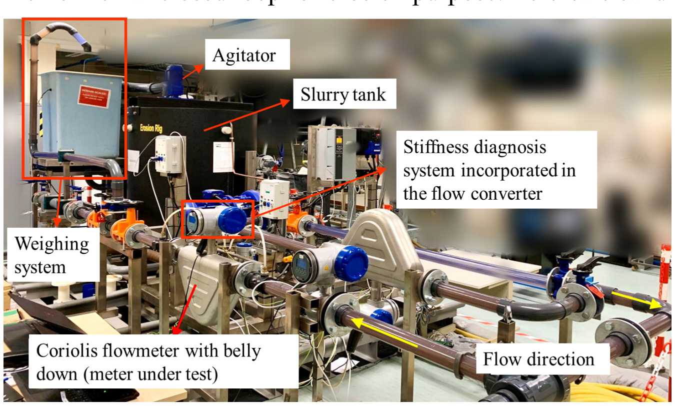

Fig. 5. Photo of the test rig.

Before erosive tests, the measurement performance of the meter under test was verified with water. The uncertainty in mass flowrate measurement was examined by performing start-stop batching procedures with the weighing system of the test rig. Five different mass flowrates (8200, 12000, 14300, 17000, 20000 kg/h) were tested, with three repeats at each flowrate. Fig. 6 displays the results, illustrating that the meter under test performs well within the specification, 0.1% uncertainty in mass flowrate measurement. Additionally, the density measurement of the meter was also calibrated in situ, in comparison with the actual density of water.

After initial verification of the meter with water, erosive tests

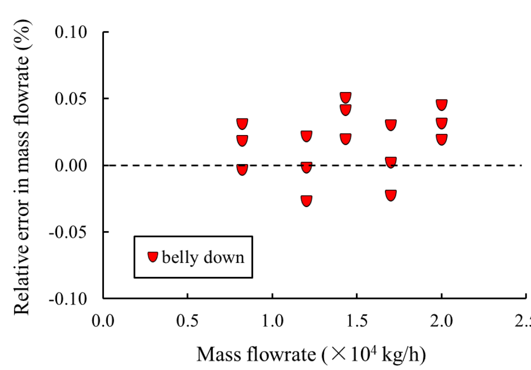

Fig. 6. Initial in-situ verification of the meter with water.

were carried out with dilute slurry flow at mass flowrate approximately 20,000 kg/h with ambient temperature varying from 18 °C to 28 °C. The average flow velocity in the tube of the meter is approximately 7.20 m/s. Such high flow velocity is beyond the recommended velocity limit of 1−4 m/s using the least wear-resistant material available [1] so as to speed up the erosive process. The sand used here is a type of natural and graded silica sand in size between 300 µm and 600 µm. The shape of sand particles is rounded to sub-rounded. The sand concentration of slurry flow is approximately 4% by weight (around 1.5% by volume) according to the density reading of the meter under test.

B. Results of Stiffness Diagnosis

Equation (8) indicates that N off-resonant frequencies (f_{or}) yield N SRDP values (k_C). The use of more than one f_{or} offers an overdetermined solution to determine k_C so as to improve the performance of the stiffness extraction. In this work, two off-resonant frequencies were fed into the drive signal with an offset ($\Delta f = f_{or} - f_r$) at ±20 Hz, respectively. Accordingly, two SRDP values were determined from the responses of the two off-resonant frequencies and further averaged as one SRDP value. The processing time of the stiffness extraction and diagnosis is 1 s, which means that the fastest sampling rate of the raw SRDP data is 1 sample/s. In this study, the time interval of SRDP data logging is selected as 1 min, yielding one SRDP data point per minute. Such data logging rate is high enough to monitor the process of the potential tube erosion due to dilute slurry flow. In future applications, the data logging rate can be adjusted by the end user according to the requirements of different applications

Before the erosive tests, the baseline of SRDP (k_R) was pre-established with water which is a typical single-phase flow condition. During the erosive tests, SRDP data were logged periodically and the logging period was set as 1 hour for each time of the data logging. In order to reduce the possible influence of flow noise resulting from the movement of sand particles, SRDP data were collected at a low mass flowrate nearly 5000 kg/h and a low sand concentration below 0.1% by volume. Besides, since the meter was still able to measure the flow during the stiffness diagnosis, all relevant data, including mass flowrate, density, resonant frequency, temperature, amplitudes of drive and sensor signals, were also recorded simultaneously.

The relative changes in SRDP (Δk_C) were computed with respect to the baseline. The trend of Δk_C during the erosive process is displayed by Fig. 7. It can be seen that the SRDP values drift negatively from the baseline, which agrees with the expected thinning of the tube wall associated with the internal erosive wear. The declining tendency of Δk_C suggests that the meter is gradually eroded due to the continuous impingement of sand particles. According to the values of Δk_C, the erosive process was divided into two stages, stages I and II, for performing the meter recalibration with water so as to verify the potential erosion on the tube. Recalibration I was carried out at the end of Stage I when Δk_C reached −0.59%. Recalibration II was conducted at the end of Stage II when Δk_C approached

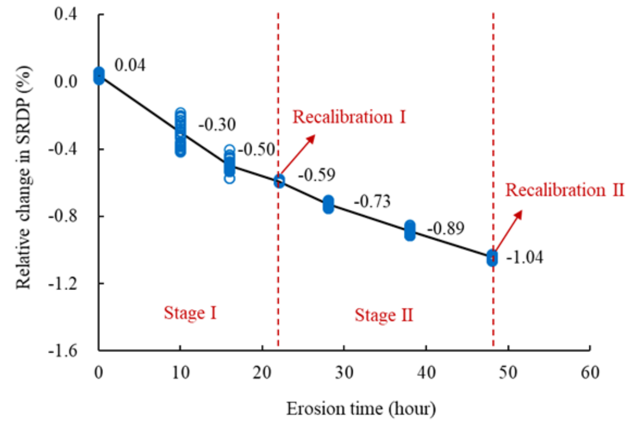

Fig. 7. Trend of relative changes in SRDP during erosive tests.

−1.04%. As illustrated by Fig. 7, SRDP values collected in Stage I exhibit some fluctuations, while SRDP values become more stable in Stage II as the erosion increases with time.

A Coriolis flowmeter is commonly designed and manufactured as a symmetry oscillation system [11]. For a Coriolis flowmeter keeping its structural integrity, the difference between the signal amplitudes of the inlet and outlet sensors is always negligible. Owing to the complex nature of the wear behaviour, the tube wall is highly likely eroded away nonuniformly which can cause an asymmetry between the inlet and outlet segments of the tube. The asymmetry of the tube is evaluated by comparing the signal amplitudes of inlet and outlet sensors,

$$\Delta A_y = \left(\frac{S_I/S_O}{S_{IR}/S_{OR}} - 1\right)100\% \tag{10}$$

where S_I and S_O denote, respectively, the signal amplitudes of the inlet and outlet sensors, S_{IR} and S_{OR} the corresponding baseline data which are obtained with water, respectively.

Fig. 8 depicts how the asymmetry changes during the erosive tests, well proving the asymmetry resulting from the uneven material loss of the tube wall. The upward tendency in the positive direction implies the asymmetry is increasing with the erosion time. The positive values illustrate that the signal amplitude of the inlet sensor is greater than that of the outlet sensor, which agrees with the experimental finding reported in an earlier publication [6]. The reason for the lower signal

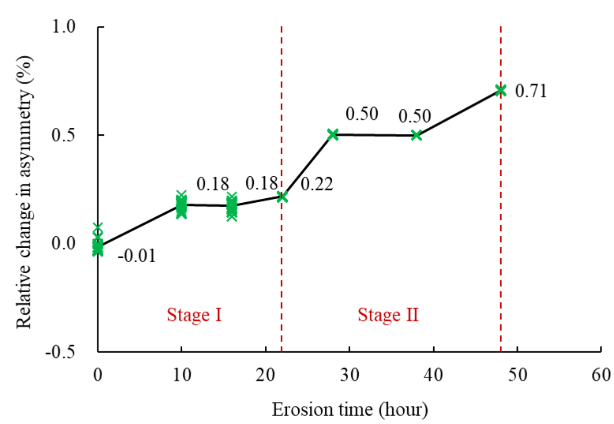

Fig. 8. Trend of relative changes in the asymmetry during erosive tests.

amplitude of the outlet sensor is probably that the outlet side of the tube may experience more severe erosion than the inlet side, resulting in more energy loss at the outlet. A previous experimental investigation [6] by sectioning the tube after the erosion suggested that the more noticeable erosion occurring in the outlet side of the tube.

V. Meter Recalibration with Water

A. Results of Recalibration

In order to verify the degree of tube erosion and further establish the link between the stiffness changes and the resulting measurement errors, the meter under test was recalibrated with water twice (recalibrations I and II) at stages I and II during the erosive process. Meter recalibration was carried out on a gravimetric calibration rig which is UKAS accredited with a reference uncertainty of 0.035% [22]. Fig. 9 shows a layout of the calibration rig. A water supply tank was utilized to provide water at a temperature from 16 °C to 18 °C. Relative errors in mass flowrate measurement were identified by means of a start-stop gravitational method. At the same time, relative errors in density measurement were calculated with respect to a reference flowmeter sharing the exactly same model type and size. The meter under test was horizontally installed with its belly down in the same way as the installation in the erosive tests.

For each time of the meter recalibration, 15 tests were carried out at three different mass flowrates with five repeats for each mass flowrate. Figs. 10 and 11, respectively, plot the errors in mass flowrate and density measurements obtained from recalibrations I and II. As illustrated in Figs. 10 and 11, the results from repeated tests show a good repeatability whilst the results obtained at three different flowrates are roughly at the same level for each time of the meter recalibration. By averaging the results from 15 tests, measurement errors of the meter under test resulting from the erosion are calculated.

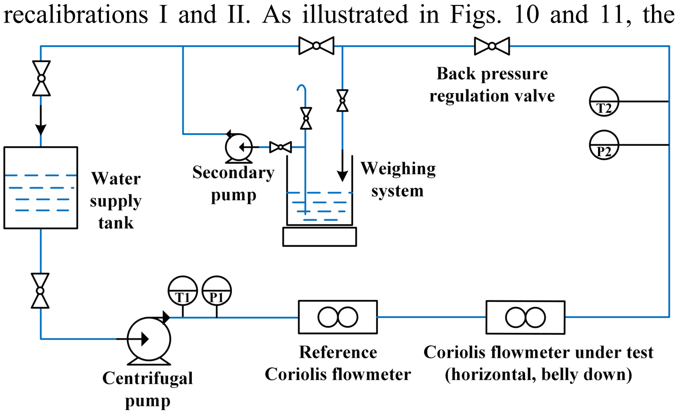

Fig. 9. Layout of the accredited gravimetric calibration rig.

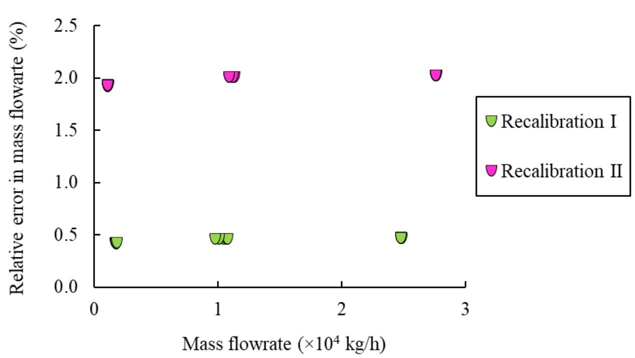

Fig. 10. Relative errors in mass flowrate measurement due to the tube erosion.

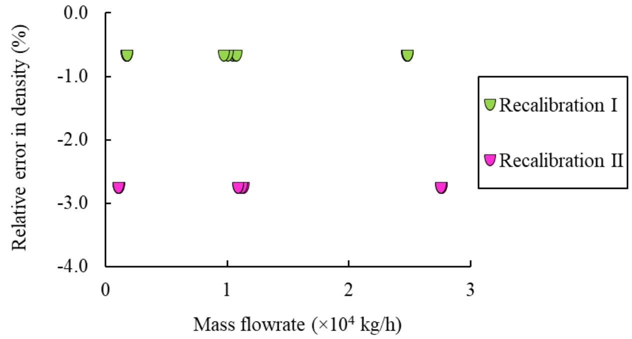

Fig. 11. Relative errors in density measurement due to the tube erosion.

Table I summarizes the results from the meter recalibration together with erosive tests, including the average values of the relative changes in SRDP and the asymmetry. According to the results from Recalibration I, mass flowrate measurement drifts positively with a relative error of around 0.45%, whereas there is a relative error of approximately −0.67% in density reading, both beyond the claimed specifications. For Recalibration II, the meter under test overestimates the mass flowrate with a relative error of 1.99%, while it underestimates the density with a relative error of −2.75%. According to Table I, mass flowrate is overestimated and density is underestimated by the meter under test, due to tube wear which is indicated by the relative changes in SRDP. Apart from the changes in SRDP, the asymmetry problem of the tube is also found from the meter under test. For example, when the relative change in SRDP reaches −1.04%, the relative change in the asymmetry increases to 0.71%. The experimental findings demonstrate the detrimental effect of the tube erosion on Coriolis flow metering.

Moreover, it is worth noting that the change in SRDP represents the overall change in the tube stiffness. Although the erosion is usually distributed along the tube unevenly, it is not necessary to identify the exact location nor the shape of the erosion scar for the purpose of meter diagnosis. The overall change in the tube stiffness reports the occurrence of tube wear,

TABLE I
Measurement Errors and Relative Changes in SRDP and Asymmetry

Average value (%) \ Meter Recalibration	I	II
Relative change in SRDP	−0.59	−1.04
Relative change in asymmetry	0.22	0.71
Relative error in mass flowrate measurement	0.45	1.99
Relative error in density measurement	−0.67	−2.75

which is useful to guide the user to recalibrate or replace the meter. Furthermore, because of the uneven thinning of the tube wall associated with the local erosion, the asymmetry problem of the tube highly likely occurs. The asymmetry problem can adversely affect the zero point and measurement accuracy of a Coriolis flowmeter [2], [11], [17]. Consequently, it becomes practically difficult to predict or compensate the errors in mass flowrate and density measurements from the change in SRDP, although in theory there is a direct link between the measurement errors and the tube stiffness, as described in Section II.

B. Analysis of Tube Erosion

Internal erosion on the tube causes a thinner wall and accordingly the tube becomes less stiff [2], [6], [7]. Because of the reduction in the tube stiffness, C_F would drift negatively from the initial value stored in the transmitter. If the flowmeter still uses the initial value of C_F which becomes larger than its true value, the mass flowrate will be overestimated, according to (1). Consequently, positive errors in mass flowrate measurement are produced, as shown in Table I.

The errors in density measurement are illustrated by (3) and (4). There are two terms that affect density measurement, including the stiffness (k) and the lumped mass (m). As erosion happens, both terms, k and m, would decrease due to the loss of the material of the tube. Nevertheless, these two factors lead to the opposite effects on density measurement. The reduction in k causes the overestimation of the flow density while smaller m results in the underestimation of the density. Thus, the overall influence on the density measurement depends on which factor is dominant, which may depend on the type of the meter design by different manufacturers. According to the results from the meter recalibration, the drift in density reading should be governed by the negative impact of mass loss so underestimation in the density occurs in the flowmeter under test.

To further analyze the influence of erosion on density measurement, (4) is rewritten as,

$$\rho_f = \frac{k}{\omega_r^2 V_t} - \frac{m_t}{V_t} = C_{D1}\,\frac{1}{f_r^2} - C_{D2} \tag{11}$$

where C_{D1} and C_{D2} are the two calibration factors related to the density measurement.

When the measuring tube is eroded, k and m_t would decrease while V_t would increase. As a result, both C_{D1} and C_{D2} would become smaller. As illustrated by (11), since the true density values (ρ_f) are known and the resonant frequencies of the flowmeter (f_r) are always available, two unknown variables (C_{D1} and C_{D2}) can be solved using two simultaneous equations which are established with two different flow media, for instance, water and air. In order to identify the contributions of the changes in C_{D1} and C_{D2} to the underestimation in the density, f_r was recorded with pure water and air, respectively, at the end of Stage I of the erosive process. By substituting the values of ρ_f and f_r with water and air into (11), the new values of C_{D1} and C_{D2} are solved. In comparison with the initial values of C_{D1} and C_{D2} stored in the transmitter, the relative changes in C_{D1} and C_{D2} are recognized as −0.55% and −0.92%, respectively. The reductions in C_{D1} and C_{D2} lead to the error of −0.67% in density measurement from Recalibration I (Table I). The results from meter recalibration suggest that the reduction in C_{D2} contributes more to the density measurement than C_{D1}. In other words, the change in C_{D2} that is related to mass loss is dominant, thus causing the negative error in the density measurement.

Equations (1) and (11), respectively, illustrate the errors in mass flowrate and density measurements resulting from the changes in the tube stiffness. According to the analysis above, a Coriolis flowmeter eroded can overestimate mass flowrate. The errors in density measurement can be positive or negative, dependant on the dominant contribution from C_{D1} and C_{D2}. A previous experimental investigation [6] identified the positive error in density measurement of one Coriolis flowmeter but negative density error of the other Coriolis flowmeter from a different manufacturer, providing the experimental support of the theoretical analysis presented in this study.

At last, after Recalibration II, the relative change of −1.04% in SRDP was also correlated with the physical phenomenon of erosion. A small inspection camera was employed to observe the erosion on the inner surfaces of the tube wall (Fig. 12). Fig. 13 shows an erosion scar on the outer radius of the outlet bend of the tube, while the erosion on the inlet side is less noticeable. The visible erosion from the outlet bend well supports the experimental finding of the asymmetry problem of the tube (Fig. 8), which is caused by the unbalanced material loss of the tube wall between the inlet and outlet sides. Such erosion, though hardly observable through visual inspection (Fig. 13), results in noticeable errors in mass flowrate and density measurements (Table I), highlighting the benefits of the in-situ early detection of tube wear.

Fig. 12. Photo of visual inspection.

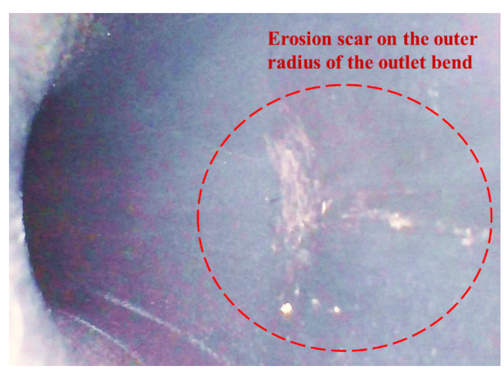

Fig. 13. Photo of observed erosion scar from the tube.

In summary, through the erosive tests and the meter recalibration together with the visual inspection, the performance of the stiffness diagnostic method is experimentally evaluated under laboratory conditions. The results suggest that it is reasonable to preset the alarm threshold which is the limit of permissible change in SRDP (k_{lim}) as 1%. The alarm threshold of 1% achieved in this study is lower than the previous 4% claimed in the published work [2], which gives an earlier warning of tube wear, thereby reducing the negative effect of tube wear on Coriolis flow metering as well as unplanned process outages. Furthermore, since the physical stiffness of the tube is also related to several parameters, such as fluid temperature and pressure [2], [23], rapid changes or large fluctuations in flow conditions may influence the outcomes from the stiffness diagnosis. Hence, careful consideration might be given on the application of the stiffness diagnosis to complex real-world industrial processes.

VI. Conclusion

This paper has provided the theoretical basis and experimental validation of an in-situ structural health monitoring technique for the early detection of tube wear of a Coriolis flowmeter through stiffness diagnosis. By feeding two off-resonant frequencies into the drive signal, a stiffness related diagnostic parameter (SRDP) has been obtained for tracking the potential wear occurring on the tube. The results from the erosive tests have illustrated that, when the relative reduction in SRDP reaches −1%, the monitoring technique successfully recognizes tube wear. Moreover, the detrimental effect of tube wear on the measurement accuracy of a Coriolis flowmeter is well demonstrated through the meter recalibration with water. In comparison with the previous work claiming an alarm threshold of 4% for structural diagnosis [2], the method presented in this paper is capable of giving an earlier warning of tube wear with a lower threshold down to 1%. In addition, recalibration results have illustrated that the reduction of −1.04% in SRDP leads to errors of 1.99% and −2.75% in mass flowrate and density measurements, respectively. The theoretical analysis of the tube erosion has indicated that the error in mass flowrate measurement is always positive whilst flow density can be overestimated or underestimated. Apart from further studies through computational modelling, evaluations of the developed technique with different types of Coriolis flowmeter and under real-world flow conditions will be conducted in future.

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