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Theoretical analysis and experimental study of Coriolis mass flow sensor sensitivity

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ABSTRACT

The measuring tube is the core sensitive unit of the Coriolis mass flow sensor. Its design parameters directly influence natural frequency and sensitivity, such as shape and structure dimensions. In this study, we obtained under concentrated force the equivalent elastic coefficient of the measuring tube by adopting static analysis and calculating static deflection curves, including the respective U-shape, slightly curved, and straight tubes. We then obtained the resonant frequency from the second-order vibration equation. Additionally, the maximum sensitivity and position coordinates were obtained by calculating the torsional displacement curve of the measuring tube under the distribution of Coriolis force during a rated flow. Sensor models with different measuring tube shapes were designed by applying this theoretical analysis. Calibration tests for sensors were performed using a static gravimetric method. Theoretical analysis and test results show that the resonant frequency and sensitivity of the sensors calculated by applying static mechanical analysis and Coriolis distributing force align with the experimental results, thereby proving the validity of the theoretical method. Furthermore, the proposed method simultaneously obtained the relation curve of the measuring tube structure dimensions and natural frequency and sensitivity. It therefore provides theoretical evidence for the sensor design and detector installation position.

1. Introduction

The Coriolis mass flowmeter is a high-accuracy measuring instrument that can measure fluid mass flow and density. It is widely used in petroleum, chemical, medical, and food safety industries. Its characteristics include high accuracy, a wide-range ratio, and good repeatability (Shanmugavalli et al., 2010; Anklin et al., 2006).

The Coriolis mass flow sensor operates under resonant conditions. Owing to the Coriolis effect, when fluid flows, the equal but opposite Coriolis forces generated at the inlet and outlet portion of the measuring tube cause the tube to twist. This action generates a phase difference that forms a proportional relationship with the fluid mass (Bobovnik et al., 2004). Because the sensor operates under harmonic vibration, it is hypersensitive to external vibration noise and stress states. In early development, the operating frequency of the Coriolis mass flow sensor is low at approximately 60–120 Hz. Because this frequency is close to the industry-site vibration disturbance and power-operating frequency, the test accuracy and range ratio is limited, especially when testing for repeatability of a low flow section.

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Currently, the operating frequency of products from companies, such as Rosemount in the US, is increased to 240 Hz or above. This effectively avoids the coupling effect of the site vibration disturbance and power frequency. Nevertheless, the operating frequency increase presents a higher real-time requirement for the detection system. Thus, studying the operating frequency, sensitivity calculation, and analysis method of different tube-shape structures of the mass flow sensor is meaningful in optimizing its design, shortening its development cycle, and guiding the transmitter design (Sultan and Hemp, 1989; Luo et al., 2012, Hemp, 2002).

Sultan and Hemp (1989) introduced a mathematical modeling method for the U-shape CMF. The method assumes the tube is a Euler beam and the fluid is a solid passing through the tubes in a constant velocity without friction. Different modules were used to compute its numerical results, and experimental and numerical examples were presented. In addition, Sultan (1992) introduced a study of a single straight tube mass flowmeter. The effect of central mass on the tube sensitivity was plotted; however, only one reference was given for this purpose. Experimental results for zero shift of the meter due to variable temperature and external excitation were given with no analytical or numerical explanation.

Lange et al. (1994) used the perturbation theory to model straight pipe conveying fluid as a Euler beam with a moving string. The effect of fixing two masses (detectors) at a symmetric position relative to mode mid-span was studied. The authors concluded that the detector positions should be carefully chosen because the instrument calibration becomes dependent on the fluid density if the masses of the detectors are not negligible compared to the pipe mass. Furthermore, Raszillier et al. (1994) showed that the concentrated mass is attached at the midpoint of a straight fluid conveying pipe segment. They considered the tube a Euler beam and the fluid a moving string. The effect of the concentrated mass on the modes (symmetric and antisymmetric) of the meter and measured phase difference at certain points were studied. The perturbation theory was also used in their solution.

Kutin and Bajsic (2002) introduced a method to derive approximate, analytically expressed, and theoretical characteristics for a straight, slender-tube Coriolis meter, which can be used in any of its working modes. Their mathematical model is based on the theories of the Euler beam and one-dimensional fluid flow; moreover, it includes the effects of axial force, added masses, damping, and excitation. They obtained the analytical approximations of the Coriolis meter by applying a Taylor-series expansion to the solutions of the Galerkin's method, which were considered a superposition of the Euler-beam modal functions. Moreover, Kutin and Bajsic (2001) presented an analytical investigation by assuming a straight slender tube that neglects the masses of the exciter and detectors. Their approach to the mathematical solution was Galerkin's method. They gave some figures of the variation of the first three-order natural frequencies with the flow velocity and variation of the phase difference between the two symmetric points with flow velocity.

Stack et al. (1993) introduced a finite element model of a pipe conveying fluid. The pipe was modeled as a Timoshenko beam, and the fluid was idealized as incompressible and inviscid. The domain of the problem could be discretized by assuming the form of the solution for spatial variables. Hamilton's principle was used in the derivation. The shape function was used to model the transverse displacement. Furthermore, the rotation was developed based on a static equilibrium consideration that is typical of the Timoshenko beam formulation. In addition, Hulbert and Darnell (1995) introduced a finite element analysis, including the effect of axial tension in tubes. They demonstrated the importance of including this axial term. They placed the measuring tube according to the Timoshenko beam model and obtained the influence of the mass flow rate on the change in natural frequency.

Wang and Baker (2004) proposed a finite element analysis. They included in their finite element model the stress due to clamping or welding processes, additional masses, and structures added on account of design constraints. Wang et al. (2006) introduced a finite element model for a straight pipe conveying fluid by assuming the pipe as a Timoshenko beam. The model has some advantages, including the structure damping effect and the fluid. A hammer test was applied to the tube. The response was detected by two detectors, and a Q factor was obtained by using a circle fitting procedure. Furthermore, Mole et al. (2008) realized a numerical model by coupling a finite volume code for fluid flow analysis with a finite element code for structural analysis using the conventional staggered solution procedure.

Bobovnik et al. (2005) presented a finite volume model for the fluid and a finite element for the tube. They used this method to find natural frequencies and phase differences in a straight Coriolis mass flow meter. The results are in good agreement with those of Stack et al. (1993). However, the results do not agree well with the Euler Bernoulli beam model. Moreover, Cheesewright and Shaw (2006) determined that the errors in CMF finite element modeling are not due to the modeling methods; rather, they are due to the round-off errors in the numerical solver of the eigenvalue problem.

Based on a review of this existing literature, our theoretical analysis of the CMF sensor adopts the measuring tube simplification for the Euler or Timoshenko beam. Then, the mode of vibration and resonant frequency are analyzed with a lower sensitivity analysis. However, finite element analysis of CMF sensors only analyzes the vibrating mode and resonant frequency. Although phase difference analysis is mentioned for the coupled finite-volume/ finite-element modeling of the straight-tube Coriolis flow meter (Bobovnik et al., 2005), no experimental verification of the result exists.

Owing to the above limitations, we therefore demonstrate a static analysis of the measuring tube, obtain the sensor measuring tube static mechanical model, and analyze the resonant frequency, rated flow sensitivity, and relationship between the structure parameter, resonant frequency, and sensitivity. From designing and machining mass flow sensors of different diameters and shapes, our experimental results show that the resultant frequency and sensitivity from the static