

# A METHOD TO DETERMINE INFLUENCE OF MULTIPHASE FLOW ON VIBRATION CHARACTERISTICS OF CORIOLIS MASS FLOWMETER'S MEASURING TUBE

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**Abstract** – Coriolis mass flowmeter (CMF) is a preference for mass flow rate measurement for its high accuracy. However, with multiphase flow, CMF has deducted accuracy and is prone to fail due to the lack of stable vibration of measuring tube, which is the premise of CMF's accurate measurement. This paper presents a method to determine the influence of multiphase on vibration characteristics of CMF's measuring tube. At first, the measuring tube with multiphase flow is drove at a series of frequencies to obtain its frequency responses. Then transfer function of the vibration system is identified by amplitude-frequency curve fitting and phase-frequency curve fitting. At last, vibration characteristics of the measuring tube with multiphase flow are derived from the transfer function. To verify this method, experiments of pure water, gas, and gas/liquid flow are conducted and the results are presented. Discussions and conclusions about influence of multiphase flow on measuring tube's vibration characteristics have been carried out and are expected to lay the foundation of vibration control for CMF in multiphase flow. Further research about the vibration characteristics of any type of measuring tube with various multiphase flows such as solid/liquid flow and heavy oil can be conducted with the method presented in this paper.

**Keywords:** Coriolis mass flowmeter, multiphase flow, vibration characteristics, measuring tube

## 1. INTRODUCTION

Mass flow rate is a crucial physical quantity, especially in oil trade, chemical industry, pharmacy, food and beverage, where it's directly related to quality control and economic benefits. As a direct mass flowmeter, Coriolis mass flowmeter has attracted much focus for its high accuracy (to 0.1%), large turn down ratio (100:1 or better), and good repeatability (0.1%), since its first appearance in 1970s [1]. With technology development in recent years, CMF can acquire very high accuracy in single phase flow and has become a preference for mass flow rate measurement. However, with extended applications come new challenges, and multiphase flow is one of the most common. On the one

hand, phases separation is usually difficult and expensive; on the other hand, physical properties of multiphase flow are complicated and nonlinear, which makes it difficult to measure. Thus, multiphase flow is recognized as a bottleneck for not only CMF but also any type of flow rate measurement [2].

CMF works with its measuring tube vibrating at one natural frequency and the measuring signals are directly derived from vibration signals. Stable vibration amplitude and accurate frequency tracking of vibration system are the premise of CMF's high accuracy [3]. So far, PID control is most commonly used for vibration control of CMF's measuring tube for its simplicity and low-cost. But its optimal performance depends on detailed knowledge of the controlled plant. However, due to the density changes and interaction of phases in multiphase flow, vibration characteristics of the measuring tube will differ from that of stable single phase flow and fluctuate tremendously, which leads to the accuracy deduction or even failure of CMF.

There are many existed researches about the influence of multiphase flow on CMF's measurement error. One of the most conspicuous is bubble theory [4]. An analytical model is built to predict the measurement errors of gas/liquid flow in reference to gas void fraction. The model is concise and conforms to experimental results to a certain degree [5]. Further theoretical and experimental efforts were made to understand, model, and reduce errors due to multiphase flow in a CMF in [6]. Explanation of phase decoupling induced by multiphase interaction and some practical advices for users were provided. More experimental works have been done to discover how multiphase flow affects the measurement accuracies of CMF [7][8]. In all those works, measuring signals were assumed normal, that is stable vibration amplitude and accurate frequency tracking in multiphase flow. But in fact, multiphase flow was mentioned to have effects on vibration characteristics of the measuring tube, which makes stable vibration unavailable and leads to discrepancy between theoretical analysis and

experimental results. Even though, no deeper research about vibration characteristics of CMF's measuring tube with multiphase flow has been carried out.

This paper presents a method to determine influence of multiphase flow on vibration characteristics of CMF's measuring tube. A practical dual U-type CMF is adopted here. The measuring tube is first drove at a series of frequencies to obtain its frequency responses. Then the transfer function of the vibration system is identified accordingly. At last, vibration characteristics including natural frequency, damping, and amplitude gain are derived from the transfer function. To verify this method, experiments of pure water, pure gas, and gas/liquid flows with a series of void fractions are carried out. Basing on analysis of experimental results, discussion and conclusion of how multiphase flow will influent the vibration system were conducted and expected to lay the foundation of vibration control for CMF in multiphase flow. What's more important, method presented in this paper can be used for vibration characteristics determination of any type of measuring tube or further research about the influence of various multiphase flows on vibration characteristics of the measuring tube such as solid/liquid flow and heavy oil.

## 2. METHOD

As the physical properties and interactions of phases in multiphase flow are complicated and nonlinear, it is hard and impractical to build an analytical model for the vibration system. Thus, a method based on experiment-derived data is presented in this paper to determine the vibration characteristics of CMF's measuring tube with multiphase flow.

### 2.1. Experimental apparatus

A practical dual U-type CMF is adopted in this paper. Diameters of the flow pipe and measuring tube are 12 mm and 6 mm. An electromagnetic driving sensor (EMD) is installed at the middle of the tube while two electromagnetic velocity sensors (EMVS) at symmetrical locations. Vibration system of the CMF consists of the measuring tube, EMD, EMVSs, and fluid in the tube. During the experiment, driving signal  $V_{in}$  is supplied to the EMD while vibration signal  $V_{out}$  is picked up by the EMVS.

Block diagram of the experimental system is shown in Fig. 1. A syringe is located at the inlet of the measuring tube to add gas into the tube. Gas void fraction is adjusted manually by capacity control of the syringe. A signal generator is applied to supply the driving signal to EMD and an analog data acquisition card (DAQ) is used to collect driving signal  $V_{in}$  and vibration signal  $V_{out}$  synchronously.  $V_{in}$  and  $V_{out}$  are both sinusoidal signals and regarded as the input and output of the vibration system. They are transferred into Labview, where their frequency domain information is extracted. Then, the extracted information is used to identify the transfer function of the vibration system with the System Identification Toolbox of MATLAB.

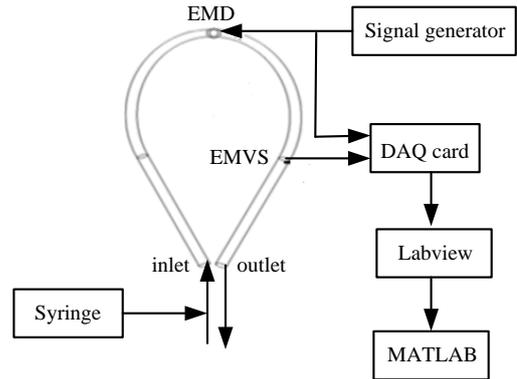


Fig. 1. Block diagram of the experimental system

### 2.2. Derivation of vibration characteristics

To determine vibration characteristics of the measuring tube with specific fluid media, the vibration system is drove at a series of frequencies to obtain its frequency responses. Because the measuring tube has a high Q factor, sampled frequencies should be centered in neighborhoods of the vibration system's first natural frequency. At first, the first natural frequency of the vibration system is distinguished roughly by supplying a driving signal with fixed amplitude but tunable frequency (between 80 Hz to 100 Hz) to the EMD. Amplitude of vibration signal changes with driving frequency and reaches a distinct peak value when the first natural frequency is found. To get enough information of the vibration system and avoid overmuch work at the same time, sampled frequencies are selected to be intensive near the first natural frequency but sparse in the distance. For each case, 25 frequencies are sampled. The sampled frequencies distribute symmetrically about the first natural frequency and frequency intervals increase with the distance between sampled frequency and the first natural frequency. The frequency interval sequence from near to far is: 0.01Hz, 0.01 Hz, 0.02 Hz, 0.02 Hz, 0.05 Hz, 0.05 Hz, 0.1 Hz, 0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz. At last, a frequency range of almost 10 Hz around the first natural frequency is covered, which turns out to be enough for the vibration system identification.

Furthermore, each test at a specific frequency consists of three runs. During each run, three parameters are calculated from the input and output signals in Labview: amplitude ratio, phase difference, and driving frequency. Amplitude ratios and phase differences of three runs are averaged for noise reduction for each test. In the end, three arrays of amplitude ratio, phase difference, and driving frequency will be obtained for each type of fluid media.

To build the transfer function  $G(s)$  of the vibration system, the three arrays which represent its frequency responses are first imported into the System Identification Toolbox of MATLAB as working data. Then before model identification, the working data is split into two halves: the first half becomes the estimation data and the second half becomes the validation data. To model the vibration system appropriately, the most commonly recommended mass-spring-damper model of measuring tube is adopted here, as

seen in (1). Parameters  $a$ ,  $b$ , and  $c$  in the transfer function are to be estimated by amplitude-frequency curve fitting and phase-frequency curve fitting. During the estimation process, output prediction errors, which denote the errors between estimated and real amplitude ratios and phase differences, are calculated with the estimation data. A Loss Function equalling sum of squares of output prediction errors normalized by the number of data points is defined to estimate the fitness of the transfer function parameters. And the fitness is improved iteratively by minimizing the Loss Function and the iterative search is only stopped when a set residual error or maximum iterative number is reached. Then the parameters are validated by the validation data set. Only when the bestfit of model estimation is beyond 85%, the parameters are accepted.

At last, with identified transfer function  $G(s)$ , the vibration characteristics including the first natural frequency  $f_n$ , damping  $\zeta$ , and amplitude gain  $k$  can then be derived as (2), (3) and (4). Vibration characteristics of any type of measuring tube with different fluid media can be determined with the procedure described above.

$$G(s) = \frac{cs}{s^2 + as + b} \quad (1)$$

$$f_n = \frac{\sqrt{b}}{2\pi} \quad (2)$$

$$\zeta = \frac{a}{2\sqrt{b}} \quad (3)$$

$$k = c \quad (4)$$

### 3. RESULTS

Work of this paper is only partially accomplished up to now. Experiments of pure water, pure gas, and one set of gas/liquid flow have been conducted and the identified vibration characteristics are presented in Table 1. The first column is explanation of fluid media in the measuring tube. Pure water has the biggest density while pure gas has the smallest. The second column presents the first natural frequencies  $f_n$  of the vibration system. As can be seen, the first natural frequencies of this measuring tube are around 90 Hz and large density of fluid flow leads to small natural frequency of the vibration system. Dampings are presented in the third column of Table 1 and they are generally small. But it's worth noting that the gas/liquid flow owns the largest damping, which is more than twice of pure water. Column three presents the amplitude gains which denote no explicit tendency.

Table 1. Vibration characteristics of measuring tube with three fluid media

Fluid media	$f_n$ / Hz	$\zeta$	$k$
Pure water	86.58	1.93e-4	0.022366

Gas/liquid flow	87.26	4.38e-4	0.015652
Pure gas	89.30	3.30e-4	0.02636

### 4. CONCLUSIONS

This paper presents a general method to determine influence of multiphase on vibration characteristics of CMF's measuring tube. Three key vibration characteristics are also proposed and procedure of the method is described in detail. The method is verified by experiments of pure water, pure gas and a set of gas/liquid flow. With the experiment results presented above, some primary conclusions about the influence of multiphase flow on vibration characteristics of CMF's measuring tube can be made. Firstly, average density of the fluid flow and the first natural frequency of the vibration system are in inverse proportion, which has nothing to do with the fluid components. Secondly, multiphase flow will induce much larger damping than single phase flow undoubtedly. Thirdly, amplitude gain of the vibration system is affected by the fluid flow somehow.

It's explicit that how multiphase flow affects natural frequency of the measuring tube, but principles for damping and amplitude gain are not clear enough. More experimental data are needed for revelation of the intrinsic laws, especially of gas/liquid flows. To accomplish and perfect this paper, experiments of gas/liquid flows with different void fractions will be carried out in the future. However, the method presented in this paper can be applied to determine the vibration characteristics of any type of measuring tube with various multiphase flow such as solid/liquid flow and heavy oil.

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