Experimental Studies on Vibration Testing of Pipe Joints using Metal Gaskets

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Abstract: Pipe joints have been widely utilized in industrial plants, where dynamic load of vibration is considerably harmful for sealing performance. However, there is a lock of design codes and experimental procedures developed for vibration testing of pipe joints. This paper proposes an experimental setup for testing of pipe joints, which use metal gaskets, in vibratory conditions. Also, a flexible piezoelectric film sensor is introduced into this test rig for monitoring of stress in pipes. With the proposed test rig, vibration testing of pipe joints can be conducted, therefore further investigations such as fatigue analysis of the contact surfaces, and computational analysis of metal gaskets and seal devices are readily available. Finally, some experimental results of a gasketed flange joint, which uses a 1.5-inch diameter stainless steel gasket, were reported.

Key–Words: Pipe joints, Metal gasket, Vibration testing, Sealing performance, Leak-free.

1 Introduction

Pipe joints are one of the most frequently used elements in power plants, food processing equipment, pharmaceutical industries, *etc.* Elastomeric material has long predominated the field of static sealing technology. Due to the progress in industrial techniques, new demands have gone up rapidly for pipe joints working under high pressure, high vacuum, very high temperature, and various chemical operation conditions. To deal with these demands, a variant of metal and semi-metallic gaskets have been developed [1]-[3]. Although these gaskets offer a high level of sealing performance, since they are usually designed to work with flanges, which are made of much stiffer materials, it is recommended not to reuse these gaskets due to unrecoverable deformation in gasket contact surfaces.

Recently, a new concept of metal gasket, called SUSDETOP® stainless steel gasket[1], was proposed [4]. During assembly process, an annular seal line is formed with an tapered face of gasket and the edge of inner wall of the groove in ferrule (see Fig. 1). Since this gasket uses the same stainless steel material as pipe ferrules, good recovery characteristics can be expected.

In most pipe systems, vibration is a critical problem [5],[6]. At pipe joints, vibration-induced loosening of joint assembly may finally result in sealing failure. Especially, in case of metal gaskets, vibration may also cause fluctuation of gasket stress and fatigue of sealing surfaces. In order to achieve reliable sealing performance, pipe joints, especially those using metal gaskets, should be examined under vibration conditions.

So far, many researches have been conducted to investigate characteristics of gaskets using experimental methods and/or computational analysis, such as finite element modeling (FEM) [7]-[10]. Also, International organizations like ASME, CEN, and ISO have been engaged in developing design and test standards for gaskets and pipe joints [11]-[13]. However, most of the concentration has been focused on hydraulic leak testing and stress-strain terms in pipe joints under internal pressurized and unpressurized conditions, such as bolt stress and contact stress of gasket [7]-[9]. Although, Nash and Abid [7] had studied combinations of operation loads on gasketed flange joints, where load of bending moment was considered, it was just examination of static load. Fatigue of gasket was examined under pulsate cycle of working pressure, however, bending moment was not considered in this study, and the gaskets used were non-metallic [10].

To the authors' knowledge, there is no guideline and standard issued for testing of pipe joints with metal gaskets under vibration operation conditions yet. In this paper, we propose a testing method for

[1]SUSDETOP® is the trademark of Toki Engineering Co., Ltd.

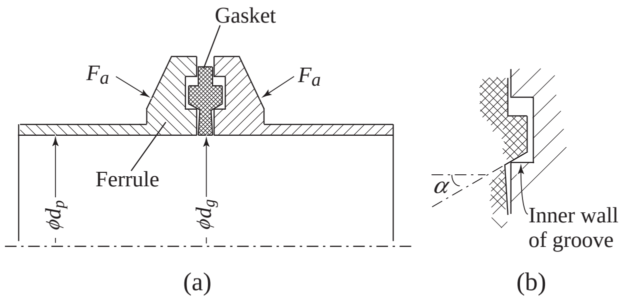

Figure 1: The SUSDETOP® metal gasket. (a) A schematic view of a pipe joint assembled with two ferrules (F_a: assembly force). (b) An enlarged view of the seal area.

examination of metal gasket's sealing performance in cyclic vibration conditions. The frequencies and amplitudes of vibration are considered as parameters in this testing method. Also, a flexible piezoelectric film sensor [14] is introduced into the proposed test rig to monitor stress of pipes. With the proposed method, vibration testing of a variant of gasketed flange joints and pipe fittings can be conducted. Based on the experimental results, further investigations such as fatigue analysis of the contact surfaces, and detailed researches combined with FEM analysis of metal gaskets and seal devices are available.

This paper is organized as follows: the next section will briefly introduce the SUSDETOP® stainless steel gasket, which is used in the experiments in this paper. Then, Section 3 describes the proposed vibration test rig and the experimental procedure. Some preliminary experimental results of our study are given in Section 4. Finally, Section 5 concludes this paper.

2 The SUSDETOP® Metal Gasket

The SUSDETOP® type of metal gasket is designed for ferrules or flanges with grooves on the contact surfaces. Fig. 1 depicts a schematic view of a pipe joint that consists of a gasket and two ferrules. For joints using ferrules, assembly can be made by an adjustable two or three-part clamp with a tapered ring or two loose hubbed flanges using bolts.

One of the major features of this metal gasket is the seal area that is formed with the gasket's taper-face and the inner edge of flange groove. Since sealing performance is proportional to the contact stress at the interface between the gasket and the flanges, the smaller the seal area is, the higher the contact stress may be. An annual seal line may be the best choice for seal area, especially in case that both gasket and flanges

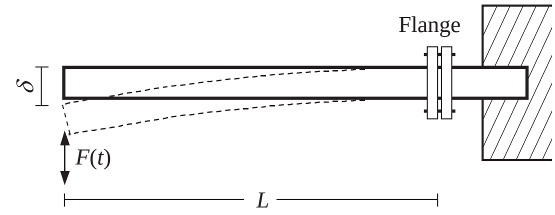

Figure 2: A cantilevered structure of pipe.

are made of same stiff material like stainless steel. Given the angle of the taper-face as α, if the angle between the inner wall of flange groove and the horizontal line (denoted as β) is smaller than α, $\alpha > \beta$, a seal line can be satisfied theoretically. In Fig. 1.(b), $\beta = 0$. It means that a wide range of ferrules and flanges can be used with this type of gasket. During assembly process, assembly force F_a is applied to the joint, and the gasket self-adjusts to form a seal line. Also, it is considered that a taper-type sealing can be used over and over again [1]. Structure of this gasket is very simple, this makes it easy to manufacture and low-cost. With this metal gasket, effective and *leak-free* pipe joints can be expected.

It should be noted that the inner diameter of this gasket is same as that of the pipe, $d_g = d_p$ (see Fig. 1.(a)). There is no gasket extrusion in pipelines, which is considered as a big problem in sanitary fittings where some elastomeric gaskets are used. As a result, fluid holdup and contamination can be significantly reduced. Since this gasket is made of stainless steel, it is well suited to FDA-compliant sanitary applications, and can be used with many kinds of chemical fluids. Furthermore, it fits well with ferrules and pipe joints defined by ISO 2852 [11], it can readily be used for applications in food and pharmaceutical industries.

3 Vibration Testing Setup

This section describes the proposed vibration testing equipment and the experimental procedure.

3.1 Vibration Testing Equipment

In this study, a cantilevered structure of pipe, as shown in Fig. 2, is considered. Let's suppose a sinusoidal excitation force $F(t)$ as

$$F(t) = F_0 \sin(2\pi f t), \tag{1}$$

which is applied on the pipe at L from the flange. Here F_0 is the amplitude of the excitation force and f denotes the frequency. Then, the displacement δ can be

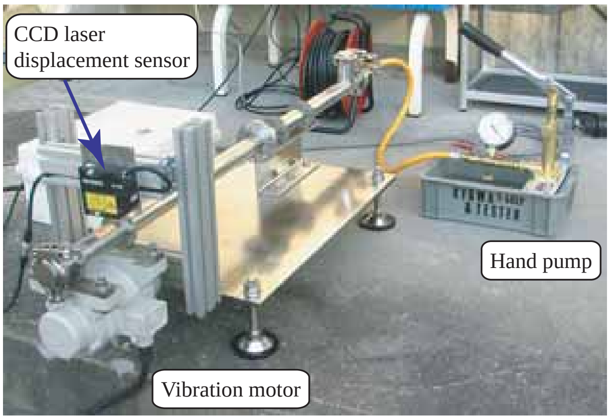

Figure 3: An example of the proposed vibration testing rig.

calculated with equivalent stiffness and equivalent inertial on the vibration side. Since $\delta(t)$ has the same frequency f as $F(t)$, it can be simply expressed as

$$\delta(t) = \delta_0 \sin(2\pi f t), \tag{2}$$

where δ_0 stands for the amplitude of displacement. Therefore, a cyclic bending moment $M(t)$ is applied on the flange joint.

The proposed test rig is shown in Fig. 3. The pipe is tightened to the base. A hand pump is used to give the internal pressure. For the excitation force, a vibration motor is used in this study. The motor is mounted on the vibration side, $L = 500$ mm. Since the direction of $F(t)$ turns at the frequency f, not only bending, but also torsional vibration is worked on the flange joint. The motor is controlled with an inverter, by which the frequency f is modulated. Output force F_0 of the vibration motor differs for different f. δ_0 is a function of the equivalent stiffness, the equivalent inertial and F_0, therefore it is also a function of f. With a given vibration motor, a series of (f, δ_0) pairs can be determined, also one can adjust δ_0 with motors of different force output. A CCD laser displacement sensor is utilized to measure δ in the vertical direction. In this testing method, the frequency f and the amplitude of displacement δ_0 are considered as the major parameters.

3.2 Measurement of Pipe Wall Stress

Usually it is difficult to measure contact stress of interface between gaskets and flanges directly. This is the reason why FEM analysis has been widely used for evaluate characteristics of flanges and gaskets. The vibration testing proposed in this paper is much complicated, both bolt stress and stress in the pipe walls should be measured, with which one can estimate the

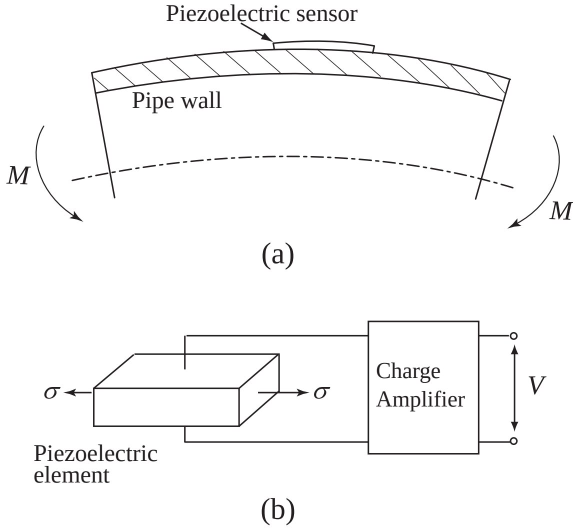

Figure 4: (a) A piezoelectric thin film sensor adhered to a pipe to measure stress of the pipe wall. (b) Transversal effect of a piezoelectric element.

contact stress and have a more precise analysis using FEM methods. So far, piezoelectric transducers have been utilized in pipe analysis, for reasons that piezoelectric sensors are light, can be easily adhere to pipe walls, use little power, and are sensitive to small changes in strain and vibration [15]. Also, transversal effect of piezoelectric element is particularly suited to measure strain in pipe wall (see Fig. 4).

A smart piezoelectric thin film sensor, proposed by Ueno et al. [14], is incorporated in the test rig for stress measurement. This sensor is made of aluminum nitride (AlN), and has high thermal stability. The AlN is deposited on polyethylene terepgthalate (PET) films. A laminated sensor structure was developed [14]. The sensor consists of Pt electrode (0.1 μm thick), AlN (1.0 μm thick), and PET film (9.0 μm thick) to obtain sensitivity, flexibility, and fatigue durability [16]. The AlN thin film sensor is adhered to the middle of the pipe, 250 mm from flange joint. A charge amplifier is used to convert the sensor's output into voltage signals.

3.3 Experimental Procedure

Firstly, the pipe joint is properly assembled, with the vibration motor not mounted on the pipe. Then, an internal pressure of 2.5 MPa is applied to the testing rig by a hand pump. A tee pipe segment is used to let air in the pipe out. During the whole testing process, the internal pressure level is not changed, and leakage is examined visually. If no leakage is found for five min, the vibration motor is mounted to the vibration side of the pipe, and displacement sensor is then setupped to

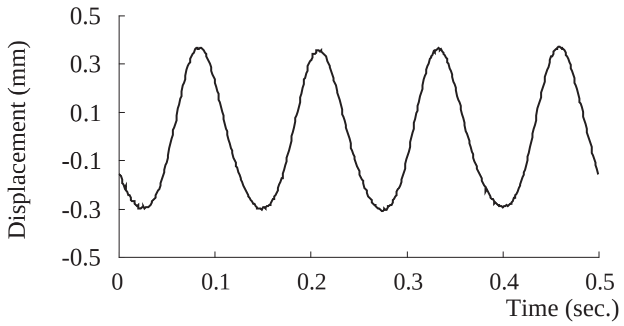

Figure 5: An example of displacement δ ($f = 8$ Hz).

the test rig as well.

Frequency f is modulated from five Hz. For each frequency, the testing time is ten min. If no leakage is found, the frequency is increased by one Hz. Testing stops when leakage is found or displacement δ exceeds 2.5 mm. This limit is set for safety consideration. In this test process, signals of piezoelectric sensors and displacement sensor are recorded (Sampling frequency: 1000 Hz).

4 Experimental Results

As a preliminary study of our project, a SUSDETOP® metal gasket (1.5-inch diameter, SUS315J2) is examined with the proposed vibration testing method. Stainless steel pipes (1.5-inch) is used. Assembly with both two-part clamp and loosen hubbed flange are tested. Two loosen hubbed flanges assemble pipe ferrules and a gasket with six M5 bolts.

A vibration motor (KM5-2PA, Exen Corp. Japan) provides maximum output force 490 N at 60 Hz, and its weight is 5.5 kg. A CCD laser displacement sensor (sensor head: LK-030; amp unit: LK-2000, Keyence) was used to measure displacement δ. A 14-bit A/D converter (USB-6009, National Instruments) was used for data acquisition. An AlN piezoelectric sensor (size: 50 mm $\times$ 5 mm) was adhered with epoxy glue along the longitudinal direction at the top side of the pipe. One scene of the experiments is shown in Fig. 3.

4.1 Vibration and Displacement

After setup of the test rig, the experiments started with $f = 5$ Hz according to the procedure described in Section 3. When $f = 8$ Hz, pipe joint assembled with a two-part clamp leaked. On the other hand, no leakage was found in pipe joint with loosen hubbed flange. It is because that two-part clamp provides less assembly force than flanges, and that the structure of clamp is not strong enough for large bending moment. Fig. 5 shows an example of displacement δ, when $f = 8$ Hz. The plus sign in this figure corresponds to the vertical downward direction of $F(t)$. A cyclic vibration of 8Hz can be confirmed from this figure. Also, an average amplitude of displacement $\bar{\delta}_0 = 0.340$ mm is achieved with this test rig.

Table 1: A summary of the averages and standard deviations of displacements in the vibration experiments using loosen hubbed flanges (5–11 Hz).

Frequency (Hz)	Displacement (mm)
$f = 5$	0.1166 ± 0.0075
$f = 6$	0.1631 ± 0.0078
$f = 7$	0.2409 ± 0.0079
$f = 8$	0.3400 ± 0.0095
$f = 9$	0.5354 ± 0.0079
$f = 10$	0.9437 ± 0.0195
$f = 11$	1.9364 ± 0.1163

Mean $\pm$ S.D.

Fig. 6 shows an example of displacement of 11 Hz. When $f = 11$ Hz, the amplitude of displacement varies largely, it is considered that the excitation force was too large, and vibration of the test rig can not be ignored. Since the displacement for 12 Hz exceeded 2.5 mm, the test experiment stopped. By then, no leakage was found in the pipe joint assembled with loosen hubbed flange.

Table 1 gives a summary of averages and standard deviations (SDs) of displacements for variant frequencies with the vibration motor (KM5-2PA). It can be found that for frequencies, $f < 10$ Hz, vibration of the test rig was relative stable. On the other hand, for frequencies of 10 Hz, and 11 Hz, since motor provides a large excitation force, the test rig turned to be unstable. Also, amplitudes of displacement increased largely, resonance frequency of the test rig may be close to 11 Hz.

4.2 Strain of Pipe Wall

Due to the cyclic vibration and bending moment applied on pipes, stress of the pipe wall occurs. The stress of the top side of pipe was measured with the AlN piezoelectric sensor. Fig. 7 depicts signals of the AlN piezoelectric sensor for vibration ($f = 11$ Hz). Comparing between Figs. 6 and 7, the data shows well agreement with each other. The correlation ratio between data shown in Figs. 6 and 7 is high, $\eta = 0.9958$.

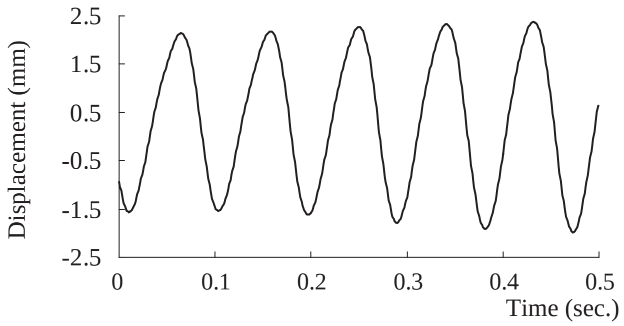

Figure 6: An example of displacement δ ($f = 11$ Hz).

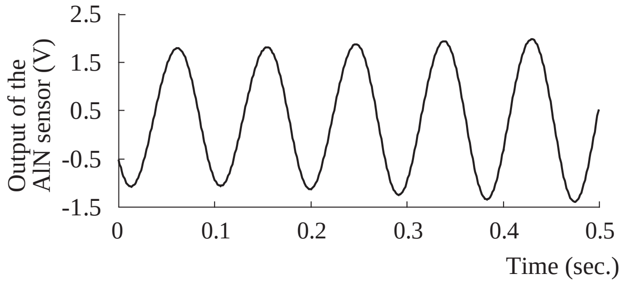

Figure 7: Examples of signals of AlN piezoelectric sensor.

It can be concluded that the AlN piezoelectric sensor can measure vibration-induced stress of pipe wall. Further studies are needed to investigate in detail the relationship between the stress and the voltage of sensor.

5 Conclusion

Lack of standard and testing method for vibration testing of metal gaskets motivated this study. In this paper, we have proposed a new test equipment and examination procedure for vibration testing of pipe joints using metal gasket. Using a vibration motor and a cantilevered structure of pipe, both bending and torsional vibrations are applied on the seal surface. Experiments with a SUSDETOP® type of metal gaskets were conducted. In the experiments, amplitude and frequency of vibration are modulated to simulate vibrations of different degrees.

In our future research, we will focus on the improvement of the proposed testing method. For example, resonance frequency of the test rig should be considered with respect to range of frequency for testing. Vibration with higher frequency but less amplitude should be considered. This kind of vibration can be widely found in pipe systems, and is a major reason of fatigue of sealing. Also, for detailed investigation on contact stress in vibration, computational analysis using FEM should be conducted in conjunction with experimental results of vibration testing. Test and experiments with some other types of metal gaskets should be achieved as well.

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