International Journal of Pressure Vessels and Piping 137 (2016) 38–45

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

# Development of noncontact measurement methods using multiple laser displacement sensors for bending and torsional vibration stresses in piping systems

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ARTICLE INFO

*Article history:*
Received 10 June 2014
Received in revised form
17 March 2015
Accepted 19 May 2015
Available online 27 May 2015

*Keywords:*
Noncontact measurement
Laser sensor
Piping vibration
Vibration induced stress
Piping system
Fatigue failure
Maintenance

ABSTRACT

In this study, two methods to measure bending and torsional vibration stresses of piping systems conveniently and quickly are proposed. The proposed methods are composed of a modeling approach of piping vibration and noncontact measurement techniques. The methods assume the vibration modes as a primary mode within the measuring range without the mode-identification and then estimate the vibration stress by approximating the vibration displacements measured in a noncontact manner as a primary mode. This paper presents the principles and calculation formulas of both methods and shows the measurement techniques for the bending and torsional vibration stresses using laser displacement sensors. Finally the applicability of one method is discussed based on the results of a vibration experiment.

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## 1. Introduction

Many failures of piping systems in nuclear power plants have occurred due to vibration fatigue [1–7]. The fatigue failures were associated with fluid vibration [8–10] and mechanical vibration [11] induced by vibration sources such as pumps during plant operation. To prevent the fatigue failures, the vibration-induced stress (vibration stress) has been evaluated for piping systems in the plants [12–14]. However, the evaluation requires a lot of time and effort because of the number of pipes to be measured. Therefore, new measurement and evaluation methods should be developed, which are easy to implement in the on-site measurement and can provide the necessary measurement accuracy promptly.

The conventional methods to measure the vibration stress in piping systems include the following three methods; the first uses a contact vibration sensor [15], the second glues a few strain gauges directly on the object to be measured [16,17], and the third attaches many accelerometers within the target area of the object as well as over a wide range around the target area. In the third, the vibration mode of the object based on accelerometer measurements is then identified, and the strain and stress produced in the area is determined through calculation [18–20]. However, all these methods exhibit certain problems. The contact vibration sensor is useful only for frequency bands lower than the resonance frequency of the system composed of the vibrometer in contact with the object to be measured and the spring that presses the vibrometer to that object. Furthermore, the accuracy of measurements is dependent on the skills of the workers placing the vibrometer in contact with the object and predicting the vibration behaviors and modes. The method using strain gauges requires many man-hours to set up the measurement equipment, involving a tremendous workload. In addition, it is not applicable to high-temperature objects. The method using accelerometers also requires time for the setup of the measurement equipment and processing of obtained data. Accordingly this method is time-consuming and requires vibration

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http://dx.doi.org/10.1016/j.ijpvp.2015.05.002
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analysis skills. Experts who perform vibration analysis need to be highly experienced because the deformation of the object is obtained indirectly and strain and stress are calculated based on the deformation.

As a solution to these problems, fiber-optic vibration sensors have been undergoing research and development work [21,22]. These sensors use the concept that the frequency of light changes when light passes through an optical fiber, and the change depends on external effects (such as strain, vibration, impact shock, and supersonic waves). The advantages of this method are that it can be used to measure high-temperature areas and can be used for a wide frequency range. Its disadvantages are that the equipment is complicated and large and that the sensor needs to be installed on the object and a measurement network needs to be installed throughout the facilities.

A noncontact vibration measurement system using laser Doppler vibrometers has also been proposed [23]. This system only used the laser Doppler vibrometers in place of accelerometers in existing methods. Therefore, additional work to identify the vibration modes of objects to be measured had to been done.

From the above discussion, all the conventional methods need to determine the vibration modes of 3D complex geometries of piping systems and they require highly specialized skills and a lot of work. These are inherent disadvantages of all the conventional methods.

On the other hand, a vibrating beam-like structure, such as piping, is subject to vibration strain, consisting chiefly of bending deformation. The vibration behavior of piping can be assumed as a primary bending deformation of a cantilever by focusing on the narrow measurement range even though complex vibration modes occur in the piping with complicated geometries. This assumption is thought to enable measurement of vibration strain and vibration stress on the basis of the formula of primary bending deformation in beam theory. This approach can omit the complicated calculation of vibration mode identification. Furthermore, only the visible deformation must be measured and measurements of derivative values such as strain and acceleration are not needed. In short, the noncontact measurement is useful and the contact measurement by detectors attached on the object to be measured is not needed because very accurate measurements are not required. This leads to a simple and rapid measuring operation.

The combination of the modeling approach and the noncontact measurement techniques can create a new measurement method of piping vibration.

The authors have previously proposed the concept of directly measuring the vibration stress using noncontact displacement sensors as a new approach to solving the above-mentioned issues of the conventional methods [24]. In the proposed method, piping displacement due to bending vibration is measured at three positions using noncontact sensors. The piping strain caused by vibration-induced deformation is calculated based on the difference among the displacement measurements, thus estimating vibration stress.

In this paper, a laser displacement sensor is proposed to be used as a noncontact displacement sensor in order to remove the application range of the method such as size and location of pipes. The noncontact measurement of bending vibration stress of piping can be conducted using three laser displacement sensors, which is called an original method in this paper. In a more advanced variation of this method, the vibration stresses of piping caused by bending vibration and torsional vibration can be estimated by measuring six vibration displacements, which is called an advanced method [25]. When using laser displacement sensors, in this paper, the principles of these noncontact measurement methods of vibration stresses are presented and the calculation formulas are derived. Finally, the applicability of one of the proposed methods to piping vibration is verified based on the experimental results.

## 2. Principle of measuring vibration stresses

### *2.1. Measurement of bending vibration stress by laser displacement sensors*

The first part of this section presents how to measure bending vibration-induced stress in piping by measuring three vibration displacements. The discussion assumes the measurement technique using three laser displacement sensors.

Fig. 1 outlines the measurement system used to estimate vibration stress based on the originally proposed method when the bending vibration occurs in the piping. In this method, the deformation of the target area is measured at three positions using three laser displacement sensors. The stress in the object to be measured, which is caused by vibration deformation, is obtained from the difference between the displacement measurements. The stress values are easily calculated by a simple calculation formula that is proposed.

When this method uses multiple laser displacement sensors fixed on one common holder, the error that would arise because of the relative deformation or tolerance of the sensor-installed positions can be prevented. Thus the proposed method and system can realize accurate vibration-displacement measurement and can estimate the accurate vibration stress. In addition, because the three laser displacement sensors directly measure the deformation of the target area in the noncontact manner, the influence by disturbance can be minimized, consequently the measurement accuracy is improved.

Fig. 2 illustrates the principle to measure bending vibration-induced vibration stress using three laser displacement sensors. The figure, which is a top view, shows that laser beams are irradiated at right angles to the vibrating surface of the piping exhibiting horizontal bending vibration, and that the amplitude of the bending vibration is measured from the laser-beam irradiation.

The equations shown below are used to obtain the vibration stress in the piping based on the measured displacement values. The individual symbols are as follows.

$D$: Pipe outer diameter
$r$: Radius of the curvature resulting from vibration-induced piping deformation
$u_1$, $u_2$ and $u_3$: Amplitudes of vibration displacement in piping measured by laser displacement sensors
$X_0$ and $Y_0$: Positions of the laser displacement sensors from the center of curvature whose radius is expressed by $r$

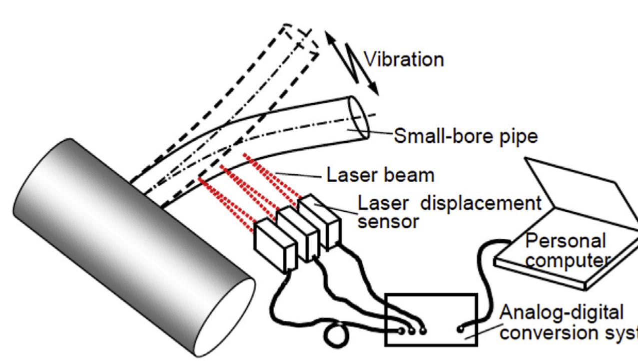


**Fig. 1.** Conceptual illustration of measurement using laser displacement sensors for bending vibration-induced stress.

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