DIAGNOSTIC TECHNIQUES FOR FLOW INDUCED VIBRATION

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ABSTRACT

Flow induced vibration (FIV) is a key factor leading to failure of fuel rod in a reactor core. So, how to mitigate the flow induced vibration of the reactor core components becomes a paramount important task when designing the reactor core. Laser Doppler Vibrometer (LDV) as a noninvasive and high accurate vibration measurement technique becomes a best candidate for investigating the flow induced vibration of reactor core components considering small scale of fuel rod, tiny gap of rod bundle and complex coolant flow field within rod bundle. In this study, the simultaneous calibration tests between LDV and accelerometer have been performed to measure the vibration occurring in air, in a rectangular plexiglass channel with air inside and in a rectangular plexiglass channel with water inside. For the case of vibration occurring in air, the measured vibration velocities under various inspired frequencies and forces by LDV and accelerometer have good agreement with each other. The maximum measured vibration velocity error between two measuring techniques error is less than 10%. For the case of vibration occurring in the rectangular plexiglass channel with air inside, the measured signal by LDV shows big noises due to the light reflecting at the plexiglass surface. Such noise could be mitigated through adjusting the laser incidence angle to be 2º while not affect the measured vibration velocity value. For the case of vibration occurring in the rectangular plexiglass channel with water inside, due to the refractivity of water, the measured raw value by LDV has to be modified by dividing the refractivity of water. The research work performed in this study greatly improved the skill of applying LDV into investigation on the flow-induced vibration of reactor core components.

KEYWORDS

Flow-induced vibration; laser Doppler vibrometer (LDV); accelerometer; calibration; rod bundle

1. INTRODUCTION

Vibration due to fluid flow occurs in many industrial applications. The corresponding flow-related phenomena are called “Flow Induced Vibrations” (FIV). In nuclear power plant system, there are a lot of FIV phenomena and these vibrations are undesirable and often accompanied by serious and safety relevant damages in some cases. So, investigations on FIV are paramount important for nuclear power safety.

Till now, some scientific research related with FIV have been performed for nuclear power plants. Altstadt et al. [1] developed a theoretical vibration model which based on a finite element method for on-line monitoring the whole primary circuit of VVER-440 reactors. Kang and Seong [2] applied piezoelectric accelerometers to monitor a core internal vibration for the core support barrel in ULJIN nuclear power plant unit 1 in Korea so as to realize the real time monitoring of the core support barrel condition. Choi et al. [3] used modal analysis including finite element analysis and modal test to identify the dynamic characteristics (FIV) of the reactor internals for “System-Integrated Modular Advanced ReacTor” (SMART). Besides the investigations on the FIV of whole primary circuit, theoretical and experimental research on special components (steam generator [4], heat exchanger [5], pipe with elbow [6], fuel rod bundle and spacer grid, etc.) were also performed. In defense-in-depth safety strategy, the fuel rod cladding is first safety barrier for preventing leak of radioactive material. However, fretting wear-induced failure of fuel rod has been occurred frequently in nuclear power plants and it is proved that the FIV is the main root cause [7-9]. In order to resolve such safety issue, more and more attentions have been paid on investigations of FIV for the fuel rod and spacer grid. Bhattacharya and Yu [10] used a MEMS-based accelerometer and a non-contact type displacement sensor to investigate angular misalignment effects on flow-induced vibration of two simulated 43-element CANDU fuel bundles in an out-reactor fresh water loop. It is concluded that the flow in the bundle-to-bundle interface region plays an important role in flow-induced vibration of CANDU fuel bundles. Mohany and Hassan [11] numerically predicted the vibration response of CANDU fuel bundle and the associated fretting wear considering turbulence-induced excitation and seismic excitation. Based on an operational modal analysis technique, Pauw et al. [12] analyzed a turbulent axial flow of heavy metal for the lead-bismuth eutectic cooled MYRRHA reactor through a single fuel pin mockup which keeps similar flow conditions as in the reactor core.

A further understanding and corresponding sophisticated theoretical modeling for the FIV of fuel bundle require the support of more detailed and reliable experimental data while traditional accelerometers could not satisfy such requirement. In order to resolve such contradictory, Pauw et al. [13] investigated various vibration measurement methods including a laser Doppler vibrometer (LDV), a grid method (GRID), fiber Bragg grating sensors (FBGs), electrical strain gages and two types of accelerometers, which are available for the reactor fuel bundle. Through comparing tests for a single simulated fuel pin, it is concluded that the laser Doppler vibrometer is the most performant measurement technique. However, the tests were performed for a single fuel pin in a simple environment as in air and lack of operation experience in a real test condition that the fuel bundle immersed in water and laser needs to transmit through the transparent window and water which will lead to complex reflections and refractions. The purpose of this study is to calibrate the LDV and accelerometer with each other and investigate the application of LDV on measuring the FIV of reactor fuel bundle under real testing conditions.

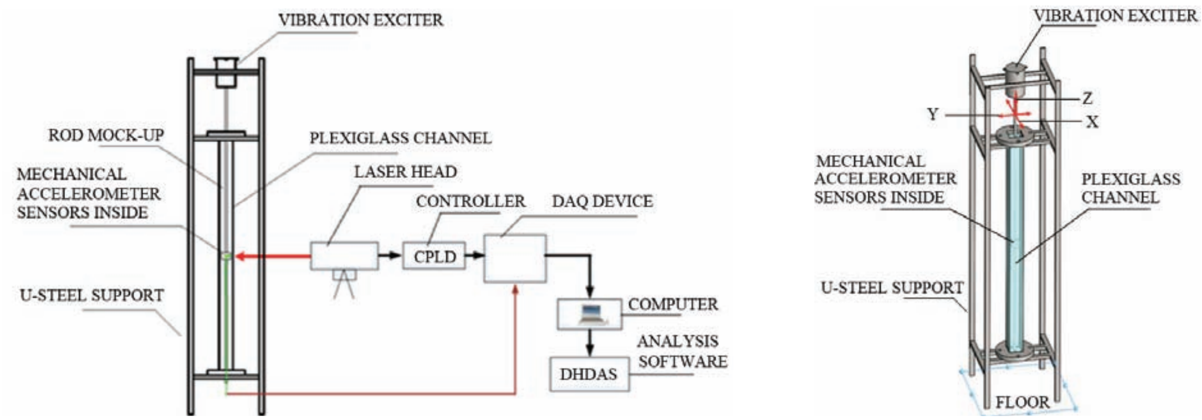
2. EXPERIMENTAL METHOD

2.1 Test facility

The test facility, as shown in Fig.1, is designed and developed to investigate the application of LDV on measuring flow induced vibration of reactor core components. A square plexiglass channel is fixed on a stainless steel support by two flanges on both sides. A dummy fuel rod made of stainless steel tube is installed inside the plexiglass channel and its bottom side is fixed on the bottom flange. A vibration generator (KDJ-2) is mounted on the stainless steel support and various standard vibrations are produced and delivered to the rod mock-up through a rigid connection at the top of the rod. A LDV system and two accelerometers are used to measure the vibration of the rod at its center simultaneously.

2.2 Test section

The details of the test section are shown in Fig.2. The dummy fuel rod includes a cubic stainless steel box in the center with inner space of 26mm*26mm*26mm and wall thickness of 2mm which used to hold an mechanical accelerometer inside. The total length of the rod is 1500mm which is fixed inside the square plexiglass channel with inner space of 50mm*50mm*1000mm.



(a) (b)

Figure 1. Schematic of the experimental facility.

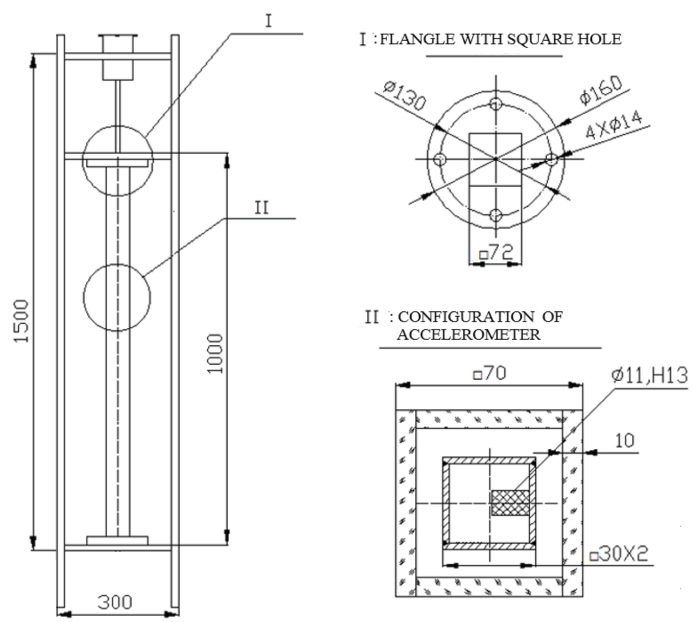


Figure 2. Detailed diagram of the test section.

2.3 Vibration measurement techniques

Two diagnostic techniques are applied to vibration measurement in this study. One is mechanical accelerometer which gives the acceleration value of vibration. It has a measuring range of 0-50 times of gravity acceleration and an error of ±5% within frequency range of 1Hz-6kHz. Its transverse sensitivity is less than 5% and the weight is 8.8g. The other is one-dimension LDV which gives the velocity value of vibration. The measuring range of the LDV is 5mm/s - 1000mm/s, the maximal frequency is 100kHz and the maximal linear error is 1%. A mechanical accelerometer is fixed on inner plane of the square box to measure the vibration of y-direction which is parallel to output direction of the vibration generator. The laser head of LDV is set up and its laser focuses on the same position where the accelerometer measures the vibration of y-direction. Data acquisition and analysis system (DHDAS) is used to get the experimental results. The vibration acceleration measured by mechanical accelerometer and the vibration velocity measured by LDV can be displayed in real time. At the same time, the corresponding frequencies are analyzed and obtained by FFT analysis method. Since the direct measured value of the two techniques are different and the corresponding values are vibration velocity and vibration acceleration. In order to calibrate them with each other intuitively, the direct measured value of vibration acceleration by the accelerometer is transformed to equivalent vibration velocity as Eq. 1.

$$v = \frac{a}{2\pi f_v} \quad (1)$$

Where v represents the vibration velocity, a represents the vibration acceleration and f_v represents the vibration frequency.

The main principle of LDV relies on Doppler Effect as shown as the Eq. 2.

$$\Delta f = \frac{2v_x}{\lambda_0} \quad (2)$$

Where, f is the frequency of the laser, v_x is the vibrating velocity of the measured object and λ is the wavelength of the laser.

When the dummy fuel rod is immersed in water, the LDV measured vibration results should be modified. As shown in Fig. 3, the LDV emits the laser beam with a velocity of c, a frequency of f and a wavelength of λ which will transmit in air and water, and reach the vibrating dummy fuel rod surface, then be reflected back into LDV. During such process, the characteristic parameters of velocity, frequency and wavelength will change from (v_0, f_0, λ_0) to (v_5, f_5, λ_5). At beginning, the laser beam goes from air into water, the frequency remains while the velocity changes based on the refraction principle,

$$f_1 = f_0 \quad (3)$$

$$v_1 = c/n \quad (4)$$

Where, n is the refractivity of water. So, the wavelength of the laser beam becomes,

$$\lambda_1 = \frac{v_1}{f_1} = \frac{c/n}{f_0} = \frac{\lambda_0}{n} \quad (5)$$

When the laser beam reaches the vibrating object in the water, the wavelength remains while the frequency changes due to the Doppler Effect,

$$\lambda_2 = \lambda_1 = \frac{\lambda_0}{n} \quad (6)$$

$$f_2 = f_1 + \Delta f_2 = f_0 + \frac{nv_x}{\lambda_0} \quad (7)$$

Where, v_x is the vibrating velocity of dummy fuel rod. When the laser beam is reflected by the vibrating surface, the Doppler Effect occurs again,

$$\lambda_3 = \lambda_2 = \frac{\lambda_0}{n} \quad (8)$$

$$f_3 = f_2 + \Delta f_3 = f_0 + \frac{2nv_x}{\lambda_0} \quad (9)$$

Then, the laser beam travels in the water and the properties keeps constant,

$$\lambda_4 = \lambda_3 = \frac{\lambda_0}{n} \quad (10)$$

$$f_4 = f_3 = f_0 + \frac{2nv_x}{\lambda_0} \quad (11)$$

After that, the laser beam goes into air and back into LDV,

$$f_5 = f_4 = f_0 + \frac{2nv_x}{\lambda_0} \quad (12)$$

$$\Delta f_5 = \frac{2nv_x}{\lambda_0} \quad (13)$$

Comparing Eq. 2 with Eq. 13, it can be concluded that the vibration velocity of the dummy rod in the water should be modified by the refractivity of the water as Eq. 14.

$$v_x = v_{x,m}/n \quad (14)$$

Where, $v_{x,m}$ is the measured vibration velocity value by the LDV.

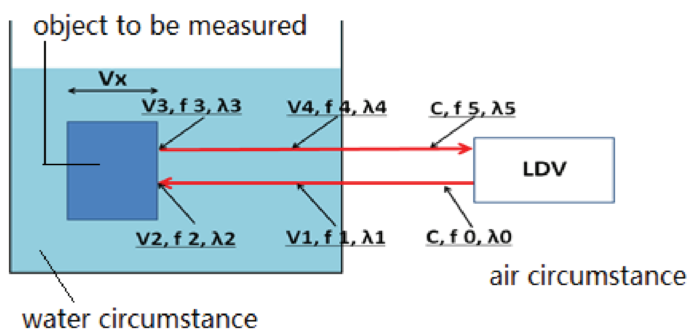


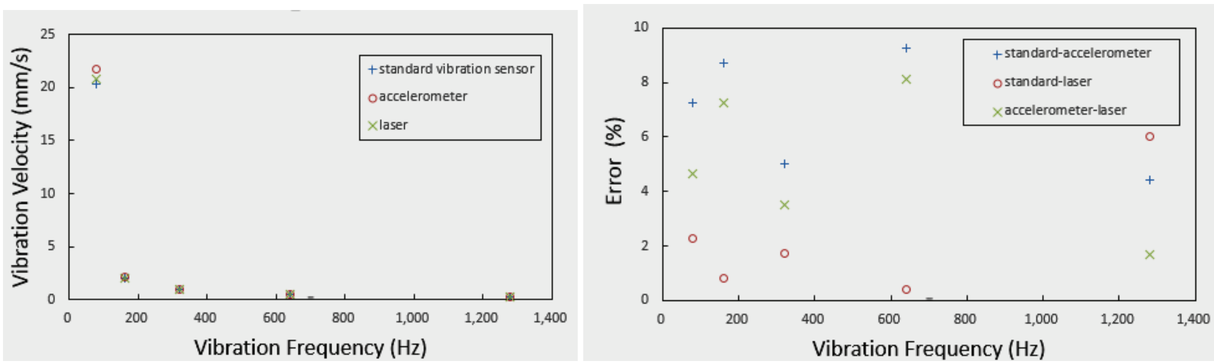
Figure 3. Laser beam transmission process of vibration measurement by LDV for a measured object immersed in water.

2.4 Test procedures

In order to investigate the feasibility of LDV on measuring FIV of reactor core components, various calibration tests are conducted between LDV and mechanical accelerometer.

Firstly, the LDV and mechanical accelerometer are calibrated by a standard vibration calibration facility of JX-3B. The calibrated results are plotted as in Fig. 4a and corresponding errors are plotted in Fig. 4b. It shows that the mean error of LDV is 2.2% and its maximal error is less than 5% while the mean error of the accelerometer is 6.9% and the maximal error is less than 10% which are comparable with the corresponding nominal accuracy of the vibration measurement technique. The calibration results further prove that the LDV has a better accuracy than the mechanical accelerometer.

Then, the simultaneous calibration tests between LDV and accelerometer have been performed to measure the vibration under various exciting frequencies (1000Hz, 2000Hz, 3000Hz) and different exciting forces which occurring in air, in a rectangular plexiglass channel with air inside and in a rectangular plexiglass channel with water inside.



(a) Vibration velocity (b) Error

Figure 4. Calibration for LDV and accelerometer by a standard vibration calibration facility of JX-3B.

3. EXPERIMENTAL RESULTS AND DISCUSSION

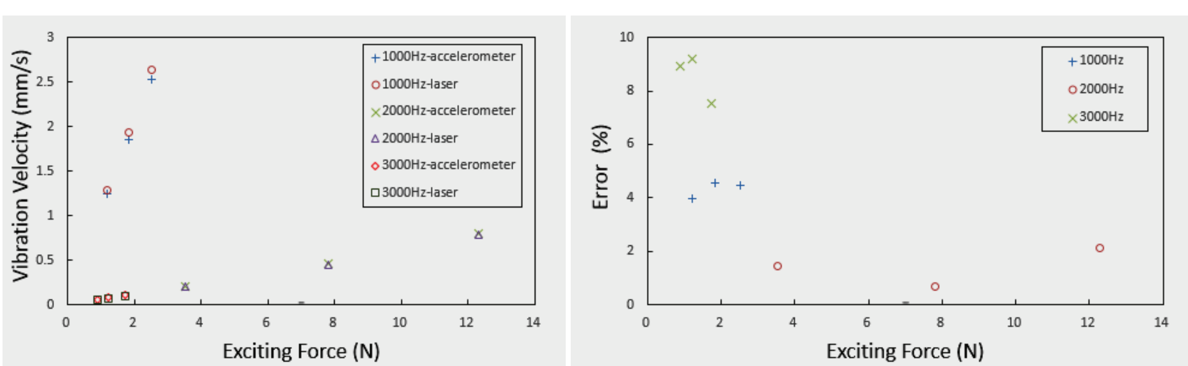
As mentioned above, in order to easily compare the measured results by both techniques, the vibration acceleration value obtained by the accelerometer is transformed to the corresponding vibration velocity value through Eq. 1. In addition, the LDV measured values are set as the standard for error analysis by Eq. 15.

$$\varepsilon = \frac{|v_1 - v_2|}{v_1} \quad (15)$$

Where v_1 represents the vibration velocity measured by the LDV and v_2 represents the equivalent vibration velocity (transformed by Eq. 1) measured by the accelerometer. The detailed testing results are as following.

3.1 Calibration tests for vibration occurring in air

Fig. 5 shows the measured vibration results when the vibration occurring in air. The vibration velocity linearly increases with the increment of exciting force for certain given exciting frequency. The simultaneously measured vibration velocities by the LDV and the accelerometer show a good consistency. The measurement errors between two vibration measurement techniques under various conditions are plotted in Fig. 5b. It shows that the error is less than 5% for the operation conditions with exciting frequency of 1000Hz and 2000Hz. When the exciting frequency increases to 3000Hz, the measurement errors become bigger while no more than 10% under various exciting forces.



(a) Vibration velocity (b) Error

Figure 5. Calibration test results for vibration occurring in air.

3.2 Calibration tests for vibration occurring in a rectangular plexiglass channel with air inside

When the measured dummy rod is vibrating in a rectangular plexiglass channel, the laser beam of LDV will pass through the plexiglass and then reach the surface of dummy fuel rod, which leads to the reflection and refraction of the laser beam at the both surfaces of plexiglass and produces extra noise as shown in Fig. 6a. Such noise could be mitigated through adjusting the laser incidence angle to be 2^o while not affect the measured vibration velocity value. The measured LDV signal based on this adjusting method is shown in Fig. 6b. Based on this adjusting method, the calibration tests are executed. Fig.7 shows the calibration test results for vibration occurring in a rectangular plexiglass channel with air inside. The vibration velocity linearly increases with the increment of exciting force for certain given exciting frequency. The simultaneously measured vibration velocities by the LDV and the accelerometer show a good consistency. The measuring differences between the two methods are less than 8% for all three exciting frequencies which are consistent with the errors of calibration tests for vibration occurring in air without the plexiglass channel. It also proves that the properly adjusting the incident light is valid to mitigate the measuring noise of LDV due to the existence of plexiglass channel.

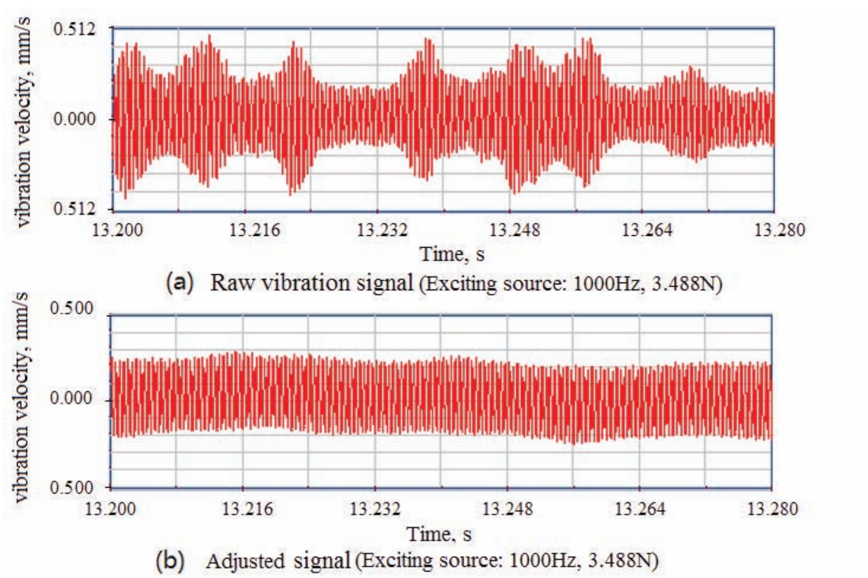


Figure 6. Diagram of vibration signal by LDV.

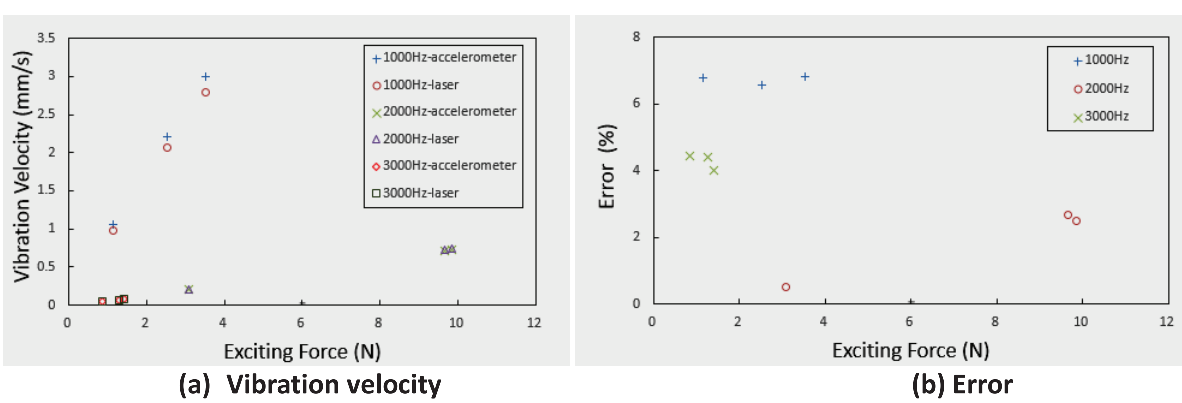


Figure 7. Calibration test results for vibration occurring in a rectangular plexiglass channel with air inside.

3.3 Calibration tests for vibration occurring in a rectangular plexiglass channel with water inside

For the vibration occurring in water, the LDV measured velocity value should be modified by Eq. 14. Fig. 8 shows the calibration results for vibration occurring in a rectangular plexiglass channel with water inside. Comparing with the vibration in air environment mentioned above, the vibration velocity in water environment under similar exciting conditions will be much smaller due to the damping of vibration in water is much bigger than in air. The vibration velocity plotted in Fig. 8a also shows a linear increase with exciting force under various exciting frequencies. The maximal measuring differences between the two methods are up to 18% as shown in Fig. 8b. The reason is that much lower vibration velocity could be obtained in water environment comparing with that in air environment and its value is close to minimal resolution of mechanical accelerometer due to limited output power of vibration generator.

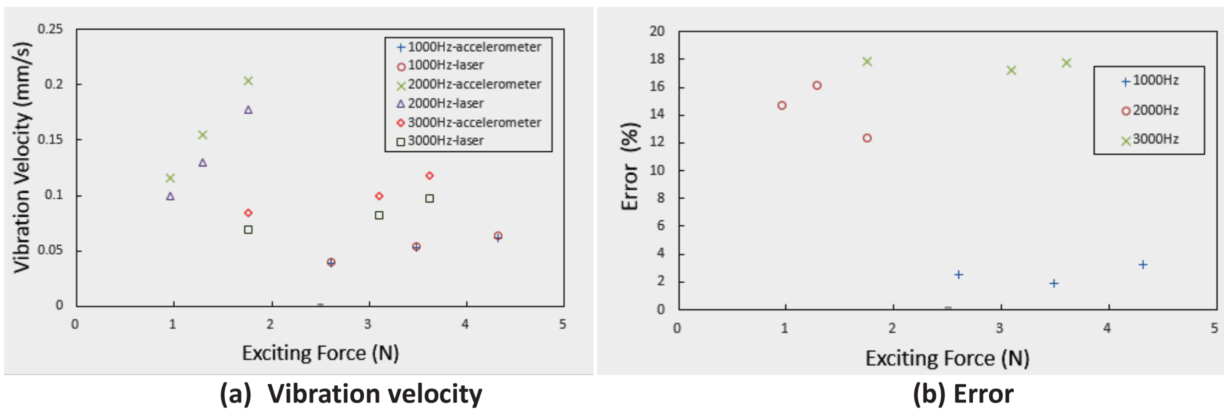


Figure 8. Calibration test results for vibration occurring in a rectangular plexiglass channel with water inside.

4. CONCLUSIONS

Motivated by developing a vibration diagnostic technique available for investigation on FIV of reactor core components, a LDV and a mechanical accelerometer are chosen to perform calibration tests for a dummy fuel rod vibration occurring under various conditions (air environment, rectangular plexiglass channel with air inside and rectangular plexiglass channel with water inside). According to experimental results, some experiences and conclusions can be drawn as following:

1) The calibration tests based on a standard vibration calibration facility (JX-3B) show that the LDV has a higher measurement accuracy (5%) than the mechanical accelerometer (10%).
2) The vibration amplitude value linearly increases with the increasing of exciting force and the water medium damps the vibration much greater than the air medium.
3) The LDV is sensitive to measurement conditions. For the case of vibration in a rectangular plexiglass channel with air inside, the 2^{o} laser incidence angle helps to mitigate the noise of measurement signal while not affect the measured vibration velocity value. For the case of vibration in a rectangular plexiglass channel with water inside, a modification for the measured vibration velocity value is necessary by dividing refractivity of water.
4) The calibration tests between the LDV and mechanical accelerometer show a good agreement with each other. The differences between them are mainly affected by the vibration amplitude and minimal resolution of the mechanical accelerometer.

As a result, it is believed that the LDV has a good reliability for the measurement of vibration under various complex conditions of the vibrations occurring in air, in a rectangular plexiglass channel with air inside and in a rectangular plexiglass channel with water inside. This study make a good preparation for the application of LDV in FIV research on reactor core components.

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