Effects of helical strakes on the vortex-induced vibration over a thermowell in a pipe flow

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Abstract A thermowell is a device to protect a thermometer used for measuring temperature in many industrial application. The thermowell is exposed to vortex-induced vibration when the flow speed in a pipe is large so that shedding frequency due to Karman vortex streets downstream of the thermowell corresponds with its natural frequency. The vortex-induced vibration can cause fracture of the thermowell structure by cyclic loading. This phenomenon has long been a research topic in the field of marine engineering. Now, it can be a concern in metrology area.

The present study investigates the suppressing effect of the vortex-induced vibrations of the thermowell by means of helical strakes. Flow visualizations can show that the helical strakes can suppress the vortex-induced vibration by generating three-dimensional shedding vortices with short spanwise length. The three-dimensional shedding vortices does not give resonance to the thermowell effectively because the vortices generate asynchronous forces along the thermowell. In this study, flow visualizations of the thermowell vibrations and resonant frequency measurements were attempted to investigate the suppressing effect of the helical strakes for safely using the thermowell in operating conditions with high flow speeds.
Keywords: helical strakes, thermowell, vortex-induced vibration

1 Introduction

A thermowell is a device to protect a thermometer for measuring temperature of an internal flow in a pipeline [1]. The thermowell is used in many industrial applications, such as in a nuclear power plant, in a gas turbine, or in a space rocket. Although the thermowell is a protective device, it is prone to be broken under harsh environment with high temperature, high pressure and high flow speed. Thermowell breakage can lead to severe damage to the whole engineering system. One example would be the accident happened in a nuclear power plant located in Monju, Japan. In this accident, liquid sodium leaked out of a pipeline because a broken part of a thermowell hit some important part of the nuclear reactor. The cause of the thermowell breakage was due to cyclic loading on the thermowell which was forced by vortex shedding downstream of the thermowell.

The vortex-induced vibration can be observed if the shedding frequency of an object agrees with the natural frequency of the object [2]. Karman vortex streets are generated downstream of a thermowell. Vortex shedding is a part of the Karman vortex streets and its period is regular such that shedding frequency can be defined by means of Strouhal number [2]. Because the Karman vortex streets generates lateral forces on the thermowell, the thermowell vibrates with the same frequency as the shedding frequency. If the shedding frequency is correspondent with the natural frequency of the thermowell, the amplitude of thermowell vibration increases indefinitely, which leads to thermowell breakage.

Helical strakes can protect the thermowell from the vortex-induced vibration by disorganizing the vortical structures of shedding vortices [3-9]. The helical strakes can be attached around the thermowell with a regular distance. Because the helical strakes are protruded from the thermowell surface, the spanwise length of shedding vortices can be defined. This means that a two-dimensional vortical structure can be disrupted into three-dimensional and irregular vortical structures. Then, the thermowell with helical strakes can vibrate at the shedding frequency with less excitation force than that without helical strakes does.

Most studies on the helical strakes focused on the suppressing effect of vortical structures downstream of a circular cylinder in wind tunnels [3-9]. Main application area was marine engineering because stable mooring of a mechanical structure was an important issue in offshore platforms. The present study aims at another application area such as metrology or plant engineering because safety issue due to the vortex-induced vibration can be main concern in this area.

The present study investigates the suppressing effect of helical strakes on the thermowell vibration when the thermowell is installed in a pipe flow. As an initial phase of research, only two kinds of thermowells, i.e., the thermowell with and without helical strakes, are investigated when the shedding frequency agrees with the natural frequency of the thermowells. A 3-axis accelerometer and a hydrophone are used to find the suppressing effect of the helical structures by measuring the frequency response due to the shedding vortices downstream of the two thermowells. A high-speed camera is also used to capture images of fluid-structure interactions by the shedding vortices. With the above methods, the suppressing effect of the helical strakes on the thermowells is explained.

2 Experimental Method

Two thermowells with and without helical strakes were manufactured as shown in Fig. 1. The thermowells were designed according to ASME PTC 19.3 [1]. However, the helical strakes were not be manufactured based on other standards. It was because there was no such design rules for standardizing the helical strakes. Instead, the helical strakes were designed referring to the literature [3-9]. The helical strakes were made of stainless steel wire with diameter of 2 mm (Hisco, South Korea). Three helical strakes were stranded around the thermowell with an inclination angle of 58° and a pitch interval of 5 mm. The length of the stranded region was 100 mm, within which area the thermowell was protruded into the pipe. On the contrary, the diameter of the thermowell was 15 mm and its length was 350 mm.

The natural frequency of the thermowell without helical strakes was designed to be 124.3 Hz. In this design, the surrounding fluid was assumed to be air because the natural frequency of the thermowell was measured in a laboratory for vibration testing. The frequency response curve of the thermowell was obtained by the vibration testing. The natural frequency of the thermowell without helical strakes was 127 Hz and that with helical strakes was 125 Hz. In case that surrounding fluid was assumed to be water, the natural frequency was changed to be 116.5 Hz. Finally, the thermowell was designed to be operating with flow speeds less than 8 m/s, satisfying the safety condition of $r < 0.4$ as stated in the ASME PTC 19.3 [1].

For hydrodynamic testing, two thermowells with and without helical strakes were installed in a T-shaped pipe as shown in Fig. 2. The thermowells were installed in a row to visualize the fluid-structure interaction due to shedding vortices. This flow configuration was used only for visualization purposes with a 12-bit high speed camera (pco.dimax hs4, PCO, Germany). The frame rate of the visualized images was 2,000 frames/s and exposure time for each image was 0.4 ms. After that, one of the thermowells was removed from the downstream tee and a hydrophone (8100, B&K, Denmark) was installed as shown in Fig. 3. The purpose of the hydrophone was to measure the shedding frequency of the shedding vortices downstream of the thermowell. However, in this study the shedding frequency was not measured very well. It was because there were other noise sources except the shedding vortices, such as the noise from flow control valves downstream of the thermowells.

A 3-axis accelerometer (4524B, B&K, Denmark) was also installed on top of the thermowell to measure resonant frequency of the thermowells due to the vortex-induced vibration. Directions along the thermowell axis (x), perpendicular to the main flow (y), and along the main flow (z) were discerned. In this study, the acceleration signal perpendicular to the main flow was only considered as the signals for thermowell vibration because it was expected that the shedding vortices excited the thermowell in the direction perpendicular to the flow direction. Thus, the peak frequency and its amplitude of the acceleration signals (y) were considered as the resonant frequency and its amplitude of the thermowells.

An in-house program (LabVIEW 2014, NI, U.S.A.) was coded to measure the hydrophone and the accelerometer signals. The sampling rate of the signals was 4,096 Hz and the sampling duration was 40 s. Thus, the data size of each signal was 4,096 Hz × 40 s = 163,840 samples.

The Strouhal number was defined as follows.

$$St = \frac{fd}{U} \tag{1}$$

Here, f is the shedding frequency [Hz], d is the thermowell diameter [mm], and U is the mean flow speed [m/s]. St could be defined as 0.2 with a wide range of Reynolds numbers [2]. When d was 15 mm and the resonant frequency was 116.5 Hz, U was calculated to be 8.74 m/s. Thus, it was expected that the thermowell vibrations would occur above the flow rate Q of 556 m^3/h with diameter of 150 mm.

3 Experimental Results

Some of visualizations on the thermowell vibrations are shown in Fig. 4. Unfortunately, the displacement due to the thermowell vibrations was too small to be discerned as still cuts. However, move clips, which were consecutive images of the still cuts, showed that there was noticeable vibrations on the thermowell without helical strakes. On the other hand, the thermowell with helical strakes showed vibrations due to shedding vortices with less amplitude than the case without helical strakes. The amplitude of the thermowell vibrations was stronger at 660 m^3/h than 550 m^3/h.

At the onset of the flow rate change with more than 800 m^3/h, air bubbles were formed downstream of the thermowells because dynamic pressure at the location of thermowells was lowered than vapor pressure of water. The vortical structures due to the thermowell with helical strakes showed shorter spanwise length than the vortical structures due to the thermowell without helical strakes. The shedding vortices seemed to be tripped by the helical strakes. As a result of this, the vortical structures became stronger and three-dimensional. Otherwise, the vortical structures seemed to be coherent along the spanwise direction of the thermowell. Since the helical strakes were stranded with short pitch interval, the size of the three-dimensional vortical structures was confined within the interval by the helical strakes.

The resonant frequency and its amplitude of the thermowell vibrations are displayed as a function of flow rate in Fig. 5. The thermowell without helical strakes showed significant increase of the peak amplitude as flow rate was increased to 700 m^3/h. Then, the peak amplitude was decreased when the flow rate was increased between 700 m^3/h and 800 m^3/h. On the other hand, the thermowell with helical strakes did not show any significant increase of the peak amplitude in the flow region between 450 m^3/h and 800 m^3/h. The peak frequencies was located between 109 Hz and 122 Hz. This means that the peak frequency corresponded with the natural frequency of the thermowells when the surrounding fluid was water. Note that the measuring quantity was different from the quantities used in the previous studies, i.e., the shedding frequency. The peak frequency was belonged to the resonant frequency because the spectrum was obtained from the accelerometer signals.

4 Conclusions

The suppression of the vortex-induced vibrations of a thermowell was investigated by applying the helical strakes around the thermowell. Two kinds of thermowells with or without helical strakes were prepared. The helical strakes were manufactured according to the previous studies and they were stranded on the thermowell at a regular interval to trip flow separation at the regular interval. With a flow visualization in a water pipe flow, it was found that the shedding vortices downstream of the thermowell with helical strakes were three dimensional with short spanwise length along the thermowell. In contrast, the thermowell without helical strakes generated shedding vortices with longer spanwise length, which made vortex-induced vibrations to the thermowell above 550 m^3/h in this study.

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Fig. 1 Thermowell with/without helical strakes

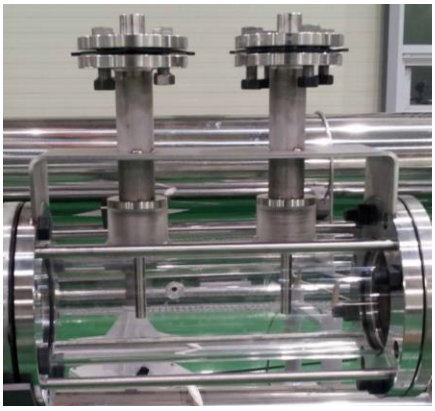

Fig. 2 Experimental setup for visualizing the vortex-induced vibration

Fig. 3 Experimental setup for resonant frequency measurement

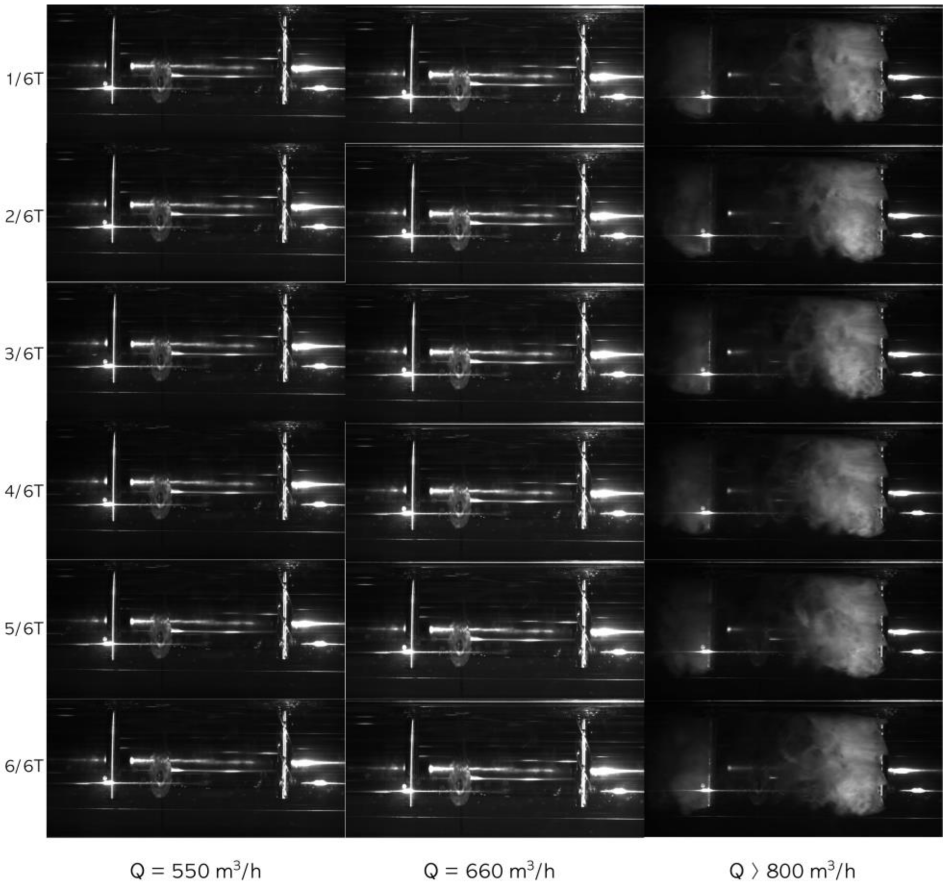

Fig. 4 Flow visualization of two thermowells

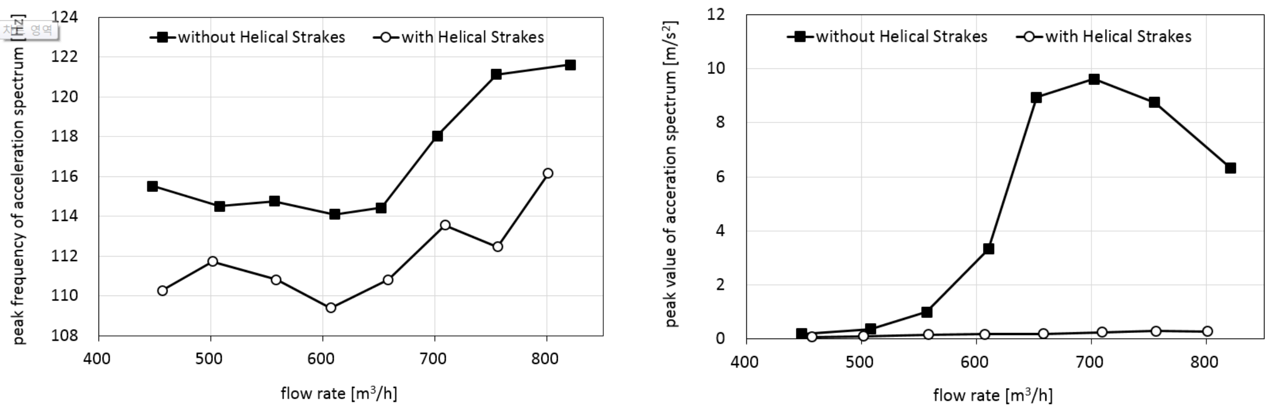

Fig. 5 Experimental results of resonant frequency measurement