Experimental Design Procedure for Tubes in Turbulent Cross Flow

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1. Introduction

Where turbulent flow encounters the surface of a structure, some of the momentum in the flow is converted into fluctuating pressures. Random surface pressure fluctuations are produced by the turbulent velocity component. Although turbulence-induced random vibration of a tube bundle, frequently referred to as subcritical vibration, is usually of much smaller amplitude than that experienced in fluid-elastic instability, it is of great practical importance because it always exists whenever there is flow over a tube bundle. They can produce a long-term progressive damage at the supports through fretting wear or fatigue.

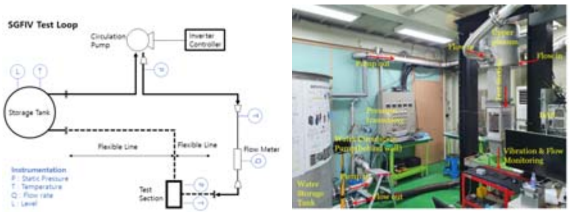
Experimental design procedure for tubes in turbulent cross flow is developed and proved.

2. Methods and Results

An experimental setup and formulas to obtain parameters of random turbulent excitation (RTE) are described. The RTE parameters include correlation length, joint acceptance factor, power spectral density function and a random excitation coefficient.

2.1 Test Loop

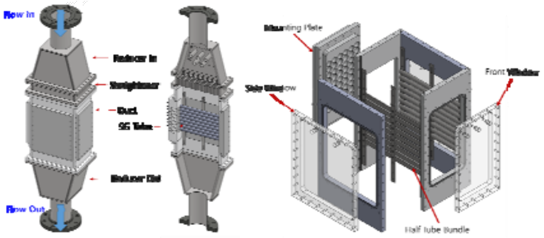
The test facility was constructed to investigate the Fluid-Induced Vibration (FIV) characteristics of the tube bundle for the steam generator. For the test, a small-scale water circulation loop was built. As a working fluid, single-phase pure water was used. The test loop for the tube bundle consists of the main circulation pump, water storage tank, flow meter, and test section as shown in Fig. 1. The main circulation pump of 34 kW can circulate water at the maximum flow rate of 180 m^3/hr. The maximum rotation speed of the pump having five blades is 3600 rpm. An inverter can control the flow rate into test section.



(a) Schematic Diagram (b) Facility in Laboratory
Fig. 1 Test Loop of RTE test for tube bundle

2.2 Test Section

The test section for the RTE test is shown in Fig. 2 (a). The section consists of four parts. One was a downward plenum chamber to make the entrance flow uniform, of which the upper part was connected to the 5-inch pipe of the main loop. Another was a straightener in front of the main test section (duct) to stabilize the flow. A third was a duct, with visualization transparent window, where instrumentation and dummy tubes were installed. A fourth was an outlet reducer in the downstream lower part, connected to the main loop again. Fig. 2 (b) show design configuration of the test section and the detailed view of the mounting plate. For RTE test, the duct has a rectangular shape with four flat plates. Both sides and front side are made of transparent acrylic to allow visual observation. One mounting plate where the instrument and dummy tubes are installed was made of thick stainless steel to add more integrity that is mechanical. The basic arrangement of the tube bundles required by the test is determined by the holes of the mounting plate. The basic array of tube bundle is a 6x9 array, and the half-cut rods were mounted on both sides with semicircular cross section.



(a) Test Section (b) Bundle Mounting
Fig. 2 Test Section of RTE test for tube bundle

2.3 Instrumentation Tube and DAS

The instrumentation tube for RTE test consists of a tube specimen (to meet the cross flow), annular slender root, and tube cap as shown in Fig. 3. Measured pressure fluctuation responses was recorded at the data acquisition system All measured response signals from sensors were coupled with signal conditioning amplifier, digital-converted and recorded into data acquisition system (NI PXIe 4496, and PCB 441B104 Amp.) with signal processing and analysis software (m+p Analyzer version 5.3). Optional filter during signal processing would be applied to cut off the high and low frequency components out of interested frequency range. Minimum sampling rate for vibration response should be over 1k sample/second.

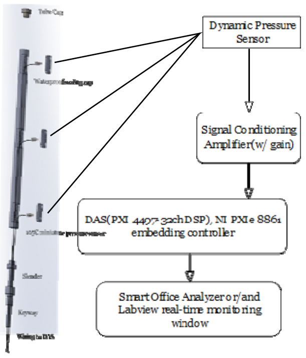


Fig. 3 Instrumentation Tube and DAS

2.4 Correlation Length and Joint Acceptance Factor

The correlation length can be obtained from a pair of dynamic pressure measurement. The three dynamic pressure sensors in an instrumentation obtain two pairs of coherence. The tests were conducted with variation of gap flow velocity, which is flow velocity lower than that at fluid elastic instability for tube array. From the measured coherence defined as eq. (1), correlation length, l_c, was calculated according to eq. (2) with sensor distance in the instrumentation tube [1].

$$\Gamma(x_1,x_2,\omega) = \frac{S_{pt}(x_1,x_2,\omega)}{S_{pt}(\omega)} \qquad (1)$$

$$\Gamma(x_1,x_2,\omega) = e^{-2|x_1-x_2|/l_c} \qquad (2)$$

Joint acceptance factor was obtained from eq. (3) with the mode shape.

$$J_{jj}^2 = \frac{1}{l}\int_0^l\int_0^l \phi_j(x_1)\;\Gamma(x_1,x_2,\omega)\;\phi_j(x_2)\;dx_1\,dx_2 \qquad (3)$$

2.5 Random Excitation Coefficient

The power spectral density S(f) of the random turbulence excitation deduced from response of a clamped-free beam as follows [2]:

$$S(f) = \overline{y^2}(x)\frac{64\pi^3 f_1{}^3\xi}{\phi_1(x)\phi_1(x)} / \int_0^l\int_0^l \phi_1(x)\phi_1(x')dx\,dx' \qquad (4)$$

Where

$$\phi_n = B_n\{A_n(Cos\beta x - Cosh\beta x) + (Sin\beta x - Sinh\beta x)\} \qquad (5)$$

$$A_n = (Cos\beta_n l + Cosh\beta_n l)/(Sin\beta_n l - Sinh\beta_n l) \qquad (6)$$

$$\beta_n = \sqrt[4]{\frac{m\omega_n^2}{EI}} \qquad (7)$$

$$B_n = \frac{1.4669445}{\sqrt{m}} \qquad (8)$$

$\overline{y^2}(x)$ is response measured with the strain-gauged instrumentation tube in the random turbulence excitation flow that is in the range of lower flow velocity than the start velocity of vortex shedding. The resultant vibration amplitude is the root mean square of the vibration amplitude components in both the flow (drag) direction the normal (lift) to it. When the tubes were exposed to RTE flow field, the vibration response and the spectral density of the random forces are roughly related to the square of flow velocity that is defined as eq. (9). Random excitation coefficients, C_R, was deduced from the strain measurement of instrumentation tube with variation of the flow rate in random turbulence region in vortex shedding test.

$$[S_{Ft}(\omega)]^{1/2} = C_R\;\rho V_r^2 d/2 \qquad (9)$$

Where C_R is called the random turbulence excitation coefficient, ρ is the fluid density, V_r is the gap velocity, and d is the rod diameter [1].

3. Conclusions

Experimental design procedure for tubes in turbulent cross flow is developed. The RTE parameters were obtained from formulas and experimental data. The parameter was proved by comparing of previous data.

REFERENCES

[1] Appendices N-1300, ASME Section III Division I, Flow-induced vibration of tubes and tube banks, 2007.

[2] M.J. Pettigrew and D.J. Gorman Vibration of Heat Exchange Components in Liquid and Two=phase Cross-flow, AECL-6184, 1978