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## INVESTIGATION OF CRITICAL FLOW VELOCITY OF A TRIANGULAR U-TUBE BUNDLE SUBJECTED TO TWO-PHASE FLOW

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### ABSTRACT

Fluid elastic instability is one of the most severe vibration phenomena in tube bundles exposed to flow. Recently, the occurrence of in-plane (stream-wise) fluid elastic instability was indicated by observation of tube-to-tube wears in steam generators. Then, many experimental investigations have been conducted with straight tube bundle flow tests. However, the evaluation guideline of the in-plane fluid elastic instability for U-bend tube bundle with triangle arrays has not been established yet.

In this paper, the critical flow velocity of fluid elastic instability was investigated based on two types of test rig for triangle arrays in two-phase flow (SF<sub>6</sub>-ethanol) which simulates steam-water flow in high temperature and high pressure condition. One test rig consists of 156 rows and 6 columns of straight tube bundles. The influences of the number of flexible tubes, void fraction and vibration directions on fluid elastic instability were investigated. The other test rig consists of 126 rows and 6 column of U-bend tube bundle with 5 anti-vibration bars. Six flow inlets can produce various flow velocity distributions in the U-bend tube bundle. The influences of flow velocity and void fraction distributions on fluid elastic instability were investigated.

### NOMENCLATURE

$\alpha$	Void fraction
$\beta$	Gas volumetric flow ratio
$f_n$	Natural frequency of tube (Hz)
$D$	Tube diameter 9.53 mm
$P$	Tube pitch 12.7 mm
$m(s)$	Tube mass (structural + fluid added) per length (kg/m)
$m_0$	Average of $m$ (kg)
$\delta$	Logarithmic decrement ( $= 2\pi\zeta$ )
$\zeta$	Damping ratio of tube immersed in the fluid
$\zeta_{ip}$	Damping ratio of two-phase flow ( $= \zeta - \zeta_{st}$ )
$\zeta_{st}$	Structural damping ratio of tube
$\rho(s)$	Mixture density ( $= \alpha\rho_g + (1-\alpha)\rho_l$ or $\beta\rho_g + (1-\beta)\rho_l$ ) (kg/m <sup>3</sup> )
$\rho_0$	Average of $\rho(s)$ (kg/m <sup>3</sup> )
$\rho_g$	Gas density (kg/m <sup>3</sup> )
$\rho_l$	Liquid density (kg/m <sup>3</sup> )
$j_{gp}$	Superficial gas pitch velocity (m/s)
$j_{lp}$	Superficial liquid pitch velocity (m/s)
$V_i$	Interfacial velocity (m/s)
$V_r$	Reduced velocity ( $= U/fD$ )
$s$	Axial position of the tube

# 1 INTRODUCTION

Fluid elastic instability (FEI) is one of the most significant vibration phenomena in tube bundles. Recently, the occurrence of in-plane (stream-wise) fluid elastic instability was indicated by observation of tube-to-tube wears in steam generators. However, the evaluation guideline of the in-plane fluid elastic instability for U-bend tube bundle has not been established yet. In the Japan Society of Mechanical Engineers (JSME), an evaluation guideline of out-of-plane FEI for U-bend tube bundle of square arrays was established [1]. The evaluation method for stability ratio of FEI proposed by Connors was used [2]. This method needs the Connors' constant K. In the JSME guideline, the Connors' constant K was based on the flow tests. Therefore, for the establishment of the evaluation guideline of FEI for triangle array, Connors' constant K of out-of-plane and in-plane FEI are necessary. Many experimental investigations for FEI with triangle array have been conducted. However in the most of flow test, flow conditions were air or water single phase or air-water two-phase. Moreover short straight tube bundles were used. In this paper, flow tests U-bend tube bundles of triangular array in two-phase flow (SF<sub>6</sub>-ethanol) which simulates steam-water two-phase flow was conducted. Furthermore, flow tests with straight tube bundles were performed to investigate the effect of the natural frequency of tube and number of flexible tube on Connors' constant K.

## 2 EXPERIMENTAL APPARATUS

### 2.1 Simulant Fluids

Fluids in prototype steam generators are steam and water at high pressure and high temperature. However, it needs an extensive pressure retaining vessel and heat input to simulate such conditions. Instead of steam and water, SF<sub>6</sub> (gas) and ethanol (liquid) were used as working fluids in order that fluids density and surface tension, important fluid parameters, are almost the same to steam-water under low pressure condition such as approximately 0.7 MPa. Comparisons of physical properties between steam-water and SF<sub>6</sub>-ethanol are shown in Table 2.1.

TABLE 2.1: Properties of Simulant Fluid

Properties	Unit	Prototype plant	Simulant fluid
Fluid	-	Steam-water	SF <sub>6</sub> -ethanol
Pressure	MPa	7.6	0.68
Temperature	deg.C	291	30
Liquid Density	kg/m <sup>3</sup>	730	783
Gas Density	kg/m <sup>3</sup>	40	43
Density Ratio	-	18	18
Surface Tension	mN/m	16	22

### 2.2 Straight Tube Bundle Test Rig

The test rig consists of 156 rows and 6 columns of straight tube bundles as shown in Fig.2.1. For two-phase fluid flow, a mixture of SF<sub>6</sub> and ethanol is used. The pitch and diameter of tube are 12.7mm and 9.53mm (P/D=1.33), respectively. The tube is made of a stainless steel. This test rig contains three sets of flexible tube bundles which are interchangeable. Other tubes are mounted rigidly. There were three types of flexible tubes.

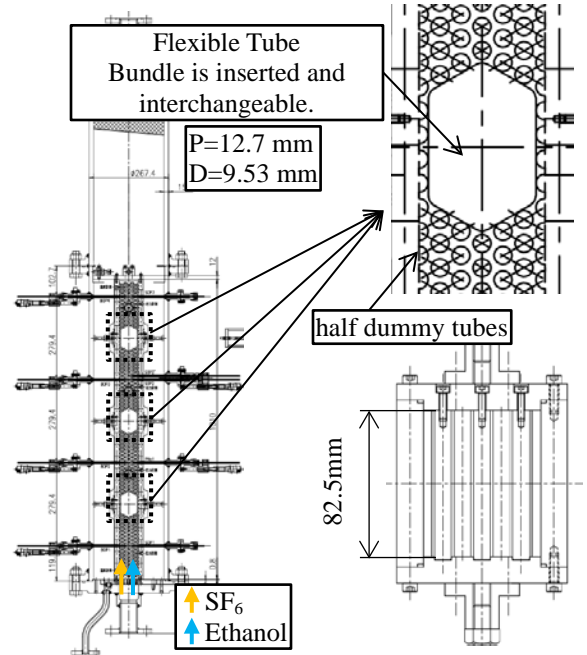


FIGURE 2.1: Straight Tube Bundle Test Section

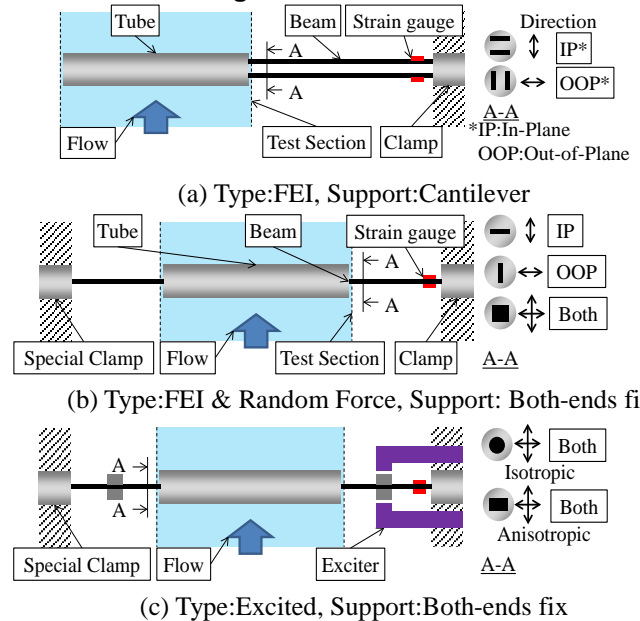


FIGURE 2.2: Flexible Tube Assembly

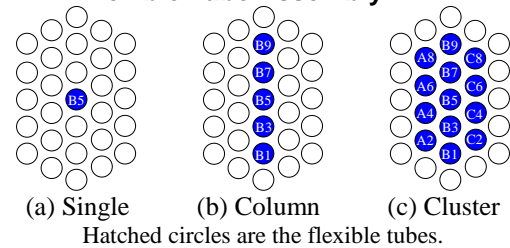


FIGURE 2.3: Pattern of Flexible Tube

The first one was prepared to measure vibration in order to measure a critical velocity (FEI tube). The second one was for the random exciting fluid force measurements (Random force

tube). The third one equipped electromagnetic exciter to measure the two-phase fluid damping (Excited tube). FEI tube was supported by two support types of thin beams. One was cantilever type; the other was both ends fixed as shown in Fig.2.2 (a,b). In order to investigate the influence of flexible tube number to critical velocity, FEI tube had 3 patterns of flexible tubes as shown in Fig.2.3. Random force tube was supported by a prismatic beam as shown in Fig.2.2 (b). Excited tube was fixed at the both ends and had electromagnetic exciter at the one side as shown in Fig.2.2 (c). In order to obtain two-phase damping of various natural frequencies, isotropic and anisotropic beams were used. For vibration measurement, strain gauges were mounted on the beam near the clamped end. All types of measurement tubes are summarized in Table 2.2.

**TABLE 2.2: Flexible Tube Type**

Name	Type (Fig.2.2)	Support (Fig.2.2)	Direction <sup>*2</sup> (Fig.2.2)	Pattern (Fig.2.3)	Freq. [Hz]
IP-30-13 <sup>*1</sup>	FEI	Both-ends fix	IP	Cluster	30
IP-70-13 <sup>*1</sup>	FEI	Cantilever	IP	Cluster	70
IP-150-5 <sup>*1</sup>	FEI	Both-ends fix	IP	Cluster	150
IP-150-13 <sup>*1</sup>	FEI	Both-ends fix	IP	Column	150
OOP-70-13 <sup>*1</sup>	FEI	Cantilever	OOP	Cluster	70
OOP-150-1 <sup>*1</sup>	FEI	Both-ends fix	OOP	Single	150
OOP-150-13 <sup>*1</sup>	FEI	Both-ends fix	OOP	Cluster	150
RF	Random Force	Both-ends fix	Both	Single	900
Ex-70-1	Excited	Both-ends fix	Both	Single	70
Ex-30/150-1	Excited	Both-ends fix	Both	Single	30/150 <sup>*3</sup>
Ex-150-1	Excited	Both-ends fix	Both	Single	150/300 <sup>*3</sup>

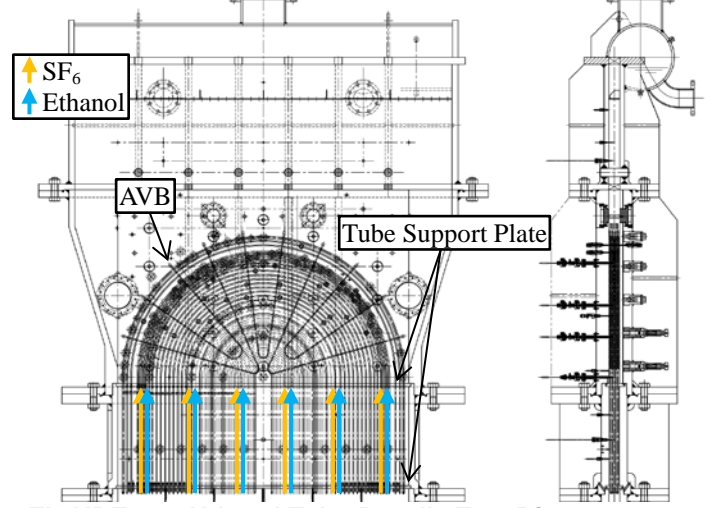
\*1 Direction – Natural Frequency – Number of tubes  
 \*2 direction for measurement  
 \*3 the former is for In-plane, the latter is for Out-of-plane

**2.3 U-bend Tube Bundle Test Rig**

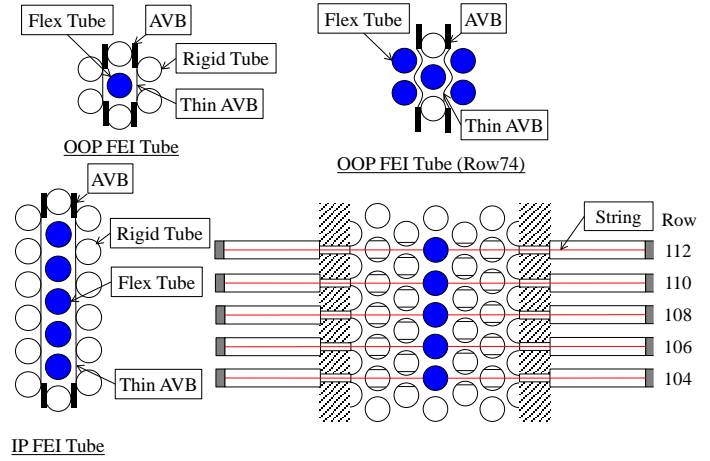
Test rig consisted of 126 rows and 6 columns of U-bend tube bundle. Gas and liquid were injected from 6 inlets which were able to produce various flow distributions as shown in Fig.2.4. The working fluids, the pitch and diameter of tube were the same as straight tube bundle test. In this tube bundle, some anti vibration bars (AVBs) are inserted. Tubes were supported by AVBs at 6 to 10 points except for flexible tubes. 9 sets of flexible tubes in the out-of-plane direction were installed from 66 to 122 rows in the center column of the tube bundle. There is a single flexible tube except Row74 as shown in Fig.2.5. The tube of Row74 is located in the center of 5 flexible cluster tubes. 5 tubes, flexible in the in-plane direction, were also installed from 104 to 112 rows. The flexible tubes in the out-of-plane direction were supported by AVBs and the tube support plate. Some support points by AVBs had large gap so that FEI could occur. Similarly, the tubes for in-plane FEI measurement were not supported by AVBs. At the unsupported point, AVBs were cut and welded with thin plates (0.2mm). Consequently, the nominal gaps between FEI tube and AVB were 1.3mm in each side. The FEI tubes for in-plane had supports in out-of-plane direction by strings to prevent the out-of-plane FEI before in-plane FEI occurs to avoid producing friction damping which

is difficult to be measured. The representative support condition is shown in Fig.2.6.

An accelerometer for vibration measurements was mounted inside of each flexible tube at the center of support span.



**FIGURE 2.4: U-bend Tube Bundle Test Rig**



**FIGURE 2.5: Flexible Tube Assembly**

Row	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Direction
66	F	F	F	F	P	P	P	P	P	P	OOP
70	P	P	F	F	F	F	F	F	F	F	OOP
74	F	F	F	F	F	F	F	F	F	F	OOP
78	P	P	P	P	P	P	F	F	F	F	OOP
82	P	P	F	F	F	F	F	F	F	P	OOP
86	F	F	F	F	F	P	P	P	P	P	OOP
90	P	P	P	P	P	F	F	F	F	F	OOP
94	P	F	F	F	F	F	F	F	F	P	OOP
104											
106											
108	F	F	F	F	F	F	F	F	F	F	IP
110											
112											
118	F	F	F	P	P	P	P	P	P	P	OOP
122	P	P	F	F	F	F	F	F	P	P	OOP

(× & P) : Supported, (○ & F) : Unsupported

**FIGURE 2.6: Support Condition**

**3 TEST PROCEDURES**

**3.1 Straight Tube Bundle**

At first, damping ratio and natural frequency in air atmospheric condition were obtained by tapping test. In the flow test, the flow velocity was incremented in a stepwise manner keeping constant void fraction or gas volumetric flow ratio. The pitch velocity  $U_p$  is related to the upstream flow

velocity  $U$  as defined in the following equation. It is assumed that the flow velocity is uniform over tube axial direction.

$$U_p = \frac{P}{P-D} U \quad (3.1)$$

In the test, superficial gas and liquid pitch velocity  $j_{gp}+j_{lp}$  was used as  $U_p$ . In each flow velocity condition, root mean square (RMS) of vibration strain response, peak frequency and damping ratio at peak frequency were obtained. As flow velocity increases, vibration amplitude increases and damping ratio decreases rapidly at certain flow velocity. This flow velocity is judged as a critical flow velocity. For Excited tube, sin sweep excitation was carried out on each flow velocity conditions. A damping ratio was evaluated from the transfer function between the excitation input and the vibration response, and then two-phase damping ratio was estimated by subtracting the structural damping ratio by the tapping test in the air from damping ratio by excitation in the flow. Connors' constant  $K$  is defined as shown in the equation below.

$$\frac{U_c}{f_n D} = K \sqrt{\frac{m_0 \delta}{\rho_0 D^2}} \quad (3.2)$$

### 3.2 U-bend Tube Bundle

At first, damping ratio and natural frequency were obtained by a tapping test. In the flow test, various flow velocity and void fraction distributions were produced by controlling the gas and the liquid flow rates from the 6 inlets. The flow velocity was incremented in a stepwise manner with keeping constant gas volumetric flow ratio  $\beta$ . The judgement method of FEI and evaluation method of Connors' constant  $K$  were the same as the straight tube bundle test. However, the distribution of flow velocity and void fraction should be taken into account for  $U_c$ ,  $\delta$ ,  $m_0$  and  $\rho_0$  in the equation (3.2). The effective velocity  $U_e$  at the critical velocity condition was identical to  $U_c$ . For in-plane FEI, mode shape includes both of the axial and the normal directions to the tube axis as follows [2].

$$U_e^2 = \frac{\int_0^L \frac{\rho(s)}{\rho_0} U^2(s) \phi_n^2(s) ds}{\int_0^L \frac{m(s)}{m_0} \tilde{\phi}_n^2(s) ds} \quad (3.3)$$

In order to obtain the flow velocity distribution in two-phase flow, a Bi-optical probe (BOP) is used. Therefore, the interfacial velocity  $V_i$  was measured, then superficial gas and liquid pitch velocity  $j_{gp}+j_{lp}$  was transferred from  $V_i$  using calibration result in the straight tube bundle test. The interfacial velocity was measured by time delay between void signals at each probe of BOP. The mass per length  $m$  and the density  $\rho$  were derived from void fraction measurements by BOP. BOPs were installed at specific 3 rows and were located constantly in the circumferential direction. The void fraction and the interfacial velocity at unmeasured location were estimated by interpolating the measurement results. The two-phase damping ratio is also related to void fraction. Assuming that the tube mass is uniform and the two-phase damping ratio is treated as a modal damping ratio, dissipated energy evaluation method for

single degree of freedom is extended for continuum. The damping ratio was obtained by taking vibration mode into account as shown in the following equation.

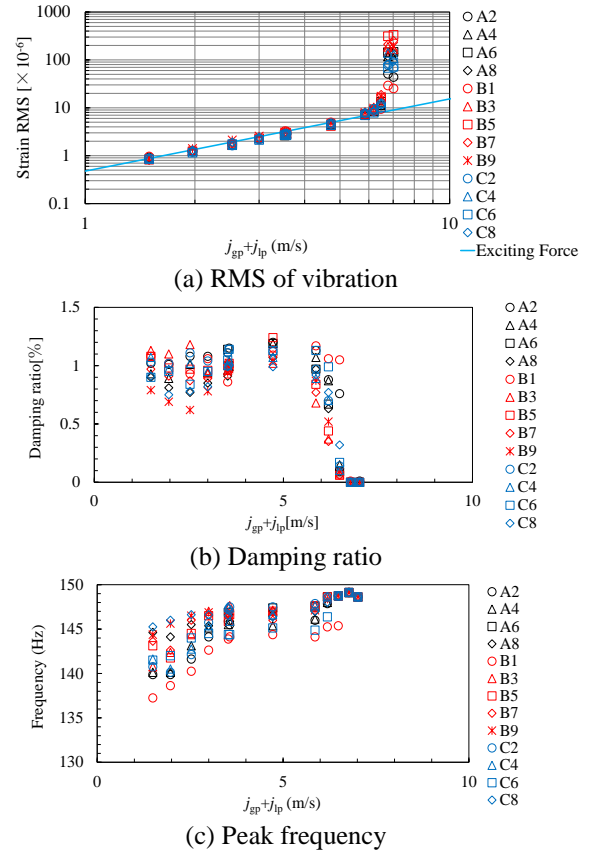
$$\bar{\zeta}_{tp} = \frac{\int \zeta_{tp}(s) \phi^2(s) ds}{\int \phi^2(s) ds} \quad (3.4)$$

The damping ratio for calculation Connors' constant  $K$  is the sum of structural and averaged two-phase damping ratio.

## 4 TEST RESULTS

### 4.1 Straight Tube Bundle

The flow test was conducted under the range of void fraction between 0.7 and 0.99. The representative cases of the test results for FEI tube are shown below.



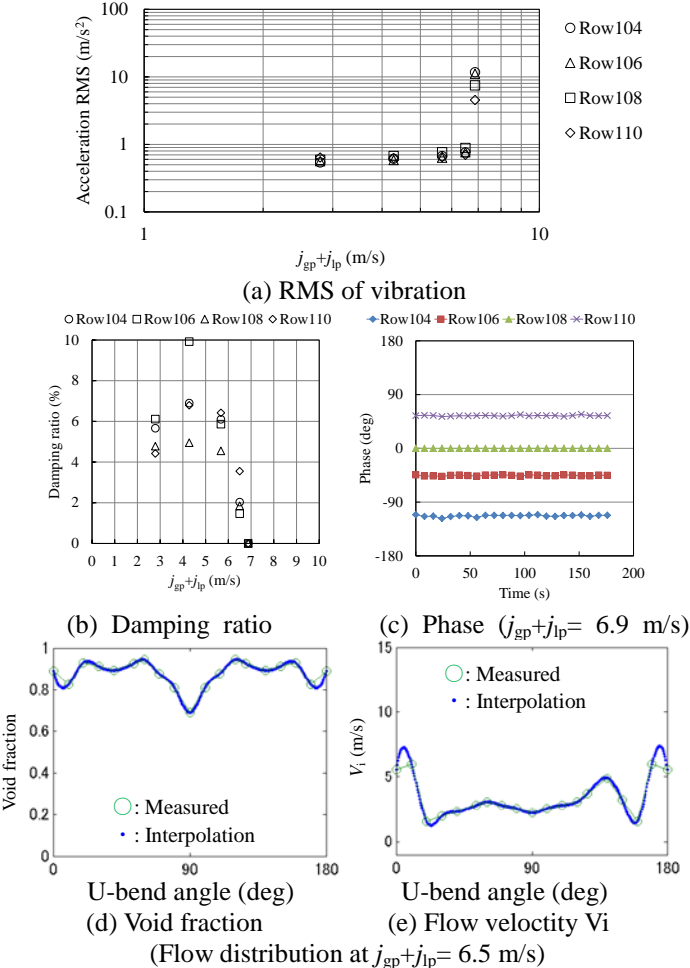
**FIGURE 4.1: Vibration response (IP-150-13)**

The RMS value of vibration strain response with superficial pitch velocity is shown in Fig. 4.1(a). As pitch velocity increases, the RMS value of vibration increases rapidly in approximately 6.5m/s. Before RMS value of vibration increases, upward tendency of RMS value is similar to random fluid exciting force measured by Random force tube. Hence, it follows that FEI tube vibrates randomly for velocities under 6.5m/s. The damping ratio of FEI tube is shown in Fig. 4.1(b). As pitch velocity increases, the damping ratio increases gradually then decreases rapidly to zero. In addition, peak frequency of all tubes coincides with each other at around 6.5m/s. Therefore, the critical flow velocity was judged 6.5m/s

in this case. The critical flow velocities of other cases were determined as well as this case.

#### 4.2 U-bend Tube Bundle

The U-bend tube bundle flow test was conducted for 5 flow distribution cases for out-of-plane FEI and 9 cases for in-plane FEI. These flow cases include the condition similar to a steam generator case, varied void fraction distributions and simple distributions such as uniform flow.



**FIGURE 4.2: FEI Tube In-plane Column**

The representative test result for in-plane FEI is shown in Fig.4.2. The RMS value of vibration acceleration response with superficial pitch velocity is shown in Fig. 4.2(a). The in-plane FEI tubes consisted of 5 flexible tubes (Row104-112) at the center column which were intended to be free in the in-plane direction. However, the Row112 tube was probably contacted with rigid tubes and consequently its natural frequency was higher than other flexible tubes. Therefore, this tube was omitted from evaluation. In this figure, averaged superficial pitch velocity which equals a sum of 6 inlets flow rate divided by a flow area at outmost row (Row126) is represented in the horizontal axis. As superficial pitch velocity increases, the RMS value of vibration increases rapidly in approximately 6.5m/s. The damping ratio also decreases rapidly to zero in 6.5m/s as shown in Fig.4.2 (b). The phase based on Row108

continued constant over the whole measurement time as shown in Fig.4.2 (c). Therefore, the critical flow velocity was judged to be 6.5m/s in this case. The distributions of void fraction and the interfacial velocity  $V_i$  which was measured by BOP in the condition of critical flow velocity at Row125 is shown in Fig4.2 (e). The  $V_i$  and void fraction distributions were obtained by interpolating the measurements.

The critical flow velocities of other cases were determined as well as this case.

## 5 DISCUSSIONS

The representative data of Connors' constant K are shown in Table 5.1 and 5.2.

**TABLE 5.1: Representative K value in Straight tube test**

Tube Name	$f$ (Hz)	$\beta$	$\alpha$	$V_r^{*1}$	$\frac{m_0 \delta^{-1}}{\rho_0 D^2}$	$K^{*1}$
IP-30-13	31.8	0.998	0.992	25.4	4.1	12.5
IP-70-13	75.5	0.998	0.981	4.1	4	2.1
IP-150-5	148.5	0.991	0.983	4.6	2.9	2.7
IP-150-13	149.1	0.99	0.983	4.6	3.1	2.6
Ex-70-1(OOP)	75	0.98	0.965	4.6	2.7	2.8
OOP-70-13	75.8	0.998	0.98	4.6	3.3	2.5
OOP-150-1	149	0.998	0.991	4.5	3.9	2.3
OOP-150-13	150.4	0.998	0.991	4.7	3.5	2.5

\*1 Based on  $\beta$  and  $j_{gp}+j_{lp}$

**TABLE 5.2: Representative K value in U-bend tube test**

Direction	Row	$f$ (Hz)	$\bar{\alpha}^{*1}$	$V_r^{*2}$	$\frac{m_0 \delta^{-1}}{\rho_0 D^2}$	$K^{*1}$	Fig
OOP	86	32.4	0.85	5.2	1	5.2	-
	94	26.1	0.66	4.3	1.2	3.9	
	122	37.5	0.76	5.1	1.1	5	
IP	104	16.4	0.85	23.9	2.9	14	Fig. 4.2
	106	16.4	0.85	23.9	2.9	13.9	
	108	16.4	0.85	23.9	2.9	13.9	
	110	16.4	0.86	23.9	2.9	13.9	

\*1 Void fraction is averaged by vibration mode as following

$$\bar{\alpha} = \frac{\int \alpha(s) \phi(s)^2 ds}{\int \phi(s)^2 ds} \quad (5.1)$$

It's used for Fig.5.1 (b).

\*2 Based on  $\beta$  and  $j_{gp}+j_{lp}$

(1) Influence of number of flexible tubes in the straight tube bundle test

The differences of Connors' constant K are small as shown in Fig.5.1 (a). However, Increments of vibration responses of cluster flexible tubes during occurring FEI are clearer than single and column flexible tubes as shown in Fig.4.1 (a) and Fig.5.2. It was considered that coupling forces of cluster flexible tubes were greater than single and 1 column flexible tubes.

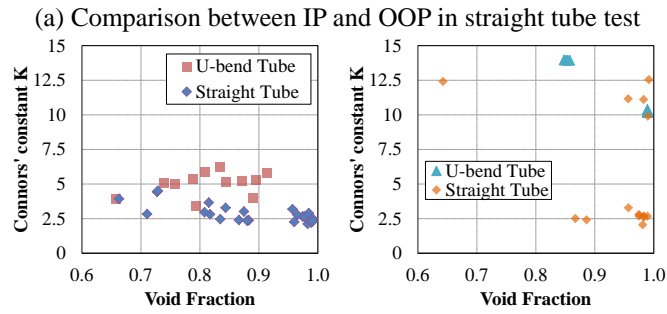
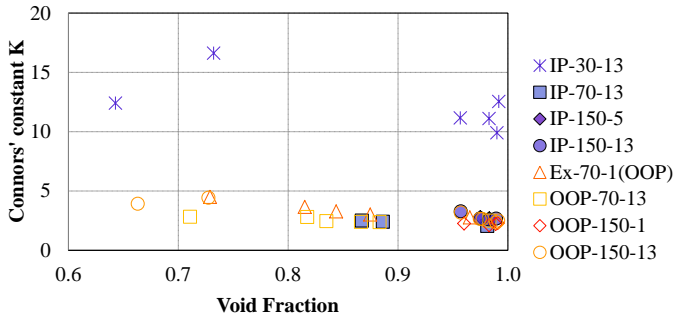
(2) Influence of natural frequency in the straight tube bundle test

The effect of the void fraction on Connors' constant K in the out-plane direction is negligible as shown in Fig.5.1 (a). On the other hand, the K in the in-plane direction is divided into 2 groups as shown in Fig.5.1 (a). The K of 70Hz and 150Hz tubes were almost identical, however the K of 30Hz tubes was higher because of high critical velocity. Because the stiffness of 30 Hz

tubes is lower, the fluctuation of the tube arrangement and phase relationship are more sensitive by random fluid force. It might cause disturbing the coupling.

(3) Differences between out-of-plane and in-plane FEI  
Connors' constant K of in-plane FEI was higher than out-of-plane FEI in the past research which was conducted by the straight tube bundle test in the air single phase flow [3]. In this straight tube bundle test, the K of in-plane 30Hz FEI tube bundle was higher than the K in the out-of-plane direction, but the K of in-plane 70Hz and 150Hz tube bundle were similar as shown in Fig.5.1 (a). In this U-bend tube test, the K in the in-plane FEI tube was clearly higher than out-of-plane FEI tube as shown in Fig.5.1 (b).

(4) Difference between straight tube test and U-bend tube test  
For out-of-plane and in-plane FEI, Connors' constant K of U-bend tube was equivalent to or higher than straight tube. As shown in Fig.5.1 (b). U-bend tube has distribution of flow velocity and void fraction against straight tube bundle test, therefore distribution of two-phase damping and complicated flow might increase the critical velocity. Because K of 30 Hz tubes and U-bend tube for in-plane are almost equivalent, the condition of 70Hz and 150Hz cases in straight tube bundle may not be normal.



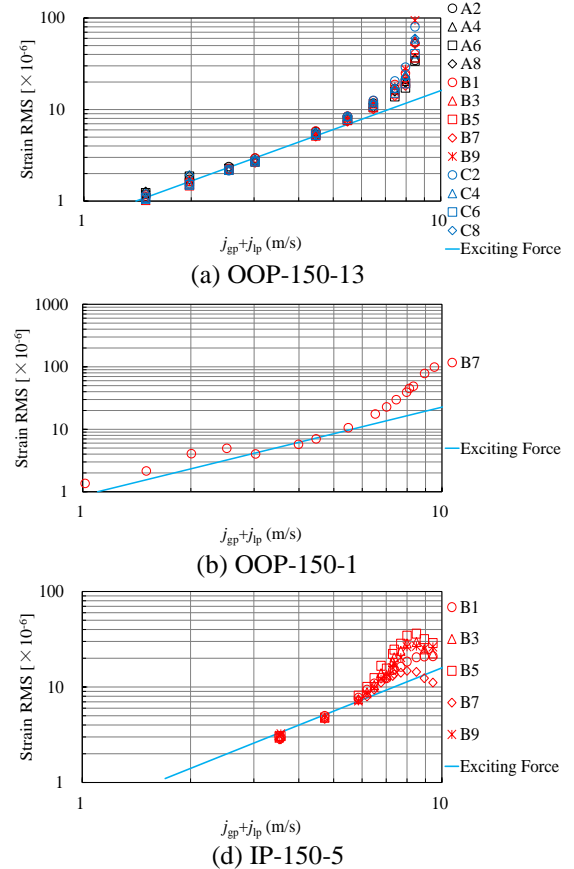
(a) Comparison between IP and OOP in straight tube test  
(b) Comparison between straight tube and U-tube  
 $j_{gp}+j_{ip}$ , and  $\beta$  are used to evaluate K value

**FIGURE 5.1: Summary of critical velocity test result**

## 6 CONCLUSION

Triangular array straight tube bundle test and U-bend tube bundle test were conducted using 1/2 scale model and simulant fluids. Connors' constants K for the evaluation of FEI stability ratio in triangular array tube bundle were obtained. The K of IP FEI is likely to be greater than OOP FEI. However, in the specific conditions, the K of IP is close to OOP FEI. In addition, the K in U-bend tube bundle is equivalent to or

greater than straight tube bundle by the effect of flow distribution. In order to explain the differences of Connors' constant K between in-plane and out-of-plane directions in the specific conditions and flow distribution effect on FEI, further investigations such as analytical approach are necessary.



**FIGURE 5.2: Influence of Number of Tube on FEI**

## ACKNOWLEDGMENTS

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