STRUCTURAL INTEGRITY EVALUATION OF NUCLEAR FUEL WITH REDUCED WELDING CONDITIONS

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Welding is required for a connection between two different components in the nuclear fuel of a pressurized water reactor. This work relies on a mechanical experiment and analytic results to investigate the structural integrity of nuclear fuel in a situation where some components are not welded to each other. A series of lateral vibration tests are performed in a test facility, and the test structures are examined in terms of dynamic behavior. In the tests, the displacement signal at every grid structure that sustains fuel rods is measured and processed to identify the dynamic properties. The fluid-elastic stability of the structure is also analyzed to evaluate susceptibility to a cross flow with an assumed conservative cross flow distribution. The test and analysis results confirm that the structural integrity can be maintained even in the absence of some welding connections.

KEYWORDS : Nuclear Fuel, Welding, Structural Integrity, Dynamic Behavior, Fluid-elastic Stability

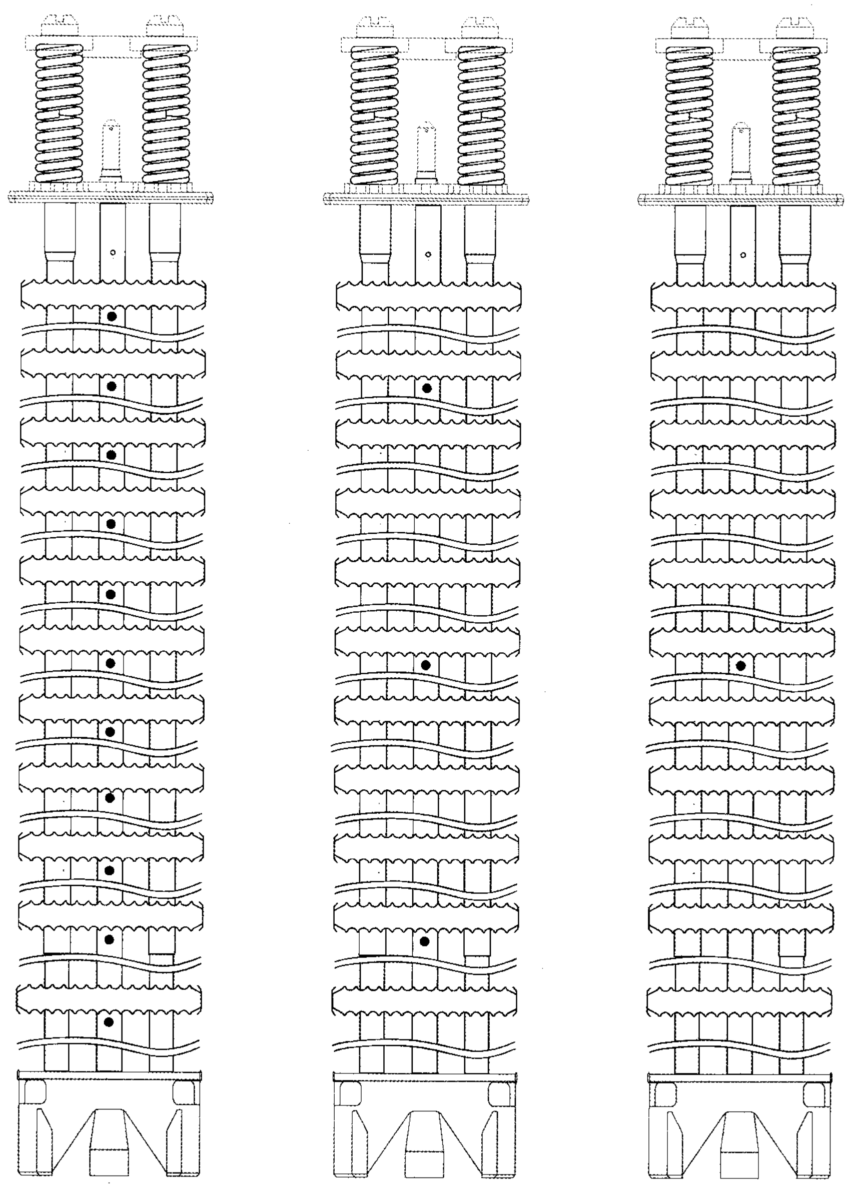
1. INTRODUCTION

A nuclear fuel assembly for a pressurized water reactor (PWR) has multiple components: namely, 11 structural grids, five guide tubes, a top nozzle, a bottom nozzle, and hundreds of fuel rods. The guide tube in the center position, which corresponds to the instrument tube, provides a guidance path for an in-core instrument used to monitor the reactor. Every fuel assembly should be designed so that the lateral stiffness is adequate for virtual accidents, such as a seismic shutdown earthquake or a loss of coolant accident; furthermore, the performance should be verified through a series of tests [1]. Thus, all grids structures are welded to five guide tubes to ensure sufficient lateral rigidity. The center guide tube, in particular, which is about 4 m long, is manufactured to have tens of lateral dimples along its length, and the dimples are required to have a diameter that is small enough to sustain an in-core instrument. The cross-sectional mechanical properties in the center guide tube are irregular; hence, a uniform circular cross section cannot be maintained due to the dimples. The sleeves on a grid structure are welded to a guide tube, but the irregular cross section impedes the welding process between the tubes and each sleeve on the grid structure. Accordingly, although controlled automatic welding can be used between a corner guide tube and the sleeves on grids, another welding process must be used for the welding of the center guide tube to grid structures. Consequently, the productivity of the fuel assembly is unlikely to be enhanced until either the center guide tube configuration or the welding process is modified.

This work proposes a fuel assembly with a modified center guide tube welding process and presents some of the mechanical behavior of the fuel assembly with the changed design. The main feature in the fuel assembly is a drastic reduction of the welding points in the center guide tube and grids. A four-point spot welding process between a spacer grid sleeve and the center guide tube is maintained but with a reduced number of welded sleeves on the center guide tube along the axial length. With the modified fuel assembly design, we performed a series of lateral vibration tests at a test facility at the Korea Atomic Energy Research Institute. In previous designs all grids are welded to the center guide tube. However, our test results show that the absence of some welded connections does not cause any significant deviation. We can therefore deduce that some welding points in the center guide tube are not necessary to sustain flexural rigidity.

2. CONFIGURATION OF THE TEST STRUCTURE AND TEST PROCEDURE

A fuel design with a modified welding feature for a PWR is proposed, and a skeleton assembly, which is a fuel assembly without fuel rods, is used in the test instead of a



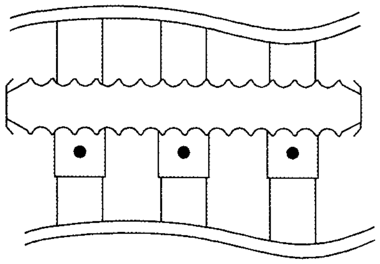
(a) Previous design (b) Modified design 1 (c) Modified design 2

Fig. 1. Welding Locations (Dark Circles Denote the Welding Positions along the Center Guide Tube; the Welding Points on the Outer Guide Tubes are not Shown)

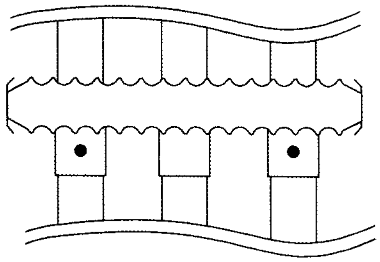
regular fuel assembly because the fuel rods are independent of the welding of the skeleton assembly. Every grid structure is accompanied by five sleeves in the bottom plane of the grid structure, and the sleeves are welded on four guide tubes and one center guide tube. Fig. 1 shows the existing and proposed design concepts; the welding points on the four outer guide tubes are not indicated. Every grid is permanently connected to the guide tubes via welding between the sleeves and the guide tubes. The sleeves are not shown in Fig. 1, and, unlike the existing design, the first design has only three welding points and the second design has only one welding point.

To confirm the new design's mechanical performance, such as the dynamic characteristics of the assembly, we performed a series of mechanical tests. The lateral vibration test results are discussed in the paper because they provide enough information for a structural integrity evaluation. In the vibration test, the displacement signal at every grid is measured while the fuel assembly is excited by a dynamic shaker at the sixth grid. After the measured signals are processed, the modal properties, such as the natural frequency and mode shapes, can be determined on the basis of the measured signals.

Upon the completion of the vibration test to identify



(a) Before the welding is removed (present design)



(b) After the welding is removed in the center guide tube (modified design)

Fig. 2. Conceptual Spot Welding Configuration (Dark Circles Denote the Welding Positions along the Guide Tubes)

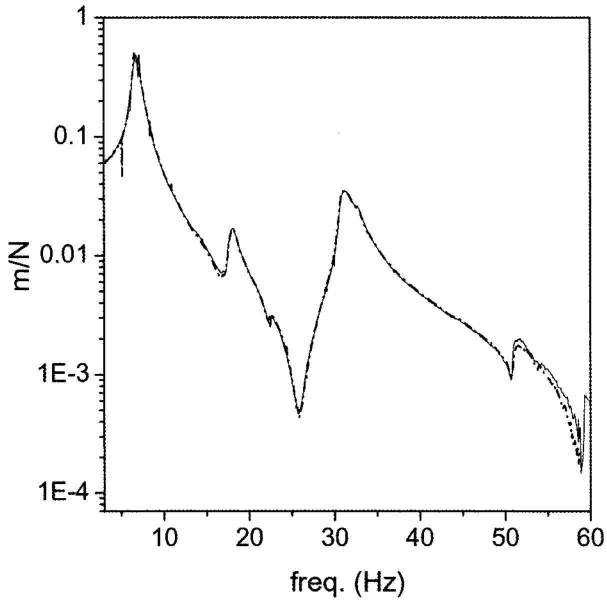


Fig. 3. Measured Response Functions (Solid: Forward Sweep; Dash Dot: Backward Sweep)

dynamic characteristics of the existing design, we removed the spot welding points in the test fuel assembly except at the three locations shown in Fig. 1(b). The welding connection can be removed by rasping off the welding point on a sleeve. Fig. 2 shows the enlarged fuel configuration before and after the removal of the welding connection. The dynamic properties of the assembly can then be determined by analyzing the measured signal. After all the welding points except the center position have been removed, as shown in Fig. 1(c), the same vibration test is performed.

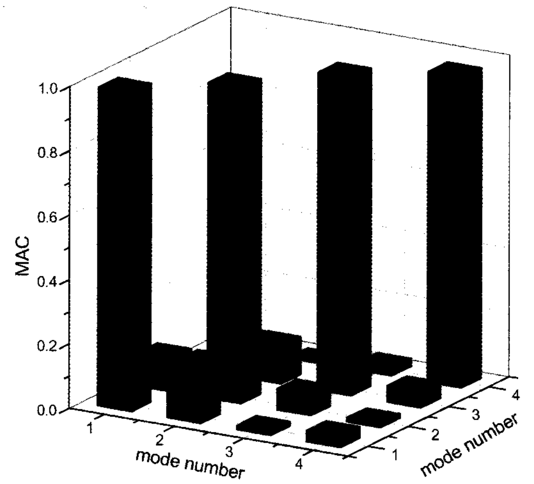
The top and bottom nozzles are loaded into reactor core simulators, which restrict the movement of the nuclear fuel; the two nozzles are actually in contact with the simulator. The test assembly is nonlinear because friction is unavoidable and the usual boundary condition cannot be implemented. Furthermore, the swept sine excitation is known to maximize the signal-to-noise ratio in structures with nonlinearities; thus, the excitation is preferred in the test. A total of 11 frequency response functions are measured with 11 linear variable displacement transducers on every spacer grid.

3. TEST RESULTS AND DISCUSSION

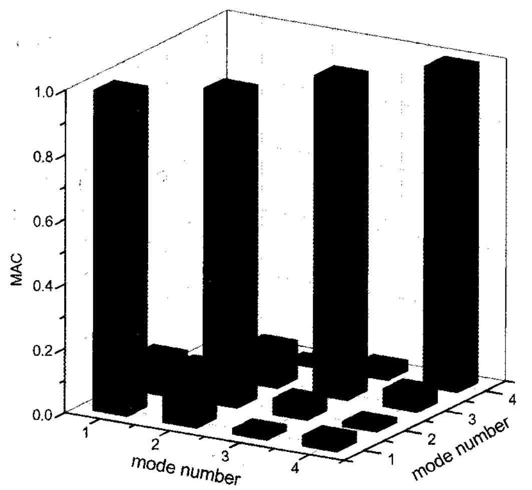
Measurements were taken in the forward and backward sweep directions in a range of 3.2 Hz to 60 Hz with a frequency resolution of 0.05 Hz. Fig. 3 shows the measured frequency response functions. The same test process is executed in the skeleton assembly with the removed welding connections. The measured natural frequencies for each test structure are listed in Table 1. The natural frequency deviation from the previous design is less than 3.4%, and the maximum occurs at the second mode in the forward sine sweep test. The deviation in the natural frequencies of the modified design are thought to be within a moderate range because of the impossibility of avoiding measurement

Table 1. Measured Natural Frequencies (Hz) during Forward Sweeping

Mode number	1	2	3	4
Previous	6.8	17.7	31.0	51.4
Modified 1	6.9	18.3	30.5	51.2
Modified 2	6.7	18.3	30.4	50.7
Max. deviation (%)	1.5	3.4	-1.6	-0.8



(a) Previous vs. modified 1



(b) Previous vs. modified 2

Fig. 4. Mode Shape Similarity of the Previous and Modified Designs

errors in the resonance frequencies where the structural linearity is very low. A backward sweep test was also performed, but the natural frequency changes are not as notable as those of the forward test results; the maximum deviation is 2.5% in the second mode.

The mode assurance criterion (MAC) is a useful index for comparing the mode shape similarity between two mode sets [2]. The MAC can be derived by computing the inner product of two mode shape vectors. The normalized one is shown in Fig. 4 and listed in Table 3 and Table 4. As the index approaches unity, the modes have great similarity. The off-diagonal terms in the MAC imply similarity between cross modes. Useful information can be found by examining the diagonal terms that compare the two mode sets in order. The smallest MAC in the diagonal terms is 0.97, and, based on the tables, each mode in the modified structures is almost equal to the mode of the existing fuel.

To compare the difference on the test objects, we calculated the frequency response assurance criterion (FRAC) and the frequency domain assurance criterion (FDAC). The FRAC, which compares the frequency response functions at a particular degree of freedom, is defined at a measurement point as follows [2]:

$$FRAC = \frac{\left|\left\langle H_{Ai}^{*}, H_{Bi}\right\rangle\right|^{2}}{\left\langle H_{Ai}^{*}, H_{Ai}\right\rangle\left\langle H_{Bi}^{*}, H_{Bi}\right\rangle}, \tag{1}$$

where H_{Ai}, which denotes the measured frequency response function at a location, i, on test object A, consists of n-number of measured frequency components; the superscript * denotes a complex conjugate; $\langle \bullet, \bullet \rangle$ denotes the inner product of two vectors; and H_{Bi} is also the corresponding measured value for test object B. An index value of unity indicates a perfect correlation, and a low value indicates a poor correlation. The calculated FRAC, which is listed in Table 2, shows that every set is quite similar. Note also that the similarity at each frequency can be judged by computing

Table 2. FRAC of the Two Different Test Objects

Measurement position	Previous Vs. modified 1	Previous Vs. modified 2
Mid-grid 1	0.91	0.91
Mid-grid 2	0.92	0.92
Mid-grid 3	0.94	0.95
Mid-grid 4	0.93	0.95
Mid-grid 5	0.93	0.95
Mid-grid 6	0.93	0.96
Mid-grid 7	0.93	0.96
Mid-grid 8	0.92	0.95
Mid-grid 9	0.90	0.93

Table 3. MAC Value of the Previous Design and Modified Design 1

Mode number	1	2	3	4
1	0.99	0.13	0.02	0.04
2	0.11	0.98	0.07	0.02
3	0.03	0.12	0.99	0.05
4	0.04	0.01	0.03	0.97

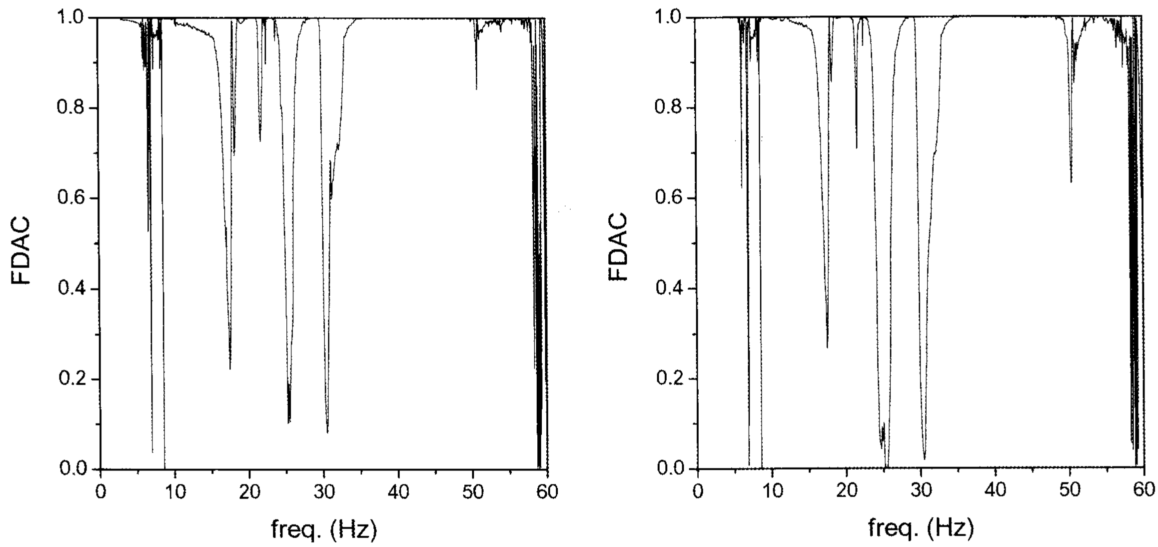
Table 4. MAC Value of the Previous Design and Modified Design 2

Mode number	1	2	3	4
1	0.99	0.13	0.02	0.04
2	0.12	0.98	0.05	0.02
3	0.02	0.12	0.99	0.06
4	0.03	0.01	0.04	0.99

the FDAC according to the following definition [2]:

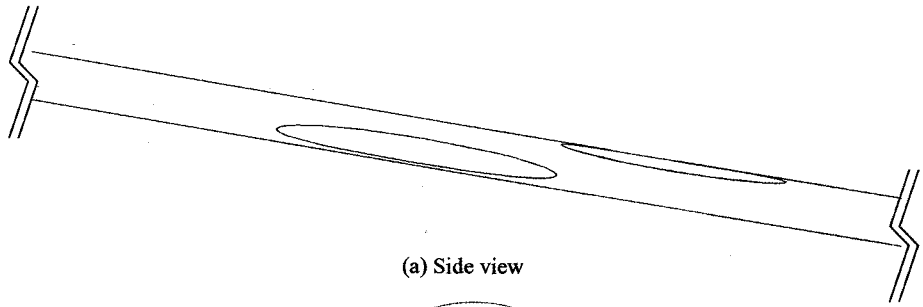
$$FDAC(\omega_i,\omega_j)=\frac{H^*(\omega_i)_A\cdot H(\omega_j)_B}{|H(\omega_i)_A||H(\omega_j)_B|}, \quad (2)$$

where ω_i means the i-th circular frequency component. Unlike the FRAC, the FDAC gives information about the similarity of the frequency response function at each frequency. It compares the frequency response function values for all possible combinations of frequencies, (ω_i,ω_j). Hence, the deviation level of the two functions at each frequency can be evaluated while taking into account the phase relation between the two sets. Furthermore, the value of unity indicates a perfect correlation, but a low value approaching zero indicates a poor correlation. Fig. 5 shows the calculated diagonal terms of the FDAC, and no big deviation can be found except for the resonances. Because the linearity at the resonances is well below other frequencies, the low level of the index around those resonances is not extraordinary.

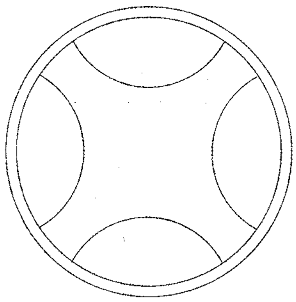


(a) Previous vs. modified 1 (b) Previous vs. modified 2

Fig. 5. FDAC of the Previous Design and Modified Design



(a) Side view



(b) Top view

Fig. 6. Geometry of a Center Guide Tube

4. FLUID-ELASTIC STABILITY

The fuel assembly is exposed to severe turbulence in a reactor. Accordingly, it is common to demonstrate this behavior in the reactor simulator under flow conditions that are similar to those of a reactor. On the other hand, because a steam generator U-tube or fuel rod is not fixed but simply supported by support structures such as support plates and grid structure, the fuel rods are very susceptible to cross flow conditions. If the structures are exposed to a terrible cross flow condition, their behavior becomes unstable; thus, the fluid-elastic stability analysis should be followed to validate the design. Given that several welding points are eliminated in the center guide tube, the stability of the center guide tube should also be verified. In this study, the stability of the structure with the removed welding is also analyzed in terms of structural integrity under a specific cross flow condition.

Connors' equation, which is useful for predicting the critical flow velocity that marks the beginning of unstable motion in a slender tube structure, is expressed as follows [3,4]:

$$\frac{V_c}{f_n D_o} = \beta\left(\frac{m_t}{\rho D_o^2}\right)^a (2\pi\varsigma_n)^b, \qquad (3)$$

where V_c is the critical flow velocity; D_o is the outer diameter of the tube; f_n is the n-th natural frequency; ρ, m_t and ξ_n denote the fluid density, the total mass per unit length of the tube, and the damping ratio in the n-th mode, respectively; and a, b and β are constants that depend on

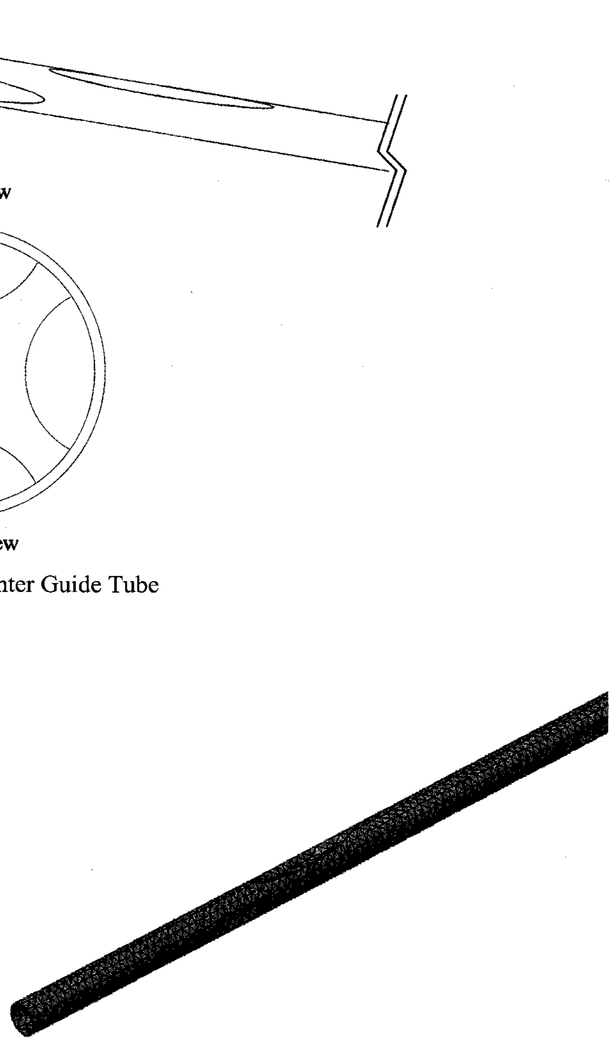


Fig. 7. A Part of a Finite Element Model

the geometry of the tube, though ASME [4] guidelines recommend a value of 2.4 for β and 0.5 for a and b to cover overall conditions.

The fluid-elastic stability is defined as the ratio of effective velocity over critical velocity; if the ratio is less than 1, it is stable. The effective velocity [3] for cases in which every density is constant can be written as

$$V_e^2 = \frac{\int V_p^2(x)\phi_n^2(x)dx}{\int \phi_n^2(x)dx}. \qquad (4)$$

When the effective velocity is calculated as shown in Eq. (4), the mode shape should be provided as a function of position, x. To predict the critical flow velocity with Eq. (3), we need the natural frequency and damping ratio.

Table 5. Natural Frequencies (Hz) in an Air Condition

Mode number	1	2	3	4	5	6
FE model	5.90	16.26	31.85	52.57	78.35	109.21
Analytic	5.98	16.47	32.29	53.37	79.73	111.36

Table 6. Mechanical Parameters in the Straight Beam

Young's modulus (MPa)	Density (kg/m^3)	Cross section area (m^2)	Area 2nd moment of inertia (m^4)
76000.90	7030.69	7.62E-5	5.45E-9

Table 7. Fluid-elastic Stability Ratio

Mode number	1	2	3	4	5	6
Vc (m/s)	0.140	0.387	0.759	1.255	1.875	2.619
Ve (m/s)	0.107	0.131	0.151	0.163	0.171	0.178
Ve/Vc	0.76	0.33	0.19	0.13	0.09	0.06

Vc: Critical velocity; Ve: effective velocity

(a) First mode (b) Second mode

Fig. 8. The First Two Modes in a 3-D Model

Natural frequencies can be determined experimentally or analytically, but we preferred the analytic method in this work. It is difficult to identify the damping ratio of the structure in a water condition; thus, 1% damping is assumed for a conservative critical velocity.

As shown in Fig. 6, the cross section of the center guide tube is not uniform because of the dimples that are pressed in the surface. Although the cross section is irregular, the behavior is thought to be very similar to that of a beam with a uniform cross section because the slenderness ratio is quite large. To support the supposition, we used the commercial software COSMOSWorks to build a 3-D finite element structure. The model, shown in Fig. 7, consists of about 282,000 degrees of freedom, and the translational motions at both ends are fixed because the ends are slip fitted into counter bores at the top and bottom nozzles. On the other hand, as shown in Table 5, the solutions of the straight beam with clamped boundary conditions are quite similar to those of the finite element analysis. The mechanical parameters needed to formulate the straight beam equation are provided in Table 6. Fig. 8 shows the mode shapes of the first two modes; their shapes including the shapes of the other modes are fairly similar to the shapes of the straight beam. It is possible therefore that the 3-D center guide tube model could be replaced with the straight beam.

The total mass of the center guide tube is equal to the sum of the material, the mass of water contained in the tube, and the hydrodynamic mass [3, 4]. That is, the total mass can be expressed as

$$m_t = \rho_t A_t + \rho_w \frac{\pi}{4} D_i^2 + C_h \rho_w \frac{\pi}{4} D_o^2, \tag{5}$$

where ρ_t is the tube density; ρ_w is the water density under

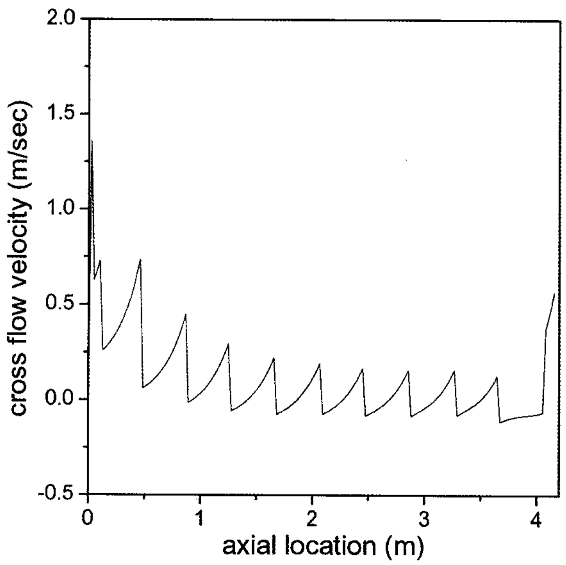


Fig. 9. A Specific Cross Flow Velocity Distribution

reactor conditions where the pressure is 15.5 MPa pressure and the temperature is 315°C; A_t, D_i and D_o denote the tube cross section area, the inner diameter of the tube, and the outer diameter of the tube, respectively; and C_h is the hydrodynamic mass coefficient with an assumed value of 1 because only the tube is considered in this study.

A specific flow condition is shown in Fig. 9, and the critical velocities and effective velocities calculated on the basis of Eqs. (3) and (4) are listed in Table 7. Because every stability ratio is less than 1, the motion of the structure is stable. On the other hand, if every welding point is removed, the tube may be unstable because the effective velocity is very close to the critical velocity at the first mode. If a welding point at the middle of the tube is made, the first mode and every odd mode disappear because the grid structure welded to the tube provides support at that position. Consequently, a minimum of one welding point at the middle of the tube is required to guarantee an adequate fluid-elastic stability margin.

5. CONCLUSION

In the existing design, the center guide tube of the fuel assembly is welded to every grid sleeve. Because the welding process in the center guide tube with several dimples is not efficient, a fuel assembly with a modified center guide tube welding process is proposed in the work. The main feature in the fuel assembly is that the welding points in the center guide tube are drastically reduced because some of the sleeves are not welded to the center guide tube. There are two candidate designs: in the first option, only one sleeve is welded to the center guide tube at the fifth mid-grid; in the other option, three sleeves are welded at the first, last and fifth mid-grids. A lateral vibration test was performed to identify some of the mechanical behavior of the fuel assembly with the changed design. The test results reveal that the mechanical behavior in the modified design is almost equal to that of the existing design. The fluid-elastic stability due to the coolant flow was also examined, and we concluded that one welding point at the middle of the tube is the minimum requirement to guarantee stability. The test results and analysis confirm that the modified design with limited welding at the center guide tube is sufficient to sustain flexural rigidity.

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