Letters

Basic Performance Tests on Vibration of Support Structure with Flexible Plates for ITER Tokamak Device

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The vibration experiments of the support structures with flexible plates for the ITER major components such as toroidal field coil (TF coil) and vacuum vessel (VV) were performed using small-sized flexible plates aiming to obtain its basic mechanical characteristics such as dependence of the stiffness on the loading angle. The experimental results obtained by the hammering and frequency sweep tests were agreed each other, so that the experimental method is found to be reliable. In addition, the experimental results were compared with the analytical ones in order to estimate an adequate analytical model for ITER support structure with flexible plates. As a result, the bolt connection of the flexible plates on the base plate strongly affected on the stiffness of the flexible plates. After studies of modeling the bolts, it is found that the analytical results modeling the bolts with finite stiffness only in the axial direction and infinite stiffness in the other directions agree well with the experimental ones. Using this adequate model, the stiffness of the support structure with flexible plates for the ITER major components can be calculated precisely in order to estimate the dynamic behaviors such as eigen modes and amplitude of deformation of the major components of the ITER tokamak device.

Keywords:

ITER, vibration, flexible plates, support structure, frequency sweep test, hammering test, stiffness, eigen modes, numerical analysis

1. Introduction

The ITER is an experimental fusion reactor which aims to demonstrate the scientific and technological feasibility of fusion energy [1]. Major components of the ITER tokamak device are superconducting magnets such as toroidal field coil (TF coil) for magnetic confinement of the deuterium and tritium plasma and vacuum vessel (VV) for tritium and activated dust as a safety boundary. These components are assembled in a doughnut-shaped configuration. The temperatures of these components are changed in the large range from room temperature to 4 K during plasma operation for TF coil and from room temperature to 200°C during baking operation for VV, respectively [2]. The respective temperature changes induce thermal deformation in the radial direction, so that the support structures of these components on the tokamak floor have to be flexible in the radial direction while sustaining any forces in the other directions. For this reason, an assembly of flexible plates is adopted as a support structure of the TF coil and VV for ITER [2]. Figure 1 shows an example of the support structure with flexible plates applied to the ITER tokamak device. The assembly of flexible plates is installed at the bottom of the TF coil and VV by bolt connection. The support structure composed of 18 assemblies of flexible plates is arranged along the toroidal direction, and the respective flexible (low stiffness) directions are arranged in the radial direction, as shown in Fig. 1.

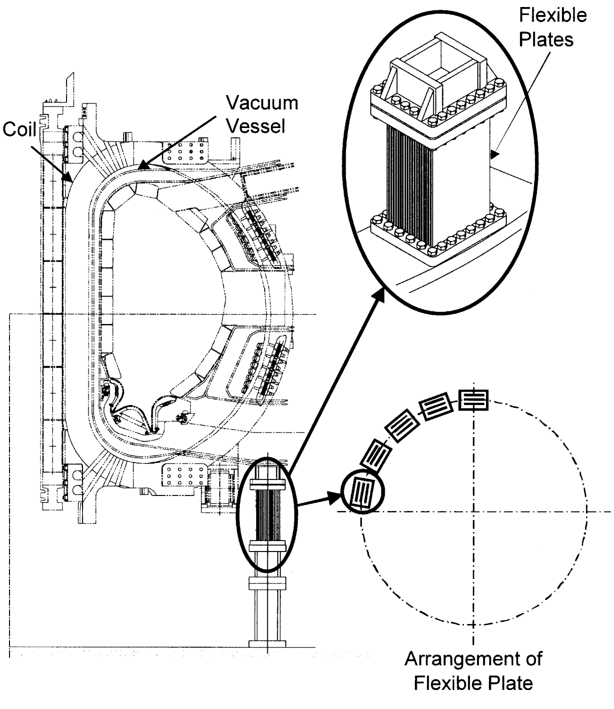

Fig. 1 An example of support structure for ITER using flexible plate.

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The stiffness of the support structure composed of flexible plates is required to be estimated as a whole system in order to ensure the integrity of the tokamak device particularly to the seismic events, because the stiffness of the flexible plates strongly depends on the loading angle from the out-of-plane direction of the flexible plates. Therefore, the vibration tests of the flexible plates are necessary to obtain in detail the mechanical characteristics such as stiffness of the flexible plates, because there is no sufficient study in particular on the dependence of the stiffness on the loading angle in the past [3].

The present paper describes the basic performance tests on the vibration of flexible plates using its small-sized model aiming to obtain the mechanical characteristics such as dependence of the stiffness on the loading angle. The experimental results are compared with that of numerical analyses in order to establish an adequate analytical model for ITER support structure with flexible plates, which will be used to estimate the dynamic behaviors such as eigen modes and amplitude of deformation of the major components of the ITER tokamak device during seismic event in the future.

2. Experimental Apparatus

Figure 2 shows a small-sized model of the support structure with flexible plates (support model), which is made of a bulk material of stainless steel (Type SS-316) and fabricated by electric discharge processing and machining. The flexible part of the support model is composed of five flexible plates. The dimension of each plate is 33.7 mm in width, 73 mm in height and 1 mm in thickness, respectively. Purpose of the experiment is to measure the respective stiffness of the support model in the several horizontal directions: 0, 25, 45, 65 and 90 degrees from the out-of-plane (low stiffness) direction of the flexible plate.

Experimental apparatus consists of a base plate, a weight and support models, as shown in Fig. 3. Four support models were used to measure the stiffness at the angles of 25, 45 and 65 degrees, while two were used for the angles of 0 and 90 degrees due to their symmetric configuration in the vibration direction. The respective support models were fixed on the base plate by eight bolts with rated torque, as shown in Fig. 2. The weight of 280 kg is also fixed on the support model by eight bolts. The stiffness of the support model was calculated from the eigen frequency based on the swaying vibration of the whole support model. Location of four or two support models is arranged on the base plate, according to the relation between installation angle of the flexible plates and vibration direction, as shown in Fig. 3.

The eigen frequencies of swaying vibration were measured from two tests: frequency sweep test and hammering test. For the frequency sweep test, a vibrating table was used to shake the base plate. The sine wave was applied to the vibration tests with the frequency range of 10 Hz to 200 Hz. Amplitudes of acceleration were kept 0.03 G for the vibration test at the angle of 0 degree (out-of-plane direction) and 0.06 G for the other angles, respectively.

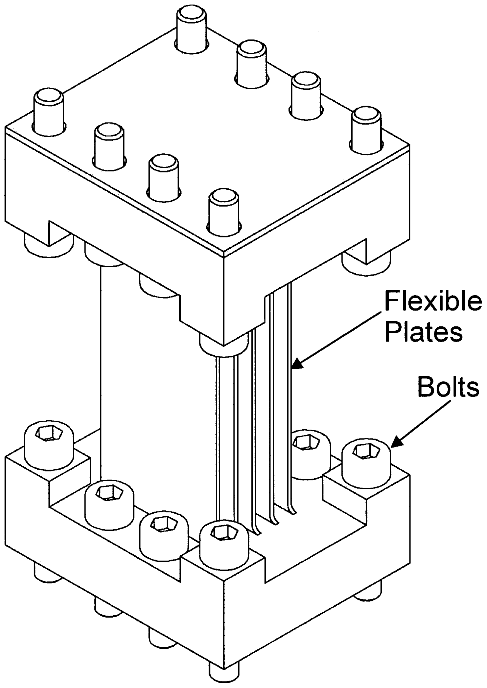

Fig. 2 Support model for vibration test.

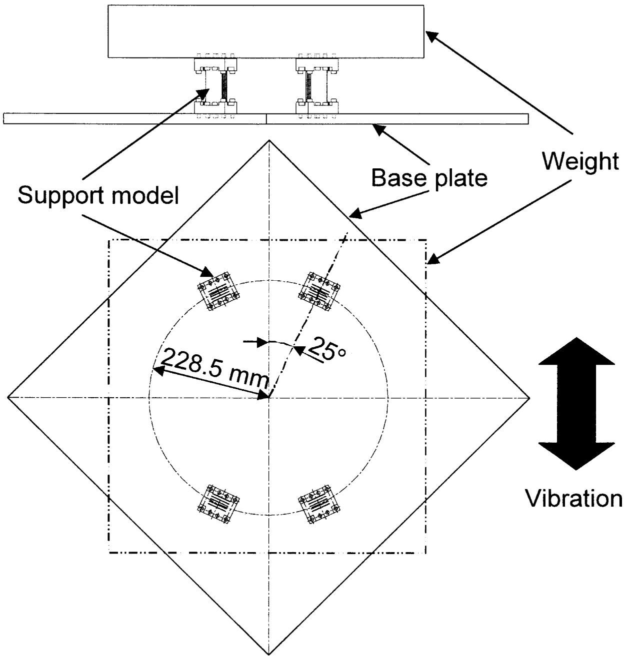

Fig. 3 Configuration of vibration test (25 degrees).

3. Numerical Analysis

In order to predict the basic eigen vibration modes and frequencies of the support model, numerical analysis was performed using the finite element method. The flexible plates of the support model are modeled by the shell element, while the bolt is assumed as a rigid body in the ideal case. Figure 4 shows the vibration modes of support model with angle of 45 degrees, as an example of the results. Table 1 summarizes the

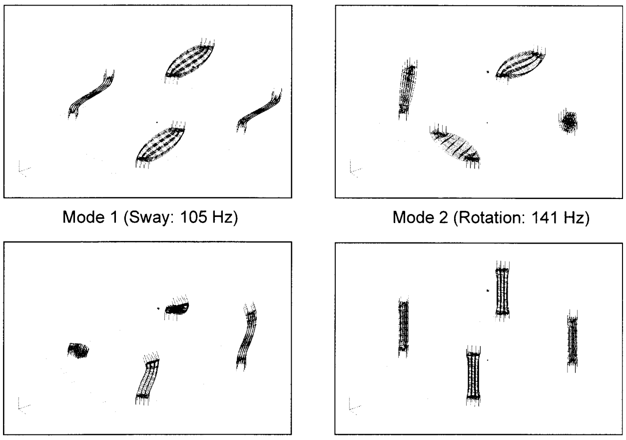
Mode 1 (Sway: 105 Hz)
Mode 2 (Rotation: 141 Hz)
Mode 3 (Rocking: 382 Hz)
Mode 4 (Vertical: 408 Hz)

Fig. 4 Eigen Modes (45 degrees).

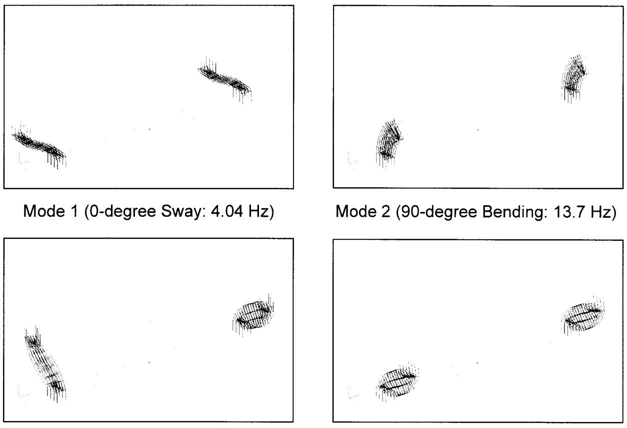
Mode 1 (0-degree Sway: 4.04 Hz)
Mode 2 (90-degree Bending: 13.7 Hz)
Mode 3 (Rotation: 99.6 Hz)
Mode 4 (90-degree Sway: 124 Hz)

Fig. 5 Eigen Modes (0/90 degrees).

Table 1 Eigen Modes and Frequencies.

0/90 degrees		45 degrees		25/65 degrees	
Mode	Frequency (Hz)	Mode	Frequency (Hz)	Mode	Frequency (Hz)
0-degree sway	4.04	Sway	105	25-degree sway	63.8
90-degree bending	13.7	Rotation	141	65-degree sway	126
Rotation	99.6	Rocking	382	Rotation	141
90-degree sway	124	Vertical	408	Rocking	246
Vertical	288			Vertical	408

modes and frequencies to the all arrangements of the angle of flexible plates. Arrangement of the location of the support models at the angles of 0 and 90 degrees as well as 25 and 65 degrees are identical, respectively, so that the results are described in the same column. As shown in Table 1, major modes in the low frequency range are “swaying mode”, which is translating vibration in the horizontal direction, “rotating mode”, which is rotating vibration around the vertical direction, “rocking mode”, which is rotating vibration around the horizontal direction, and “vertical mode” which is translating vibration in the vertical direction. It is noted as a special case of 90 degrees that the bending vibration mode is induced as shown in Fig. 5 because the weight is supported by only two supports.

Among the vibrating modes of the major components for ITER tokamak device, the horizontal swaying mode is the most important for the analysis of their seismic deformation, and is affected mainly by the horizontal stiffness of the support structure. Therefore, the horizontal stiffness of the support model depending on the angle of the flexible plates to the vibration direction was calculated from the frequency of the swaying mode in Table 1, obtained by the eigen mode analysis. The formula used for calculation of the stiffness is $k = m(2\pi f)^2$, where k, m and f are stiffness, mass of the weight and the frequency of the swaying mode, respectively.

The analytical results will be compared with the experimental ones in detail in the Sec. **5**.

4. Experimental Result

Eigen frequencies of swaying vibration, which are the most important for obtaining the stiffness as mentioned above, were measured by two methods: hammering test and frequency sweep test. In the former test, the weight was hit by a hammer and the measured waveform of acceleration was analyzed by the fast Fourier transform, as shown in Fig. 6 as a typical example. By comparing the result of the hammering test with the numerical analysis results, the peak for the sway mode can be clarified among the other modes. In the frequency sweep test, a vibrating table changing the frequency from 10 Hz to 200 Hz was used. Two different accelerations of the table for input and the weight for output were measured, respectively. The ratio of these two accelerations, or acceleration response factor, shows a peaked response at the eigen frequency, as shown in Fig. 7 as a typical example. The respective stiffness of the support model was calculated from the respective frequencies obtained by two kinds of tests: hammering and frequency sweep tests. As a result, it is found that the results of frequency and stiffness of the support model have a good agreement between two different tests, respectively, as shown in Figs. 8 and 9. Based on this result,

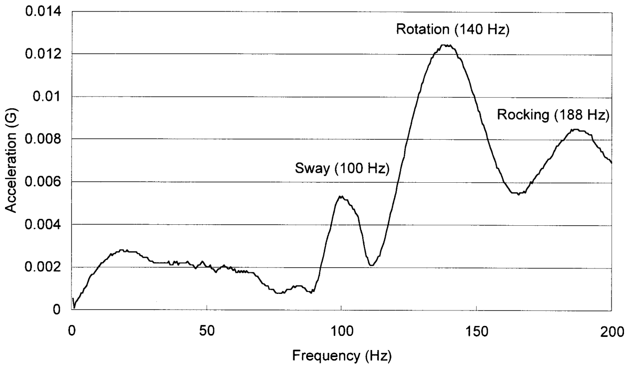

Fig. 6 Result of Hammering Test (45 degrees).

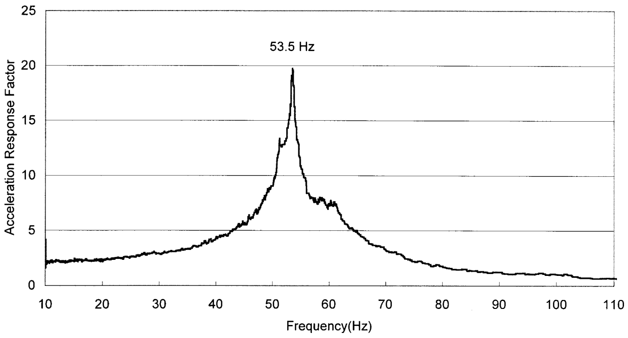

Fig. 7 Frequency Sweep Test (25 degrees).

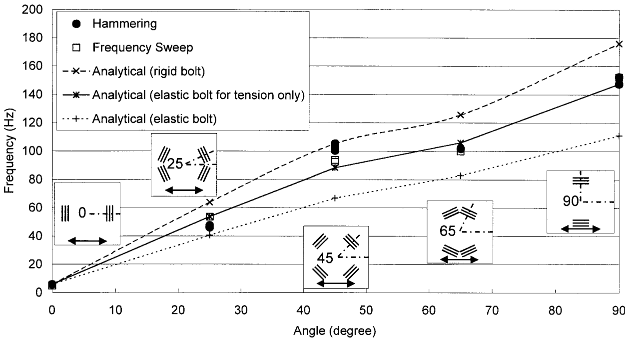

Fig. 8 Comparison of Frequency between Experimental and Analytical Results.

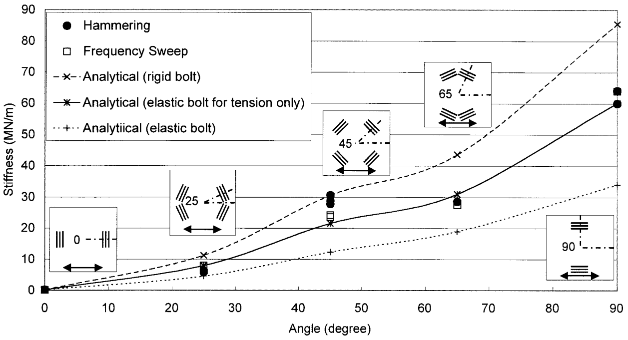

Fig. 9 Comparison of Stiffness between Experimental and Analytical Results.

mechanical characteristics such as stiffness of the support model with flexible plates are clarified as a experimental basis for the estimation of the seismic behavior of the ITER major components.

5. Discussion

In order to estimate the experimental results and to find the adequate analytical model of the support model, the experimental results are compared with analytical ones in this section. Figures 8 and 9 shows the analytical results of frequency and stiffness obtained by the analysis mentioned in Sec. **3**, plotted with broken lines. In this analysis, the connection bolts were assumed as rigid beams with infinite stiffness. From Figs. 8 and 9, the values of frequency and stiffness obtained from the experiments are lower than those from the numerical analysis. It is therefore suggested that the effect of the bolt connection cannot be ignored on the actual frequency and stiffness of the support model, because the bolt has a constant finite stiffness even though tightened with high torque.

In order to estimate the effect of bolt connection, the bolt was modeled as a beam with finite stiffness, simulating the actual dimensions and mechanical properties of the bolt. In this case, the analytical results plotted as dotted lines are however lower than the experimental ones, as shown in Figs. 8 and 9. This is because the bolts connect the support model to the base plate and the weight structure without any friction forces between them, so that the bolts act like springs without any restrictions. Therefore, an adequate analytical model in agreement with the experimental results is suggested in-between of the above two ideal analytical ones.

According to the above discussion, the stiffness of the bolts was assumed as finite only in the axial direction and infinite in the other directions, as a more realistic model of bolt connection. As a result, the analytical results plotted with solid lines agree well with the experimental ones, as shown in Figs. 8 and 9. In this analytical model, the horizontal slippage of the support structure relative to the base plate and the weight structure is prohibited, and only the extension and contraction of the bolts are considered as deformations. It is therefore found that the support models in the experiments were actually fixed tightly on the base plate by the bolts and the horizontal slippage of the support models was restricted by the friction forces. Based on this, the assumption applied here seems reasonable and the analytical model is adequate to estimate the dynamic behaviors of the support structure with flexible plates fixed by bolts. Using this analytical model, the eigen modes were recalculated and summarized in Table 2. The modes and their orders are the same as those of the rigid bolt model shown in Table 1. It is therefore confirmed that the experimental results estimated from the hammering test are not affected by the analytical model.

Regarding the dependence of the frequency and stiffness on the angle, both of analytical and experimental results on frequency and stiffness does not show smooth curves to the variation of the angle of the flexible plates. This is because

Table 2 Eigen Modes and Frequencies (elastic bolt for tension).

0/90 degrees		45 degrees		25/65 degrees	
Mode	Frequency (Hz)	Mode	Frequency (Hz)	Mode	Frequency (Hz)
0-degree sway	4.03	Sway	88.3	25-degree sway	53.6
90-degree bending	12.4	Rotation	118	65-degree sway	106
Rotation	83.5	Rocking	329	Rotation	118
90-degree sway	104	Vertical	352	Rocking	211
Vertical	249			Vertical	352

the layout and number of the support models were not the same in the experiments, as shown in Figs 8 and 9. This is however not important, because main purpose of the experiments is to estimate the basic performance on the dynamic behaviors of the flexible plates by comparison with the analytical results.

6. Conclusion

The vibration experiments of the support structures with flexible plates for ITER major components were performed using small-sized flexible plates aiming to obtain its dynamic behaviors such as dependence of the stiffness and frequency on the loading angle. The experimental results were compared with the analytical ones in order to estimate an adequate analytical model for ITER support structure with flexible plates.

The results are summarized as follows:

1. The experimental results obtained by the hammering and frequency sweep tests were agreed each other, so that the experimental method is found adequate. The basic mechanical characteristics such as dependence of the stiffness and frequency on the loading angle are obtained as a basis of the support structure with flexible plates.
2. The numerical analyses were performed for comparison with the experimental results. As a result, the bolt connection of the flexible plates on the base plate strongly affected on the stiffness of the flexible plates. Among three typical analytical models, the analytical results modeling the bolts with finite stiffness only in the axial direction and infinite stiffness in the other directions agree well with the experimental ones. This analytical model is therefore found adequate to estimate the dynamic behaviors of the support structure with flexible plates fixed by bolts.

The stiffness of the support structure for the ITER VV can be estimated, using the proposed analytical model. This analytical model can be ensured by adopting a mechanism such as a shear key to prohibit the horizontal slippage between connection interfaces of the support structure. The dynamic analysis of the whole ITER tokamak device will be performed using the proposed analytical model in the future.

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