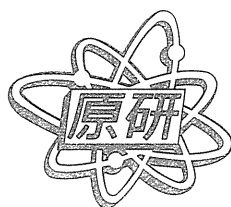


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**DYNAMIC ANALYSIS OF ITER TOKAMAK  
BASED ON RESULTS OF VIBRATION TEST USING SCALED MODEL**

**January 2005**

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and Masataka NAKAHIRA**

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## **Dynamic Analysis of ITER Tokamak Based on Results of Vibration Test Using Scaled Model**

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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 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 connection of 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. Based on this, numerical analysis regarding the actual support structure of the ITER VV and TF coil was performed. The support structure composed of flexible plates and connection bolts was modeled as a spring model composed of only two spring elements simulating the in-plane and out-of-plane stiffness of the support structure with flexible plates including the effect of connection bolts. The stiffness of both spring models for VV and TF coil agree well with that of shell models, simulating actual structures such as flexible plates and connection bolts based on the experimental results. It is therefore found that the spring model with the only two values of stiffness enables to simplify the complicated support structure with flexible plates for the dynamic analysis of the VV and TF coil. Using the proposed spring model, the dynamic analysis of the VV and TF coil for the ITER were performed to estimate the integrity under the design earthquake. As a result, it is found that the maximum relative displacement of 8.6 mm between VV and TF coil is much less than 100 mm, so that the integrity of the VV and TF coil of the ITER are ensured for the

expected earthquake event.

**Keywords:** ITER, Support Structure, Flexible Plate, Dynamic Analysis, Spring Model, Simplified Model, Earthquake, Seismic Response, Vibration, Frequency Sweep Test, Hammering Test, Stiffness, Eigen Modes, Numerical Analysis

## 縮小モデルを用いた振動試験結果に基づく ITER トカマクの動解析

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(2004年10月20日受理)

本研究では、トロイダル磁場コイルや真空容器等の ITER の主要機器に用いられる板バネを用いた複雑な構造の支持構造体に関して、剛性の荷重方向依存性等の基礎的機械特性の取得を目的として、小規模試験体を用いた振動試験を行い、この結果を元に、簡易化された動解析用支持脚数値解析モデルを提案し、さらに、提案したモデルを用いて ITER トカマクの動解析を実施している。打診試験と周波数スイープ試験とによって得られた実験結果は一致しており、実験方法の信頼性が確認された。また、適切な数値計算手法を評価するため、実験結果を数値計算結果と比較した。その結果、ボルト締結が支持構造の剛性に強い影響を与えることが明らかになった。ボルトのモデル化に関する考察の結果、ボルトの引張方向の剛性のみを有限とし、他の方向の剛性を有限とするモデルを用いた数値計算結果が実験結果と一致した。この仮定に基づき、ITER の真空容器とトロイダル磁場コイルの支持構造について数値解析を行った結果、支持脚を強軸と弱軸の剛性を模擬する2本のバネ要素のみによってモデル化したバネモデルは、実験結果に基づいて実際の構造を忠実に模擬したシェルモデルとよく一致し、バネモデルの有効性が検証された。提案したバネモデルを用いて、ITER の候補地である六ヶ所村における設計地震動に対する健全性を評価するため、真空容器とトロイダル磁場コイルの動解析を実施した。結果として、真空容器とトロイダル磁場コイルとの間の相対変位は 8.6mm であり、設計要求である 100mm を大きく下回り、地震時における ITER トカマクの主要機器の健全性が確認された。

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## 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, as shown in Fig. 1. 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, an assembly of flexible plates is adopted as a support structure of the TF coil and VV for ITER [2]. Figure 2 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. 2.

For the design of the ITER, one of the issues is displacement of major components caused by an earthquake. If the relative displacement of the components becomes large and exceeds the initial gap between them, they might be damaged by the collision. In general, the dynamic behavior of the component is strongly affected by the mechanical feature of the support structure. The stiffness of the support structure with flexible plates is relatively low in the out-of plane direction although high in-plane direction, so that the support structures of the VV and TF coil strongly affect on the dynamic behaviors. The dynamic analysis is therefore required to estimate the precise displacement of the VV and TF coil during the earthquake in order to ensure the integrity of the ITER. The ITER is however composed of 18 support structures for TF coil as well as 18 support structures for VV, arranged in the toroidal direction as shown in Fig. 2. In addition, the support structure is composed of multi-plates, flanges and connection bolts. For example, the TF coil support structure is composed of 21 trapezoidal flexible plates, whose dimensions are 1.035 m in upper width, 1.5 m in

lower width, 2.25 m in height and 30 mm in thickness, respectively. The support structure is connected by 36 bolts with nominal diameter of 100 mm (M100) on the tokamak base structure and 20 bolts with nominal diameter of 80 mm (M80) at the bottom of the TF coil through the flanges, respectively. Modeling the support structure is therefore the most critical issue for the dynamic analysis of the ITER due to complication of the precise modes of the support structures of VV and TF coil. For modeling the support structure, the mechanical characteristics such as stiffness have to be evaluated by the experiment. There are, however, insufficient studies of the support structure 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. Using the proposed model, the dynamic analysis is performed under a design earthquake assumed at Rokkasho, a candidate site of the ITER.

## 2. Experimental Apparatus

Figure 3 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 model, as shown in Fig. 4. 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, as shown in Fig. 3. 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. 4.

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.

### 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 5 shows the vibration modes of support model with angle of 45 degrees, as an example of the results. Table 1 summarizes the 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 the swaying mode in the horizontal direction, rotating modes around the vertical direction, rocking modes around the horizontal direction and the vertical vibration mode. It is noted as a special case of 90 degrees that the bending vibration mode is induced 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 analytical results will be compared with the experimental ones in detail in the section V.

#### 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 with Table 1, the peak for the sway mode can be clarified among the other modes. In the latter test, a vibrating table changing the frequency from 10 Hz to 200 Hz was used. Two deferent 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 deferent tests, respectively, as shown in Figs. 8 and 9. Based on this result, 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. Comparison of Experiment and Numerical Analysis

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 Section III, plotted with broken lines. In this analysis, the connection bolts were assumed as rigid beams with infinite stiffness. From Figs. 8 and 9, the experimental results are lower than those of the analytical ones. It is therefore suggested that the effect of the bolt connection cannot be ignored on the actual frequency and stiffness of the support model.

In order to estimate the effect of bolt connection, the bolt was modeled as a beam with finite stiffness as another ideal case. 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 just 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 expansion 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. This assumption can be realized and ensured in the real machine by adopting a mechanism such as a shear key to prohibit the horizontal slippage between connection interfaces of the support structure. 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 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 a matter, because the 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. Modal Analysis of ITER Tokamak Using Shell Model and Spring Model

Modal analyses were performed using a model of vibration system composed of a dummy weight and four support structures of the ITER components with flexible plates. The four support structures were placed on the circle with the same radius as the real machine, at the angular intervals of 90 degrees, as shown in Fig. 10. Using this model, parameter survey was performed with changing the values of angle between out-of-plane (low stiffness) and vibration directions of the support structures in order to estimate the dependence of horizontal stiffness of the support structure on the vibration direction.

The support structure was modeled with shell elements for flexible plates and beam elements for bolts fixing the support structure on the base and the component. In the analysis model, the stiffness of the bolts was assumed as finite in the axial direction only but infinite in the other directions based on the discussion in the previous section. This assumption can be realized and ensured by adopting a mechanism such as a shear key to prohibit the horizontal slippage between connection interfaces of the support structure.

The horizontal stiffness of the support structure was calculated from the eigen frequency of swaying vibration mode. The calculated stiffness of the VV and TF coil support structures at the angles  $\theta$  (0, 25, 45, 65 and 90 degrees) of the flexible plates to the vibration direction are shown as the symbols of circles and squares in Fig. 11, respectively. From these results, a spring model of the support structure was proposed for the simplification of the dynamic analysis model. This spring model is composed of only two spring elements simulating the in-plane and out-of-plane stiffness of the support structure with flexible plates including the effect of connection bolts. The vertical stiffness of the spring model can be modeled as infinite. This is because (1) the primary purpose of the dynamic analysis is to estimate the horizontal deformation of the VV and TF coil caused by the horizontal vibration, and (2) the effect of the vertical stiffness by bolt connection on the horizontal vibration is already included in the calculated horizontal stiffness. The values of in-plane and out-of-plane stiffness of the spring element were directly obtained from the results at 90 and 0 degrees shown in Fig. 11, respectively. Table 3 shows the in-plane (90 degrees) and out-of-plane (0 degree) eigen frequencies  $f_{in-plane}$  and  $f_{out-of-plane}$  for VV and TF coil obtained by the shell model, respectively. The values  $K_{in-plane}$  and  $K_{out-of-plane}$  of stiffness used for the spring models



for VV and TF coil are also summarized in Table 3, respectively. The angular dependency of the support structure stiffness  $K_{spring}$  of the spring model can be expressed as follows with  $K_{in-plane}$ ,  $K_{out-of-plane}$ :

$$K_{spring} = K_{in-plane} \sin^2 \theta + K_{out-of-plane} \cos^2 \theta \quad (1)$$

The results are shown as a broken line for VV and a dotted line for TF coil in Fig. 11, respectively. The stiffness of both spring models for VV and TF coil agree well with that of shell models although the both stiffness of the spring models are slightly lower than that of the shell models. It is therefore found that the spring model with the only two parameters, in-plane and out-of-plane stiffness, enables to simplify the complicated support structure with flexible plates for the dynamic analysis of the VV and TF coil with slightly safer side estimation.

## 7. Dynamic Analysis of ITER Tokamak Using Spring Model

As mentioned above, the horizontal displacement of the VV and TF coil of the ITER is the primary concern for the earthquake. Therefore, the dynamic analysis of the VV and TF coil were performed in order to estimate the relative displacement in the horizontal direction during the earthquake. Analytical models for VV and TF coil are shown in Fig. 12. Based on the results in the previous section, the spring models were adopted for the VV and the TF coil support structures.

The input acceleration wave for the dynamic analysis of the VV and TF coil was calculated by the response analysis of the whole tokamak building [4]. The input earthquake motion for the analysis of the building was 0.45 m/s in velocity at the base stratum [4]. This is almost the same as the maximum design seismic wave used for the nuclear facility in Rokkasho area, a candidate site for the ITER.

Figure 13 shows typical deformation results of VV and TF coil under the dynamic analysis, respectively. The maximum horizontal displacements of the VV and the TF coil were 4.1 mm at the point A and 4.5 mm at the point B as shown in Fig. 13, respectively. The point A of VV and the point B of TF coil face with a current design gap of 100 mm between VV and TF coil. The maximum relative displacement between VV and TF coil can therefore be estimated as a sum of their maximum displacement. It is therefore found that the maximum relative displacement of 8.6 mm between VV and TF coil is much less than 100 mm, so that the integrity of the major components (VV and TF coil) of the ITER tokamak device are ensured for the earthquake event.

## 8. 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. Using the model, the dynamic analysis was performed for the ITER tokamak regarding the seismic load.

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 to be 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 to be adequate to estimate the dynamic behaviors of the support structure with flexible plates fixed by bolts.
- (3) The stiffness of the support structure for the ITER VV can be estimated, using the adequate 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.
- (4) The simplified analytical model of the support structure with multiple flexible plates was proposed for the dynamic analysis of VV and TF coil as the ITER major components. The support structure with flexible plates and bolt connection was modeled as a spring model composed of only two spring elements simulating the in-plane and out-of-plane stiffness of the support structure with flexible plates including the effect of connection bolts. The stiffness of both spring models for VV and TF coil agree well with that of shell models although the both stiffness of the spring

models are slightly lower than that of the shell models. It is therefore found that the spring model with the only two parameters, in-plane and out-of-plane stiffness, enables to simplify the complicated support structure with flexible plates for the dynamic analysis of the VV and TF coil with slightly safer side estimation.

- (5) Using the simplified spring model, the dynamic analysis of the VV and TF coil for the ITER were performed for the estimation under the design earthquake at Rokkasho area. As a result, it is found that the maximum relative displacement of 8.6 mm between VV and TF coil is much less than 100 mm, so that the integrity of the major components (VV and TF coil) of the ITER tokamak device are ensured for the earthquake event.

## Acknowledgements

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Table 1 Eigen Modes and Frequencies

0/90 degree		45 degree		25/65 degree	
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

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

0/90 degree		45 degree		25/65 degree	
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

Table 3 Eigen Frequency Obtained by Shell Model and Stiffness of Support Structure

Used for Spring Model

	Weight	$f_{in-plane}$ (90 degrees)	$f_{out-of-plane}$ (0 degree)	$K_{in-plane}$ (90 degrees)	$K_{out-of-plane}$ (0 degree)
Vacuum Vessel	9,300 ton	8.7 Hz	0.48 Hz	7.0 GN/m	21 MN/m
Toroidal Field Coil	9,370 ton	8.6 Hz	0.37 Hz	6.8 GN/m	13 MN/m

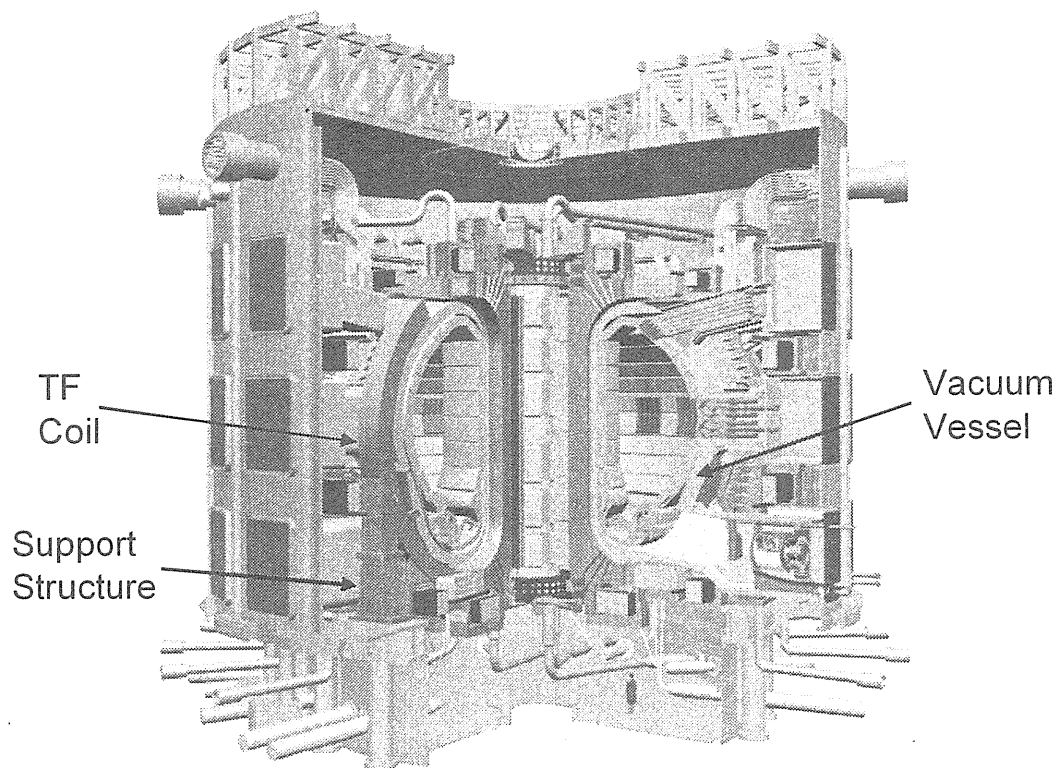


Fig.1 Overall layout of ITER

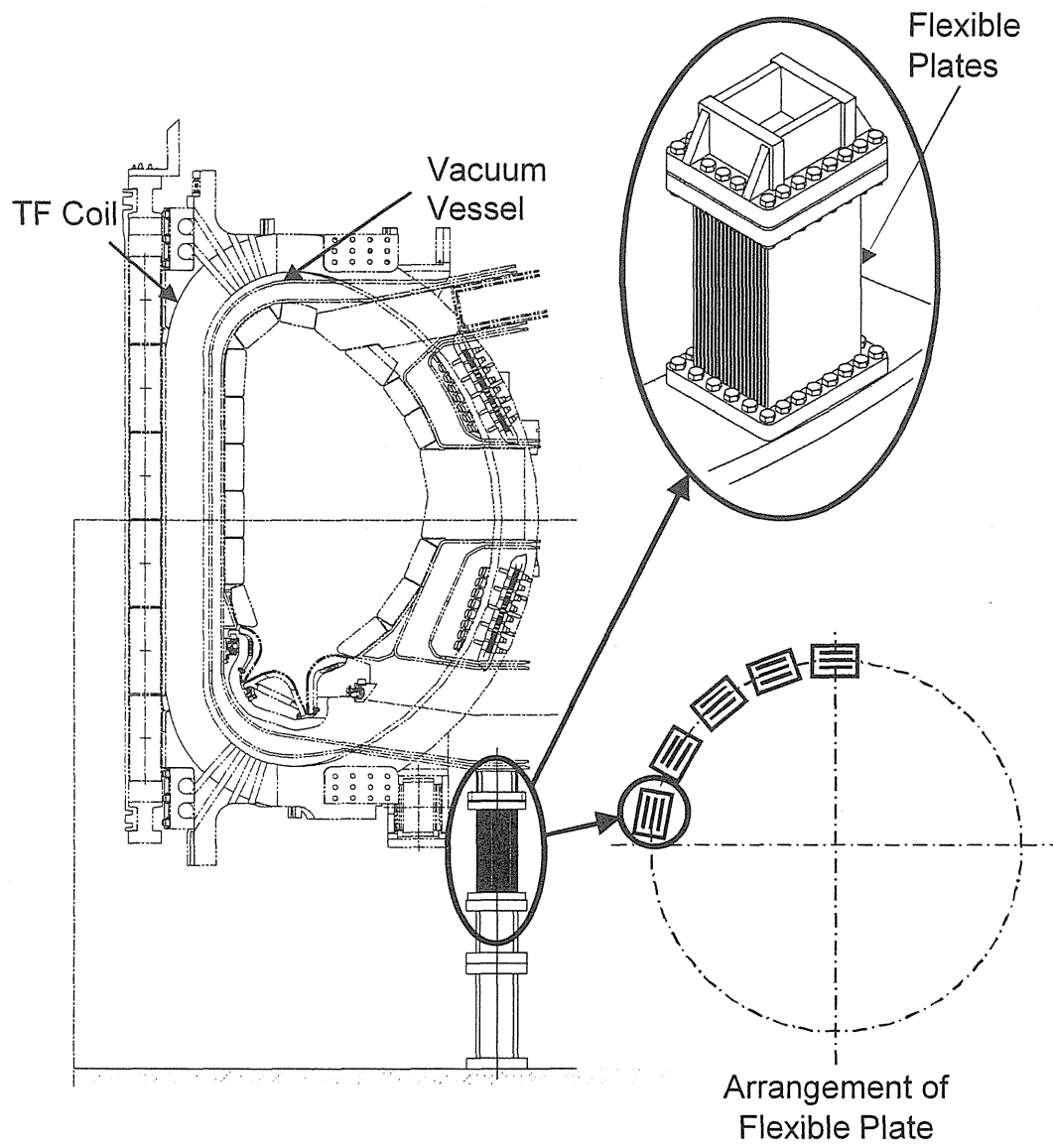


Fig.2 An example of support structure for ITER using flexible plate



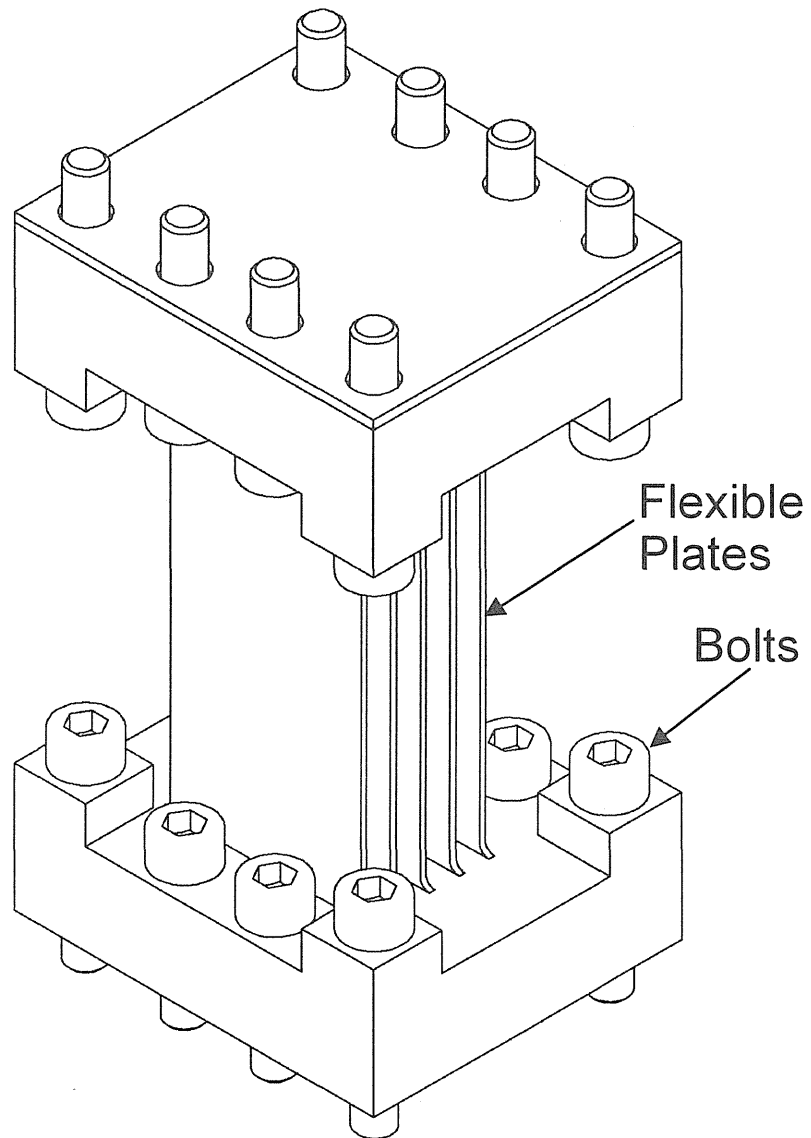


Fig.3 Support model for vibration test

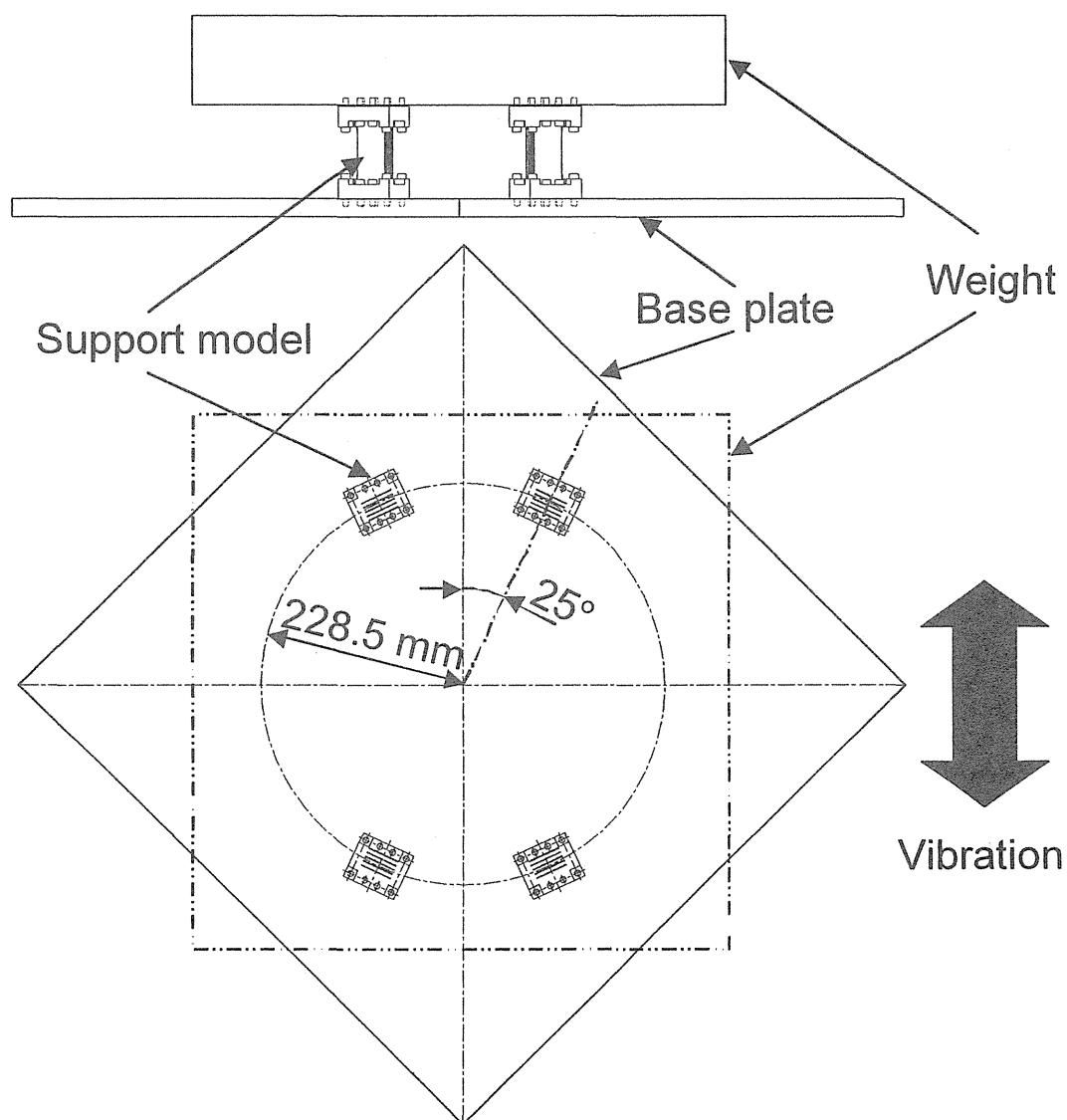


Fig.4 Configuration of vibration test (25 degree)

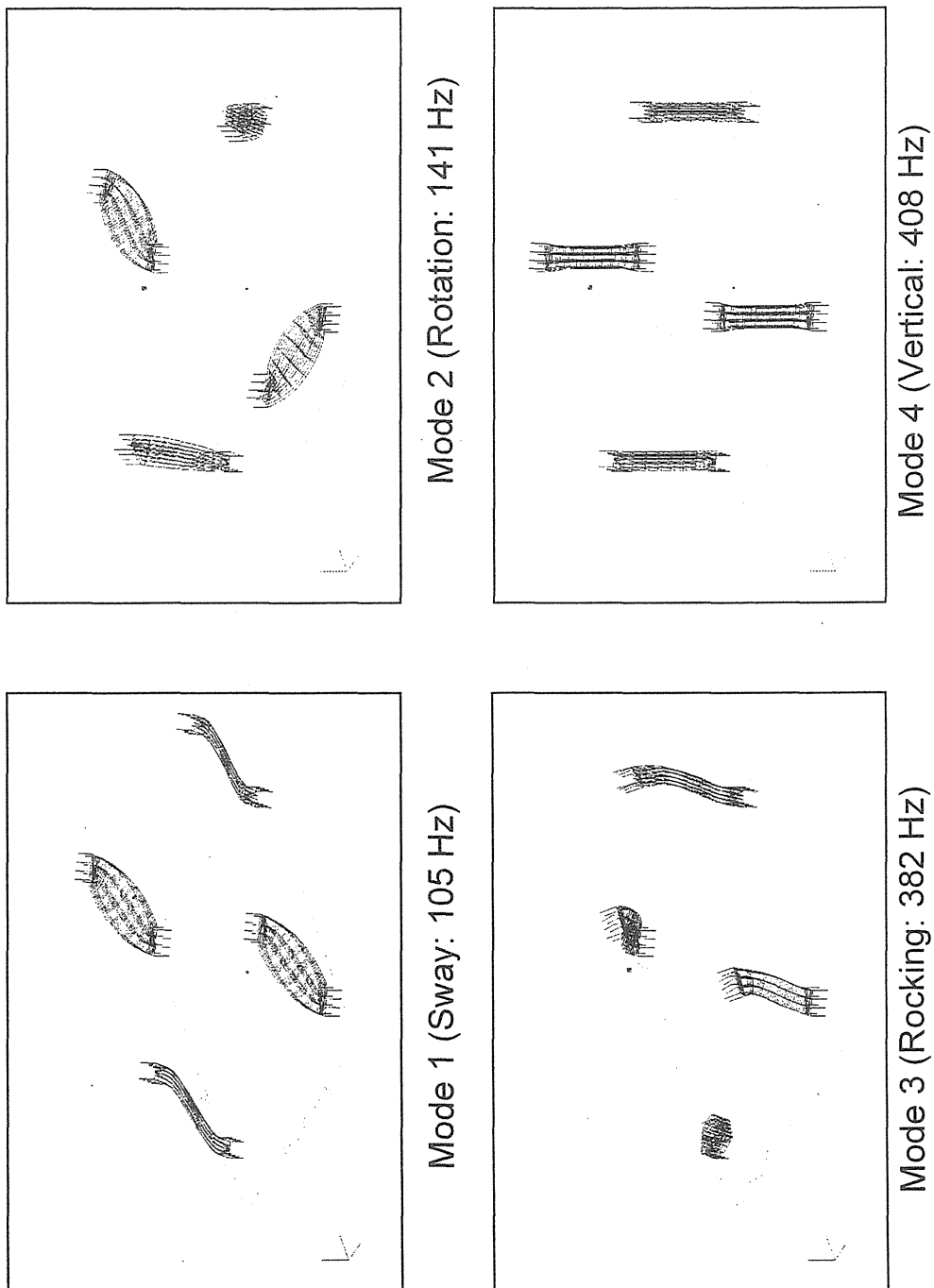


Fig. 5 Eigen Modes (45 degree)

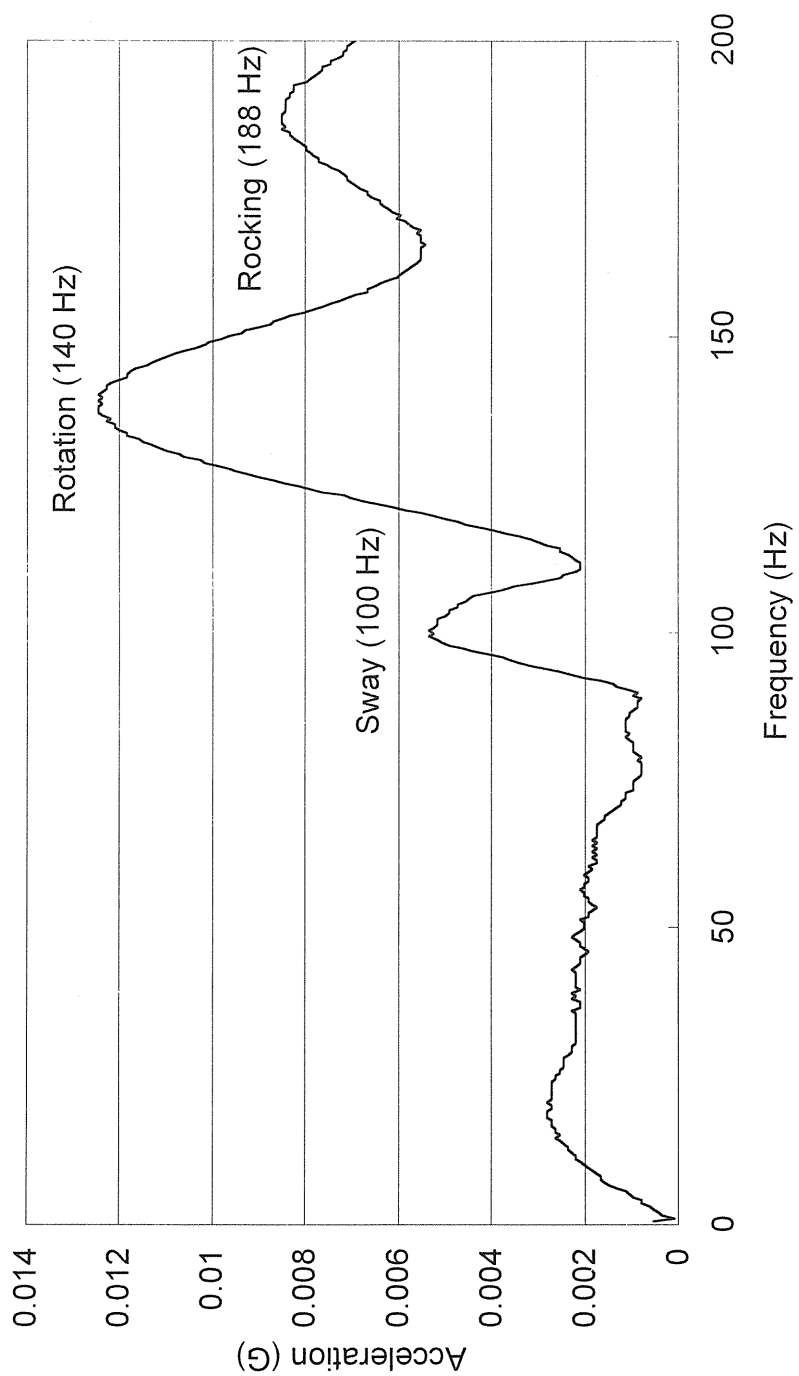


Fig.6 Result of Hammering Test (45 degree)

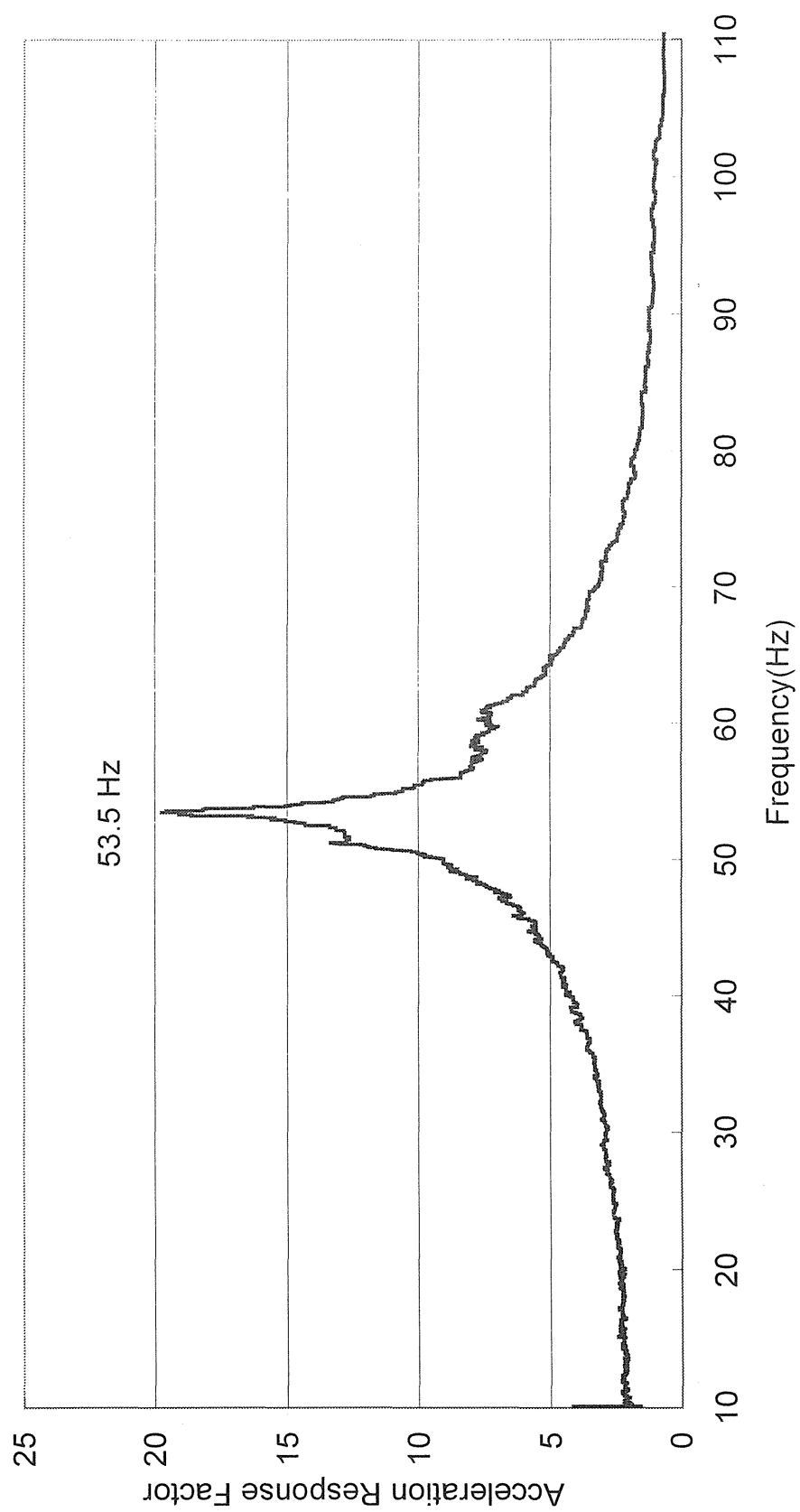


Fig.7 Frequency Sweep Test (25 degree)

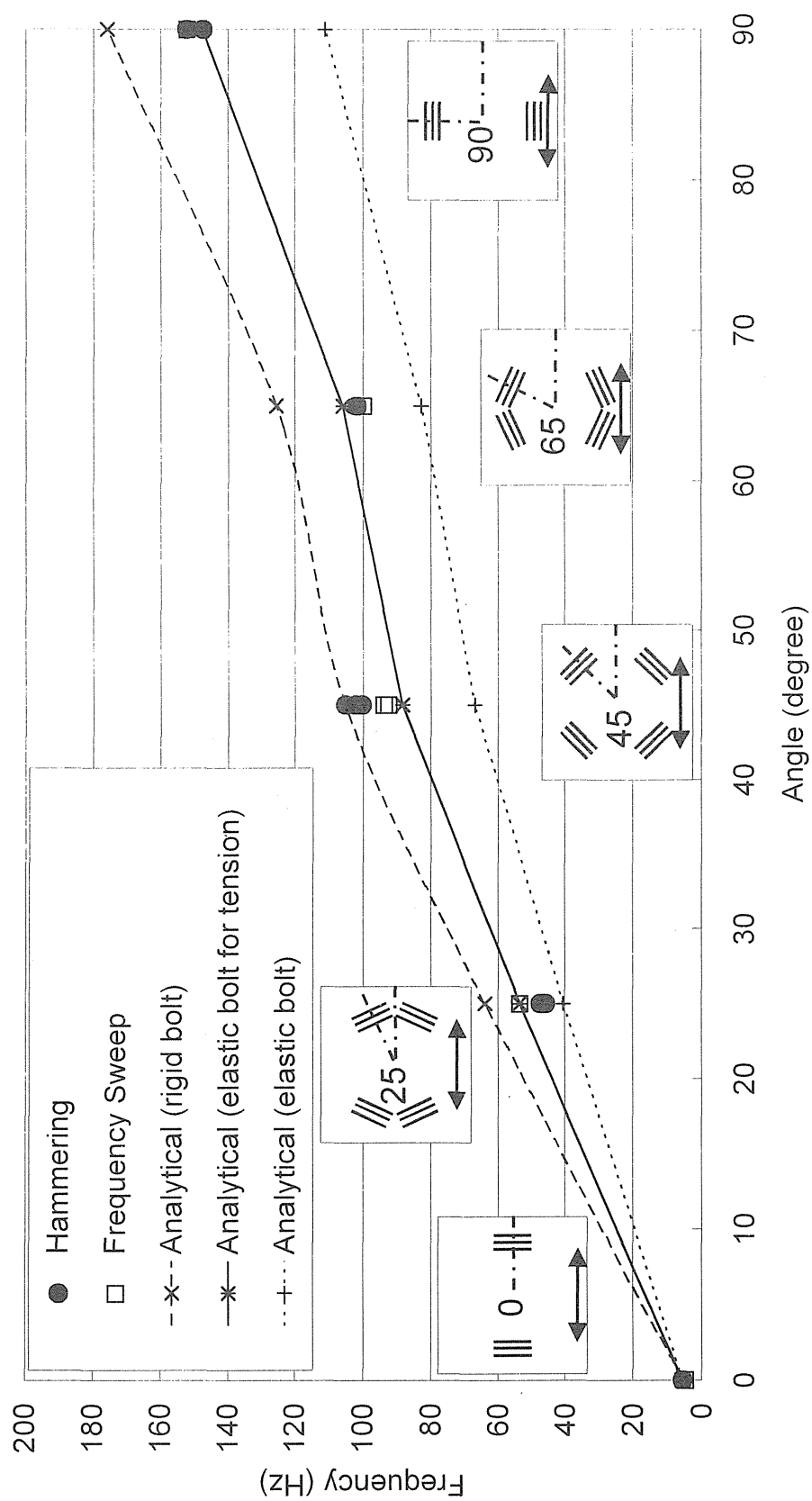


Fig.8 Comparison of Frequency between Experimental and Analytical Results

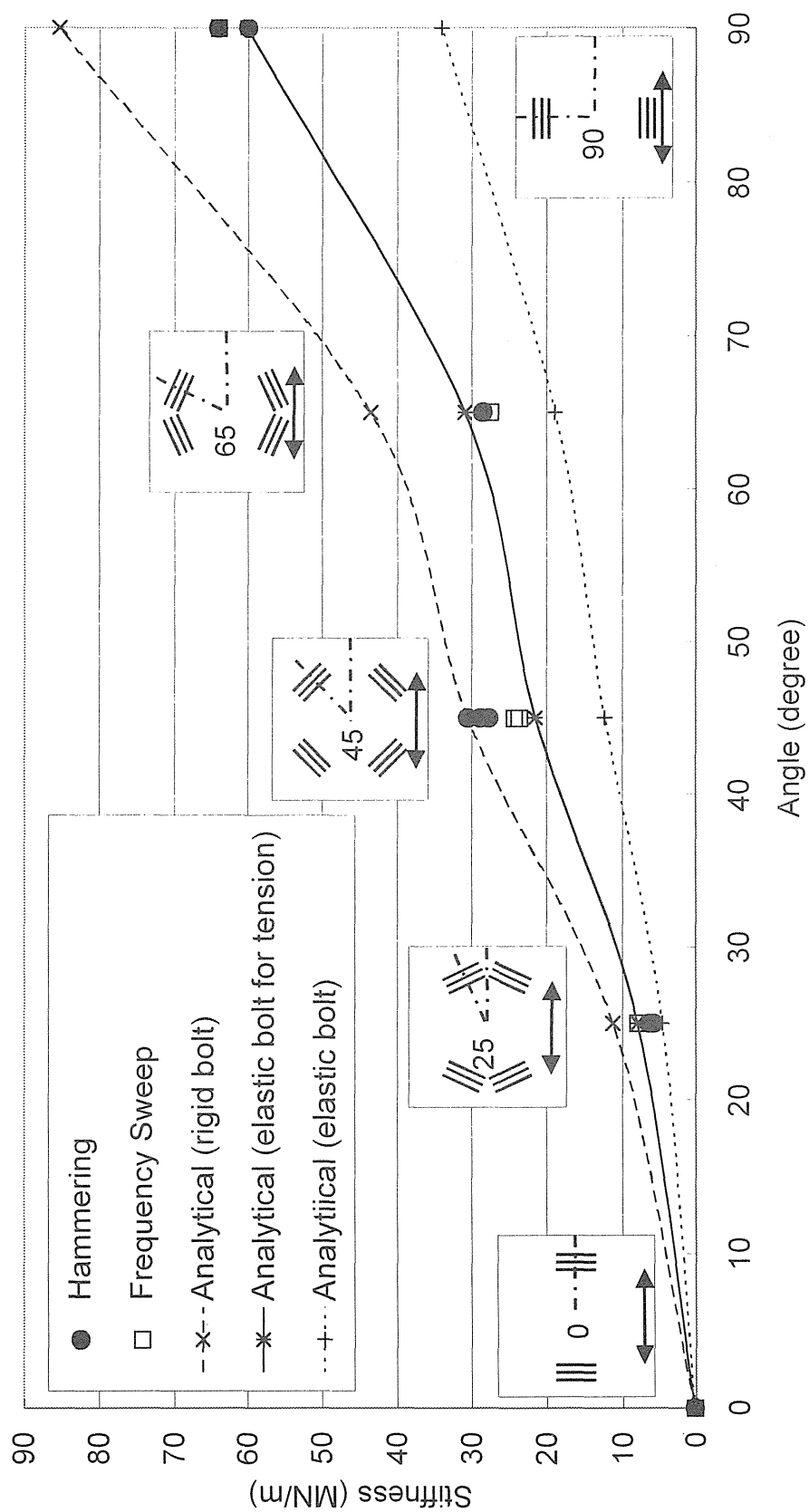
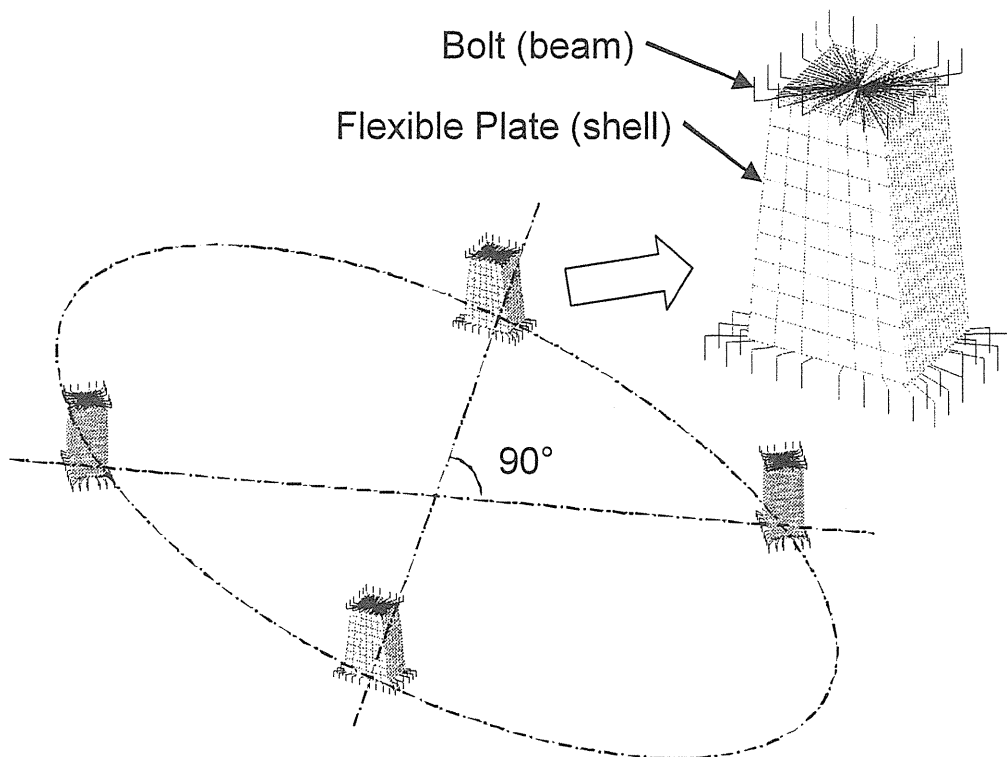
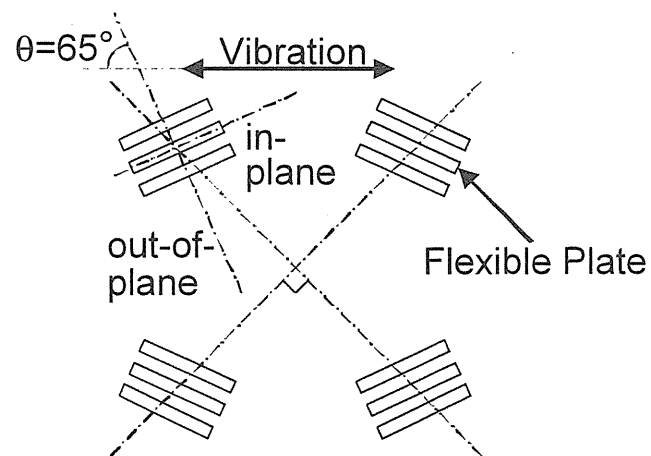


Fig. 9 Comparison of Stiffness between Experimental and Analytical Results



(a) Arrangement of support structures



(b) Schematic plan view

Fig. 10 Example of Vibration System for TF Coil (65 degree)



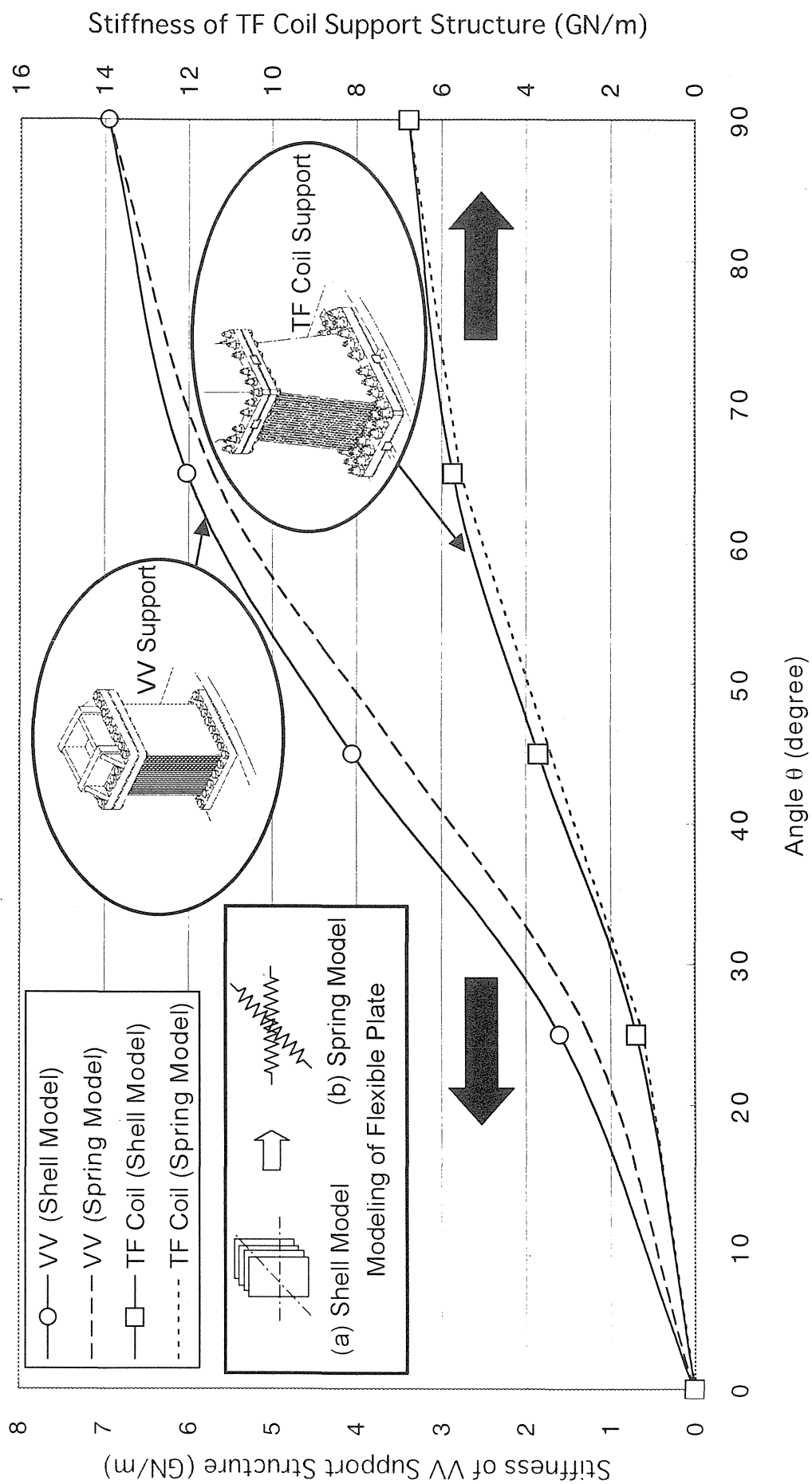


Fig. 11 Comparison of Support Stiffness between Analysis Models

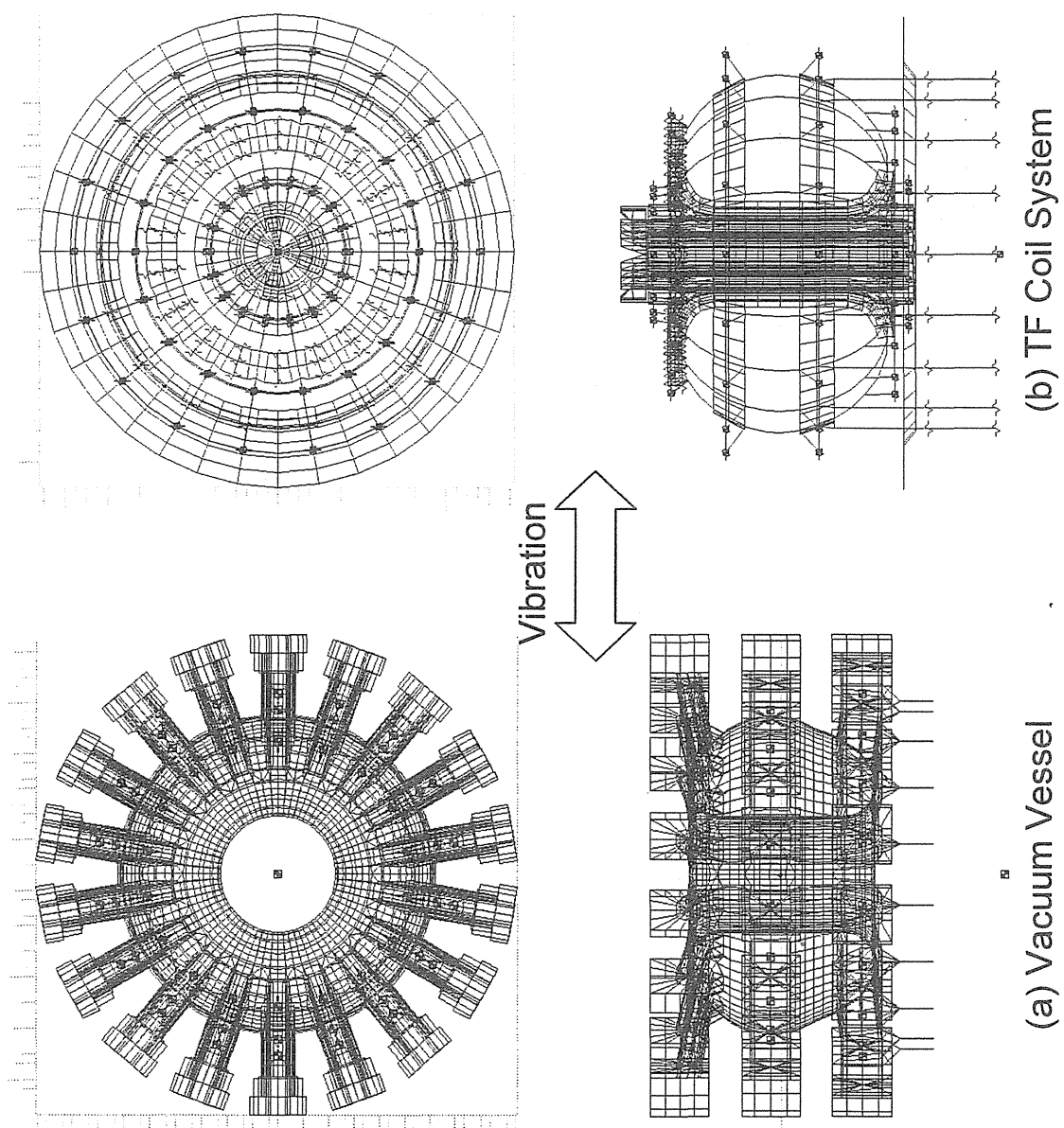


Fig. 12 Analytical Model

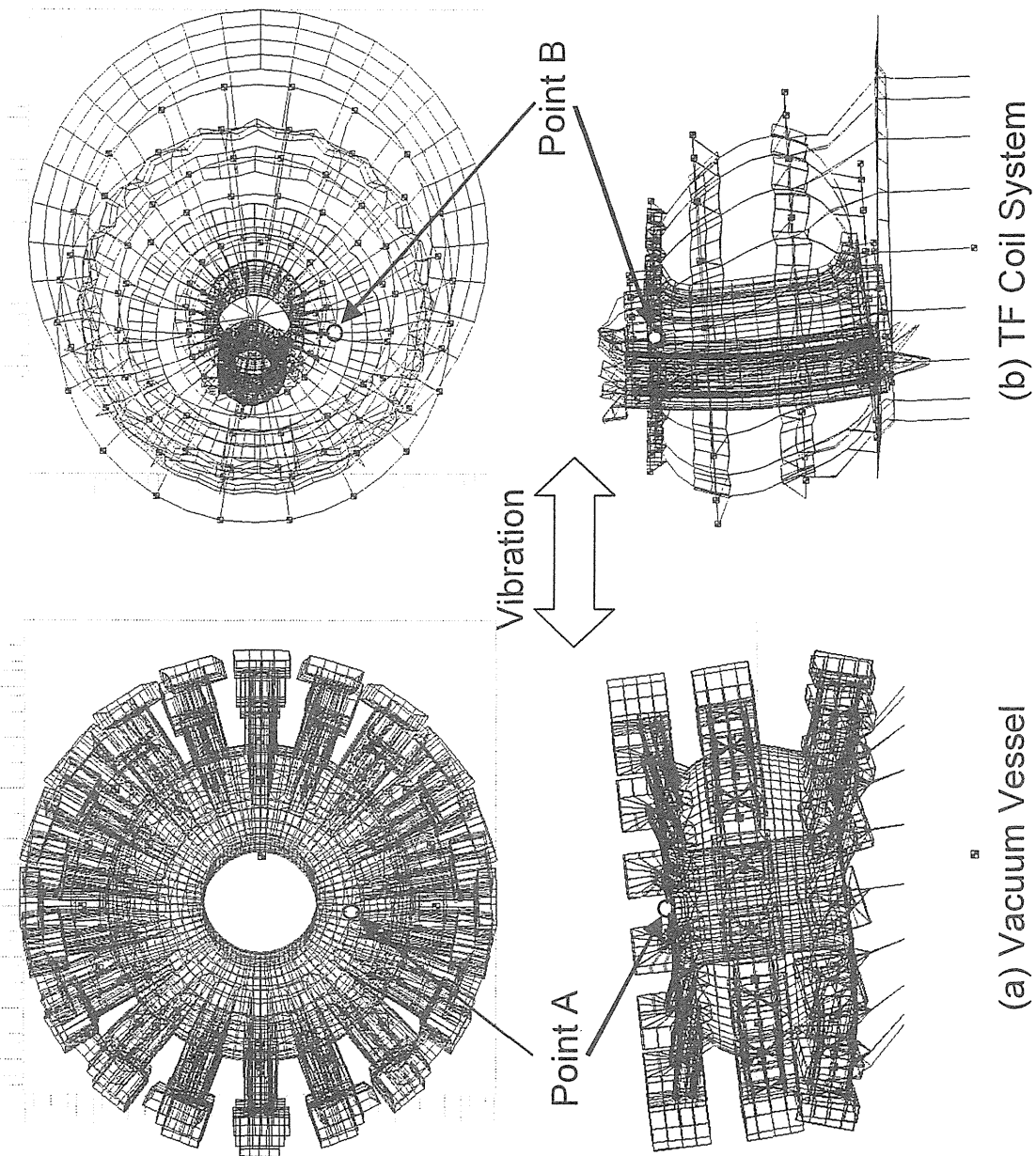


Fig. 13 Deformation and Estimation Points

## Appendix

### Effect of Support Structures on Eigen Frequencies and Modes of Vacuum Vessel and TF-CS Coil System

Table A-1 shows the eigen frequencies and modes of the vacuum vessel. In Table A-1, “Rigid Support Structure” means the results assuming infinite stiffness for the horizontal stiffness of the support structure, while “Normal Support Structure” uses the normal model with finite stiffness. The results using “Rigid Support Structure” show the eigen modes of the VV itself without the effect of the support structure. The effective stiffness  $k_{whole}$  and  $k_{VV}$  of whole system and the VV itself can be calculated from the frequencies  $f_{normal}$  and  $f_{rigid}$  of “Normal Support Structure” and “Rigid Support Structure”, respectively, as follows:

$$k_{whole} = m_{effective} (2\pi f_{normal})^2$$

$$k_{VV} = m_{effective} (2\pi f_{rigid})^2$$

where is the effective stiffness regarding to the eigen mode. The effective stiffness  $k_{support}$  of the support structure can be calculated as follows:

$$1/k_{support} = 1/k_{whole} - 1/k_{VV}$$

The contribution rate of the support structure on the effective stiffness of whole system can be defined as:

$$(1/k_{support})/(1/k_{whole})$$

The results are shown in Table A-1. For the horizontal modes, the contribution rate is highest comparing to other modes and the effect of the support structure is dominant because the rate is 62%. It also affects on the vertical mode with rather small contribution ratio, 44%. On the contrary, it does not affect on the oval mode of the VV upper half, because the lower half of the VV and the support structure does not move in this mode.

Table A-2 shows the eigen frequencies and modes of the TF-CS coil system. The effect of the support structure on the vibration of the whole system is estimated in the same manner as the VV. In Table A-2, “Out of Phase” means the TF coils and CS coil moves out of phase. The contribution rate is relatively low comparing to the VV. In the horizontal mode, the rate is 36% and even in the highest case, the rocking mode, it is 41%. This means the stiffness of the TF-CS coil system itself is comparable or relatively lower than that of the support structure.

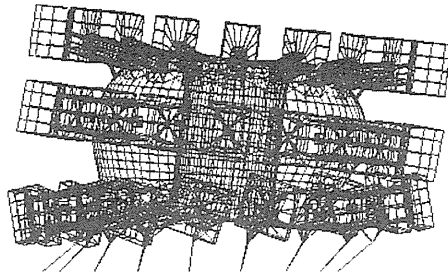
From these results, it is found that the support structure strongly affects on the vibration of the component. Therefore, it is essentially important to investigate mechanical characteristics of the support structure for the seismic design.

Table A-1 Eigen Frequencies and Modes of Vacuum Vessel

Modes	Normal Support Structure		Rigid Support Structure		Contribution of Support Structure (%)
	Frequency (Hz)	Figure	Frequency (Hz)	Figure	
Horizontal	3.94	A-1	6.41	A-2	62
Vertical	6.96	A-3	9.30	A-4	44
Rotation	7.34	A-5	7.74	A-6	10
Rocking	9.52	A-7	10.6	A-8	19
Oval (Out of Phase between Upper and Lower Half)	15.3	A-9	-	-	-
Oval (Upper Half Only)	15.4	A-10	15.4	A-11	0

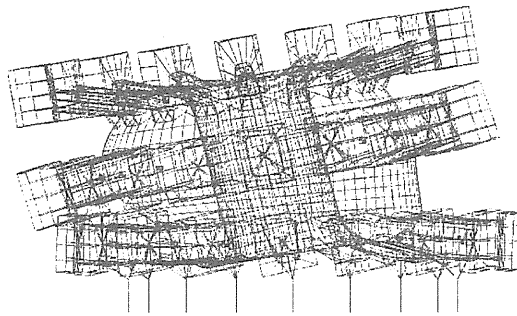
Table A-2 Eigen Frequencies and Modes of TF-CS Coil System

Modes	Normal Support Structure		Rigid Support Structure		Contribution of Support Structure (%)
	Frequency (Hz)	Figure	Frequency (Hz)	Figure	
Horizontal	5.40	A-12	6.74	A-13	36
Horizontal (Out of Phase)	9.70	A-14	9.78	A-15	1.6
Vertical	9.88	A-16	10.3	A-17	8.0
Rotation	11.4	A-18	12.5	A-19	17
Rocking	12.2	A-20	15.9	A-21	41
Rotation (Out of Phase)	16.4	A-22	16.5	A-23	1.2
Vertical (Out of Phase)	16.9	A-24	17.2	A-25	3.5
Rocking (Out of Phase)	18.2	A-26	19.7	A-27	15



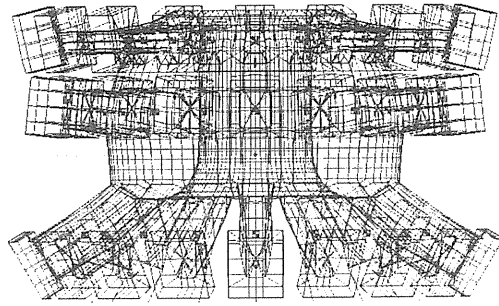
□

Fig. A-1 Horizontal Mode of Vacuum Vessel (Normal Support Structure)



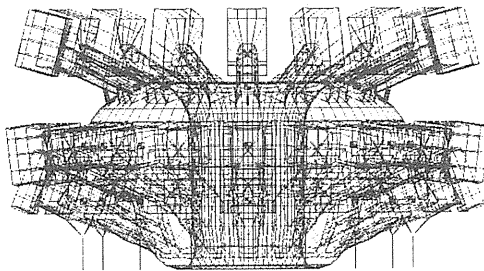
□

Fig. A-2 Horizontal Mode of Vacuum Vessel (Rigid Support Structure)



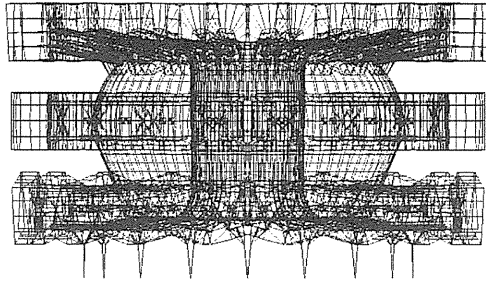
5

Fig. A-3 Vertical Mode of Vacuum Vessel (Normal Support Structure)



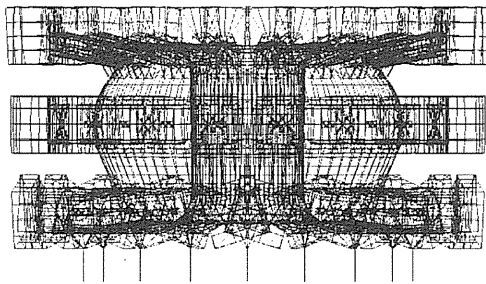
5

Fig. A-4 Vertical Mode of Vacuum Vessel (Rigid Support Structure)



5

Fig. A-5 Rotation Mode of Vacuum Vessel (Normal Support Structure)



5

Fig. A-6 Rotation Mode of Vacuum Vessel (Rigid Support Structure)



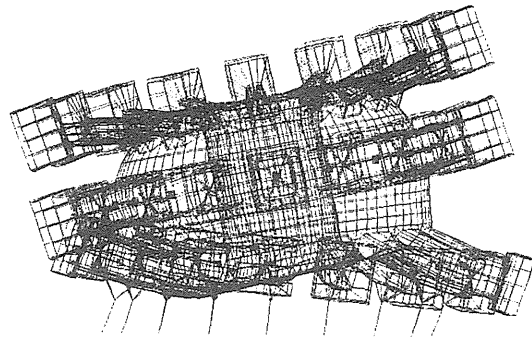


Fig. A-7 Rocking Mode of Vacuum Vessel (Normal Support Structure)

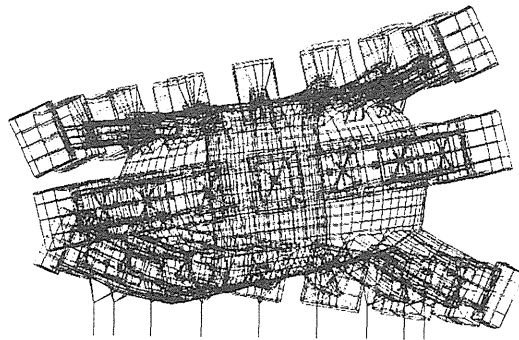


Fig. A-8 Rocking Mode of Vacuum Vessel (Rigid Support Structure)

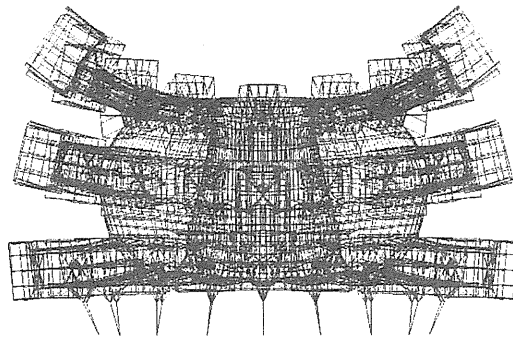
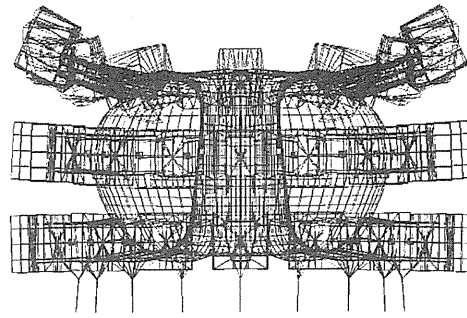
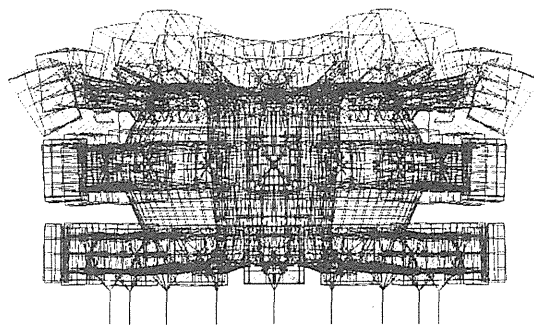


Fig. A-9 Oval Mode (Out of Phase between Upper and Lower Half) of Vacuum Vessel  
(Normal Support Structure)



5

Fig. A-10 Oval Mode (Upper Half Only) of Vacuum Vessel (Normal Support Structure)



5

Fig. A-11 Oval Mode (Upper Half Only) of Vacuum Vessel (Rigid Support Structure)

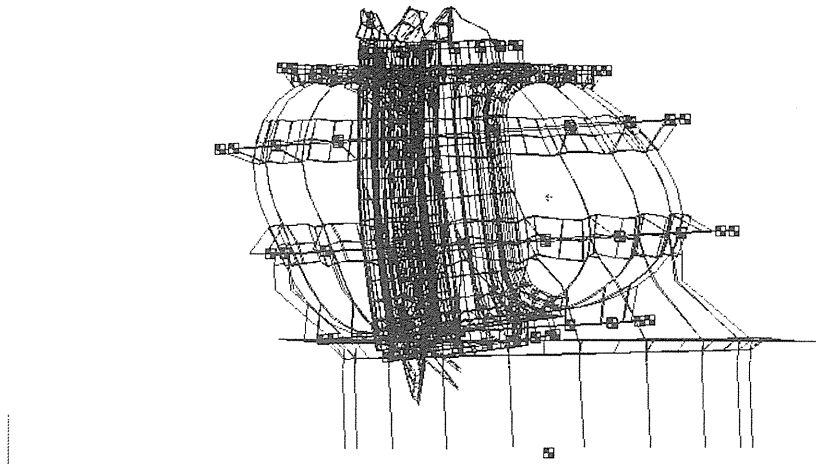


Fig. A-12 Horizontal Mode of TF-CS Coil System (Normal Support Structure)

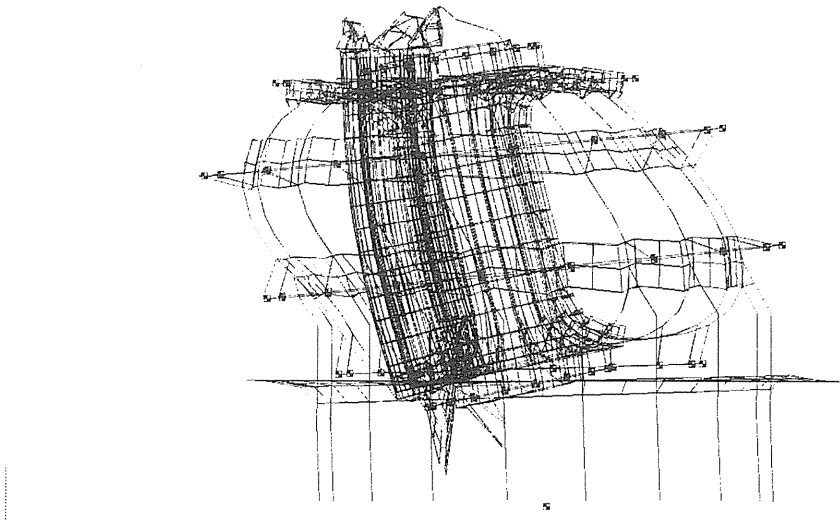


Fig. A-13 Horizontal Mode of TF-CS Coil System (Rigid Support Structure)

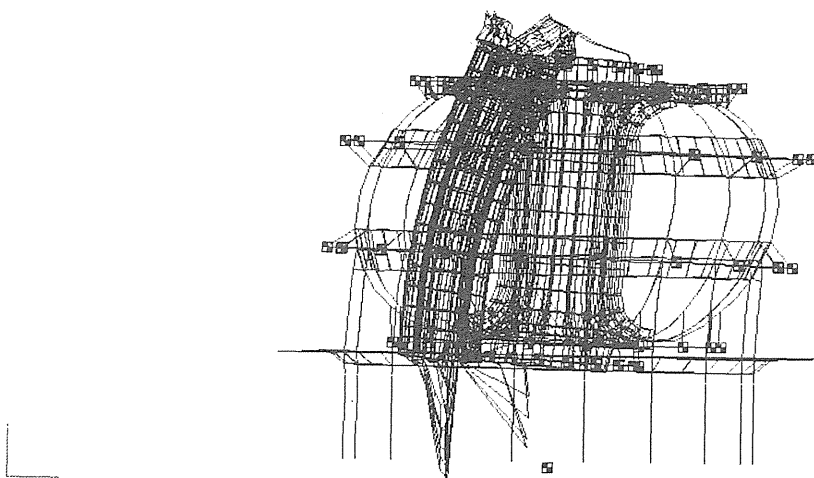


Fig. A-14 Horizontal (Out of Phase) Mode of TF-CS Coil System (Normal Support Structure)

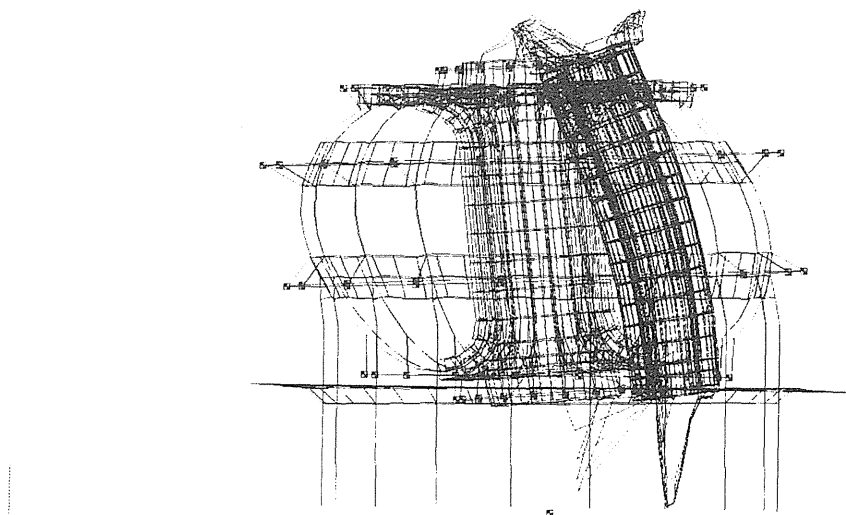


Fig. A-15 Horizontal (Out of Phase) Mode of TF-CS Coil System (Rigid Support Structure)

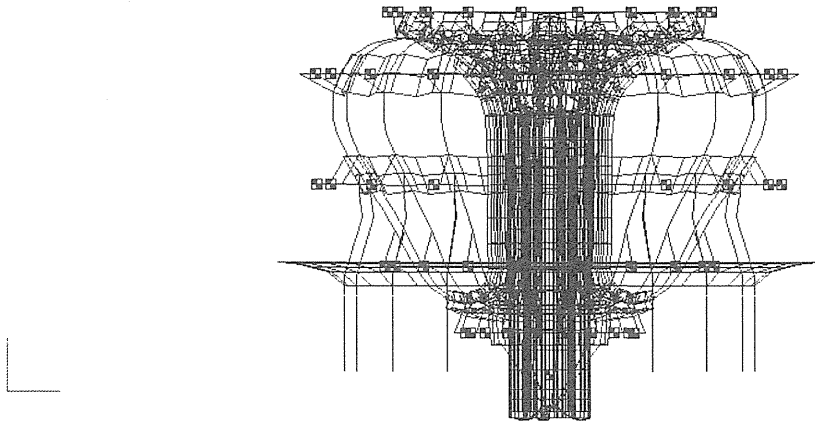


Fig. A-16 Vertical Mode of TF-CS Coil System (Normal Support Structure)

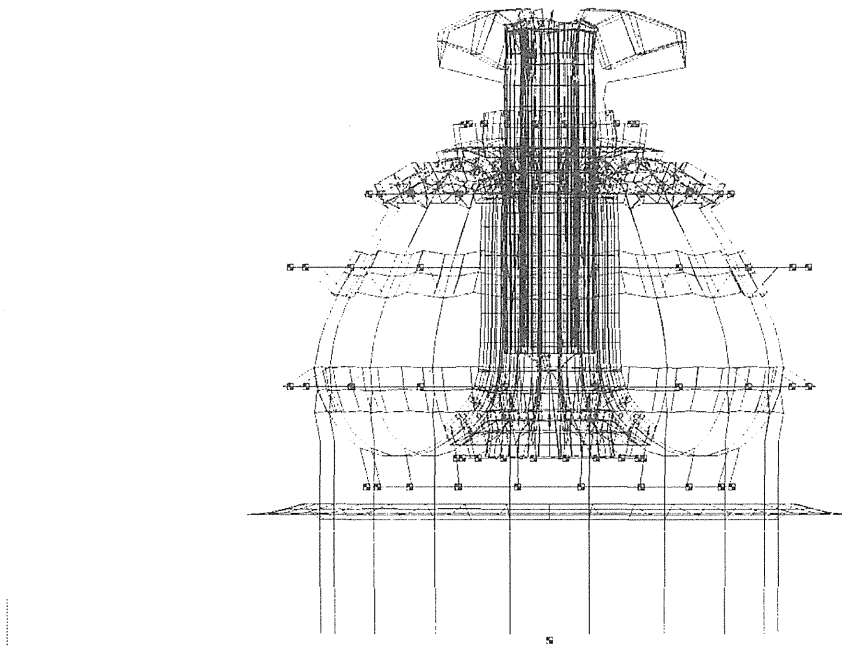


Fig. A-17 Vertical Mode of TF-CS Coil System (Rigid Support Structure)

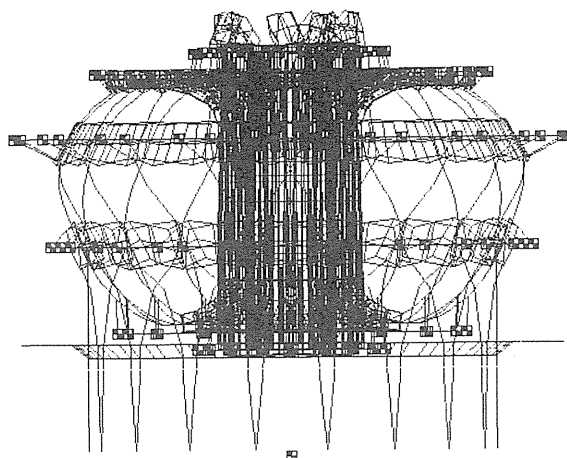


Fig. A-18 Rotation Mode of TF-CS Coil System (Normal Support Structure)

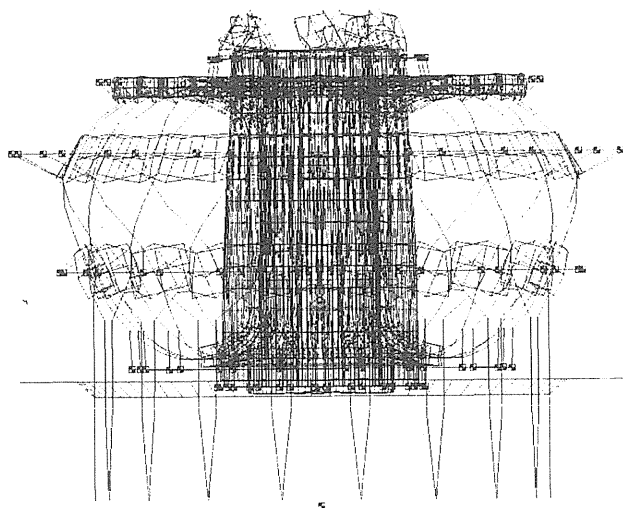


Fig. A-19 Rotation Mode of TF-CS Coil System (Rigid Support Structure)

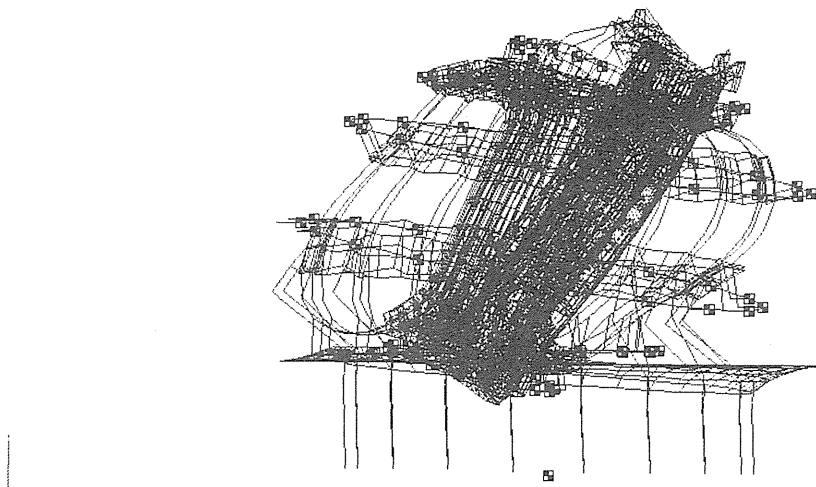


Fig. A-20 Rocking Mode of TF-CS Coil System (Normal Support Structure)

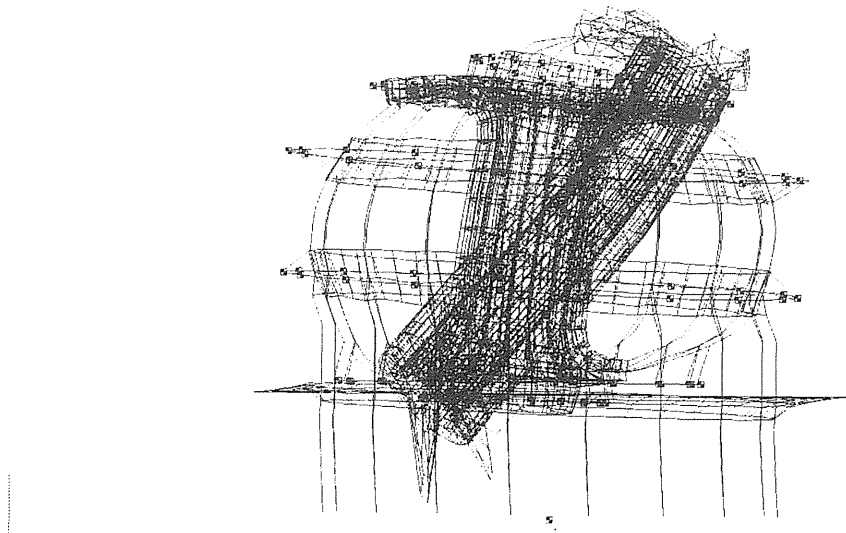


Fig. A-21 Rocking Mode of TF-CS Coil System (Rigid Support Structure)



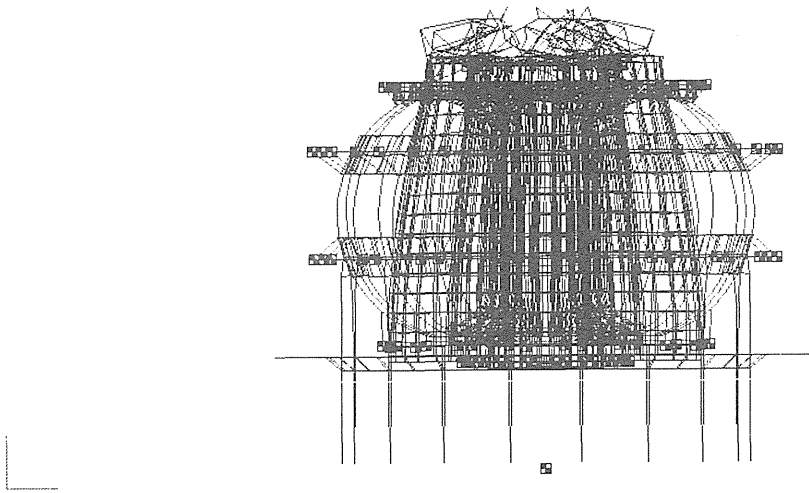


Fig. A-22 Rotation Mode (Out of Phase ) of TF-CS Coil System (Normal Support Structure)

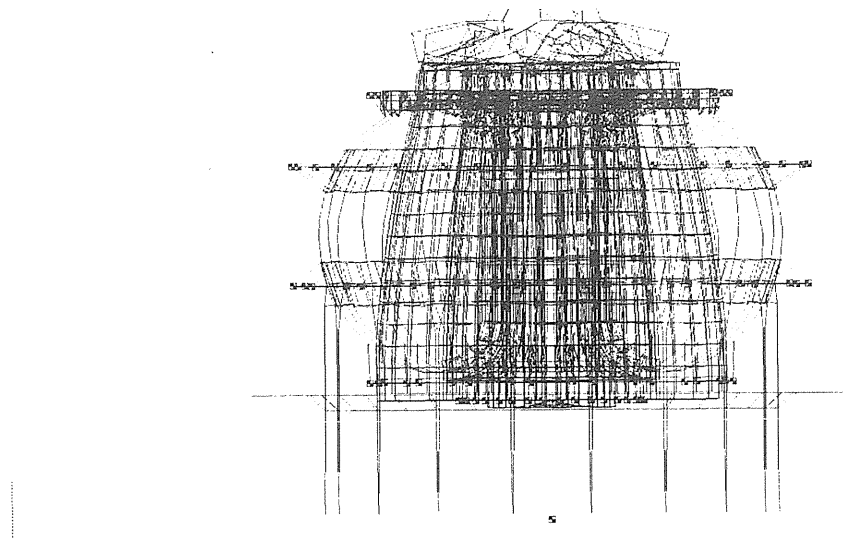


Fig. A-23 Rotation Mode (Out of Phase) of TF-CS Coil System (Rigid Support Structure)

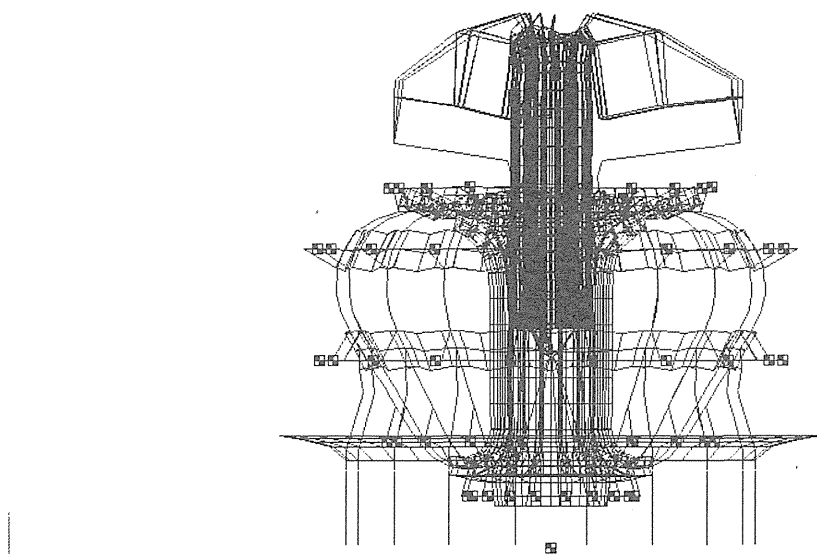


Fig. A-24 Vertical Mode (Out of Phase) of TF-CS Coil System (Normal Support Structure)

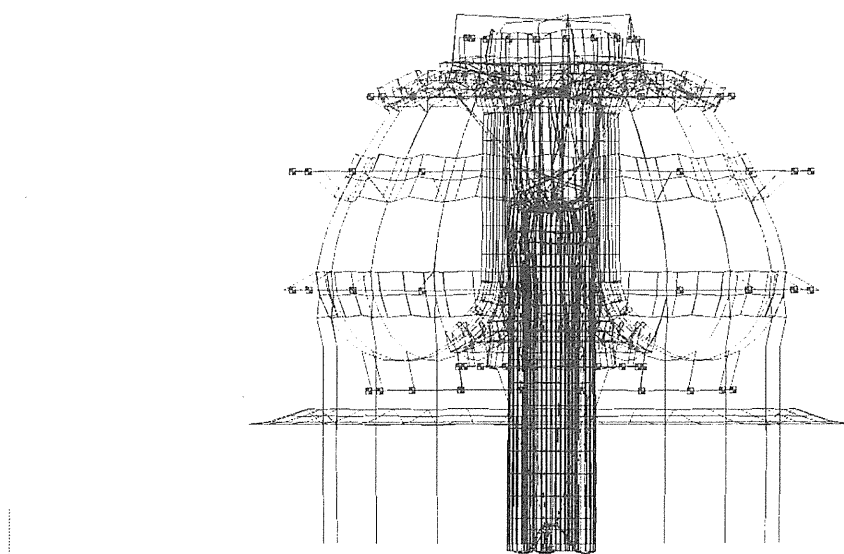


Fig. A-25 Vertical Mode (Out of Phase) of TF-CS Coil System (Rigid Support Structure)

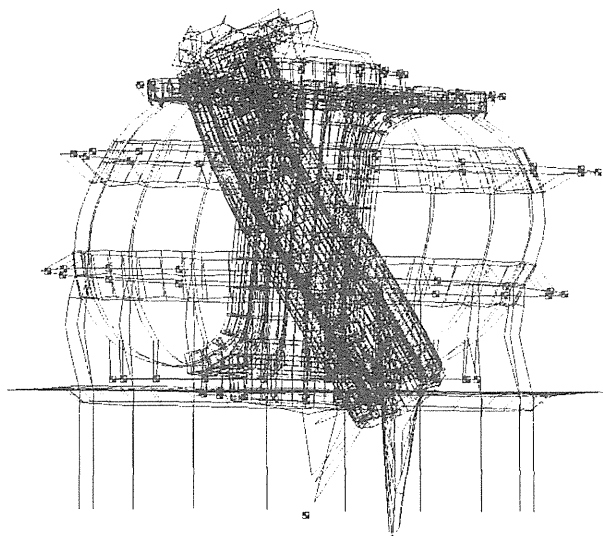


Fig. A-26 Rocking Mode (Out of Phase) of TF-CS Coil System (Normal Support Structure)

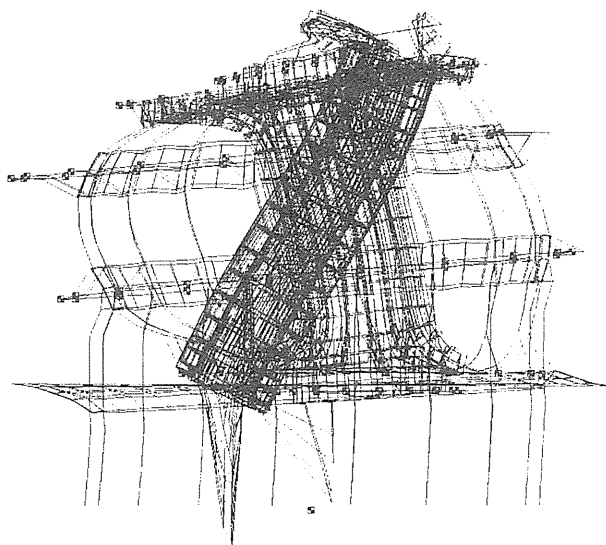


Fig. A-27 Rocking Mode (Out of Phase) of TF-CS Coil System (Rigid Support Structure)

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# 国際単位系 (SI) と換算表

表1 SI基本単位および補助単位

量	名 称	記 号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質の量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名 称	記号	他のSI単位 による表現
周波数	ヘルツ	Hz	s <sup>-1</sup>
力	ニュートン	N	m・kg/s <sup>2</sup>
圧力, 応力	パスカル	Pa	N/m <sup>2</sup>
エネルギー, 仕事, 熱量	ジュール	J	N・m
工率, 放射束	ワット	W	J/s
電気量, 電荷	クーロン	C	A・s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメン	S	A/V
磁束	ウェーバ	Wb	V・s
磁束密度	テスラ	T	Wb/m <sup>2</sup>
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光束	ルーメン	lm	cd・sr
照射度	ルクス	lx	lm/m <sup>2</sup>
放射能	ベクレル	Bq	s <sup>-1</sup>
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表2 SIと併用される単位

名 称	記 号
分, 時, 日	min, h, d
度, 分, 秒	°, ', "
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$$

表5 SI接頭語

倍数	接頭語	記 号
10 <sup>18</sup>	エクサ	E
10 <sup>15</sup>	ペタ	P
10 <sup>12</sup>	テラ	T
10 <sup>9</sup>	ギガ	G
10 <sup>6</sup>	メガ	M
10 <sup>3</sup>	キロ	k
10 <sup>2</sup>	ヘクト	h
10 <sup>1</sup>	デカ	da
10 <sup>-1</sup>	デシ	d
10 <sup>-2</sup>	センチ	c
10 <sup>-3</sup>	ミリ	m
10 <sup>-6</sup>	マイクロ	μ
10 <sup>-9</sup>	ナノ	n
10 <sup>-12</sup>	ピコ	p
10 <sup>-15</sup>	フェムト	f
10 <sup>-18</sup>	アト	a

表4 SIと共に暫定的に維持される単位

名 称	記 号
オングストローム	Å
バ ー ン	b
バ ー ル	bar
ガ ル	Gal
キ ュ リ ー	Ci
レ ン ト ゲ ン	R
ラ ド	rad
レ ム	rem

$$1 \text{ Å} = 0.1 \text{ nm} = 10^{-10} \text{ m}$$

$$1 \text{ b} = 100 \text{ fm} = 10^{-28} \text{ m}^2$$

$$1 \text{ bar} = 0.1 \text{ MPa} = 10^5 \text{ Pa}$$

$$1 \text{ Gal} = 1 \text{ cm/s}^2 = 10^{-2} \text{ m/s}^2$$

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$

$$1 \text{ rad} = 1 \text{ cGy} = 10^{-2} \text{ Gy}$$

$$1 \text{ rem} = 1 \text{ cSv} = 10^{-2} \text{ Sv}$$

(注)

- 表1～5は「国際単位系」第5版、国際度量衡局1985年刊行による。ただし、1 eVおよび1 uの値はCODATAの1986年推奨値によった。
- 表4には海里、ノット、アール、ヘクタールも含まれているが日常の単位なのでここでは省略した。
- barは、JISでは流体の圧力を表す場合に限り表2のカテゴリーに分類されている。
- EC閣僚理事会指令ではbar, barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換 算 表

力	N (=10 <sup>5</sup> dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

$$\text{粘 度 } 1 \text{ Pa} \cdot \text{s} (\text{N} \cdot \text{s/m}^2) = 10 \text{ P (ポアズ)} (\text{g}/(\text{cm} \cdot \text{s}))$$

$$\text{動粘度 } 1 \text{ m}^2/\text{s} = 10^4 \text{ St (ストークス)} (\text{cm}^2/\text{s})$$

圧	MPa (=10 bar)	kgf/cm <sup>2</sup>	atm	mmHg (Torr)	lbf/in <sup>2</sup> (psi)
	1	10.1972	9.86923	7.50062 × 10 <sup>3</sup>	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322 × 10 <sup>-4</sup>	1.35951 × 10 <sup>-3</sup>	1.31579 × 10 <sup>-3</sup>	1	1.93368 × 10 <sup>-2</sup>
	6.89476 × 10 <sup>-3</sup>	7.03070 × 10 <sup>-2</sup>	6.80460 × 10 <sup>-2</sup>	51.7149	1

エネルギー・仕事・熱量	J (=10 <sup>7</sup> erg)	kgf・m	kW・h	cal (計量法)	Btu	ft・lbf	eV
	1	0.101972	2.77778 × 10 <sup>-7</sup>	0.238889	9.47813 × 10 <sup>-4</sup>	0.737562	6.24150 × 10 <sup>18</sup>
	9.80665	1	2.72407 × 10 <sup>-6</sup>	2.34270	9.29487 × 10 <sup>-3</sup>	7.23301	6.12082 × 10 <sup>19</sup>
	3.6 × 10 <sup>6</sup>	3.67098 × 10 <sup>5</sup>	1	8.59999 × 10 <sup>5</sup>	3412.13	2.65522 × 10 <sup>6</sup>	2.24694 × 10 <sup>25</sup>
	4.18605	0.426858	1.16279 × 10 <sup>-6</sup>	1	3.96759 × 10 <sup>-3</sup>	3.08747	2.61272 × 10 <sup>19</sup>
	1055.06	107.586	2.93072 × 10 <sup>-4</sup>	252.042	1	778.172	6.58515 × 10 <sup>21</sup>
	1.35582	0.138255	3.76616 × 10 <sup>-7</sup>	0.323890	1.28506 × 10 <sup>-3</sup>	1	8.46233 × 10 <sup>18</sup>
	1.60218 × 10 <sup>-19</sup>	1.63377 × 10 <sup>-20</sup>	4.45050 × 10 <sup>-26</sup>	3.82743 × 10 <sup>-20</sup>	1.51857 × 10 <sup>-22</sup>	1.18171 × 10 <sup>-19</sup>	1

$$1 \text{ cal} = 4.18605 \text{ J (計量法)}$$

$$= 4.184 \text{ J (熱化学)}$$

$$= 4.1855 \text{ J (15°C)}$$

$$= 4.1868 \text{ J (国際蒸気表)}$$

$$\text{仕事率 } 1 \text{ PS (馬力)}$$

$$= 75 \text{ kgf} \cdot \text{m/s}$$

$$= 735.499 \text{ W}$$

放射能	Bq	Ci
	1	2.70270 × 10 <sup>-11</sup>
	3.7 × 10 <sup>10</sup>	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10 <sup>-4</sup>	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

