# 유체유발하중을 받는 상부안내구조물의 랜덤진동 및 조화응답해석

## Random Vibration and Harmonic Response Analyses of Upper Guide Structure Assembly to Flow Induced Loads


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### 요 지

원자로 내부구조물의 상부안내구조물집합체는 노심지지배럴과 내부배럴집합체와 함께 원통형의 실린더 구조이며, 유체의 난류하중과 펌프의 맥동하중으로 인한 유체유발하중을 수평방향으로 받는다. 본 논문에서는 이 유체유발하중에 대한 랜덤진동해석과 조화응답해석을 수행한 내용을 기술하였다. 이 해석을 위해 집중질량 보 요소 모델을 사용하였고, 랜덤하중과 펌프맥동하중으로 발생되는 동적응답특성을 평가하였다. 특히 원통형태의 상부안내구조물, 노심지지배럴, 내부배럴집합체 사이에서 형성되는 환형공간의 동수력 연성 효과를 고려하여 모델링 하였고, 상부안내구조물 안쪽에 설치되는 내부배럴집합체의 추가 영향을 검토하였다. 내부배럴집합체의 추가로 인한 하중조건별 최대동적응답은 구조물의 고유진동수에 영향을 받으며, 따라서 구조물의 최대동적응답은 여러 하중 조건별 동적해석 평가를 통해 보수적으로 구하여져야 한다.



**핵심용어** : 상부안내구조물집합체, 랜덤진동해석, 조화응답해석, 동수력 연성, 유체유발하중



### Abstract

The cylindrical Upper Guide Structure assembly of the reactor internals with the Core Support Barrel and the Inner Barrel Assembly is subjected to flow induced loads horizontally which include random pressure fluctuation due to turbulent flow and pump pulsation pressures. The purpose of this paper is to perform random vibration and harmonic response analyses for flow induced loads. The dynamic response characteristics due to random turbulence and pump pulsation loads were evaluated using the lumped mass beam model. Especially the model considered the annulus effects due to water gaps existing between cylindrical structures such as the Upper Guide Structure Barrel, the Core Support Barrel, and the Inner Barrel Assembly. The effect of the Inner Barrel Assembly inside the Upper Guide Structure assembly was studied. The peak dynamic responses for each loading condition due to the addition of IBA were affected by the natural frequencies of the structures. Therefore the peak dynamic responses of the structures should be conservatively obtained from evaluation of dynamic analysis for various loading conditions.



***Keywords*** : *Upper Guide Structure assembly, random vibration analysis, harmonic response analysis, hydrodynamic coupling, flow induced load*



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## 1. Introduction

The Upper Guide Structure(UGS) assembly in the reactor internals consists of UGS barrel, Fuel Alignment Plate(FAP), UGS support plate, Inner Barrel Assembly(IBA) and Control Element Guide Tubes as shown in Fig. 1. The UGS barrel consists of a right circular cylinder welded to a ring flange at the upper end. The CSB is located outside the UGS assembly with a small water gap. The IBA attached inside the UGS assembly, which is new design concept, limits cross flow and provides separation of the control element assemblies. The UGS barrel upper flange supports the IBA. Actually the CSB, the UGS, and the IBA are right circular cylinders or cylindrical shells.

The UGS assembly of cylindrical shell type requires an evaluation of dynamic responses due to flow induced loads under normal operating condition of nuclear power plant to verify the

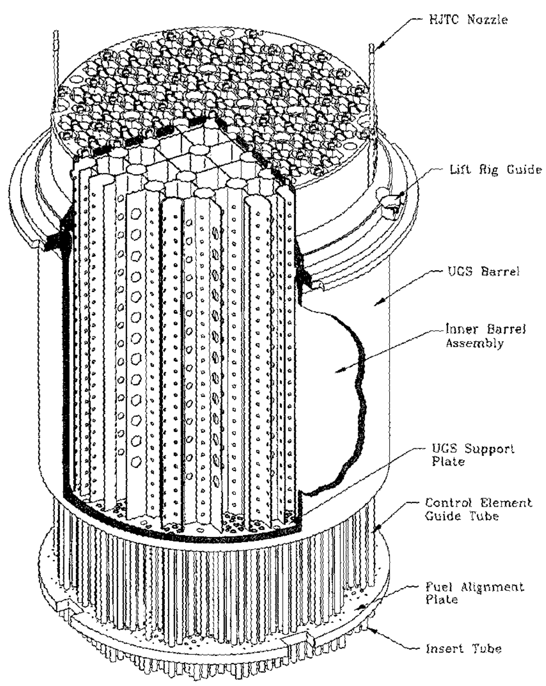



Fig. 1 Arrangement of UGS assembly

structural integrity. The flow induced loa during normal operation are flow turbulen random loads and harmonic loads generate by pump pulsation.

In the present work, the random vibratio and harmonic response analyses for flow induced loads were performed to evaluate dynamic responses. The accurate vibration characteristics should be calculated for dynamic response analyses. There are several investigations on the vibration of the cylindrical shell structure such as UGS assembly.[1)~3)] The modal analysis was performed using reduced householder method for models with and without hydrodynamic coupling, and dynamic response analyses were followed. The theoretical developments on the hydrodynamic effects were investigated by many researchers.[4)~6)] Based on the previous works, the annulus effects due to water gaps between the UGS barrel and the CSB, the UGS barrel and the IBA were evaluated using ANSYS code.[7)] The dynamic responses of the UGS assembly were evaluated for various damping and pump overspeed factors to get peak dynamic response. The effect of adding IBA inside the Upper Guide Structure Assembly was also studied.

## 2. Model Development

The UGS assembly lumped-mass-beam model was constructed using the ANSYS computer code[7)] as shown in Fig. 2. The model includes UGS barrel, Tube Bank and IBA. The UGS assembly model also includes the CSB. It contains 71 nodes that were combined into 68 Beam4 elements. The model has 32 Mass21 elements, and 2 Combin14 rotational spring elements. The annulus effects between CSB barrel and UGS, and between UGS and IBA were simulated with using 30 Fluid38 hydrodynamic coupling elements.

The UGS consists of upper flange, lower flange, UGS cylinder and UGS support plate.

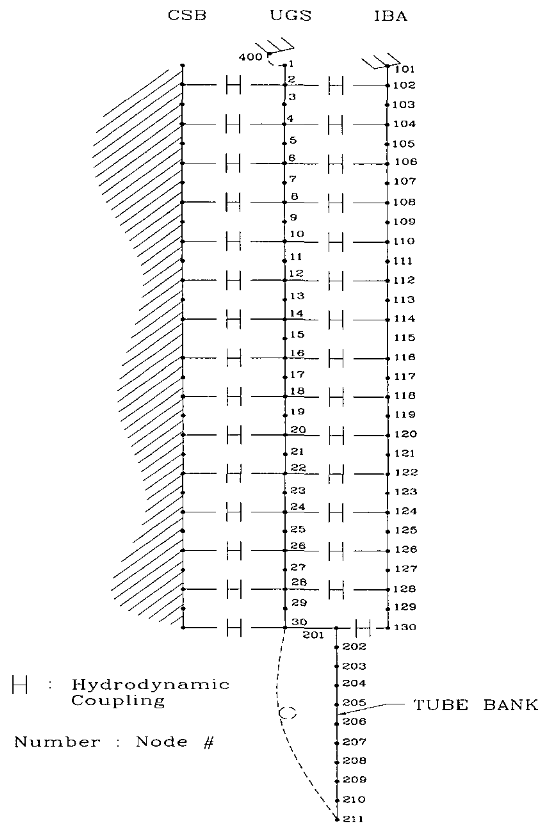



Fig. 2 Lumped mass beam model of UGS assembly

The upper and lower flanges and the UGS support plate were introduced as lumped mass in the model. The UGS model contains 30 nodes combined into 29 beam elements. The spacing between the nodes was appropriately chosen to incorporate the coherence or correlation length in the UGS specified for random loading. The nodes, located between the loaded ones, were used for hydrodynamic coupling. The UGS model contains a rotational spring(Combin14 element), which simulates the rotational stiffness at the UGS upper flange support. The fuel alignment plate rotation around the out-of-plane axis is controlled by the rotational spring. The IBA model was constructed the same way as the UGS model. The IBA was represented as 30 nodes with 29 elements. The spacing between nodes was properly chosen to incorporate the coherence length, specified for random loading.

The IBA mass was considered as a lumped mass associated with each IBA model node. The moment of inertia of the equivalent IBA model was determined based on the dynamic characteristics of the IBA, which was obtained from a separate detailed finite element model of the IBA. The IBA lumped mass beam model includes the UGS component to address IBA - UGS hydrodynamic coupling effect.

## 3. Dynamic Response Analyses

### 3.1 Modal Characteristics of the UGS Assembly

The vibration characteristics of the structures should be calculated for dynamic response analysis. Mode extraction procedure for the modal analysis is the reduced householder method.[7] Twelve modes were extracted to envelop the total range of flow induced load forcing frequencies.

The UGS assembly models with and without hydrodynamic coupling were considered for the evaluation of the small water gap effect, and the modal characteristics were summarized in Table 1. As can be found from the table, the natural frequency of the model with hydrodynamic coupling was lower than without hydrodynamic coupling. The modes were used for random vibration and harmonic response analyses and they were normalized to the mass matrix for the spectrum and harmonic analyses.

### 3.2 Random Vibration Analysis

The random vibration analysis is one of the spectrum analyses method. The response of the UGS assembly to random pressure loading caused by turbulent flow was determined by applying random loads to the UGS assembly

Table 1 Modal characteristics for the UGS assembly model

| Mode | With Hydrodynamic Coupling Model | | | Without Hydrodynamic Coupling Model | | |
|---|---|---|---|---|---|---|
| | Frequency (Hz) | Participation Factor | Effective Mass | Frequency (Hz) | Participation Factor | Effective Mass |
| 1 | 9.71 | 95.14 | 9052.03 | 23.90 | 12.97 | 168.18 |
| 2 | 18.05 | 82.14 | 6746.15 | 82.69 | 11.85 | 140.31 |
| 3 | 26.75 | -24.14 | 582.75 | 88.10 | 11.81 | 139.53 |
| 4 | 82.17 | 17.80 | 316.83 | 206.82 | -1.36 | 1.84 |
| 5 | 132.22 | -56.97 | 3246.08 | 515.72 | -2.34 | 5.47 |
| 6 | 194.47 | 3.39 | 11.49 | 517.36 | -6.57 | 43.13 |
| 7 | 238.32 | -1.42 | 2.02 | 648.76 | 8.05 | 64.87 |
| 8 | 383.29 | 32.31 | 1044.18 | 988.26 | 0.40 | 0.16 |
| 9 | 472.56 | 4.636 | 21.45 | 1384.33 | 7.18 | 51.52 |
| 10 | 510.73 | -4.17 | 17.38 | 1446.50 | 3.85 | 14.82 |
| 11 | 737.14 | -17.93 | 321.47 | 1610.40 | -0.95 | 0.91 |
| 12 | 805.96 | 15.18 | 230.47 | 2122.87 | 7.02 | 49.21 |

model. The random pressure loads on the UGS assembly were defined in the form of power spectral density(PSD) for the inner surface of the UGS barrel and outer surface of IBA(Fig. 3). The UGS assembly model has a single stick, which represents all 820 control element guide tubes. The area and node over which random pressure loading was applied, were determined based on the tube geometry and coherence length.

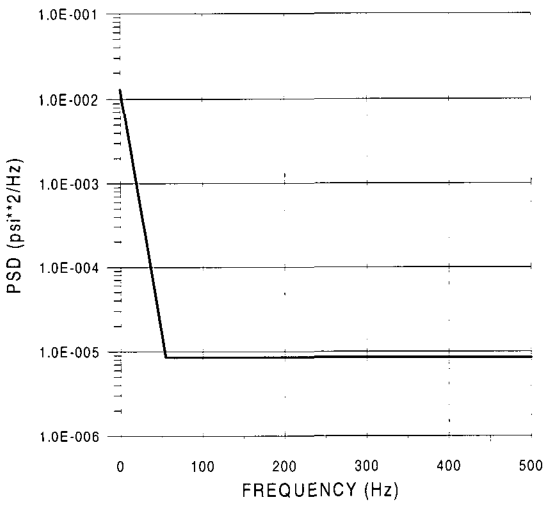


Fig. 3 PSD distribution for random turbulence on UGS and IBA

The total responses are then obtained by the SRSS(square root of the sum of the squares) of the responses on each individual tube. For the UGS barrel and the IBA, the PSD defined for the UGS barrel was applied as a fully uncorrelated loading between the UGS model individual nodes. The same PSD loading was applied to the IBA.

### 3.3 Harmonic Response Analysis

The dynamic response of the UGS assembly to pump induced pressure pulsation was determined by harmonic analyses. Lateral pump pulsation loading on the UGS assembly was defined in the form of the pressure loads versus the excitation frequencies(20, 40, 120, 240, 360 and 480Hz) for the inner surface of the UGS barrel, the IBA outer surface and the control element guide tubes(Table 2).

These pressures were applied to the projected area associated with the UGS barrel, IBA and guide tubes.

Two types of loss of load events for design hydraulic loads are defined as follows: Type 1 is loss of load where turbine generator controls function and Type 2 is loss of load where turbine

Table 2 Pump pulsation input loads for UGS and IBA

| Freq.(Hz) | UGS and IBA($N/m^2$) |
|---|---|
| 20 | 4412.6 |
| 40 | 3999.0 |
| 120 | 5722.7 |
| 240 | 28544.3 |
| 360 | 4412.6 |
| 480 | 18064.3 |

generator controls malfunction. In other words, during the Type 1 turbine overspeed loss of load event, the pump speed increases to 107.4% of the normal operating speed. During the Type 2 event, the pump speed increases to 119%. To determine the worst case for loss of load events, many cases by subdividing pump overspeed factors within the range of excitation frequencies(1.0 to 1.19) were analyzed.

## 4. Dynamic Responses

### 4.1 Random Vibration Responses

The lateral dynamic responses caused by random pressure fluctuations due to turbulent flow were calculated for the UGS and IBA. The response loads and deflections account for loading in both lateral directions. The response of a structure is proportional to the square root of the PSD.[8] The responses from random vibration analysis were reflected by adjustment factors for low temperature or operating conditions. The representative random response of each component including adjustment factor is shown in Fig. 4 for each operating condition. The responses for random turbulent loads show the lower gradient of Type 1 than Type 2 in each component. The random turbulence responses show that UGS upper flange has maximum force and moment, IBA bottom represents max deflection, during Type 2 loss of load.

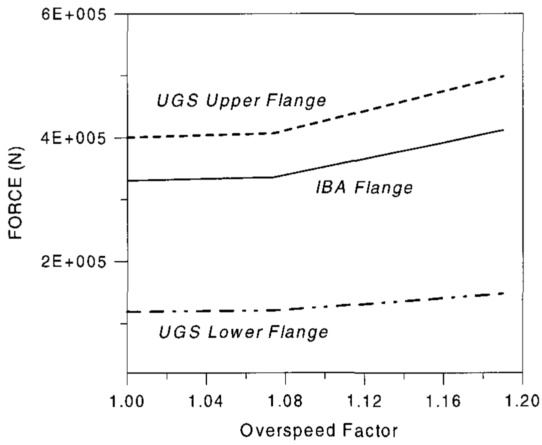



Fig. 4 Random turbulence responses of UGS and IBA

### 4.2 Pump Pulsation Responses

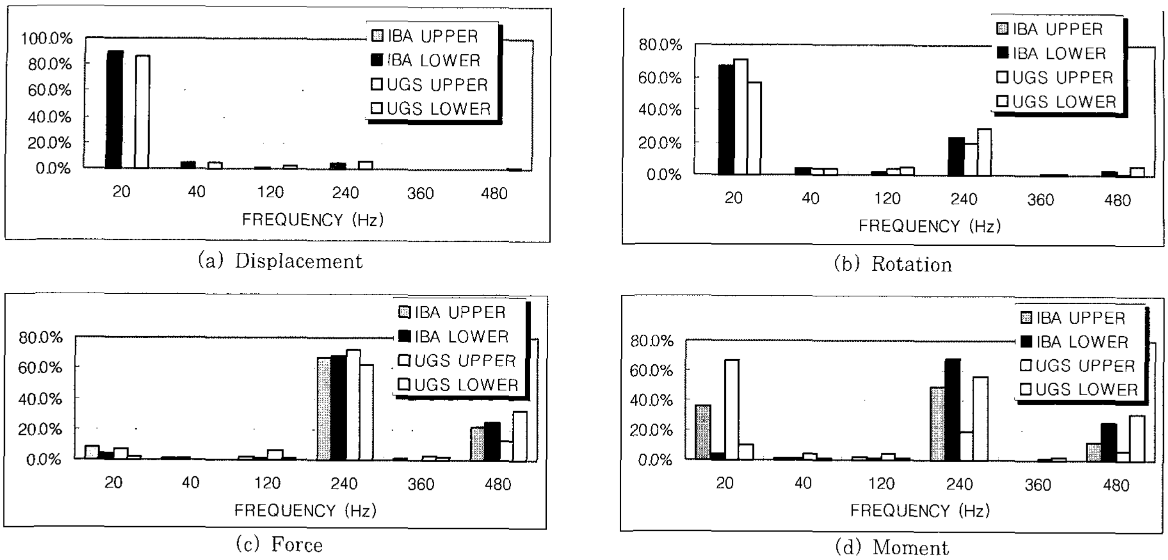
#### 4.2.1 Responses for each excitation

The dynamic responses to pump pulsation loads were calculated using the absolute summation of the response for all excitations. Each excitation response was evaluated by SRSS of the in-phase and out-of-phase components before absolute summation. To show the effect of each excitation frequency, Fig. 5 represents the fraction of responses for each excitation frequency to the total response for all forcing frequencies. The displacements mainly depend on 20Hz excitation, the rotations on 20 and 240Hz, the shear forces on 240 and 480Hz, and the moments on 20, 240 and 480Hz.

As shown in Fig. 5, the dominant excitation frequency can be found through the pump pulsation analysis. Because the pump pulsation response is affected by the resonance frequency, the responses of the resonance excitation frequency should be carefully reflected in design application.

#### 4.2.2 Hydrodynamic Coupling Effect

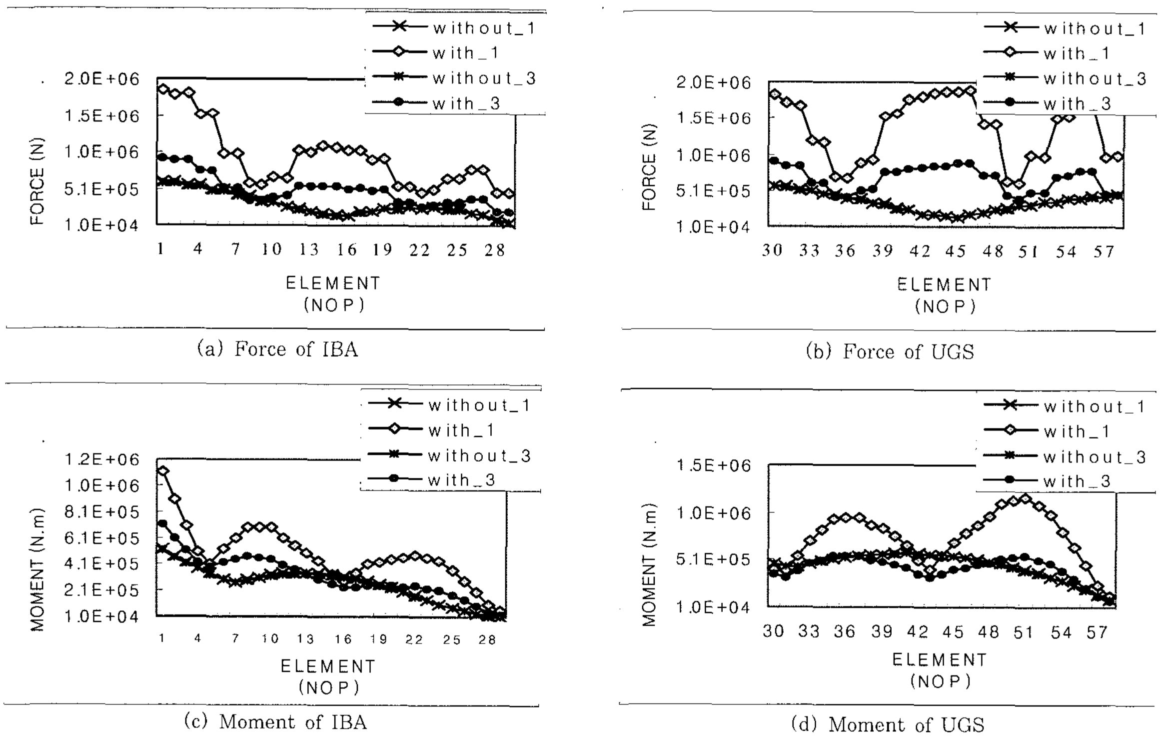
Many researchers investigated the theoretical developments on the hydrodynamic effects. Here, the hydrodynamic coupling effect of the annulus of UGS assembly was evaluated using ANSYS




(a) Displacement (b) Rotation

(c) Force (d) Moment

Fig. 5 Pump pulsation responses of the UGS assembly for each excitation frequency




(a) Force of IBA (b) Force of UGS

(c) Moment of IBA (d) Moment of UGS

Fig. 6 Hydrodynamic effects of IBA and UGS due to pump pulsation loads for NOP

code. The dynamic responses were compared with the change of damping ratio and eigen values of IBA and UGS for with/without hydrodynamic coupling models.

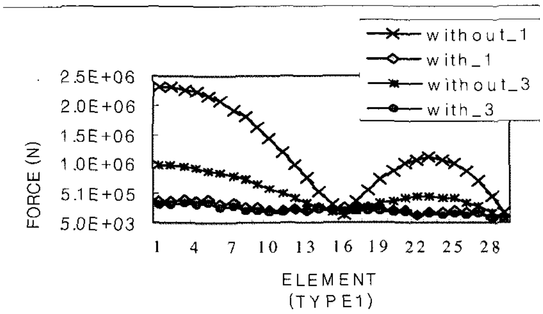
Figure 6 shows the pump pulsation responses with and without hydrodynamic coupling for IBA and UGS(In the Fig. 6~8, with: with hydrodynamic coupling, without: without hydrodynamic coupling, _#: damping ratio).

Under NOP(normal operating) condition, the dynamic responses of the model with hydrodynamic coupling were higher than those of the model without hydrodynamic coupling in IBA and UGS. They were dynamic responses affected by excitation frequency 240 and 480Hz close to natural frequency(mode 7 and mode 9) of the withhydrodynamic model, respectively. For the without hydrodynamic coupling case, the responses have no influence on damping values as shown in Fig. 6(a) through 6(d).

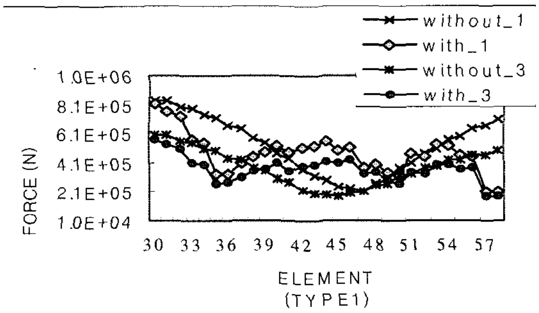
The responses for Type 1 and Type 2 were different from those of NOP condition.

For IBA of Type1, the responses of the model without hydrodynamic coupling were greater than those of the model with hydrodynamic coupling. The responses without hydrodynamic coupling were mainly from the frequency(515.72Hz) of the fifth mode. The mode 5 is IBA mode. It gives substance to the fact that the IBA responses in Fig. 7(a) and 7(c) show higher than the UGS responses in Fig. 7(b) and 7(d). For UGS of Type1, the damping ratio affects the responses of both model with and without hydrodynamic coupling. Comparing to natural frequency, the responses with hydrodynamic coupling were mainly from the frequencies(132.22Hz and 383.29Hz) of the fifth and eighth modes. For the without hydrodynamic coupling, they depend on sixth mode. For Type 2 without hydrodynamic coupling model, the responses depend on the first mode 1, which is a UGS mode. Therefore the UGS responses in Figures 8(b) and 8(d) show higher than the responses of IBA. As shown in Figures 8(a) and 8(c), the IBA responses did not change for different damping values.

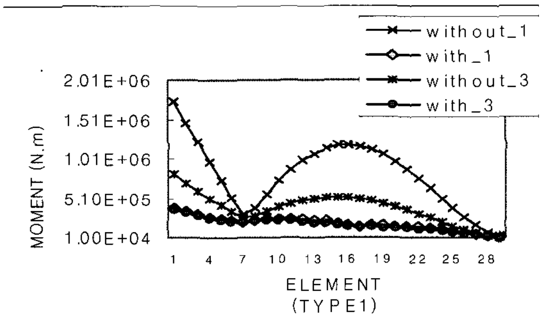
Above as discussed, the effect of damping



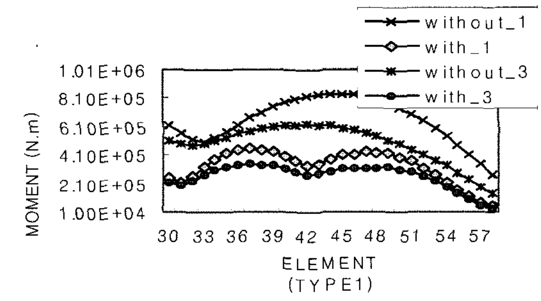

(a) Force of IBA




(b) Force of UGS

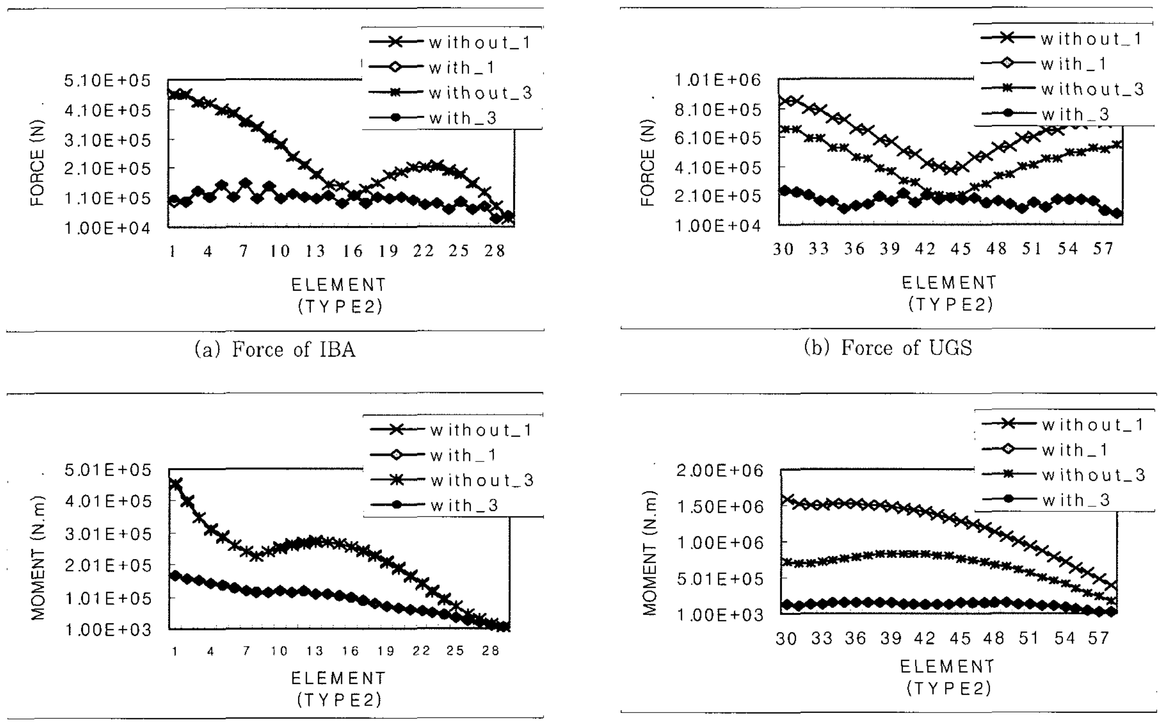



(c) Moment of IBA




(d) Moment of UGS

Fig. 7 Hydrodynamic effects of IBA and UGS due to pump pulsation loads for Type 1




(a) Force of IBA (b) Force of UGS

(c) Moment of IBA (d) Moment of UGS

Fig. 8 Hydrodynamic effects of IBA and UGS due to pump pulsation loads for Type 2

ratios was dominant when natural frequencies were close to excitation frequencies.

The responses of hydrodynamic coupling model for pulsation loading are not order of NOP, Type 1 and Type 2. It's very difficult to estimate before analysis because they represent a various modal characteristics according to model. The hydrodynamic coupling should be considered to reflect submerged UGS assembly for design application. The effect of damping values were summarized in Table 3(o: affected, x: not affected).

## 4.3 IBA Effect

The dynamic responses to random turbulence gradually increased with the increase of the pump overspeed factor or operating condition. Unlike the response to random turbulence, the pump pulsation responses did not increase with the increase of the pump overspeed factor.

Table 3 The effect of damping ratio for each loading condition on two models

| Load/Model | | IBA | UGS |
|---|---|---|---|
| NOP | With hydro coupling | o | o |
| | Without hydro coupling | x | x |
| TYPE 1 | With hydro coupling | x | o |
| | Without hydro coupling | o | o |
| TYPE 2 | With hydro coupling | x | x |
| | Without hydro coupling | x | o |

Actually, it is not easy to find out peak response for dynamic response. The peak responses depended on the relation between the natural frequencies of the structure and the forcing frequency. Fig. 9 and 10 show the responses combined pump pulsation and random vibration responses.

The maximum normalized shear force occurred at overspeed factor 1.0 and the maximum normalized moment at 1.1017 for with IBA. The maximum normalized shear force and moment

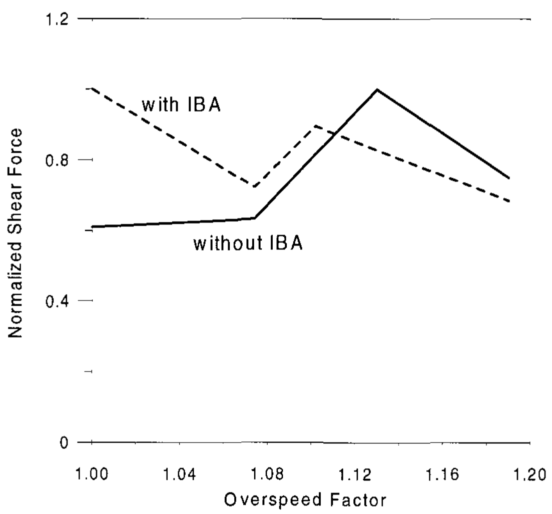


Fig. 9 Normalized shear force for overspeed factor (P.P + Random)

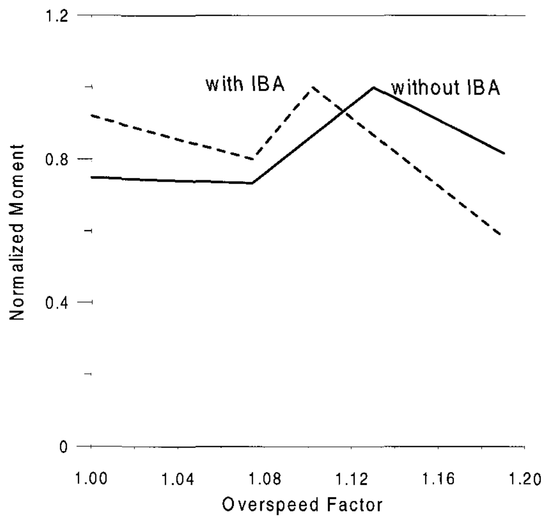


Fig. 10 Normalized moment for overspeed factor (P.P + Random)

occurred at 1.1297 for without IBA. The effect with/without IBA resulted in the movement of the peak response. The natural frequencies by the addition of IBA had an influence on the movement of peak response.

## 5. Conclusions

The dynamic response analyses of the Upper Guide Structure assembly were performed for the flow induced loads including turbulent flow random and pump pulsation loads.

- With the increase of the pump overspeed factor, the responses for random turbulence were increased, while the pump pulsation responses showed the maximum ones at a certain overspeed factor between 1.0 and 1.19 depending on the structural and excitation frequencies.
- Hydrodynamic coupling has a great effect on the dynamic responses depending on the resonance between the natural frequencies of structures and the external forcing frequencies of pump pulsation.
- The addition of the IBA inside the Upper Guide Structure assembly resulted in shifts of the pump overspeed factor where the peak dynamic response occurs.

Therefore, the peak dynamic response of the Upper Guide Structure assembly obtained from the combination of random turbulence and pump pulsation responses should be carefully evaluated by varying the pump overspeed factor to the maximum one.

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