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SEISMIC ANALYSIS OF THE REACTOR ASSEMBLY OF A 1000 MWe-LMFBR POOL REACTOR

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SUMMARY

The seismic capability of the Reactor Assembly must be ensured in the conceptual design of a 1000 MWe Pool-type LMFBR. The Reactor Assembly has to be designed to meet the seismic category I requirements. A preliminary seismic analysis was made to serve as a guide to this effect.

A finite element model based on an axisymmetric formulation was established and analyses were attempted with the spectrum method.

The response acceleration spectra at the reactor support, for both Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE), were obtained from a time history analysis of the reactor building which takes into account the coupling effect of the building and the reactor structure.

A mass element representing a 12 x 12 mass matrix was used to take into account the hydrodynamic mass effect created by liquid sodium in annuli formed by cylindrical structures. The sloshing effect, within the hot pool, was incorporated into the model based on a simplified formulation given by Housner. The sloshing frequency was substantially lower (0.17 Hz) than the lowest natural frequency of vibration of the Reactor Assembly (4.77 Hz). The wave height was found to be approximately 4 feet under the SSE condition, neglecting the damping effect of the internal structures.

Displacements and stresses were calculated for the major components of the Reactor Assembly. The functional requirements allow 1.0" relative motion between the core and control rod drive systems for the vertical OBE and 2.0" for the vertical SSE. In any horizontal excitation, only 0.6" relative motion is allowed. These functional requirements are met. Stress results from the analysis based on the OBE were combined with stresses due to loadings other than the seismic and were shown to satisfy ASME Code Requirements. Stresses due to the SSE were checked against the requirements for the faulted condition.

This preliminary seismic analysis, addressing various technical areas of importance, demonstrated that the 1000 MWe Pool-type LMFBR design is a feasible design with a high potential of success while maintaining good safety margins.

1. Introduction

In the event of a seismic occurrence near a nuclear power plant, the integrity of the reactor assembly must be ensured. To this end, the 1000 MWe Pool Type LMFBR reactor assembly was analyzed to satisfy the requirements for a Seismic Category I component. Although the final detailed and complete analysis of the reactor assembly can only be made after the design has been completed and a plant site has been chosen, preliminary analyses made at earlier stages in the design are valuable to guide the design and to provide a starting point for the final analysis.

The analysis was accomplished employing an axisymmetric finite element model. The finite element model was analyzed for seismic response by using the response spectrum method of the ANSYS [1] computer program. Input to the analysis, other than the geometry and other physical characteristics for the model, included an input seismic excitation forcing function. This function took the form of an acceleration response spectrum. Results from the analysis based on an operating basis earthquake (OBE) were combined with stresses resulting from loadings other than seismic. The final results for both OBE and SSE were then compared to ASME Code stress limits and the displacement results compared to design functional displacement limits.

2. Analysis

The closed form solution of vibration of a system is limited to a system with a simple geometry. In practice, either the lumped parameter representation or the finite element method is adopted in the seismic analysis. In the seismic analysis of the 1000 MWe Pool Reactor Assembly, the finite element method is used and the spectrum response analysis option of the ANSYS [1] computer code is applied.

2.1 An Axisymmetric Model

2.1.1 Description of the Model

The 1000 MWe pool reactor assembly as shown in Figure 1 is composed of the following major components:

(a) primary vessel
(b) guard vessel
(c) deck and reactor closure
(d) upper internals structure
(e) pumps and IHX's
(f) thermal barriers
(g) core
(h) core barrel and core restraint
(i) core support including the pressure plenums
(j) lateral neutron shield

The guard vessel is structurally independent of the primary reactor vessel and reactor internals and is non-Category I component. It is, therefore, excluded from the present analytical model. Also excluded from this seismic model are thermal barriers for the pumps and the IHXs. They do not change the dynamic behavior of the rest of the reactor structure significantly. To simplify the analysis further, the non-axisymmetric core support structure and the reactor deck structure as well as the upper internals structure, pumps, and IHX's are modeled as axisymmetric structures of equivalent stiffness. The reactor structure is thus represented by an assemblage of axisymmetric shells as shown in

Figure 2.

The mode shapes of vibration of a circular cylindrical shell are well known. They are characterized by axial modes and circumferential modes. The presence of circumferential coupling of vibration complicates the seismic analysis. This is further complicated by the restraint of the shell by vessel closure heads. In order to reduce the complexity of the model, the circumferential coupling of vibration is neglected in this analysis.

2.1.2 The Boundary Condition

The entire reactor is supported from the reactor building structure by a 1.5 inch thick steel skirt attached to the reactor deck around the edge of the deck. The boundary condition for the reactor assembly is specified at the foot of this steel skirt. The reactor is seismically excited through this point.

2.1.3 Dynamic Degrees of Freedom

Arrows shown in Figure 3 indicate dynamic degrees of freedom specified for the model. They are specified to reduce the complexity of the analysis by including only those degrees of freedom which are sufficient to characterize the dynamic behavior of the reactor structure. The mass and stiffness matrices are reduced to those corresponding numbers of dynamic degrees of freedom and the eigenvalue problem is solved. The selection of the dynamic degrees of freedom is somewhat comparable to the method of selecting lumped masses for a dynamic model.

2.1.4 The Hydrodynamic Mass Effect, Sodium Sloshing, and Damping

Whenever a solid structure that is in contact with liquid moves, a resisting fluid force that is proportional to the relative acceleration of the structural components is developed, while the liquid is displaced to accommodate the motion of the structure. Whenever the liquid must flow dynamically in small passages, the hydrodynamic (apparent and virtual) mass effect of the liquid on the dynamic characteristics of the solid structure will be significant [5,6,7]. Major components of the pool reactor assembly are in contact with the liquid metal, sodium. The inclusion of the hydrodynamic mass is necessary in some areas of the reactor assembly to obtain a meaningful result.

The dynamic fluid pressures developed during an earthquake are also of importance in the design of structures such as the pool reactor. In this analysis such a sloshing effect within the hot pool was incorporated into the model based on a simplified formulation given by Housner.[8] The sloshing frequency was substantially lower than the lowest natural frequency of vibration of the reactor assembly. Stresses in the thermal barrier due to sloshing were first obtained based on a safe shutdown earthquake (horizontal excitation). Without any prospect of additional information, the sloshing effect was then removed from the later part of the analysis.

Upon introduction of the hydrodynamic mass effect, the presence of (viscous) damping is also expected. Without a reliable datum this damping effect was neglected in the analysis to obtain a conservative result. Damping was also neglected in the sloshing model.

2.2 Seismic Excitation

Although direct integration of the equations of motion, given the time-history of the forcing function, offers more details of the transient response of the system, it would be more practical to use the response spectrum approach from the point of view of stress analysis, where, the maximum response is usually of the upmost concern. In the seismic analysis of the pool reactor assembly, the spectral analysis method was adopted. The input spectral response was obtained from a time history analysis of the reactor building, which takes into account the coupling effect of the building and the reactor structures.

3. Discussion

3.1 Assumptions

The following basic assumptions were made in the seismic analysis of the 1000 MWe pool reactor:

(a) The reactor assembly was assumed to be linearly elastic. The analysis was based on the small deformation theory. Thus, the superposition technique was applicable. Details, such as gaps between any pair of reactor components, were neglected. Detailed dynamic analysis of specific components, such as the core and the control rod assembly during an earthquake, might be necessary depending on functional requirements.

(b) Coupling of the axial and circumferential modes of vibration of the reactor components was neglected following the conventional assumptions to reduce the complexity of the analysis.

(c) A zero-period ground acceleration of 0.3g for SSE and 0.15g for OBE was assumed for the 1000 MWe power plant site as a conservative estimate.

3.2 Simplifications Made in the Axisymmetric Model

The following simplifications were made in modeling the reactor assembly:

(a) The non-axisymmetric core support structure, the reactor deck structure, and the upper internals structure were modeled with axisymmetric structures of equivalent stiffness. The thickness of the axisymmetric plate was increased to account for the additional stiffness due to the supporting webs by an equivalent cross sectional moment of inertia.

(b) Only one pump and one IHX were modeled, according to their stiffnesses and distributed masses, to account for the dynamic behavior and effect of these components. The structural stiffness of the pumps and IHX's were estimated and replaced by an equivalent axisymmetric structure (axisymmetric with respect to the axis of the reactor assembly). There are no definite phase relations among the pumps which have the same dynamic characteristics. The IHX's, similarly, do not have any phase relationship. Therefore, the rest of the pumps and IHX's were included in the model as a lumped mass.

(c) The major reactor components were represented by "thin" shells which cannot take into account <u>shear</u> across the thickness. The accuracy can be improved by using either the thick shell theory or a more detailed 3-D model.

(d) Although the stiffness of the reactor deck was grossly estimated according to paragraph (a) in Section 3.2 described above, the deck structure was much more complicated than what was allowed for in such an approximation. Additional information was available from a detailed analysis of the deck at the time of modeling the deck. Therefore, the stiffness of the deck structure was adjusted to take into account this new information.

(e) To avoid the mathematical singularity at the pole of an axisymmetric structure, a small opening was cut in the continuum which includes a point along the neutral axis of the axisymmetric reactor assembly.

3.3 Impact of Design Changes on the Analytical Results

3.3.1 The Thermal Barrier

The hydrodynamic mass effect is significant when a fluid is confined within a small annulus formed by two concentric cylinders which are allowed to have a relative radial motion. This could result in a high stress in the cylinders. Provision of spacer tubes within the annuli of the thermal barrier eliminated this relative motion and thus eliminated the potentially high stresses due to the hydrodynamic mass effect.

3.3.2 The Core Support Platform

Excessive shear deformation of the core support platform resulted in a large deflection of the core support during a seismic event, which is undesirable from the point of view of reactivity control. Provision of additional shear webs reduced the deflection substantially.

4. Analytical Results

Based on the above descriptions, with the given boundary condition and forcing functions (seismic response spectra), the structural responses of the pool reactor were calculated for OBE and SSE. Both vertical and horizontal excitations were examined.

4.1 Detailed Results from the Axisymmetric Model Analysis

The following results were obtained from an analysis of the axisymmetric model that included the stiffened core support structure.

4.1.1 Natural Frequencies of Vibration

In the seismic analysis of the axisymmetric model, two distinct modes of vibration were considered; a symmetric mode and an antisymmetric mode. The symmetric mode characterizes the vertical vibration of the pool reactor components; while the antisymmetric mode corresponds to a bending mode of vibration which characterizes the horizontal vibration of the reactor components. The natural frequencies of vibration corresponding to these two modes are shown in Tables I and II. A significant mode shape associated with the natural frequencies of vibration is shown in Figure 4 for the symmetric modes, and in Figure 5 for the antisymmetric modes of vibration. Figure 4 shows the mode shape corresponding to the vibration of the deck at a frequency of 7.5 Hz. Figure 5 shows the cantilever beam mode of vibration of the reactor primary vessel at a natural frequency of 5.25 Hz.

4.1.2 Seismic Response Based on Spectra

Seismic responses of the pool reactor structure are expressed in the form of a displacement field. The mode shapes determine the relative displacements among points in the structure. Each mode of vibration has a definite level of "participation" depending on the stiffness and mass of the entire system (structure). Given an input seismic spectrum, the displacement field is completely determined for each mode of vibration. The frequency range of concern is between zero and 33 Hz during a seismic event. Up to 24 modes of vibration can participate in the seismic responses based on the present model. However, only significant modes of vibration that contribute substantially to the seismic response are considered.

Tables III and IV show the deflections and stresses at points of interest for the vertical OBE and SSE. The deflections and stresses represent the "square root of the sum of the squares" of all significant modes of interest.

The first 9 modes of vibration were summed for the SSE. The first two modes of vibration and the last mode were less significant. Therefore, only 6 modes of vibration in the frequency range of 4.0 - 8.0 Hz were summed for the OBE. The deflection of the center of the closure head is dominated by the contribution from the 8th mode of vibration, which characterizes the deck vibration.

Tables V and VI show the lateral displacements and stresses at some key points of concern due to the horizontal SSE and OBE. The first eleven modes of vibration were summed (in the frequency range of 2.4 Hz to 11 Hz) for the SSE. Only the first six modes were needed in the OBE summation to yield a reasonably accurate result. The maximum lateral displacements were dominated by the cantilever mode of the vessel vibration.

5. Conclusions

The preliminary seismic analysis demonstrates that the 1000 MWe Pool Reactor design is a feasible design with a high potential of success while maintaining good safety margins. Iterations must be made where much more detailed calculations are needed on more extensive models, however, this analysis demonstrates sufficient conservatism and margin for success at this preliminary state of design.

6. References

[1] DE SALVO, G.J. and SWANSON, J.A., "ANSYS Engineering Analysis System - User's Manual", Swanson Analysis Systems, Inc., 1973.

[2] BLUME, J.A. and Associate Engineers for HEDL, revised by HEDL, June 1973, "Seismic Design Criteria for the Fast Flux Test Facility, Richland, Washington".

[3] WILSON, E.L., BATHE, K., PETERSON, F.E., DOVEY, H.H., "Computer Program for Static and Dynamic Analysis of Linear Structural Systems", Earthquake Engg Research Ctr., Report No. EERC-72-10, Nov. 1972, U.C. Berkeley.

[4] United Nuclear Corp., "An Interpretive Review of Seismic Design Methods", ORNL TN-2900, May 1970.

[5] FRITZ, R.J., Tr. of the ASME, J. of Engg for Industry, "The Effect of Liquids on the Dynamic Motions of Immersed Solids", 1971.

[6] LIU, L.K., "Seismic Analysis of the Boiling Water Reactor", Symposium on Seismic Analysis of Pressure Vessel and Piping Components, San Francisco, ASME, May 1971.

[7] FRITZ, R.J., and KISS, E., "The Vibration Response of a Cantilevered Cylinder Surrounded by an Annular Fluid", KAPL-M6589, February 1966.

[8] HOUSNER, G.W., "Dynamic Pressures on Accelerated Fluid Containers", Seismological Society of America, Bulletin Vol. 45 (1), pp. 15-37, Jan., 1957.

[9] WAMBSGANSS, M.W., CHEN, S.S., AND JENDRZEJSZYK, J.A., "Added Mass Damping of a Vibrating Rod in Confined Viscous Fluids", Technical Memorandum, ANL-CT-75-08, Sept 1974.

TABLE I

NATURAL FREQUENCIES OF VIBRATION FOR VERTICAL (SYMMETRIC) LOADING

MODE	FREQUENCY (CYCLES/SEC.)	MODE	FREQUENCY (CYCLES/SEC.)
1	.308+001	16	.176+002
2	.331+001	17	.185+002
3	.404+001	18	.198+002
4	.477+001	19	.210+002
5	.581+001	20	.220+002
6	.611+001	21	.243+002
7	.696+001	22	.291+002
8	.751+001	23	.305+002
9	.867+001	24	.320+002
10	.890+001	25	.357+002
11	.104+002	26	.452+002
12	.113+002	27	.463+002
13	.121+002	28	.536+002
14	.140+002	29	.576+002
15	.163+002	30	.641+002

TABLE II

NATURAL FREQUENCIES OF VIBRATION FOR HORIZONTAL (ANTI-SYMMETRIC) LOADING

MODE	FREQUENCY (CYCLES/SEC.)	MODE	FREQUENCY (CYCLES/SEC.)
1	.241+001	16	.166+002
2	.362+001	17	.178+002
3	.405+001	18	.180+002
4	.496+001	19	.190+002
5	.525+001	20	.210+002
6	.558+001	21	.212+002
7	.628+001	22	.249+002
8	.714+001	23	.313+002
9	.822+001	24	.363+002
10	.871+001	25	.436+002
11	.107+002	26	.445+002
12	.123+002	27	.466+002
13	.134+002	28	.524+002
14	.155+002	29	.559+002
15	.157+002	30	.643+002

TABLE III

VERTICAL DEFLECTIONS OF STRUCTURAL COMPONENTS

LOCATION	DEFLECTION (INCHES)	
	SSE	OBE
Center of Closure Head	0.236	.165
Inner Edge of Deck	0.146	.103
Top of Core	0.401	.273
Center of Core Support	0.420	.286
Lateral Neutron Shield Support	0.286	.195
Center of Bottom Head	1.100	.177
Vessel/Supporting Cone Juncture	0.044	.030

TABLE IV

VERTICAL STRESSES IN SOME KEY LOCATIONS OF THE REACTOR

LOCATION	STRESS (PSI)	
	SSE	OBE
Center of Closure Head	3900	5900
Vessel Support	2400	1640
Support Skirt	2850	2000
Vessel/Supporting Cone Juncture	2700	5100
Supporting Cone	3600	2430
Center of Bottom Head	45000	17000
Core Support	14000	1000
Lateral Neutron Shield Support	7400	5100

TABLE V

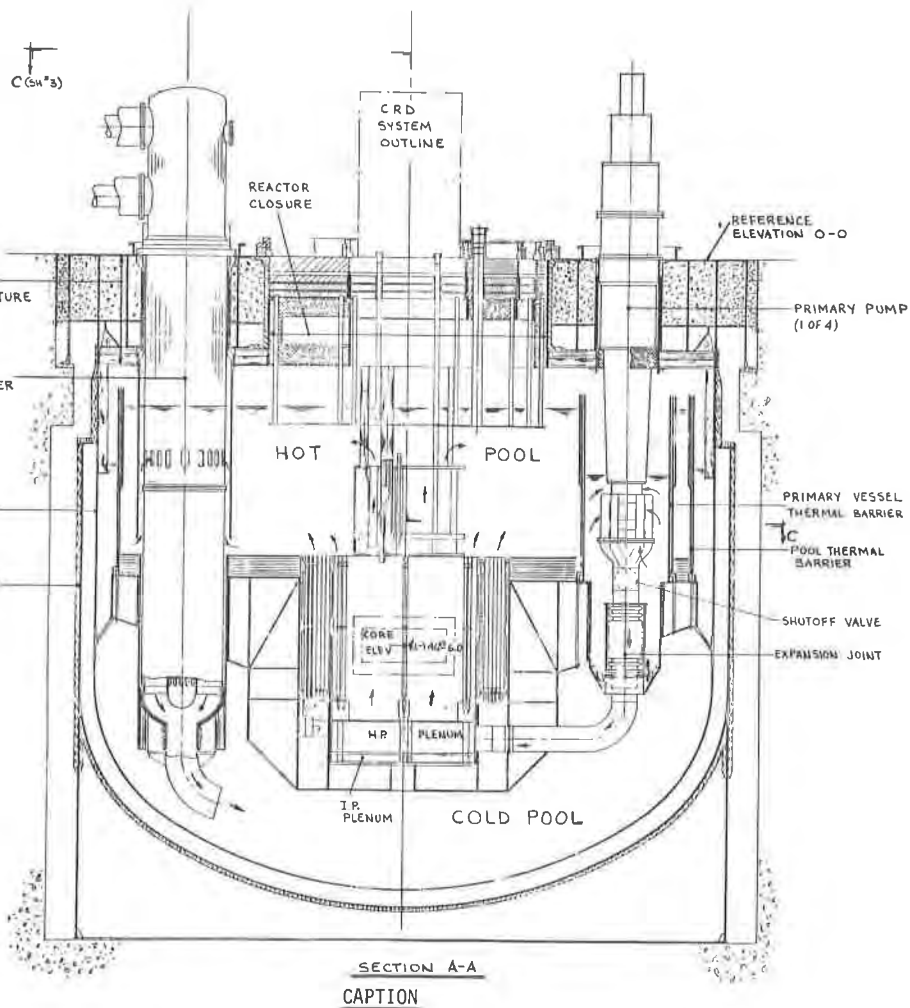
HORIZONTAL DISPLACEMENTS OF STRUCTURAL COMPONENTS

LOCATION	DISPLACEMENT (INCHES)	
	SSE	OBE
Center of Closure Head	0.0233	0.0158
Inner Edge of Deck	0.0230	0.0155
Top of Core	0.428	0.29
Center of Core Support	0.442	0.304
Lateral Neutron Shield Support	0.437	0.297
Center of Bottom Head	0.574	0.39
Vessel/Supporting Cone Juncture	0.430	0.292

TABLE VI

STRESSES DUE TO HORIZONTAL SSE AND OBE

LOCATION	STRESS (PSI)	
	SSE	OBE
Center of Closure Head	250	170
Vessel Support	8500	5800
Support Skirt	6800	4600
Vessel/Supporting Cone Juncture	14000	9400
Supporting Cone	2300	1500
Center of Bottom Head	22400	16000
Core Support	2300	1500
Lateral Neutron Shield Support	2400	1760
Thermal Barrier	24800	17000



CAPTION

1 Reactor Assembly

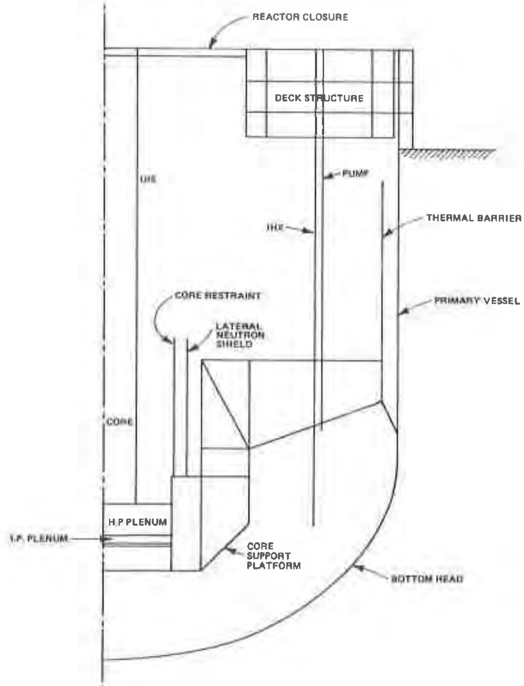


Fig. 2 Axisymmetric Model Description

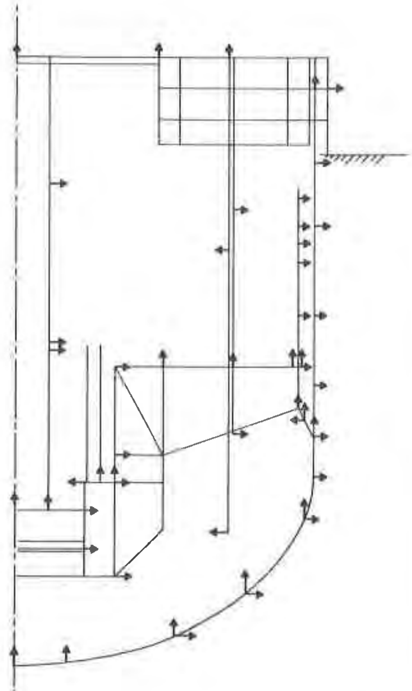


Fig. 3 Dynamic Degrees of Freedom Assigned to Axisymmetric Model

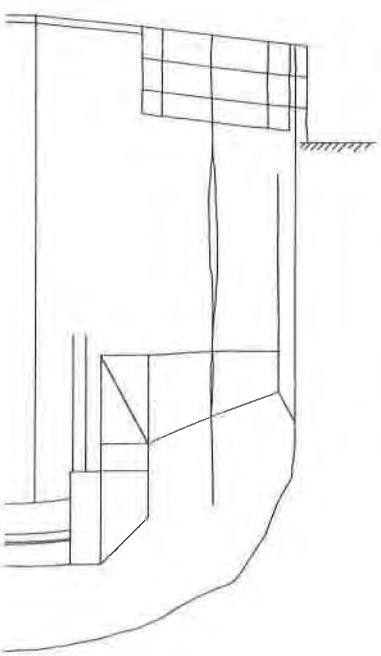


Fig. 4 Eighth Vertical Mode of Vibration (f = 7.51 Hz)

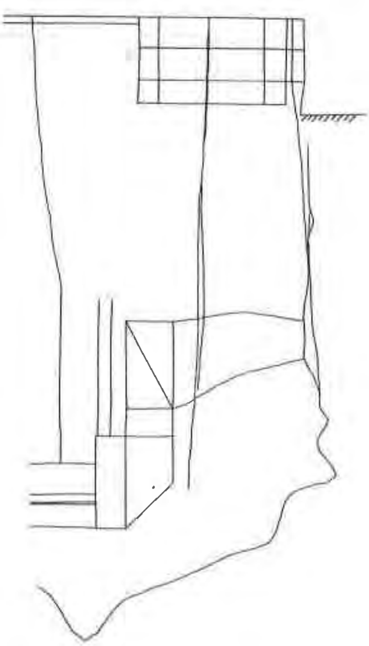


Fig. 5 Fifth Horizontal Mode of Vibration (f = 5.25 Hz)