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OPERATING FUNCTION TESTS OF THE PWR TYPE RHR PUMP FOR ENGINEERING SAFETY SYSTEM UNDER SIMULATED STRONG GROUND EXCITATION

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Results are described of operating function verification tests of a PWR RHR pump during an earthquake. Of the active reactor components, the PWR residual heat removal pump was chosen from view points of aseismic classification, safety function, structural complexity and past aseismic tests. Through survey of the service conditions and structure of this pump, seismic test conditions such as acceleration level, simulated seismic wave form and earthquake duration were decided for seismicity of the operating pump. Then, plans were prepared to evaluate vibration chracteristics of the pump and to estimate its aseismic design margins. Subsequently, test facility and instrumentation system were designed and constructed. Experimental results could thus be acquired on vibration characteristics of the pump and its dynamic behavior during different kinds and levels of simulated earthquake. In conclusion: (1) Stiffeners attached to the auxiliary system piping do improve aseismic performance of the pump. (2) The rotor-shaft-bearing system is secure unless it is subjected to transient disturbunces having high frequency content. (3) The motor and pump casing having resonance frequencies much higher than frequency content of the seismic wave show only small amplifications. (4) The RHR pump possesses an aseismic design margin more than 2.6 times the expected ultimate earthquake on design basis.

Keywords: Pump, Aseismic Test, Earthquake, Engineering Safety System, Active Component, Mechanical Impedance, Mechanical Vibration, Dynamic Response

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PWR用余熱除去ポンプの地震時機能試験

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本報は地震時におけるPWR用余熱除去ポンプの機能実証試験の成果の概要を述べたものである。PWR用余熱除去ポンプが耐震クラス，安全機能，構造・形式ならびに過去の耐震試験の実績などを勘案してアクティブコンポーネントから選定された。このポンプの振動特性に関連する構造特性や運転状態に関する調査に続いて，耐震試験用地震波を決定した。これらのデータをもとに，ポンプの振動性状ゆ耐震裕度を得るのに必要な試験計画を確立し，試験装置や計測系の設計・製作を行なった。振動性状や応答特性に関する試験結果から以下の結論を得た。(1)ポンプの運転に必要な付属配管系の剛性を高める補強金具の取付けはポンプの耐震性の改善に重要な役割をする。(2)ロータ－軸－軸受系の固有振動数（危険速度）が高いことから，地震の卓越周波数より十分高い周波数の外乱を受けない限り，回転機械系に対する耐震性は確保されると考えられる。(3)ポンプを構成する主要部品の共振周波数が高いため，地震波に対する応答倍率は十分低く，地震波の周波数成分を多少高周波数側に変えても，応答倍率にほとんど変化を与えない。(4)PWR用余熱除去ポンプでは限界設計地震の2.6倍以上の耐震裕度がある。

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1. Introduction

Nuclear power plants are designed, erected, operated and maintained so that the public and workers are subjected to essentially no radioactivity. To this end, various measures are taken so that the radioactivity is kept below a certain level and radioactive substances do not leak away in excess of the allowable limit. Furthermore, it is required that the reactor will be stopped immediately when any serious accident takes place , i.e. the loss of coolant, and that the reactor be safely secured. It is required that leakage of radioactive substances to the surroundings does not exceed the restricted value even if violent earthquakes should occur during a loss of coolant accident. The engineering safety system, that is, emergency reactor scramming devices (such as control rods and safety rods and their driving mechanism and the emergency boric acid injection system), emergency core cooling system and container spray system must have sufficient resistance against earthquakes.

This system and the associated machinery consists of complicated structural elements, which involve non-linear spring characteristics due to clearance gaps. Consequently, it is difficult to establish a correct model for aseismic analysis, and, hence, the response anayses are not widely evaluated for seismic loads at the present time. For the so called active components, that is, the structural elements for which mechanical motion is required in order to secure the reactor safety, the verification of safe functioning by means of the operating function verification test of the actual elements (or the equivalent) under earthquake conditions is especially desired.

This report presents the outline of the research results of the operating function verification test of a PWR, RHR pump during an earthquake, carried out by Mitsubishi Heavy Industries Co., Ltd. for the Japan Atomic Energy Research Institute. This RHR pump, which is expected to operate for the long term after the loss of coolant accident, is among the pumps belonging to the engineering safety systems.

2. Pump to be tested

2.1 Selection of the pump

The pumps used in the safety system of the PWR type nuclear power plants are listed in Table 2.1. These pumps are classified into A_s or A class in the aseismic categories in view of their function in the nuclear power plants. According to the pump structure, the pumps in Table 2.1 are divided as follows;

(1) Horizontal and centrifugal

a. Multiple stages: Filling up/ High pressure injection pump (3 or 4 loops), High pressure injection pumps (2 or 4 loops), Motor driven auxiliary water feed pump, Turbine driven auxiliary water feed pump.

b. Single stage: Boric acid pump, RHR pump (2 loops), Auxiliary machinery cooling water pump, container spray pump (2 loops), Depleted fuel pit pump.

(2) Vertical and centrifugal

a. Single stage: RHR pump (3 or 4 loops), Container spray pump (3 or 4 loops)

(3) Miscellaneous

a. Reciprocal: Filling up pump (2 or 4 loops)

b. Vertical and oblique flow: Sea water pump

The RHR pump has been selected for this research because it has the functions of removing residual heat when the reactor operation is suspended and cooling the core for a long term in case of a loss of coolant accident. The fact that a very large pump is not suitable for an available shaking table has been taken into consiseration.

The types of RHR pumps are different between plant outputs of 500,000 KW class (2 loops) and those of the 800,000 to 1,100,000 KW class (3 or 4 loops), as seen in Table 2.1. The former case is the horizontal type, and the latter, the vertical type. Figure 2.1 shows both the horizontal RHR pump and vertical RHR pump.

As seen in Fig.2.1, the horizontal RHR pump is connected with the motor in series through the gear coupling. The vertical RHR pump is integrated with the motor, and the motor casing and the pump casing is fastened by the bolts.

The factors causing damages to the pump's functioning are supposedly (a) contact of the pump impeller with the casing wear ring, (b) seizure and bite in the bearings supporting the pump rotor-shaft due to increased loading, (c) leakage from the shaft sealing due to variation in the pv* value in the mechanical seal and (d) mutual interference between the motor, gear coupling and pump. It is difficult to judge whether the horizontal pump or the vertical pump is more sensitive to a given earthquake. The pump type for a PWR plant of 800,000 to 1,100,000 KW class will be standardized to the horizontal type considering the ease of periodical inspections and/or repairs. Thus the horizontal pump has been selected for the test planned.

2.2 Service conditions of the pump

The pump is used in the residual heat removal system. The service conditions of the pump are given below;

(1) Functions of the RHR pump

The residual heat removal system is designed to meet various operation modes for both normal operation and loss of coolant accident and has the following functions:

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* pv means contact pressure x sliding velocity.

(i) Decrease in the temperature of the primary coolant loop following the normal shut down of the plant.

(ii) Removal of decay heat in the core to make possible fuel exchange following temperature decrease in the primary cooling system, and suppression of temperature rise in the system.

(iii) Filling the reactor cavity with water at the time of fuel exchange, and transfer of this cavity water to the fuel exchange water tank after the fuel exchange.

(iv) Injection of boric acid water contained in the fuel exchange water tank to the core, together with the action of safety injection system, in the case of loss of coolant accident.

(v) Recycling of the container sump water in the case of loss of coolant accident.

(2) Operational conditions

The operational conditions of the residual heat removal system may be summarized as follows:

(i) Normal plant operation

(a) Stand-by conditions

The system is on stand-by alert for the extremely low probable loss of coolant accident.

(b) Periodic testing

Confirmation of normal operation can be made by operating the pump periodically.

Operation frequency: Once a year

Operating duration: 15 - 30 mimutes

(ii) Plant outage

(a) During the reactor outage, the heat generated in the core is removed.

Operation frequency: Once a year

Operating duration: about three months

Water temperature: 177 - 60 °C

(b) During the fuel exchange, the water is transferred from the reactor cavity and the fuel exchange water tank.

Operation frequency: Once a year

Operating duration: about ten hours

(iii) Loss of coolant accident

(a) The pump injects the boric acid water from the fuel exchange water tank into the core, and acts as a low pressure injection pump. Furthermore, the pump recirculates the water in the reactor container sump to the core, when the water level in the fuel exchange water tank is lowered.

Operation frequency: Once in service life at most

Operating duration: One year

Flow rate: the rated flow to maximum

Water temperature: 27 - 100 °C

(3) The pump location in the building

The RHR pump is placed near the container on the lowest floor of the building so that it lies below the water level in the container at the time of the loss of coolant accident. This location meets the requirements of the NPSH* for the pump at the time of recycle and to inject the water in the container sump into the core.

* NPSH means Net Pumping Suction Head.

2.3 Structure and specifications of the pump

(1) Structure of the pump

Since the service temperature and suction pressure are high, the RHR pump is suitable for operation at elevated temperatures and high pressures, being backed up by a suitable pressure-resisting structure of the shaft sealing and cooling method.

The cross-section of this pump is shown in Fig.2.2. It is a horizontal, single stage, double suction, center supported, vertical opening type pump.

Every part of the pump wetted by liquid is made of austenitic stainless steel, except for some parts of the wear ring and so forth.

The casing is the double volute type for equilibriating the radial thrust throughout the range of flow rate.

The impeller has four vanes connected to the rotor by means of shrinkage fitting. A single stage, double suction type is used, and thus the axial thrust force is well balanced, and, at the same time, the necessary suction head is kept low.

The rotor is connected to a driver by the gear coupling of the double claw. The primary critical speed of the rotor-shaft-bearing system is 4,122 rpm which is considerably higher than the normal operating speed of 1,770 rpm.

The sealing method of the shaft is the mechanical seal type. The bellows mechanism is applied to the mechanical seal so that the sealing performance is not affected by a rapid change in temperature.

The bearing on the shaft end is JIS No.7311 DB, this double row angular ball bearing is able to support both radial and thrust loads.

The bearing on the coupling side is JIS No.6311, this single row ball bearing supports only a radial load.

Both the casing and impeller are equipped with wear rings, and the design gap is 0.33 ± 0.03 mm. Figure 2.3 shows the accessories attached to the pump.

(2) Specifications of the pump

Table 2.2 lists the specifications of the pump.

Table 2.1 List of pumps used in the safety systems of Japanese PWR plants

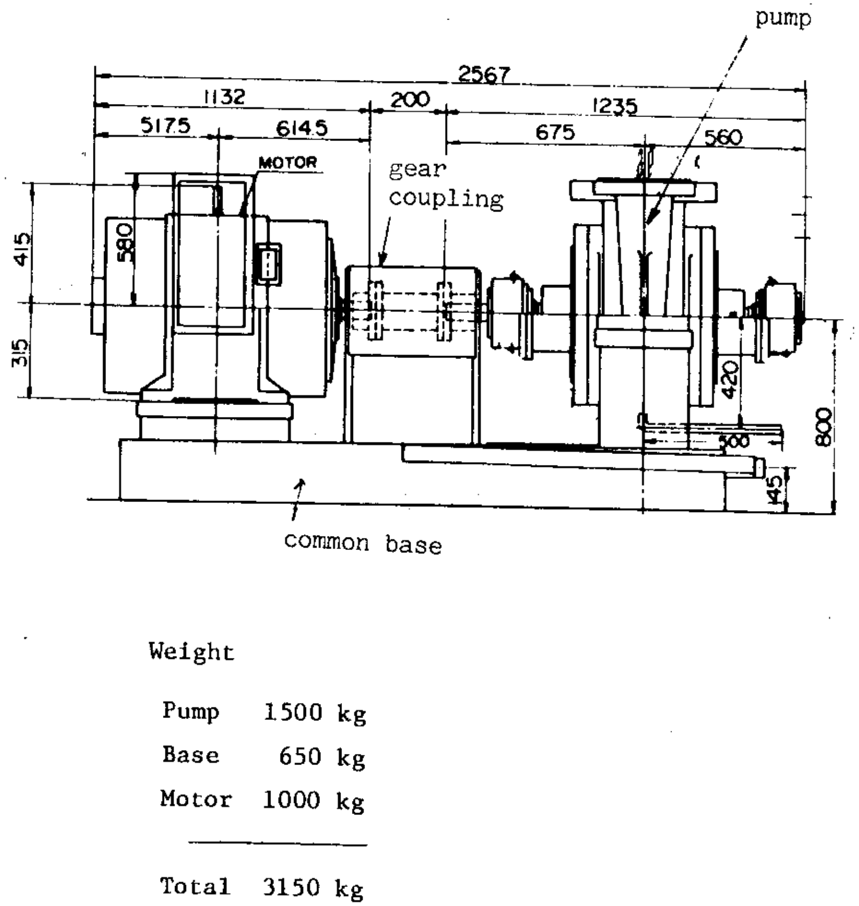
Use	Item	500,000 KW class	800,000 KW class	1,100,000 KW class
Boric acid injection pump	Kind	Horizontal, centrifugal	Horizontal centrifugal	Horizontal centrifugal
	Flow rate	10.2 m^3/h	17.0 m^3/h	17.0 m^3/h
Filling up pump	Kind	Variable speed, reciprocal	-	Variable speed, reciprocal
	Flow rate	14.3 m^3/h	-	22.3 m^3/h
Filling up/ high pressure injection pump	Kind	-	Horizontal, multistage, centrifugal	Horizontal, multistage, centrifugal
	Flow rate	-	34.1/147 m^3/h	34.1/147 m^3/h
Motor driven auxiliary feed water pump	Kind	Horizontal, multistage, centrifugal	Horizontal, multistage, centrifugal	Horizontal, multistage, centrifugal
	Flow rate	60 m^3/h	110 m^3/h	85 m^3/h
Turbine driven auxiliary feed water pump	Kind	Horizontal, multistage, centrifugal	Horizontal multistage, centrifugal	Horizontal, multistage, centrigugal
	Flow rate	110 m^3/h	123 m^3/h	171 m^3/h
Residual heat removal pump	Kind	Horizontal, centrifugal (double suction)	Vertical, centrifugal (double suction)	Vertical, centrifugal (double suction)
	Flow rate	454 m^3/h	681 - 852 m^3/h	681 - 1,020 m^3/h
Auxiliary machinery cooling water pump	Kind	Horizontal, centrifugal (double suction)	Horizontal, centrifugal (double suction)	Horizontal, centrifugal (double suction)
	Flow rate	850 - 900 m^3/h	1,100 - 1,150 m^3/h	1,140 m^3/h

Table 2.1 continued

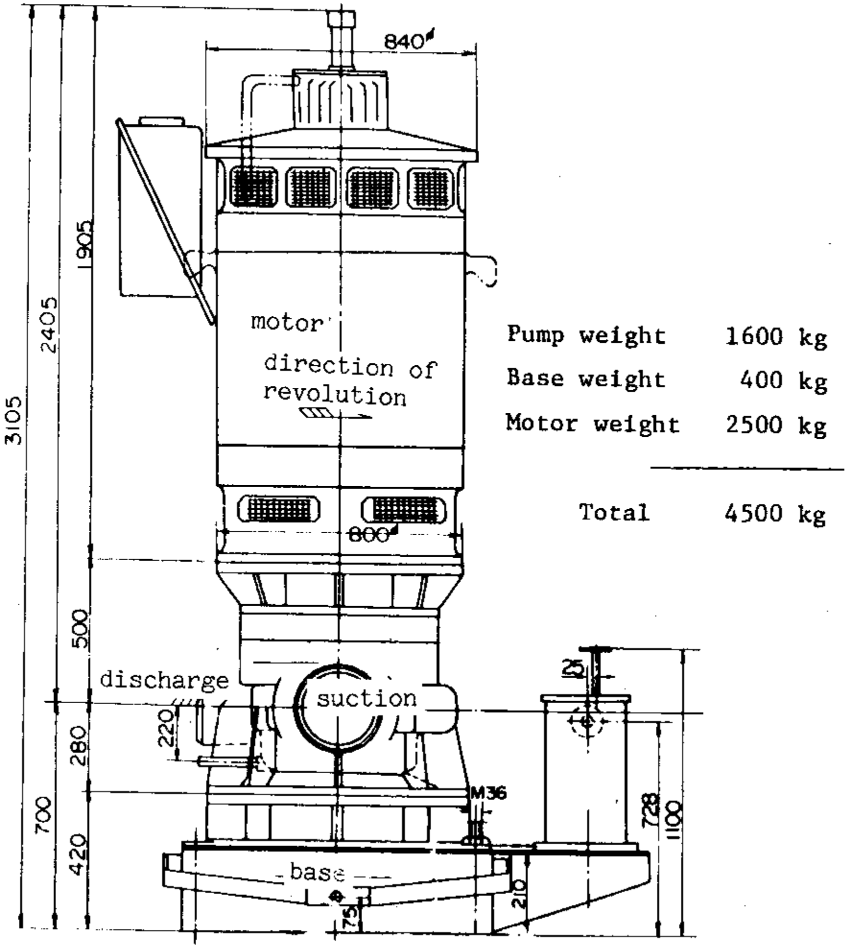
Sea water pump	Kind	Vertical, oblique flow	Vertical, oblique flow	Vertical, oblique flow
	Flow rate	2,400 - 2,500 m^3/h	3,200 m^3/h	1 1,200 m^3/h
High pressure injection pump	Kind	Horizontal, multistage, centrifugal	-	Horizontal, multistage, centrifugal
	Flow rate	159 m^3/h	-	96.5 m^3/h
Pressure vessel spray pump	Kind	Horizontal, multistage, centrifugal	Vertical, centrifugal (double suction)	Vertical, centrifugal (double suction)
	Flow rate	630 m^3/h	423 m^3/h	1180 m^3/h
Depleted fuel pit pump	Kind	Horizontal, centrifugal	Horizontal centrifugal	Horizontal centrifugal (double suction)
	Flow rate	200 - 220 m^3/h	523 m^3/h	522 m^3/h

Table 2.2 Specifications of the pump

RHR pump specifications	Type	Horizontal, single stage, double suction, Mitsubishi MLC - 15358
	Flow rate	454 m^3/h (max. 635 m^3/h)
	Total head	86 m
	Suction pressure	Min. 0 $kg/cm^2 \cdot G$, max. 35 $kg/cm^2 \cdot G$
	Design pressure	42 $kg/cm^2 \cdot G$
	Operation temperature	Room temperature - 177 °C
	Operation speed	1770 rpm
Driving motor specifications	Type	Horizontal, water protection, cage type, three-phase electric motor
	Revolutions per minute	1800 rpm (synchronous)
	Output	185 kW
	Voltage	3300 V
	Frequency	60 Hz

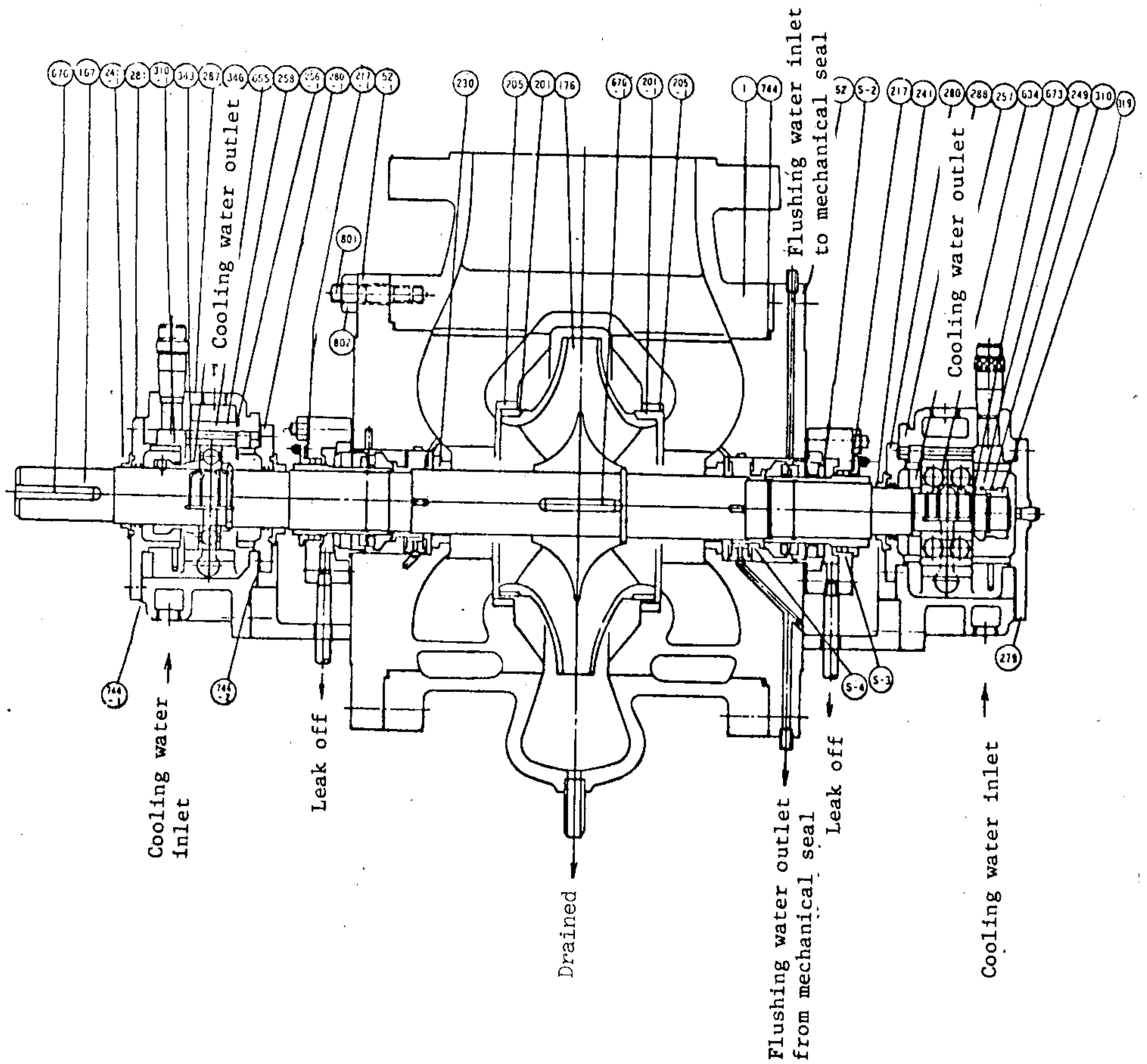


(a) Appearance of horizontal RHR pump



(b) Appearance of vertical RHR pump

Fig. 2.1 RHR pumps of horizontal type (left) and vertical type (right)



No.	Description	Material	Quantity
280-1	Bearing rubber	FCD 55	1
S-4	Gaskets	Teflon	2
S-3	Packings	VC CRAPHOLL	4
S-2	Mechanical seals	-	2 cases
802	Nuts	S 45 C	48
801	Stud bolts	SCM 3	48
744-2	Gaskets	Oil sheet	2
744-1	Gaskets	Oil sheet	2
744	Gaskets	SUS 27 & asbestos	2
676-1	Impeller key	SUS 304	1
676	Coupling key	S 45 C	1
673	Washer (on thrust side)	SPC 1	1
655	Radial ball bearing	#6311	1
654	Thrust ball bearing	#7311 DB	1
346	Radial ball bearing sleeve	535 C	1
343	Oilers	-	2
319	Oil ring retainer	S 35 C	1
310-1	Oil ring	SGP	1
310	Oil ring	SGP	1
288	Bearing box (on thrust side)	SCD 55	1
287	Bearing box (on radial side)	GVF 55	1
281	Bearing cover	FCD 55	1
280	Bearing cover	FCD 55	1
279	Bearing cover	FCD 55	1
258	Retainer split ring	S 35 C	1
257	Ring	S 35 C	1
256-1	Split ring	S 35 C	1
249	Thrust bearing nut	S 20 C	1
241-1	Water isolator	BC 6	2
241	Water isolator	BC 6	1
230	Throat bushing	SUS 304	2
217-1	Shaft sleeve	SUS 304	1
217	Shaft sleeve	SUS 304	1
205-1	Casing ring	SCS 13	1
205	Casing ring	SCS 13	1
201-1	Impeller ring	SCS 2	1
201	Impeller ring	SCS 2	1
176	Impeller	SCS 13	1
167	Rotor	SUS 304	1
52-1	Casing cover	SCS 13	1
52	Casing cover	SCS 13	1
1	Casing	SCS 13	1

Fig. 2.2 RHR pump assembly

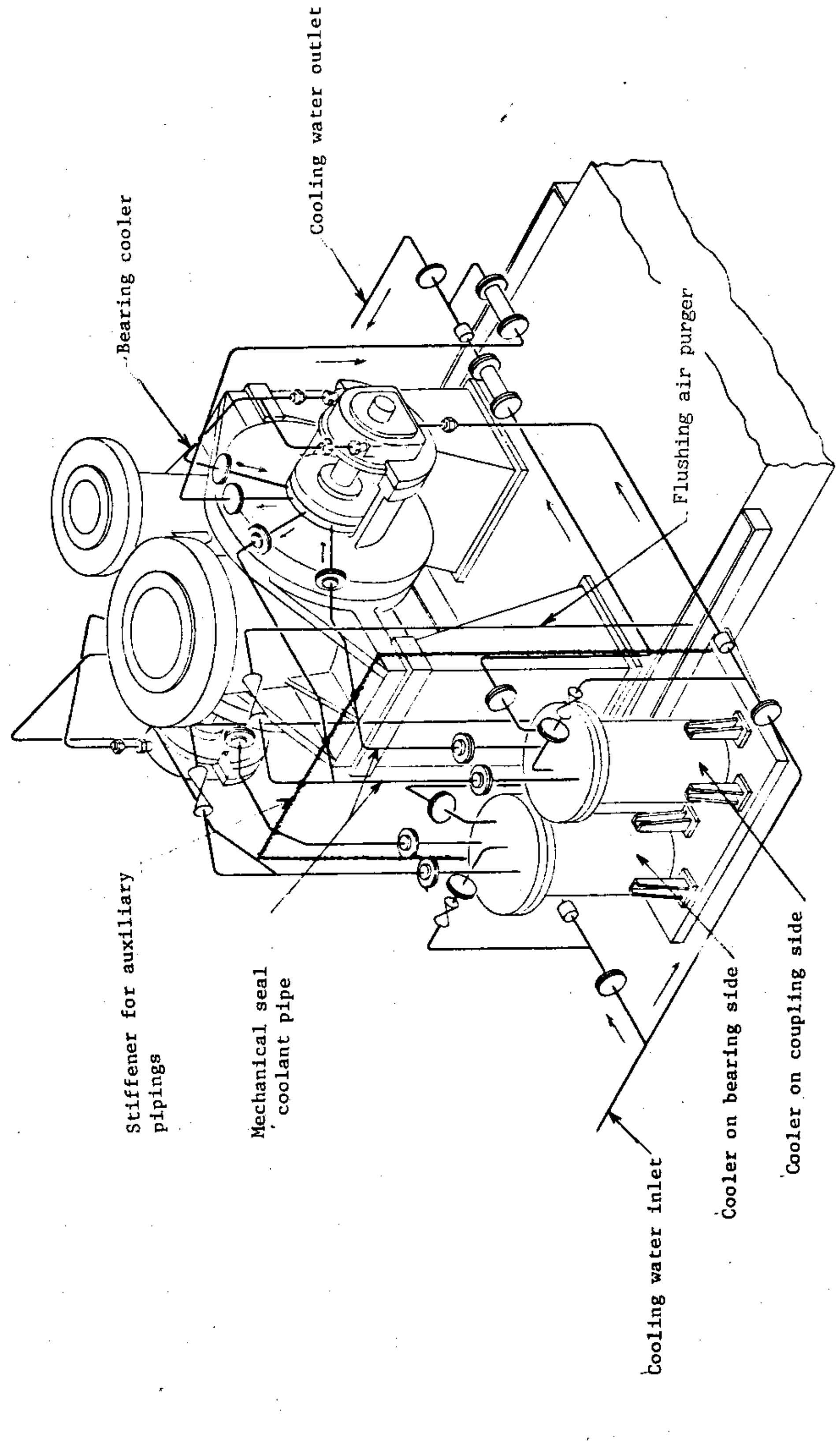


Fig. 2.3 Accessories around the pump

3. Excitation test conditions

The main aim of this aseismic test is to find the operating function limit of the pump during an expected earthquake and the resistance limit of the structure. The vibration characteristics and the dynamic response of the pump during external excitation should be elucidated in order to analyse the principal factors involved in the deterioration of the pump function and the strength of the structure. To this end, both excitation tests at key points and sinusoidal sweep tests on the shaking table were carried out at low levels of load or acceleration.

Following the above dynamic characteristics tests, the aseismic test conditions were determined as follows:

3.1 Selection of acceleration level

The acceleration level used in the aseismic design of a nuclear power plant is taken to be equal to the larger value of either the acceleration at the site (as obtained by dynamic earthquake response analysis of the building) or three times the value of the static degree of an earthquake, given in the Japan Architecture Standard Regulations. Figure 3.1 shows, for RHR pumps presently exsisting in Japan the values of the static design acceleration as "o" marks and the dynamic values as "x" marks. The static design acceleration is larger than the dynamic value since the RHR pump is placed on the lowest floor of the building.

The static design acceleration raises static force together with the mass exsisting at that location, which results in shear force and bending load on the structural members. The static force is used as the design earthquake force at the time of the static loading test. However, it seems more reasonable to take the dynamic design acceleration as the standard in the case of direct exitation of the foundation in the aseismic test of the pump. Since 300 Gal is the maximum value (Fig.3.1), 450 Gal, (300 Gal + 50%), is sufficient for the aseismic verification test of the RHR pump. However, in this test, a target value of the maximum acceleration is taken as 500 Gal.

3.2 Simulated seismic waves, taking into account input wave characteristics

The major items used to identify the input wave characteristics are the response spectrum and duration. The former indicates the frequency characteristics of the simulated seismic waves, and the latter, the duration of earthquake conditions.

The input wave can be expressed as a displacement wave, a velocity wave or an acceleration wave. The acceleration expression is used in this test to provide an easy physical concept or understanding of inertia force. The following three waves were adopted as the input waves for these aseismic tests.

(a) Observed seismic waves: El Centro 1940

(b) Artificial seismic waves: Artificial seismic waves such that the response curve envelops the design response curves of the preceding plants at the pump installation site and which take into account the duration and slope (rise-up, plateau and decaying parts) of the earthquake.

(c) Intermittent sinusoidal beat waves: Uses the beat wave form determined by consideration of the amplification of the plant building and the duration of the plateau of a seismic wave, and is a simple testing wave that always gives severe conditions regardless of the floor on which the machinery is placed.

The nature of these waves is stated in the following:

(1) Observed seismic waves

The seismic waves used are the NS and EW components of the El

Centro 1940 earthquake; the time history wave form and response spectrum are shown in Figs.3.2 and 3.3.

(2) Artificial seismic waves

The response spectrum of the artificial seismic waves is made by consideration of the followings:

(a) Earthquake conditions for the exsisting PWR plant sites in Japan

(b) Conditions for PWR plant sites expected in the future in Japan

(c) Information on the domestic and overseas standards in relation to earthquake conditions

(d) Vibration characteristics of the tested pump

When forecasting an earthquake, the magnitude and distance to the earthquake center should be determined with respect to the scale of earthquake; an in-land type earthquake of 7.0 in magnitude and 20 km in distance to the epicenter is taken as a standard design earthquake on the basis of earthquake history and geological structure. This means that the assumed input is severe since the short period component is more predominant than with an off-shore type earthquake and the natural period of the pump being tested is short. The frequency characteristics are determined based on examples of existing plants, US NRC Regulatory Guide 1.60 "Design Response Spectra for Seismic Design of Nuclear Power Plants"(1) and a paper by H.B. Seed et al.(2) on the relationship between the predominant period and the magnitude and epicenter distance.

(1) There are three examples of predominant periods (0.1 - 0.2 sec., 0.1 - 0.25 sec. and 0.1 - 0.3 sec.,) for a design earthquake at exsisting plants, depending on the rock property.

(2) The Regulatory Guide recommends 0.11 - 0.4 sec. as predominant period.

(3) According to Seed's proposal, the predominant period is 0.31 sec. for magnitude of 7.0 and epicenter distance of 20 km.

The frequency characteristic of the input seismic wave in this test considers the factors mentioned above, and the predominant period is from 0.1 - 0.4 sec. The standard floor response curve thus obtained is shown in Fig.3.4.

Much research has been reported on the method for generating artificial seismic waves. The method adopted here is that of modeling an earthquake by irregular processes which are steady in frequency and unsteady in amplitude.

This means that earthquake acceleration is determined by a pseudo steady random process $\ddot{y}_s(t)$ of the frequency characteristics expressed by superposed sinusoidal waves and the envelope function E(t) that expresses the unsteadiness of the amplitude, as given below.

$$\ddot{y}(t) = E(t).\ \ddot{y}_s(t),$$

where

$$\ddot{y}_s(t) = \sum_{n=0}^{N} a_n\ .\ \sin\ (\omega_n.t + \phi_n)$$

a_n : amplitude of nth frequency component

ω_n : nth natural circular frequency

ϕ_n : phase angle of nth frequency component

t : time.

The frequency band for a_n and ω_n is 5 - 30 Hz at the least. The uniform regular random number is allotted to ϕ_n, within the range from 0 to 2π.

The envelope form of the amplitude is shown in Fig.3.5 (as suggested by Jennings et al.[3]). Figure 3.6 shows the acceleration wave made by the means discussed above and adjusted to fit with the standard floor response curve of Fig.3.4. The maximum value is normalized to 100 Gal, and the floor response spectra are shown for damping ratios of 0.01, 0.03 and 0.05.

Figure 3.7 shows the response spectrum of the artificial seismic wave made for the aseismic test when the damping ratio is 0.01 and compares it to the floor response curve described as the standard.

(3) Intermittent sinusoidal beat waves

The vibration response of the building acts as the input to the machinery, hence, a part of the frequency component of the random seismic input is filtered by the foundation-building system. As a result it is transformed into a random sinusoidal wave, the frequency of which, becomes predominant in the vicinity of the building natural frequency and the envelope is in the form of a sinusoidal beat wave. Figure 3.8 illustrates the appliaction of the sinusoidal beat wave to the aseismic test.

The resonance test is the most severe for machinery from the stand point of the seismic test, and a sufficiently severe aseismic test can be conducted by using the resonant beat wave, assuming the resonance frequencies of the building and machine are equal. Consequently, the response amplification can be appropriately simulated for the case of the resonance of the building equal to the resonance of the machine (which takes place under the condition of an actual seismic wave), when the number of the beats, the wave number in the beat and the beat interval of the resonant beat wave are chosen suitably. Accordingly, for this simulation, the following intermittent beat wave is generated and used.

(i) Beat number : 5 (determined from the duration of seismic wave)

(ii) Beat interval : 2 sec. (least interval free from the interference between the beats)

(iii) Wave number per beat: 10 cycles (to give amplification nearly equal to the response amplification of seismic wave)

(iv) Frequency of sinusoidal wave in the beat : Natural frequency of the machine

(v) Maximum amplitude of the beat : Test acceleration at the natural period of the machine

The wave form is shown in Fig.3.9. The sinusoidal beat wave is the basis for the quasi-resonant test of the machine. The response curve of the sinusoidal beat wave is shown in Fig.3.10.

3.3 Analysis of the wave form used in the test

The wave forms described above are used in the aseismic test, but the frequency component is cut off below 4.5 Hz because the exciter used is not capable of producing a maximum acceleration equal to 500 Gal below 4.5 Hz. Figures 3.11, 3.12 and 3.13 are the acceleration waves measured on the shaking table during the test and their response spectra. A low pass filter was used to cut off the frequency components above 28 Hz in order to cut off a pump-rotation frequency component of 29.7 Hz.

Comparison is made between the response spectrum of the artificial seismic wave measured on the shaking table and the standard floor response curve in Fig.3.14. When the response spectrum of the test wave is multiplied by 1.15, the standard floor response curve is enveloped approximately. For this reason, it is necessary to divide the nominal input acceleration of the artificial seismic wave by 1.15 when the earthquake resistance of the machine is evaluated with respect to the standard floor response curve.

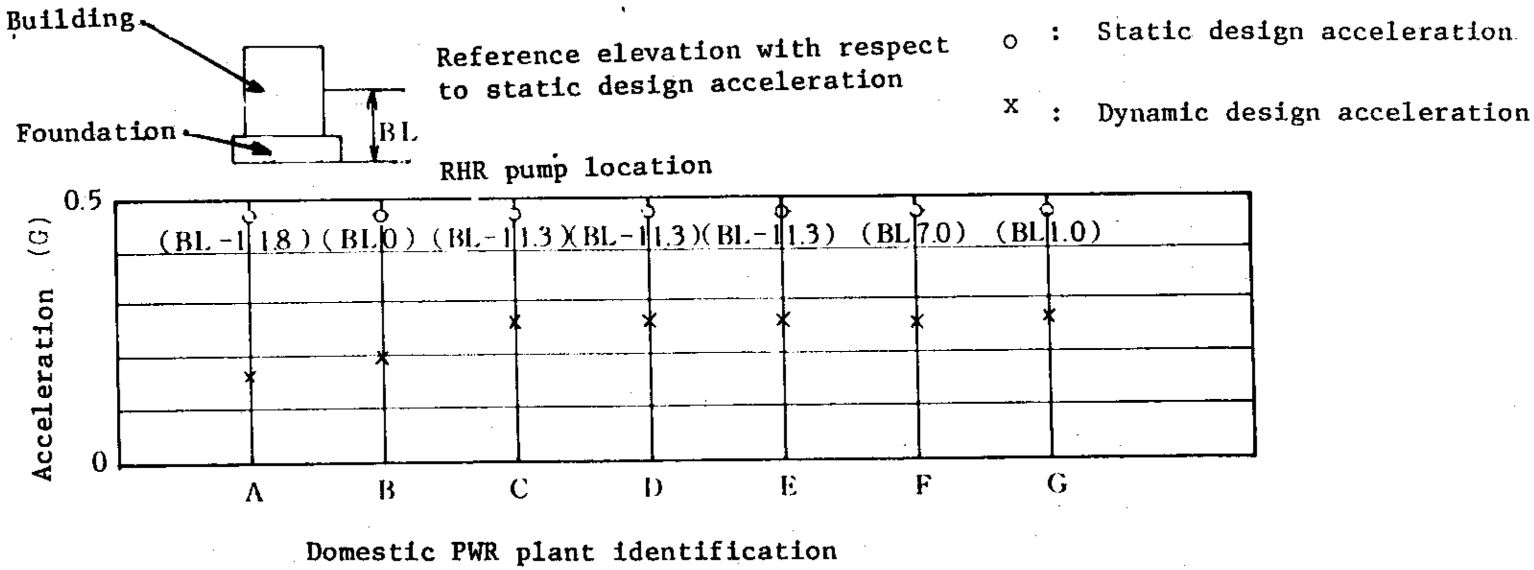
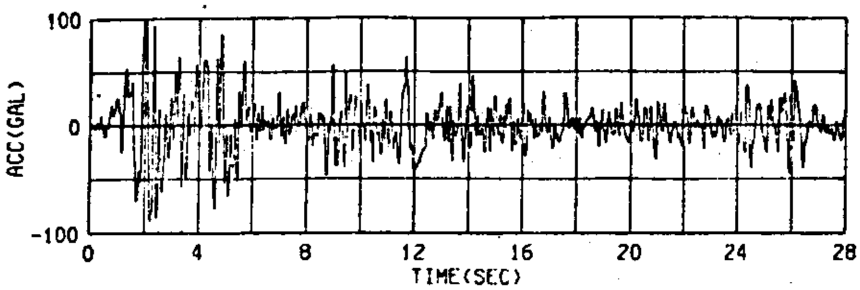


Fig. 3.1 Design acceleration at installation location of RHR pump



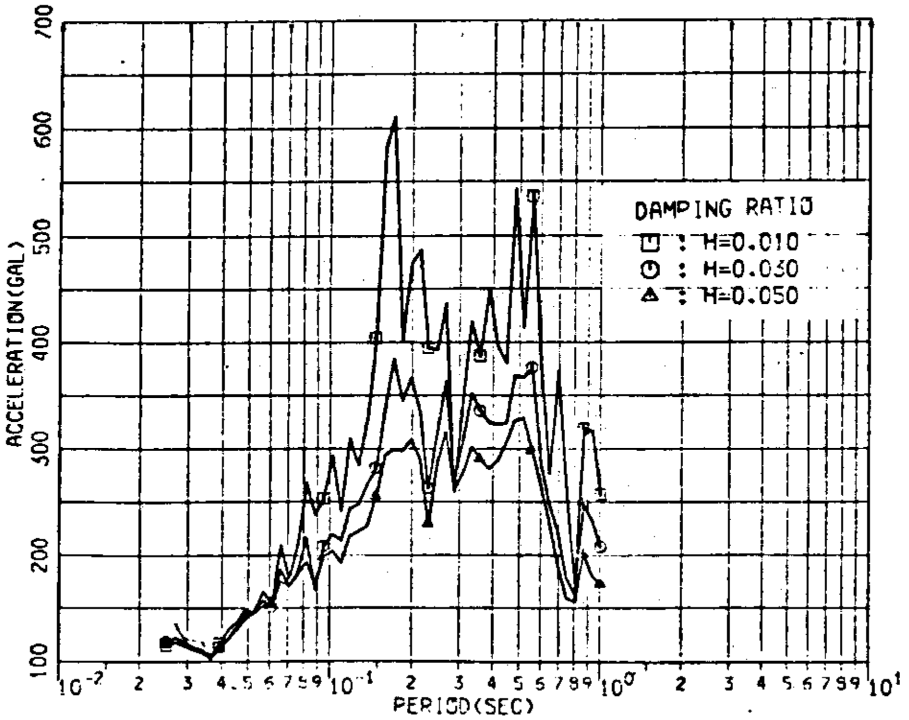


Fig. 3.2 El Centro NS 1940 wave and response spectrum

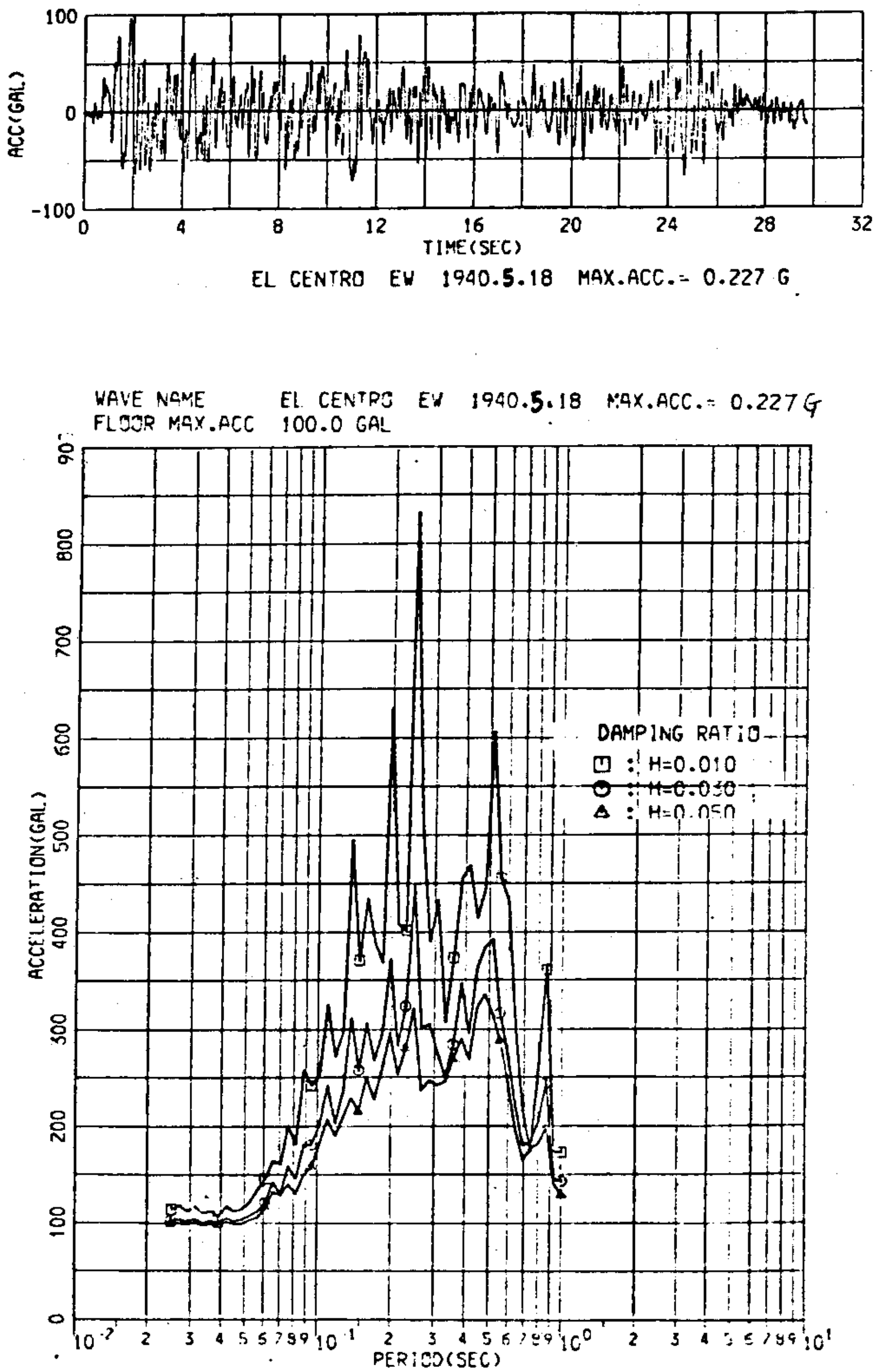


Fig. 3.3 El Centro EW 1940 wave and response spectrum

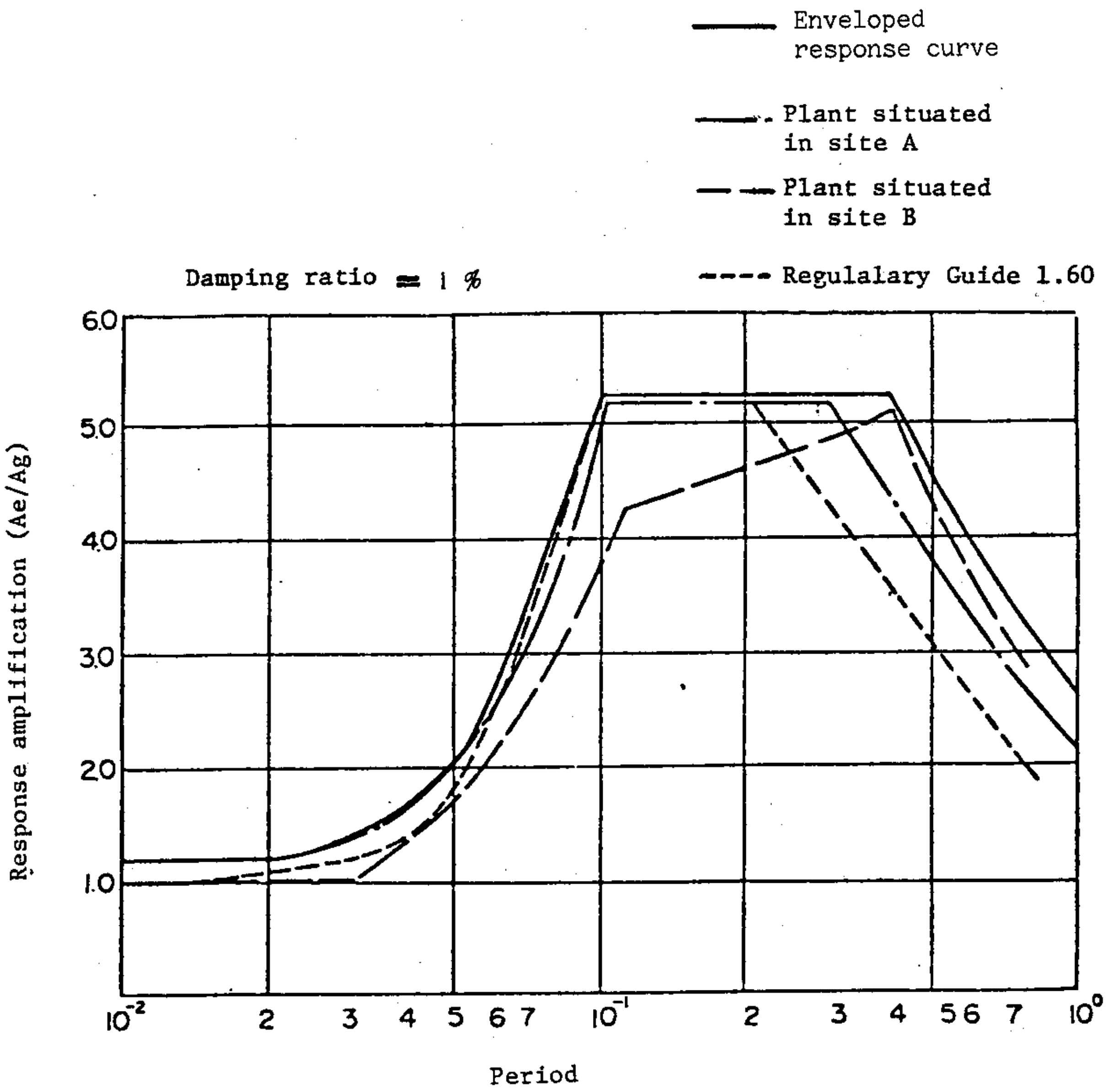
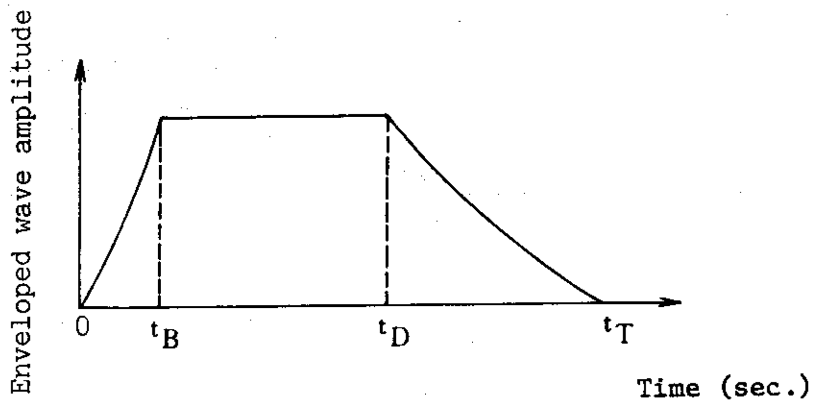


Fig. 3.4 Standard floor response curve

t_B(sec.)	t_D(sec.)	t_T(sec.)
4	15	30

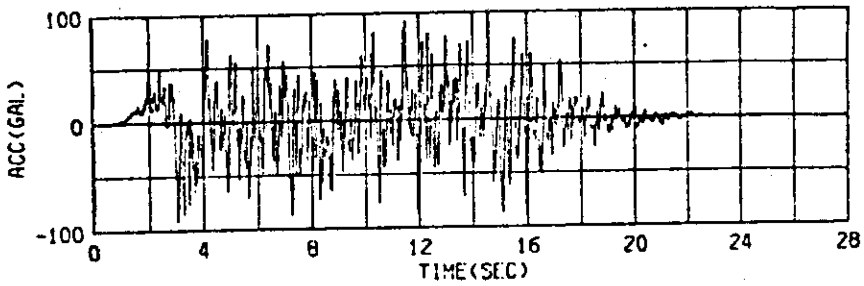


$0 \sim t_B$ (sec.) : Seismic wave rise up

$t_B \sim t_D$ (sec.) : Major motion of seismic wave

$t_D \sim t_T$ (sec.) : Decaying part of seismic wave

Fig. 3.5 Envelope of artificial seismic wave amplitude



ARTIFICAL WAVE

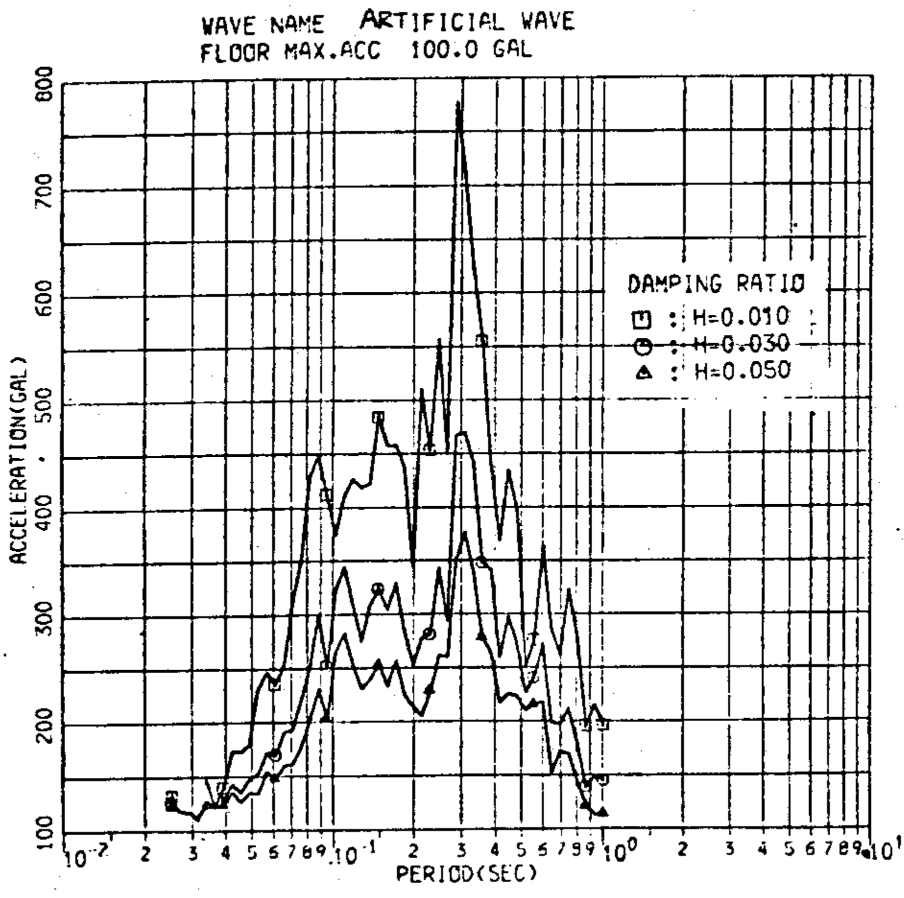


Fig. 3.6 Artificial seismic wave made for aseismic test and its response spectra

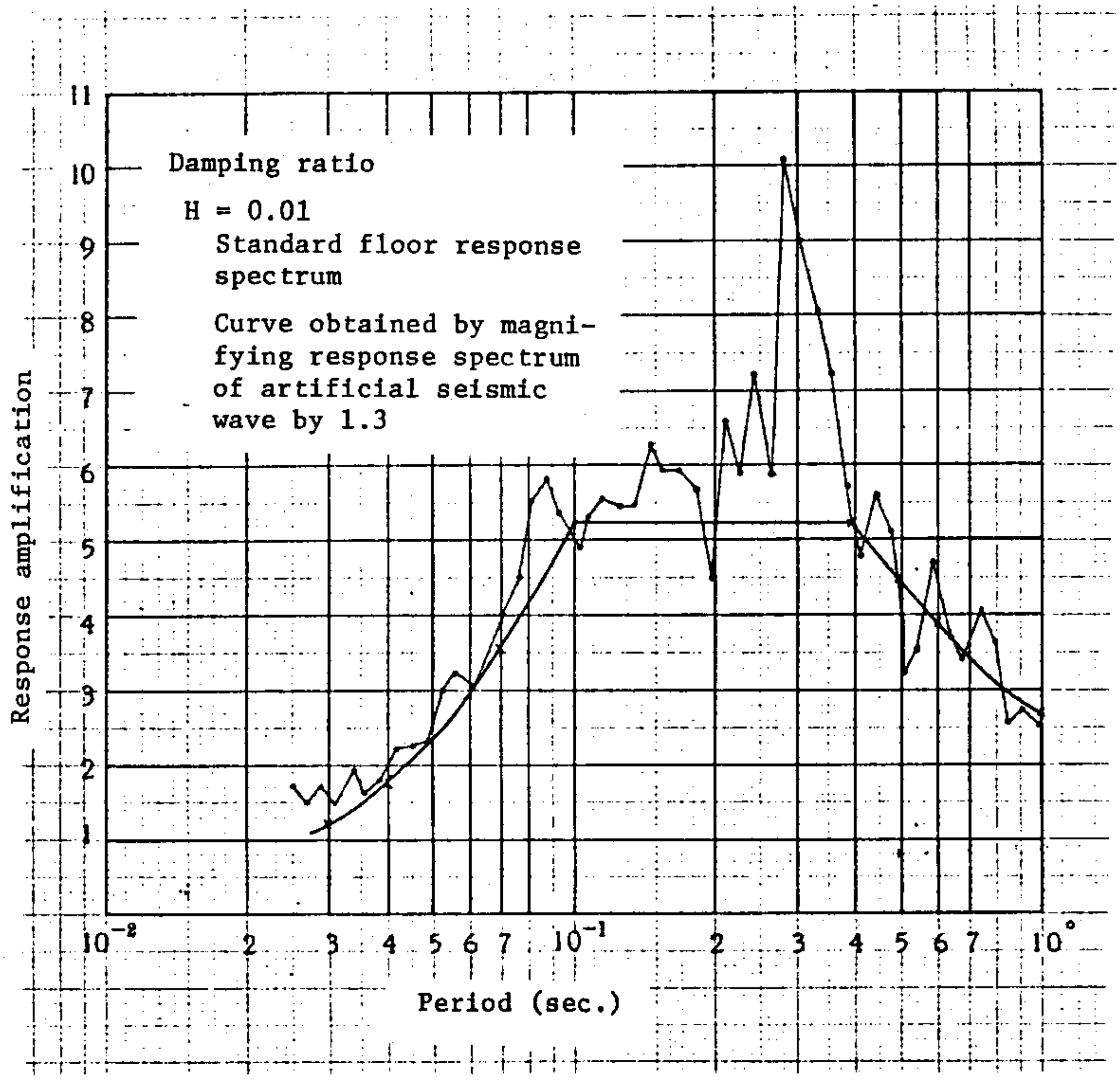


Fig. 3.7 Comparison between the standard floor response curve of the artificial wave and the response spectrum really made

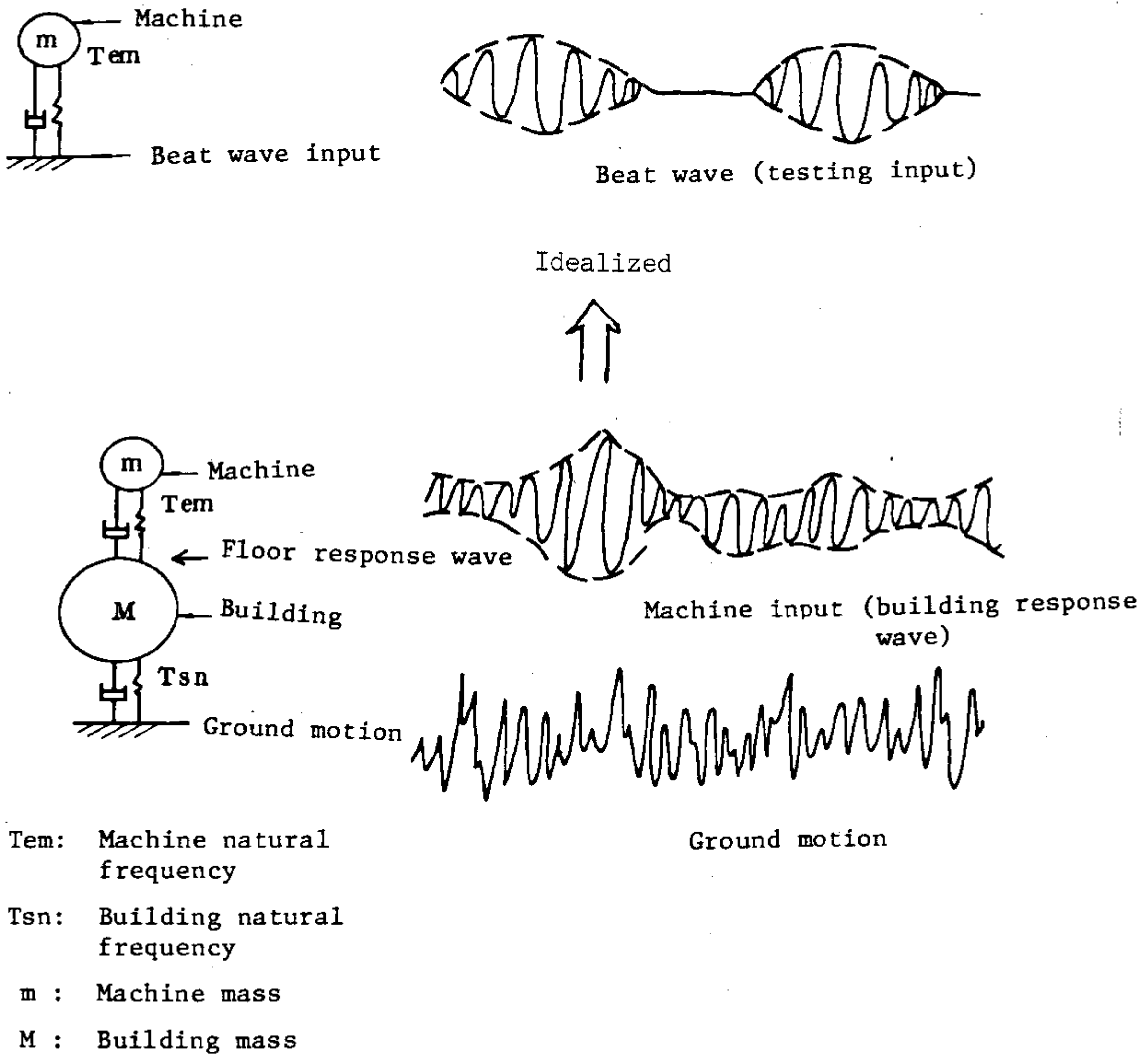


Fig. 3.8 Meaning of application of sinusoidal beat wave as aseismic testing wave

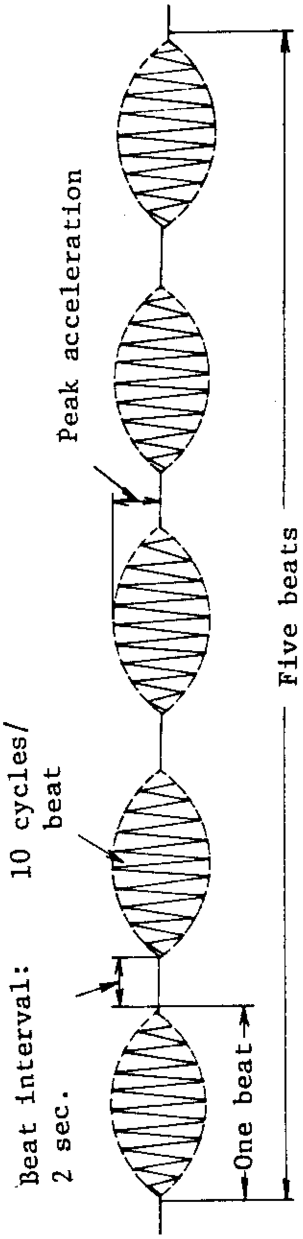
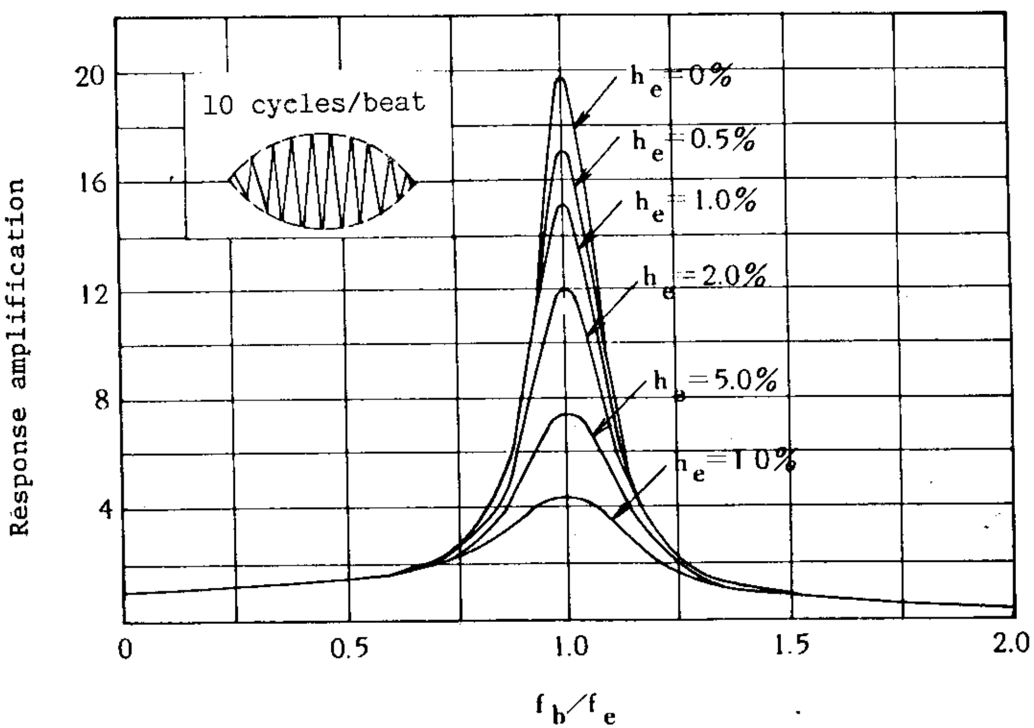


Fig. 3.9 Intermittent sinusoidal beat wave

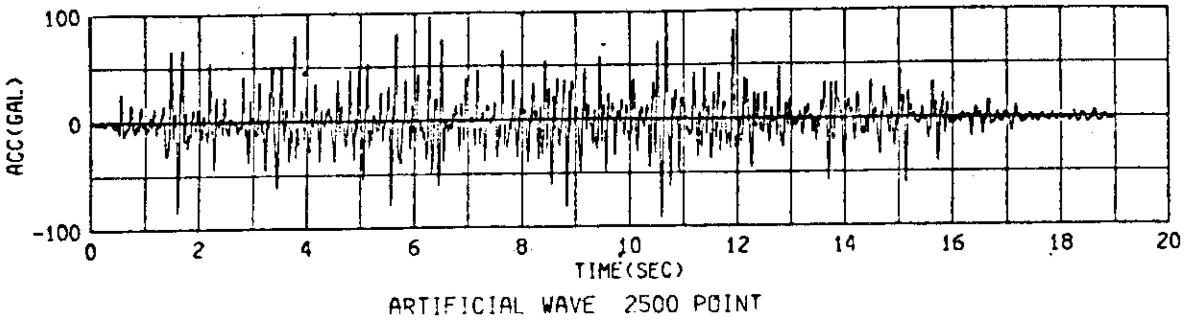


h_e; Damping ratio of machine

f_e; Machine natural frequency

f_b; Frequencies in a beat

Fig. 3.10 Response curve of sinusoidal beat wave



(Frequency components above 28 Hz and below 4.5 Hz are cut off.)

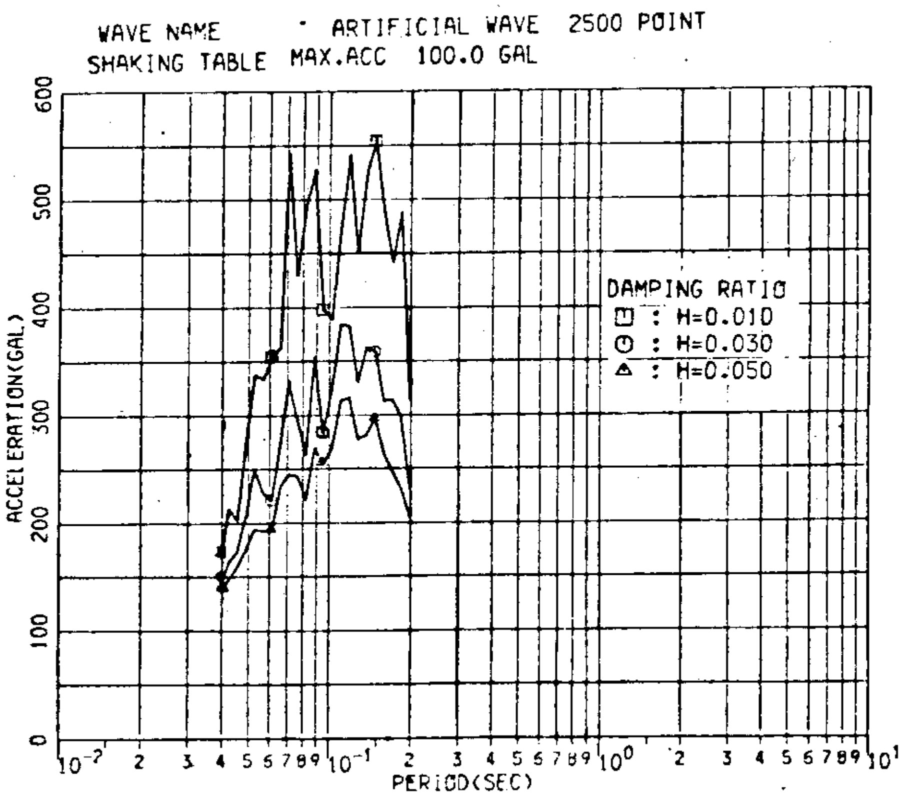
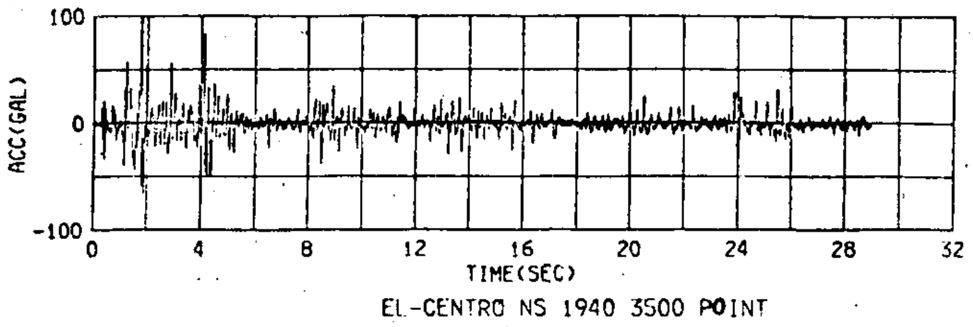


Fig. 3.11 Artificial seismic wave on the shaking table and its response spectra



(Frequency components above 28 Hz and below 4.5 Hz are cut off.)

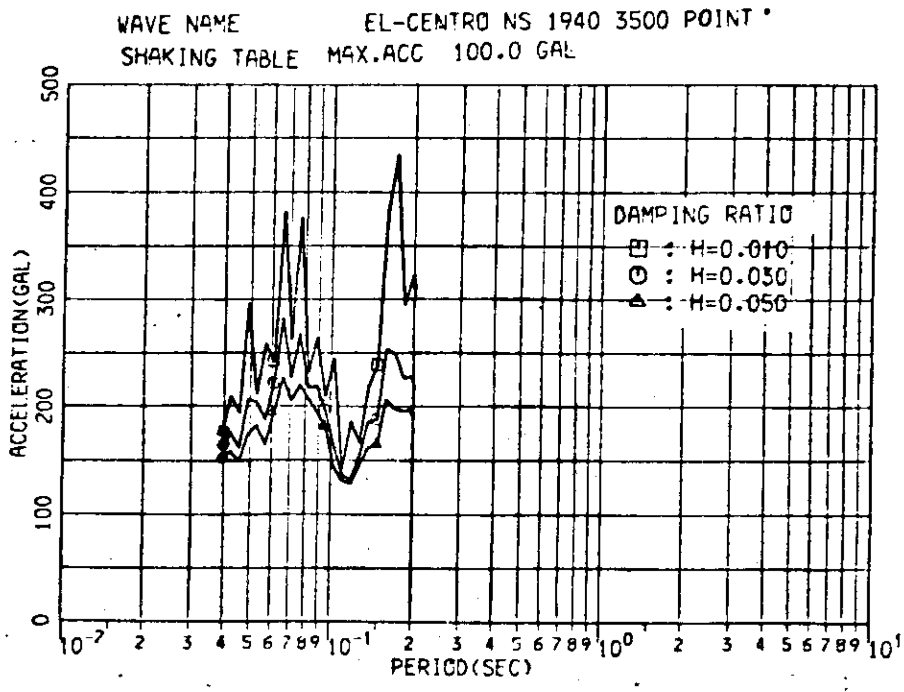
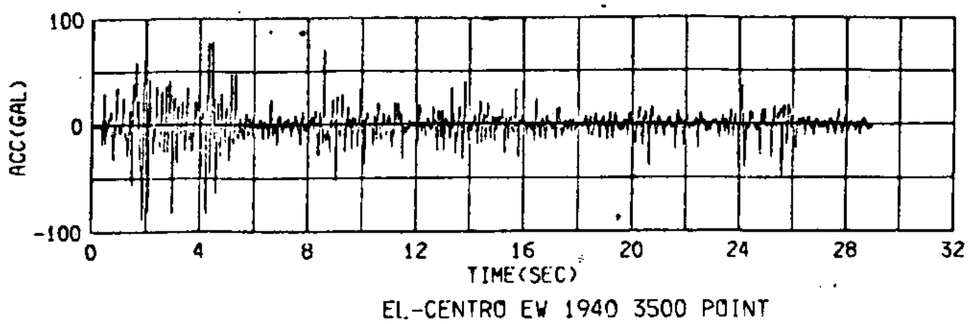


Fig. 3.12 El Centro NS 1940 wave on the shaking table and its response spectra



(Frequency components above 28 Hz and below 4.5 Hz are cut off.)

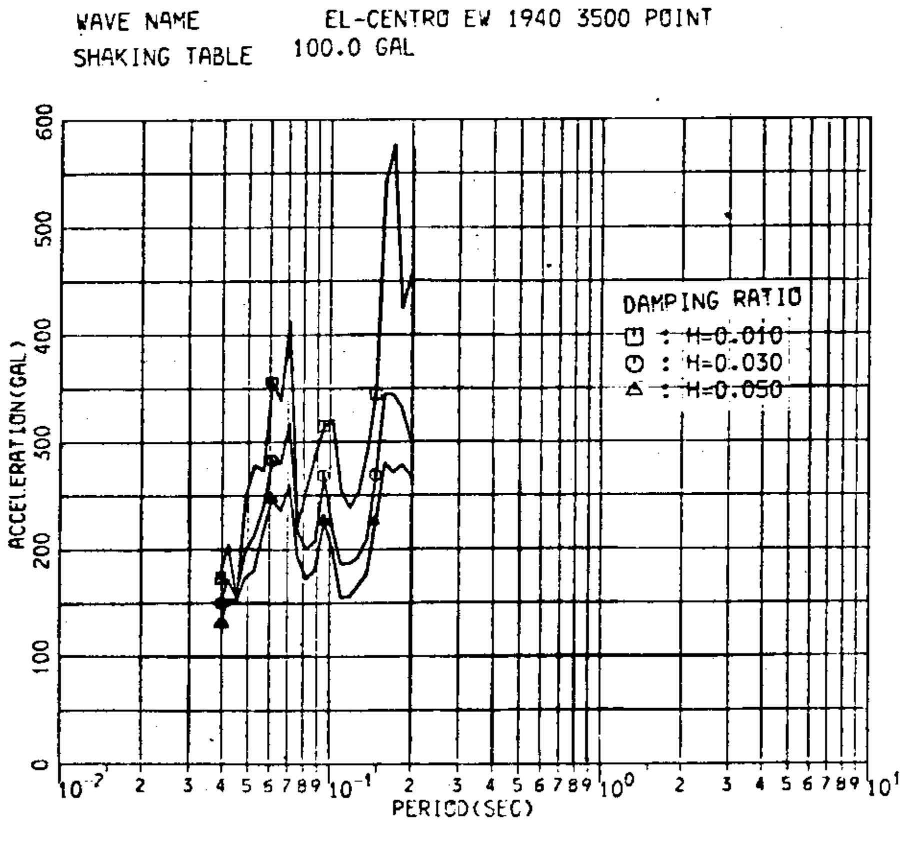
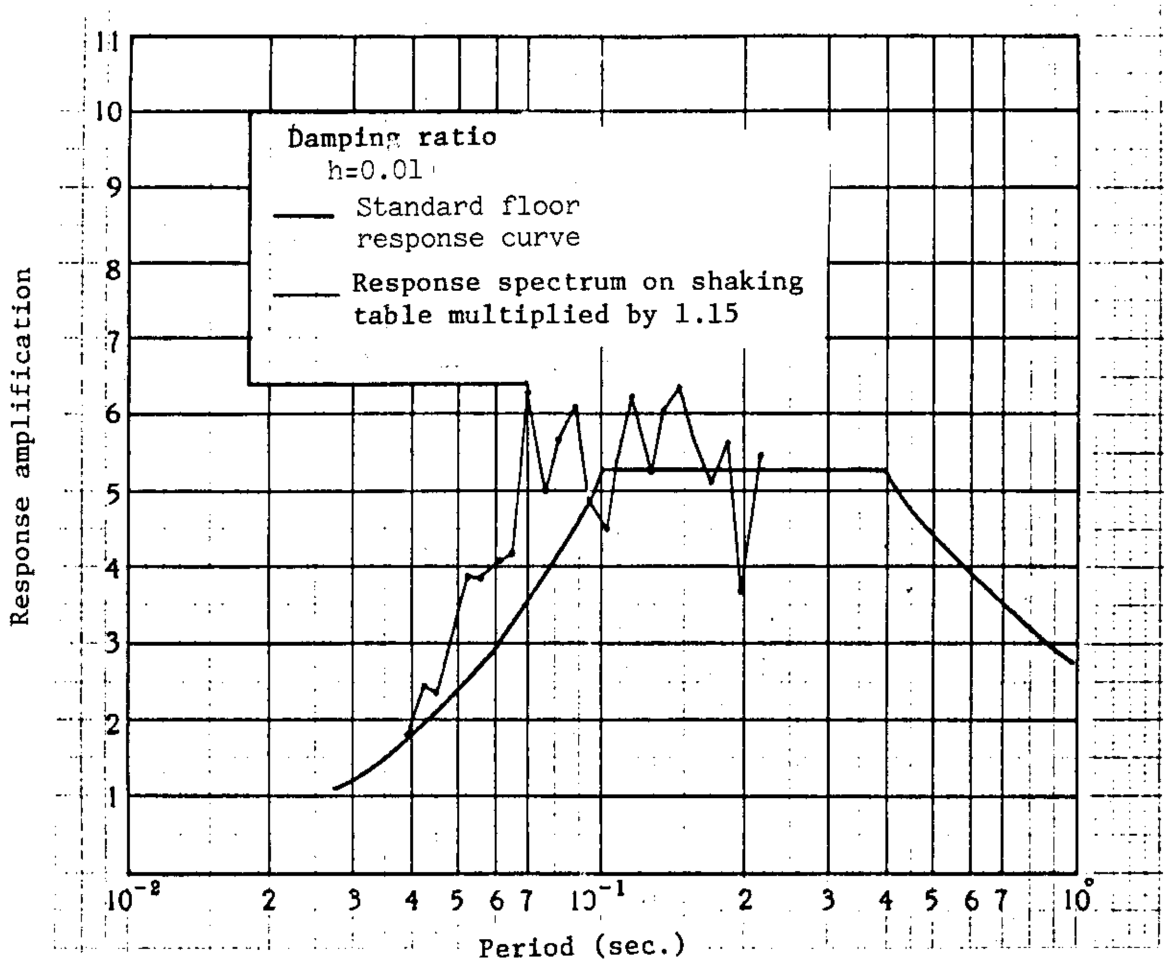


Fig. 3.13 El Centro EW 1940 wave on the shaking table and its response spectra



(Frequency components above 28 Hz and below 4.5 Hz are cut off.)

Fig. 3.14 Comparison between the artificial seismic wave response spectrum on the shaking table and the standard floor response curve

4. Test plan, facilities and instrumentation

4.1 Test plan

It is necessary to know the vibration characteristics of the pump as a rotating machine and to conduct functional verification test of the RHR pump subjected to the simulated seismic wave. The purpose is to elucidate the resistance of the operating pump during an earthquake. To accomplish this the test plan requires (1) prior-to-pump assembly test, (2) prior-to-excitation test and (3) excitation test. Table 4.1 lists the items, test ingredients, measurement items and test conditions.

4.2 Test facilities

(1) Piping loop

The flow diagram of the piping loop is illustrated in Fig.4.1. Since the loop is a closed type, the temperature of the inner liquid rises due to pump operation. A pump is therefore added to introduce water at room temperature so that the liquid temperature is kept nearly constant (at room temperature).

Flexible pipes are attached to the suction pipe, discharge pipe and cooling water so that the pump installed on the shaking table is connected indirectly to the piping loop. The flexible pipe on the discharge side is mounted on the downstream side of the outlet pressure reduction valve because of the pipe strength. The size of the pipe loop is the same as that of the actual piping (PWR 2 loop RHR pump). The piping arrangement on the shaking table is depicted in Fig.4.2.

(2) Loop operation conditions

The pump loop is operated under the following conditions in the aseismic test.

(i) Kind of water : Industrial use water

(ii) Water temperature: Room temperature

(iii) Flow rate : 454 m^3/h (rated), 635 m^3/h (maximum)

(iv) Suction pressure : 3 kg/cm^2G

(3) Shaking table

The shaking table used is installed in and owned by Takasago Research Center of Mitsubishi Heavy Industries Co., Ltd. The major specifications are given below.

(i) Excitation force: 50 tonG in two horizontal directions

(ii) Maximum amplitude: 50 mm

(iii) Table size: 6 m x 6 m x 1 m

(iv) Table weight: 21 tons

(v) Installation capacity: 100 tons (maximum)

(vi) Frequency range: 0.1 - 50 Hz

(vii) Vibration wave form: Arbitrary

(viii) Control system: Electric-coil pressure servo system

4.3 Measuring instruments used and data processing

(1) Vibration measurement

(a) Monitoring of pump operation

Rotating machines, such as the pump, always vibrate during operation owing to the unbalanced force and fluid force. Abnormal vibration is likely to take place when the bearings are damaged or wear ring seizure occurs. Thus, the following items were measured to detect abnormal vibration.

(i) Vibration acceleration of the pump bearing box

(ii) Vibration acceleration of the casing mandrel, piezo type accelerometer

(b) Measurement of vibration response

The following items were measured to find the vibration response during the excitation test.

(i) Horizontal, vertical and axial displacements of the shaft

(Fine displacement meter)

(ii) Horizontal and axial accelerations of the bearing box

(iii) Vibration acceleration of piping (on discharge and suction sides), casing and motor mandrel

(Electric resistance strain gage type accelerometer)

(iv) Bearing reaction on the coupling side (Force gage)

(v) Draw force of the pump casing fixing bolts

(vi) Draw force of the pump anvil plate fixing bolts

(Electric resistance strain gage)

The bearing reaction was measured on the coupling side, rather than on the thrust bearing side of the pump, since the two ball bearings caused difficulty in attaching the force gage. Also, the load due to the relative displacement to the motor acted to produce the coupling during the excitation of the shaking table. The stiffness of the force gage is 10^7 kg/cm, and the ball bearing stiffness is 2×10^5 - 4×10^5 kg/cm. Consequently, the vibration characteristics are hardly affected by the force gage attached to the outer case housing of the ball bearing. Fig.4.3 shows the locations of vibration measurement.

(2) Performance measurement

The pump performance was measured before and after the excitation test to find the vibration in pump performance due to the excitation test. The total head and pump efficiency were measured at 0, 25, 50, 75 and 100 % of the rated flow rate and the maximum flow rate. The measurement items were as follows:

(i) Discharge flow rate (flow rate measuring orifice manometer)

(ii) Discharge pressure

(iii) Suction pressure (Bourdon tube pressure gage)

(iv) Revolutions per minute (tachometer)

(v) Water temperaure

(vi) Motor input (Watt meter)

(3) Data processing

The data processing used in the test is outlined in the following:

(i) Frequency analysis

Frequency analysis is the basis for analysing the pump vibration. In this test, a real time analyser using the time compression method is used for the analysis.

The Band-selectable Fourier analysis method is applied to the analysis of the vibration characteristics of the pump in the case of a rated flow rate. This method is otherwise called the zoom FFT and is useful when high resolution is required, since the frequency domain can be extended in the vicinity of the frequency where the analysis is required.

(ii) Mechanical impedance measurement

Mechanical impedance was measured when the vibration characteristics of the pump rotor were analysed.

The block diagram of the mechanical impedance measurement is illustrated in Fig.4.4. The resonant frequency and damping coefficient can be read directly from the mass effect of the exciter.

Figure 4.5 illustrates the whole testing facility and measuring instruments schematically.

Table 4.1 List of tests for RHR pump used in PWR plants

No.	Test category	Test item	Test ingredient	Measurement item	Test condition	Remark
1	Prior-to-assembly test	Pump rotor single body vibration test	Vibration test of rotor single body in air	Natural frequency and mode of rotor single body	1. Free-free condition 2. Excitation test by use of exciter	
2		Prior-to-assembly inspection	Confirmation of no anomaly in each part of pump	1. Clearance of wear ring 2. Surface roughness of mechanical seal sliding faces	Prior to assembly	Compared with inspection after tests and disassembling
3	Prior-to-test test	Pump vibration characteristics test	Excitation test of pump (not operating) in the case of water absent or present	1. Natural frequency and mode of pump rotor 2. Natural frequency and mode of casing	Pump excited by exciter in not running condition with water or without water	
4		Pump performance test I	Performance test of pump operation before main test	1. Pump performance 2. Vibration during pump operation	Tested over the range covering pump capacity (0, 25, 50, 75, 100, 125 % and maximum flow rate)	
5	Main test	Vibration characteristics test	Low level sinusoidal wave sweep excitation	1. Vibration of pump parts during operation 2. Response acceleration of main parts 3. Idling time after pump driving stopped and so on	1. Operating condition a. at rated flow rate b. excited on shaking table 2. Excitation on shaking table 3. Low level excitation below 100 Gal 4. Sinusoidal wave from 4.5 Hz to 40 Hz 5. Separate excitation either in X-direction or Y-direction	

Table 4.1 continued.

No	Test category	Test item	Test ingredient	Measurement item	Test condition	Remark
6	Main test	Disassembling and inspection	Disassembling and inspection after vibration characteristics test	1. Clearance of wear ring 2. Surface roughness of sliding faces of mechanical seal	Before function verification test	Compared with the data after function verification test
7		Pump performance test II.	Pump performance after vibration characteristics test	1. Pump performance 2. Vibration during pump operation	Tested over the range covering pump capacity (0, 25, 50, 75, 100, 125% and maximum flow rate)	
8		Function verification test	Aseismic test by use of El Centro waves, artificial seismic wave and intermittent beat wave	1. Vibration of pump parts during operation 2. Response acceleration of main parts 3. Idling time after pump driving stopped and so on	1. Operating condition a. at rated flow rate b. maximum flow rate 2. Excited on shaking table 3. Three levels below 500 Gal. 4. Separate excitation either in X-direction or Y-direction & Simultaneous excitation in X-direction & Y-direction.	Confirmation of pump function during earthquake
9		Disassembling and inspection	Pump disassembling and inspection after function verification test	1. Clearance of wear ring 2. Surface roughness of sliding faces of mechanical seal	Before aseismic margin test	Compared with the data after aseismic margin test
10		Pump performance test III	Pump performance after function verification test	1. Pump performance 2. Vibration of pump during operation	Tested over the range covering pump capacity (0, 25, 50, 75, 100, 125% and maximum flow rate)	

Table 4.1 continued

No.	Test category	Test item	Test ingredient	Measurement item	Test condition	Remark
11	Main test	Aseismic marg-ing test	Aseismic test by use of resonant sinusoidal wave	1. Vibration of pump parts during operation 2. Response acceleration of main parts 3. Idling time after pump driving stopped and so on	1. Operation condition a. at rated flow rate b. at maximum flow rate 2. Excited on shaking table 3. Resonant sinusoidal wave at level more than 500 Gal 4. Separate excitation either in X-direction or Y-direction	Confirmation of aseismic margin
12		Pump perfor-mance test IV	Pump performance after aseismic margin test	1. Pump performance 2. Vibration of pump during operation	Tested over the range covering pump capacity	Confirmation of pump performance after test
13		Disassembling and inspection of pump	Checking of whether pump parts damaged by test or not	1. Clearance of wear ring 2. Surface roughness of sliding faces of mechanical seal 3. Wear of bearings	After test	Compared with situation after and during test

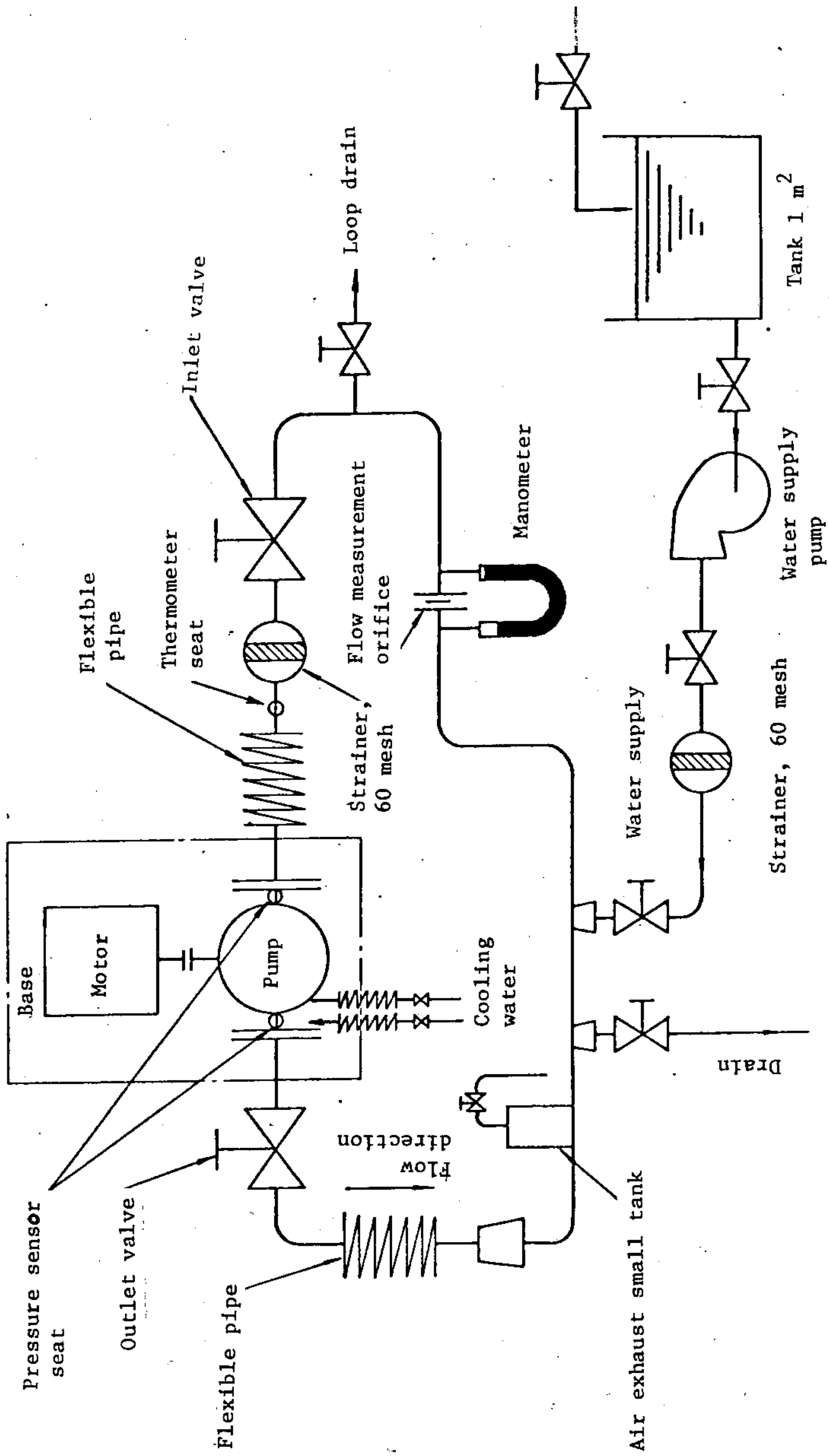


Fig. 4.1 Flow diagram of piping loop

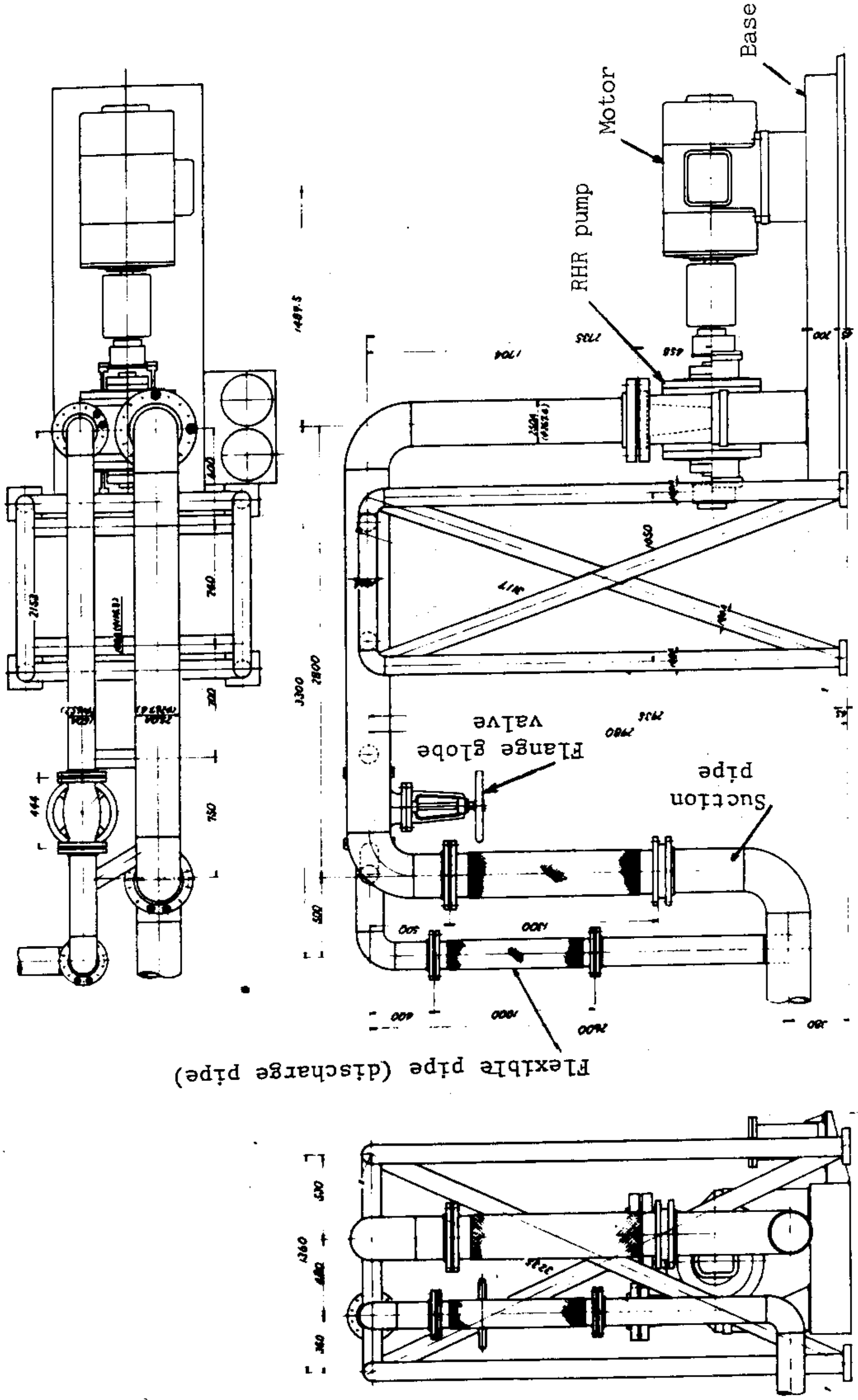


Fig. 4.2 Major piping on shaking table

Measurement points	Direction	Item	No.
Rotor on bearing side	V	Displacement	1
Rotor on bearing side	H	Displacement	2
Rotor on bearing side	A	Displacement	3
Rotor on coupling side	V	Displacement	4
Rotor on coupling side	H	Displacement	5
Casing mandrel	V	Acceleration	6
Bearing box on coupling side	V	Acceleration	7
Bearing box on bearing side	V	Acceleration	8
Bearing reaction on bearing side	V	Displacement	9
Bearing reaction on coupling side	V	Displacement	10
Vibration sound	-	Noise	11
Suction pressure	-	Pressure	12
Discharge pressure	-	Pressure	13
Bearing box on bearing side	H	Acceleration	14
Bearing box on bearing side	A	Acceleration	15
Bearing box on coupling side	H	Acceleration	16
Bearing box on coupling side	A	Acceleration	17
Casing mandrel	H	Acceleration	18
Casing mandrel	A	Acceleration	19
Motor casing	H	Acceleration	20
Motor casing	A	Acceleration	21
Discharge pipe	H	Acceleration	22
Discharge pipe	A	Acceleration	23
Anchor bolt	V	Reaction force	24
Anchor bolt	V	Reaction force	25
Anchor bolt	V	Reaction force	26
Anchor bolt	V	Reaction force	27
Pump leg fastening bolt	V	Reaction force	28
Pump leg fastening bolt	V	Reaction force	29
Pump leg fastening bolt	V	Reaction force	30
Pump leg fastening bolt	V	Reaction force	31
Suction pipe	H	Stress	32
Suction pipe	A	Stress	33
Discharge pipe	H	Stress	34
Discharge pipe	A	Stress	35
Rotation pulse	-	Revolution speed	36

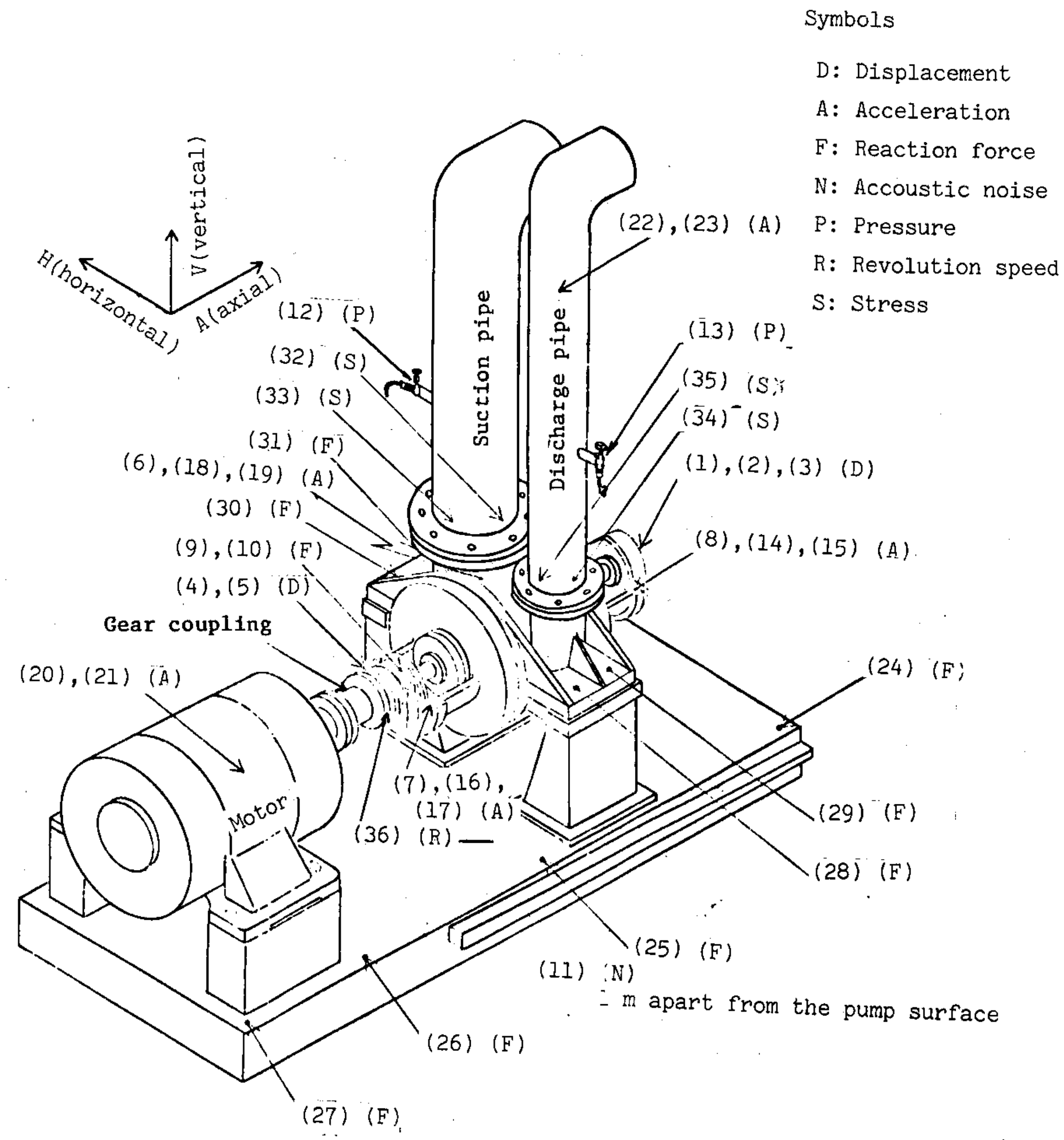


Fig. 4.3 Location of the sensors

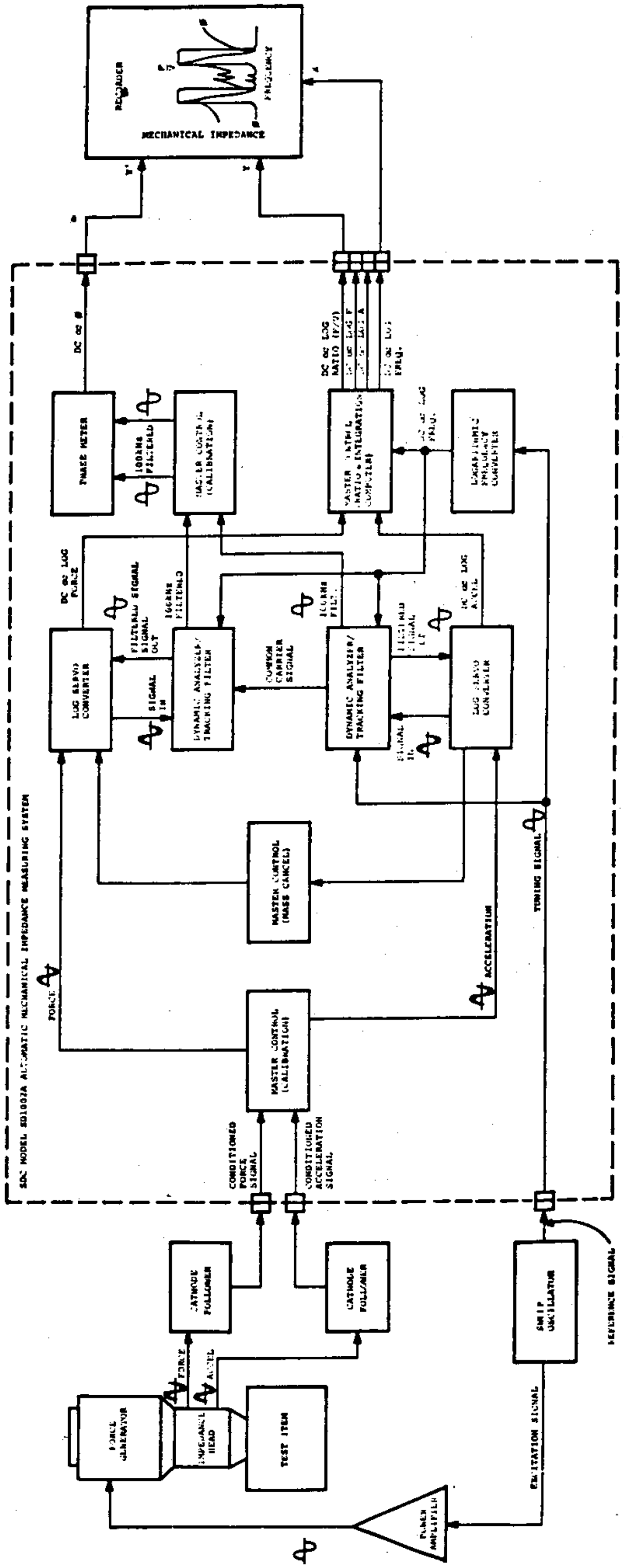


Fig. 4.4 Complete mechanical impedance test and analysis system block diagram

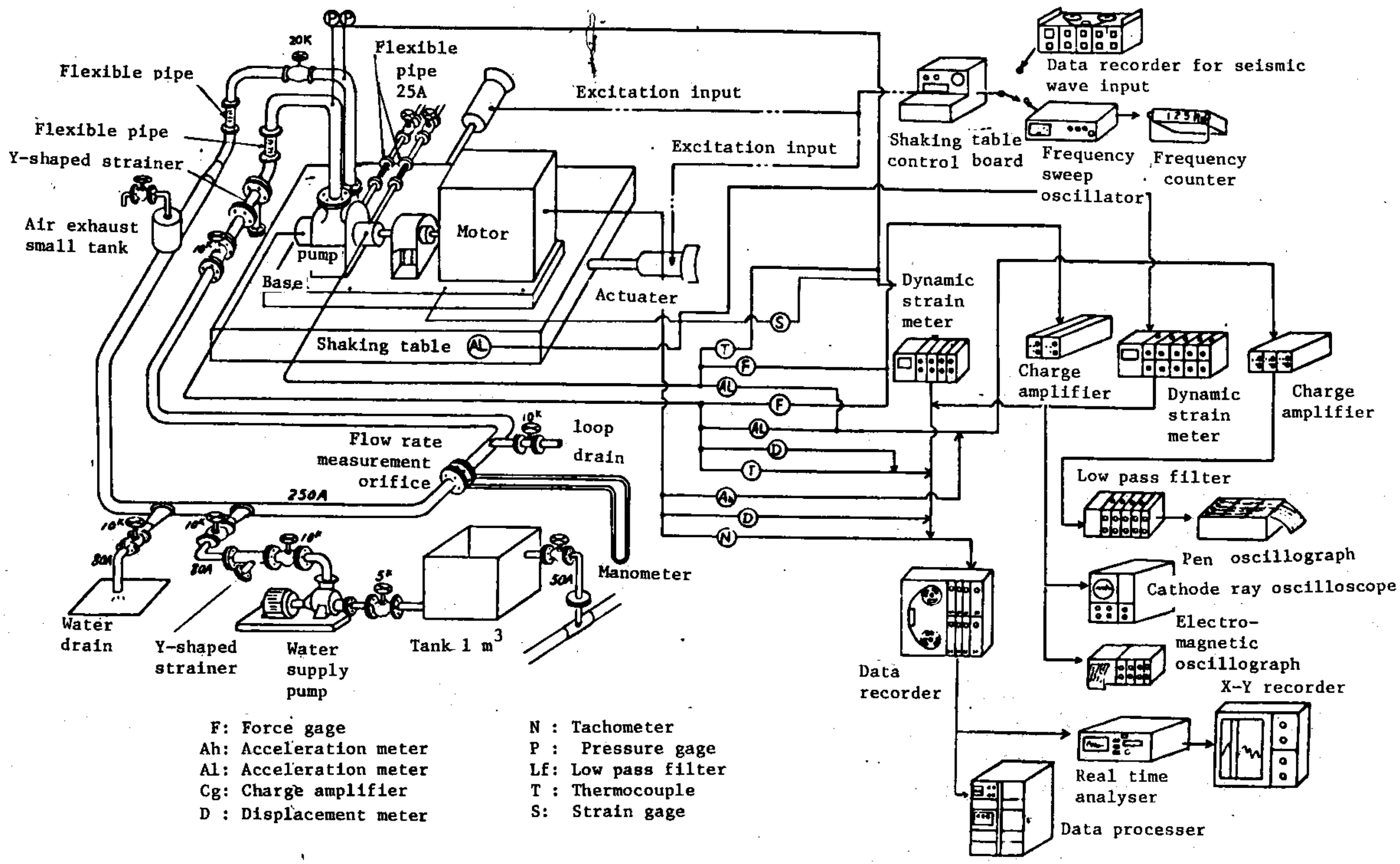


Fig. 4.5 Testing facility and its block diagram

5. Test results

5.1 Vibration characteristics test

(1) Vibration test of a single rotor

The pump rotor and shaft was hung as shown in Fig.5.1, and the mechanical impedance and eigen vibration modes were measured in the free-free condition by exciting the rotor with an electro-magnetic exciter in the horizontal direction.

Figure 5.2 shows the measured result of the point impedance, and Fig. 5.3 the vibration modes at the rotor-shaft natural frequencies obtained from this test. The test results are listed in Table 5.1.

(2) Vibration characteristics test of the pump assembly (Point excitation test)

In order to understand the vibration characteristics of the pump shaft at the pump body alone, at the pump coupled with the motor, at the pump-motor-piping assembly without water, at the pump-motor-piping assembly with water and at rated flow rate operation, the pump shaft on the coupling side was excited through a ball bearing to measure the mechanical impedance at the location of excitation.

Table 5.2 shows the natural frequencies at major modes. These frequencies were read from the results of measurement of the point impedance of the pump shaft. Among these natural frequencies, given in Table 5.2, are those at the bending primary mode of the pump shaft which are given in Table 5.3. The natural frequencies of the bending primary mode of the pump rotor-shaft are difficult to determine from measurement of the mechanical impedance for the cases where the pump-motor-piping assembly is filled with water and operating at rated flow. In these cases the band-selectable

Fourier analysis method is applied to magnify the resolution by means of the enlargement of the frequency domain under consideration.

The damping ratios in the test conditions given in Table 5.3 are calculated by reading the natural frequencies and the damping coefficients (F/V values at the frequencies) of the bending primary mode of the pump rotor-shaft and using the stiffness k read from the stiffness line, as is given below,

$$h = \frac{(2\pi f_n).C}{2k} \times 100\ \%,$$

where f_n: natural frequency Hz,

k : stiffness kg/cm,

C : damping coefficient kgsec./cm and

h : damping ratio %.

It should be noted that error is appearently included in the damping ratio to the same extent that error is included in the reading of the stiffness k. This may be as large as 20 - 30 %.

5.2 Sinusoidal sweep test

The sweep test was conducted over frequency range from 5 - 100 Hz at an acceleration level of 30 Gal. The purpose was to investigate the correspondence of these results to those obtained from the point excitation test discussed in the preceding section. The list of the resonant frequencies for excitation perpendicular to the rotor-shaft axis is given in Table 5.4. Major response modes up to 40 Hz are due to the accessory piping around the pump body and the suction and discharge pipings, as are also shown by the point excitation test, see Table 5.2.

Figures 5.4 and 5.5 show the acceleration response curves of the pump casing mandrel for excitation in the axial and perpendicular directions. Predominant modes of the response of the discharge and suction pipes exist at 20 Hz and 30 Hz in the axial and perpendicular directions respectively. Table 5.5 shows the resonant frequencies and damping ratios of these modes. In these modes the discharge and suction pipes are resonant, and the pump casing was excited forcibly.

5.3 Function verification test

The pump was verified for operation under earthquake conditions by assembling the pump, motor and piping on the shaking table and applying the following waves at input levels of 100 Gal, 300 Gal and 500 Gal in both the axial and perpendicular directions under conditions of rated flow and maximum flow:

(i) El Centro wave, NS, 1940,

(ii) El Centro wave, EW, 1940 (used only in the case of simultaneous excitation in the X- and Y-direction),

(iii) Artificial seismic wave and

(iv) Intermittent sinusoidal beat wave.

For the testing waves mentioned above, in (i), (ii) and (iii) the frequency component below 4.5 Hz was cut off in order to carry out the test up to the level of 500 Gal.

(1) Response amplification

Table 5.6 gives the response amplifications for each part. The response amplification has the maximum value at the discharge pipe in all cases. The response amplification at the discharge pipe is less than 2 for the artificial seismic wave and the El Centro waves, and the response for the intermittent sinusoidal beat wave is 5 - 15 times. From the point of view of the response amplification, the test using the intermittent sinusoidal beat wave is the most severe aseismic test.

(2) The Fourier spectrum obtained at each part of the pump during excitation test

Figure 5.6 shows the Fourier spectrum of the bearing reaction force on the coupling side for various input levels during the simultaneous excitation in two directions. The El Centro NS and EW waves were used in their tests. The spectrum shows only small changes due to excitation; the components which have frequencies much lower than 30 Hz increase with the input level.

In this functional verification test, the excitation during the pump operation was at input levels of 100 Gal, 300 Gal and 500 Gal using El Centro NS and EW waves, an artificial seismic wave and an intermittent sinusoidal beat wave. No special anomaly was detected in the comparison of the Fourier spectrum of the pump parts.

5.4 Aseismic design margin test

In order to observe the anomaly of the operating pump at the rated flow which could occur during an exccessive ground excitation, the pump was installed on the shaking table and excited in the axial and perpendicular directions using a contineous sinusoidal wave of each resonant frequency of the total assembly comprizing the pump and its major piping and support structure. The duration of the excitation was taken as about 10 seconds which corresponds to the duration of the major part of a seismic wave. The excitation levels were 300, 500, 600 and 700 Gal.

(1) Response amplification of the pump parts (Comparison with response amplification in the case of function verification test)

The response acceleration of the pump parts is plotted in Fig.5.7 for various excitation levels of the sinusoidal wave at the resonant frequency of the pump and piping assembly. It is seen in this figure that the rate of increase of the response acceleration of the pump body is different from that of the piping for various excitation levels. The acceleration response of the discharge pipe is the largest. The pump casing shows smaller response and the motor mandrel shows the least response because of the loose connection between pump and motor.

The response acceleration due to the perpendicular excitation is larger than that due to the axial excitation, but the response is varied at the input excitation level of 100 - 200 Gal. This means that the whole assembly behaves elastically at low acceleration levels. At higher levels some parts of the resonant structure enter a plastic region which results in the energy absorption and a decrease in response amplification. Namely, the major pipes of the pump and the supporting members are likely to absorb a large amount of vibration energy above the level of 100 - 200 Gal at the resonant frequency, and the possibility of member failure seems to rise.

(2) Comparison of response amplification in the aseismic margin test and function verification test

Owing to the nuclear plant arrangement, the RHR pump is considered to be subjected directly to a ground level seismic wave because the pump is installed in the lowest floor of the building. On this account, the response amplification for the seismic wave is compared with that of the resonant sinusoidal wave used in the test to check the severity of the sinusoidal wave testing. The results are given in Table 5.7.

The response amplification is 12.3 - 14.8 with respect to the discharge pipe location where the amplification takes the largest value and is nearly equal to the one for the beat wave. The amplification factor of the artificial seismic wave and El Centro waves are from 1.2 - 1.8, which gives a ratio of about eight to ten between the two tests.

(3) Response of the parts sensitive to vibration

The displacement response of the coupling that connects the pump and motor was investigated. A displacement of 1 mm is observed for the sinusoidal resonant wave of 500 Gal, but the pump function is not affected.

The bending moment was measured at root portion of the pump discharge and suction pipes. The maximum bending stress is about 4 kg/mm^2, and is lower by one order of magnitude than the yield stress of the pipe steel (=30 kg/mm^2).

Also the force in the anchor bolts that fasten the pump to the foundation and the reaction force of the bolts that fasten the pump body to the pump bench were measured. The data show that the force exceeds the proof strength of the bolts in some cases, but the bolts did not break.

In the case of the axial excitation over 500 Gal, an impulsive wave was detected on the casing mandrel. The magnitude was 15 g in acceleration and 1/400 second in duration. No anomaly, such as seizure, was discovered though the pump was disassembled and inspected carefully after the test was completed. This observation is, however, considered to be a symptom of deteriorating the pump function.

5.5 Pump performance test

The flow rate, discharge pressure, suction pressure, revolutions per minute, water temperature and motor input were measured at various flow rates within the service range of the pump (0, 25, 50, 75, 100, 125 % and maximum flow rate), and the pump perfomance was checked in regard to the total head, pump efficiency and power consumption.

Figure 5.8 shows the results obtained from the performance tests carried out before the preliminary tests and after the aseismic design margin test.

The total head remained unchanged but the pump efficiency is a little higher after the test. It may be that the sliding parts of the rotor-shaft system, such as gland packing, are made smooth by the pump operation during the aseismic test, thus giving rise to a decrease in the friction torque. Any deterioration in the pump performance is unperceptible even after a series of the tests.

5.6 Pump inspection results

The only anomaly detected up to the function verification test was the damage to the small diameter pipe around the pump. These caused no further trouble after being repaired by attaching a stiffner support.

The aseismic design margin test was done by a category of resonant testing of the whole pump assembly and, during these tests, the accessories and piping around the pump and weldment connected the main pipes with support structure were damaged. Table 5.8 gives the results of the inspection carried out by disassembling the pump after the aseismic test. No damage to the pump rotor-shaft itself was discovered in the series of the vibration and aseismic tests conducted in this research.

Table 5.1 Natural frequencies of pump rotor in free-free condition

Item / Mode	Measured	
	Damping ratio	Natural frequency
First mode	2.4 %	165.4 Hz
Second mode	2.1 %	389.1 Hz
Third mode	2.5 %	625.0 Hz

Damping ratio is calculated by the following equation

$$h = \frac{C}{2\ m\omega_n} \times 100,$$

Where h: Damping ratio (%),

C: Modal damping coefficient at excitation point (kg sec./cm),

ω_n: $2\pi f_n$; natural circular frequency (rad/sec.) and

m: Modal mass at excitation point.

C, ω_n, m are read from Fig.5.2. The accuracy of the damping ratio is determined by the reading accuracy of m.

Table 5.2 List of natural frequencies and modes

(Hz)

No	Pump state	Excitation location (excitation direction)	Vibration modes					
			Pump axial direction	Accessory pipes around pump	Motor mandrel	Accessory pipes around pump	Bending of pump axis	Pump casing
1	Pump single body, water absent	Rotor on coupling side (horizontal and perpendicular to axis)		35.1,42.9	44.0	46.0	88.3	110.0, 115.7, 123.0, 172.0, 200
2	Pump single body, water present	Rotor on coupling side (horizontal and perpendicular to axis)		35.2,42.9	44.0	46.0	64.6	110.0, 115.7 199.2
3	Pump and motor combined, water absent	Rotor on bearing side (vertical and perpendicular to axis)		40.6		47.8,54.4	99.1	151.1 156.2
4	Perpendicular direction to motor mandrel	Rotor on coupling side (horizontal and perpendicular to axis)		35.2,40.1			84.0	103.8, 112.6 146.4
5		Bearing box on bearing side (horizontal and perpendicular to axis)		39.8	44.7	49.9		125.6, 132.8, 141.7
6		Bearing box on coupling side (horizontal and perpendicular to axis)		35.4,39.7	44.5	49.9		125.3,132.6,142.0
7		Rotor on bearing side (horizontal and axial)	31.5					140.4,152.2
8	Pump, motor & pipes assembled, water present)	Rotor on coupling side (horizontal & perpendicular to axis)		33.8		46.6	60.1	101.1, 111.9, 120.0 140
9	Pump, motor & pipes assembled, rated flow rate	Rotor on coupling side (horizontal & perpendicular to axis)		34.0			68.7 69.8	144.0

Table 5.3 Measured damping coefficients and ratios of pump rotor-shaft in the first mode

Item \ Test condition	Pump single body water absent	Pump single body, water present	Pump, motor & pipes assembled, water absent	Pump, motor & pipes assembled, water present	Pump, motor and pipes assembled, rated flow rate
Natural frequency f_n Hz	88.3	64.6	84.0	60.1	68.7
Modal damping coefficient at excitation location C kgS/cm	15.0	20.0	7.0	25.0	36.0
Stiffness at excitation location k kg/cm	4.0×10^4	4.0×10^4	4.0×10^4	4.0×10^4	4.0×10^4
Damping ratio h %	10.4	10.1	4.6	11.8	19.4, 19.7

Table 5.4 Resonant frequencies for excitation in perpendicular direction to axis (Hz)

Operation condition	Measurement point	Vibration modes: Discharge & suction pipes	Accessory pipes around pump	Motor mandrel	Supporting members of discharge and suction pipes and accessory pipes around pump
Pump operated at the rated flow rate	Bearing box on coupling side	32.0	35.0	44.5	63.0 65.0 - - -
	Pump casing	32.0	-	44.5	63.0 65.0 - - -
	Bearing box on bearing side	32.0	35.0	44.5	63.0 64.5 - - -
	Discharge pipe	32.0	35.0	-	63.0 64.5 - 79.0 81.0
	Motor mandrel	32.0	-	44.5	- - - - -
Pump stopped water present	Bearing box on coupling side	32.0	-	-	63.0 64.0 71.0 - -
	Pump casing	32.0	-	-	63.0 64.0 71.0 - 81.0
	Bearing box on bearing side	32.0	-	-	63.0 64.0 71.0 - -
	Discharge pipe	32.0	-	-	63.0 64.0 72.0 79.5 86.0
	Motor mandrel	32.0	-	41.5	- - - - -
Pump stopped, water absent	Bearing box on coupling side	34.0	37.5	-	- 67.5 71.5 - - -
	Pump casing	34.0	37.5	-	- 67.5 71.5 79.5 - -
	Bearing box on bearing side	34.0	37.5	-	- 67.5 71.5 - - -
	Piping	34.0	38.0	-	- 67.5 - 74.0 - 88.0
	Motor mandrel	34.0	38.0	42.5	- - - - - -

Remarks (1) Acceleration on shaking table constant at 300 Gal
(2) The mark - means that there is no distinct peaks correspondingly to the item.

Table 5.5 Resonant frequencies and damping ratios of discharge and suction pipes for excitation on shaking table

Pump condition \ Item \ Excitation direction		Axial direction	Perpendicular direction to axis
Rated flow rate (454 m^3/h)	Resonant frequency Hz	21.4	32.0
	Damping ratio	6.0%	1.3 %
Maximum flow rate (635 m^3/h)	Resonant frequency Hz	21.4	32.0
	Damping ratio	7.3 %	2.7 %

Remarks (1) Resonant frequency at input 100 Gal on shaking table

(2) Damping ratio calculated by half power method from response curve for discharge pipe

Table 5.6 Response amplification in case of function verification test

Excitation wave form	Excitation direction	Response amplification					Remarks
		Bearing on bearing side ①	Bearing on coupling side ②	Motor mandrel ③	Casing mandrel ④	Discharge pipe ⑤	
Intermittent sinusoidal beat wave	Pump axial direction y	1.7 (1.6)*(1)	1.6 (1.6)	1.0 (1.1)	2.0 (2.0)	5.6 (5.6)	In-beat frequency 19.0 Hz
	Perpendicular direction to pump axis x	6.8 (6.8)	7.2 (7.5)	3.0 (3.2)	6.2 (6.6)	15.0 (15.0)	In-beat frequency 29.4 Hz
Artificial seismic wave	Pump axial direction y	1.1 (1.1)	1.2 (1.1)	1.2 (1.2)	1.3 (1.2)	1.6 (1.6)	
	Perpendicular direction to pump axis x	1.4 (1.5)	1.2 (1.4)	1.1 (1.1)	1.2 (1.2)	1.8 (1.8)	
El Centro NS wave	Pump axial direction y	1.1 (1.1)	1.1 (1.1)	1.2 (1.1)	1.3 (1.2)	1.3 (1.3)	
	Perpendicular direction to pump axis x	1.1 (1.1)	1.1 (1.2)	1.0 (1.0)	1.1 (1.2)	1.2 (1.4)	
El Centro NS and EW waves *(2)	Simultaneous excitation in perpendicular direction to pump axis (NS wave) and axial direction (EW wave)	1.1 (1.2)	1.1 (1.2)	1.0 (1.0)	1.1 (1.2)	1.3 (1.4)	

Remarks (1) Response amplification at maximum flow rate in parenthesis

(2) Response amplification R in case of simultaneous excitation in two directions is calculated as follows:

$$R = \sqrt{A_x^2 + A_y^2} \Big/ \sqrt{a_x^2 + a_y^2},$$

where A_x, A_y : Maximum response acceleration in x and y directions

a_x, a_y : Maximum input acceleration in x and y directions.

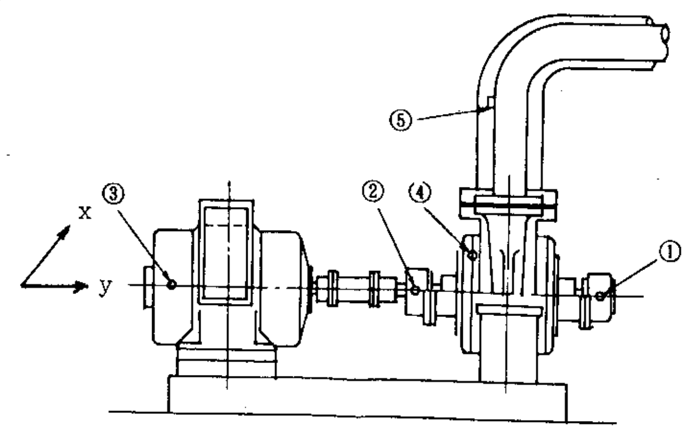


Table 5.7 Comparison of response amplifications in cases of aseismic margin test and function verification test

Test item	Excitation wave form	Excitation direction	Response amplification: Bearing on bearing side ①	Bearing on coupling side ②	Motor mandrel ③	Casing mandrel ④	Discharge pipe ⑤
Aseismic margin test	Resonant sinusoidal wave 20.8 Hz (excitation level 500 Gal)	Pump axial direction	2.5	1.7	1.8	3.0	12.3
	Resonant sinusoidal wave 29.6 Hz (excitation level 500 Gal)	Perpendicular direction to pump axis	6.8	7.8	2.5	6.2	14.8
Function verification test	Intermittent sinusoidal beat wave	Pump axial direction y (beat wave 19.0 Hz)	1.7	1.6	1.0	2.0	5.6
		Perpendicular direction to pump axis (beat wave 29.4 Hz)	6.8	7.2	3.0	6.2	15.0
	Artificial seismic wave	Pump axial direction y	1.1	1.2	1.2	1.3	1.6
		Perpendicular dirdction to pump axis x	1.4	1.2	1.1	1.2	1.8
	El Centro NS wave	Pump axial direction y	1.1	1.1	1.2	1.3	1.3
		Perpendicular direction to pump axis x	1.1	1.1	1.0	1.1	1.2
	El Centro NS and EW waves *(1)	Simultaneous excitation in perpendicular direction to pump axis (NS wave) and pump axial direction (EW wave)	1.1	1.1	1.0	1.1	1.3

Remark (1) Response amplification R for simultaneous excitation in two directions is calculated as follows:

$$R = \sqrt{A_x^2 + A_y^2} / \sqrt{a_x^2 + a_y^2},$$

where A_x, A_y : Maximum response acceleration in x and y directions

a_x, a_y : Maximum input acceleration in x and y directions.

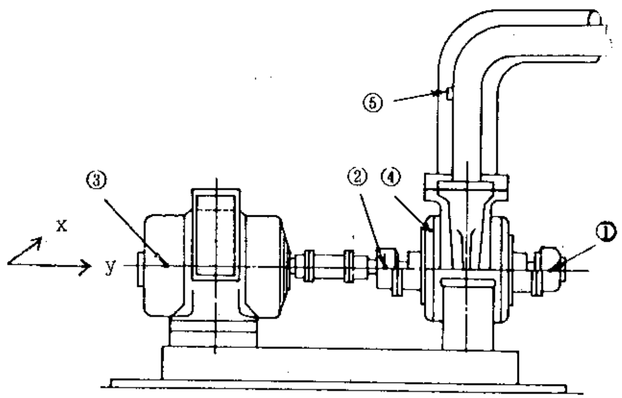


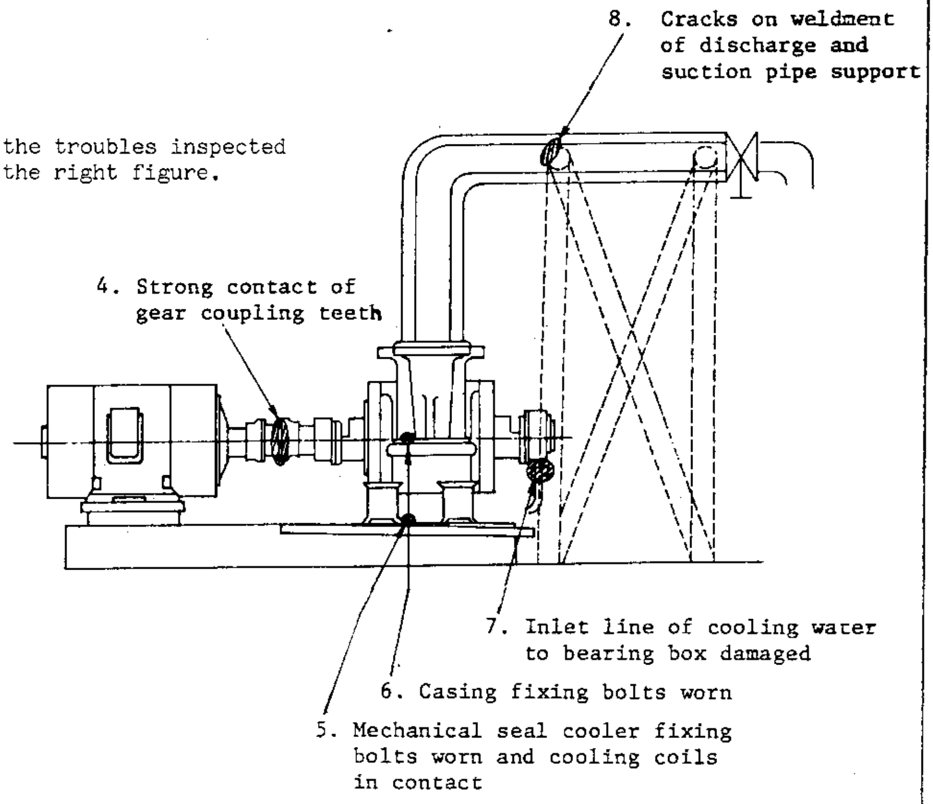
Table 5.8 Inspection results after disassembling after aseismic design margin test

Part name	State of wear and damage	Remark
1. Wear ring	No flaw on casing ring and impeller ring	
2. Bearings	(1)On thrust bearing side No flaw on balls, retainer or outer race (2)On coupling side No flaw on balls, retainer or outer race	
3. Mechanical seal sliding faces	(1) On bearing side No anomaly on runner surface Two slight flaw on ring surface and no flaw on bellows (2) On coupling side No anomaly on runner, ring and bellows	No leakage from mechanical seal during operation
4. Gear coupling ring	Grease discolored more rapidly than in usual operation (blackened) Trace of strong contact left at center of gear	Pump side vibrated fiercely during excitation test, and moving of gear coupling perceived
5. Mechanical seal cooler	Slight contact trace on cooling coil, cooling tube and spiral coil Thread of a bolt fastening cooler deformed due to resonance	Strokes remarkable at mechanical seal cooler during excitation at pump resonant point
6. Wear of casing fastening bolts	Threads of two bolts fastening casing and base on motor side deformed slightly	Threads deformed at two places subjected to vibration of major pipe

Table 5.8 continued

Part name	State of wear and damage	Remark
7. Auxiliary pipes	Fitting part of inlet line of cooling water to bearing box on bearing side damaged at time of final test	
8. Reinforcement of discharge and suction pipes	Cracks initiated in weldment of fixing frame of discharge and suction pipes during aseismic margin test	Weldment not related directly to aseismic property of pump main body

Location of the troubles inspected is shown in the right figure.



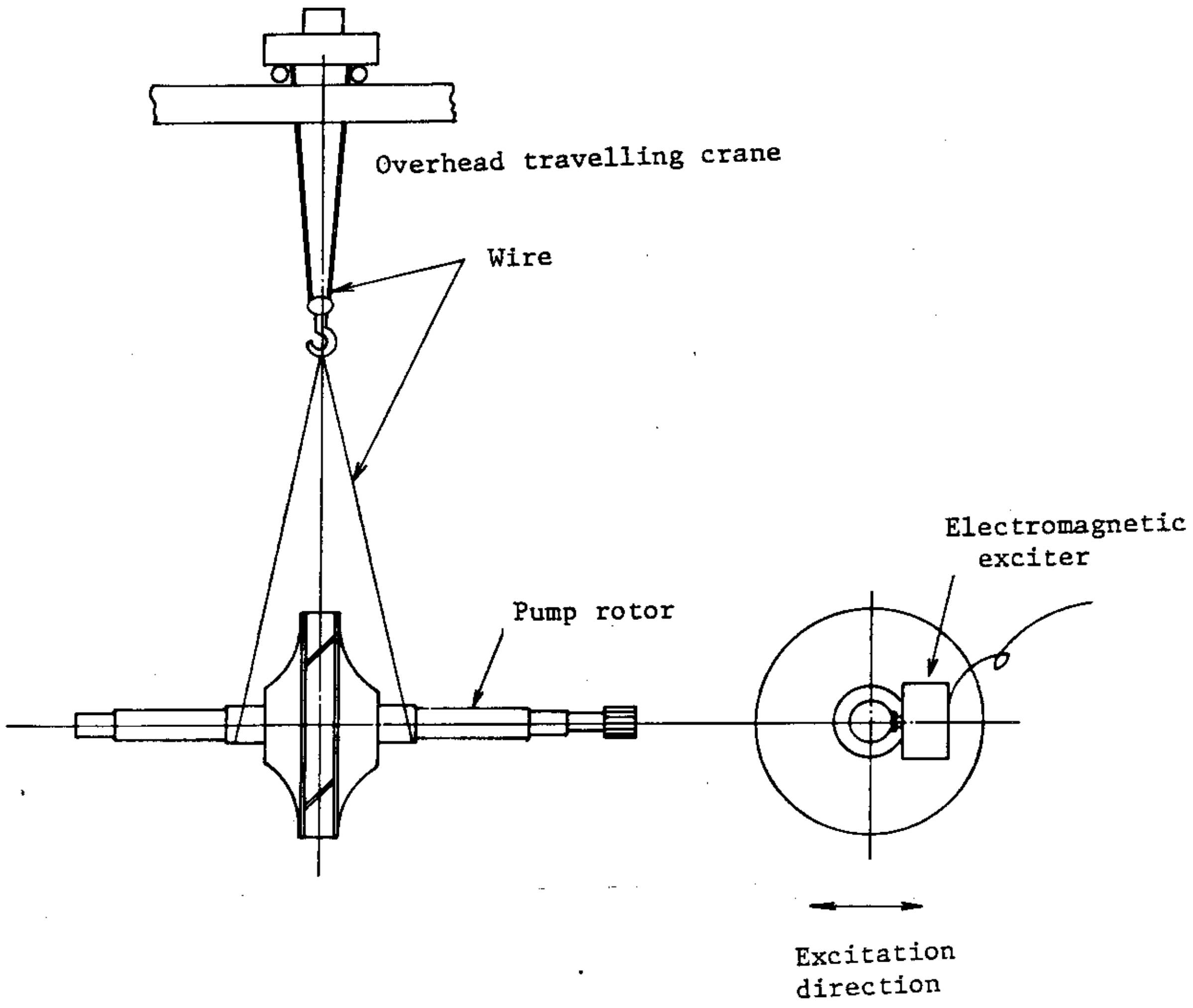


Fig. 5.1 Pump rotor excitation testing method

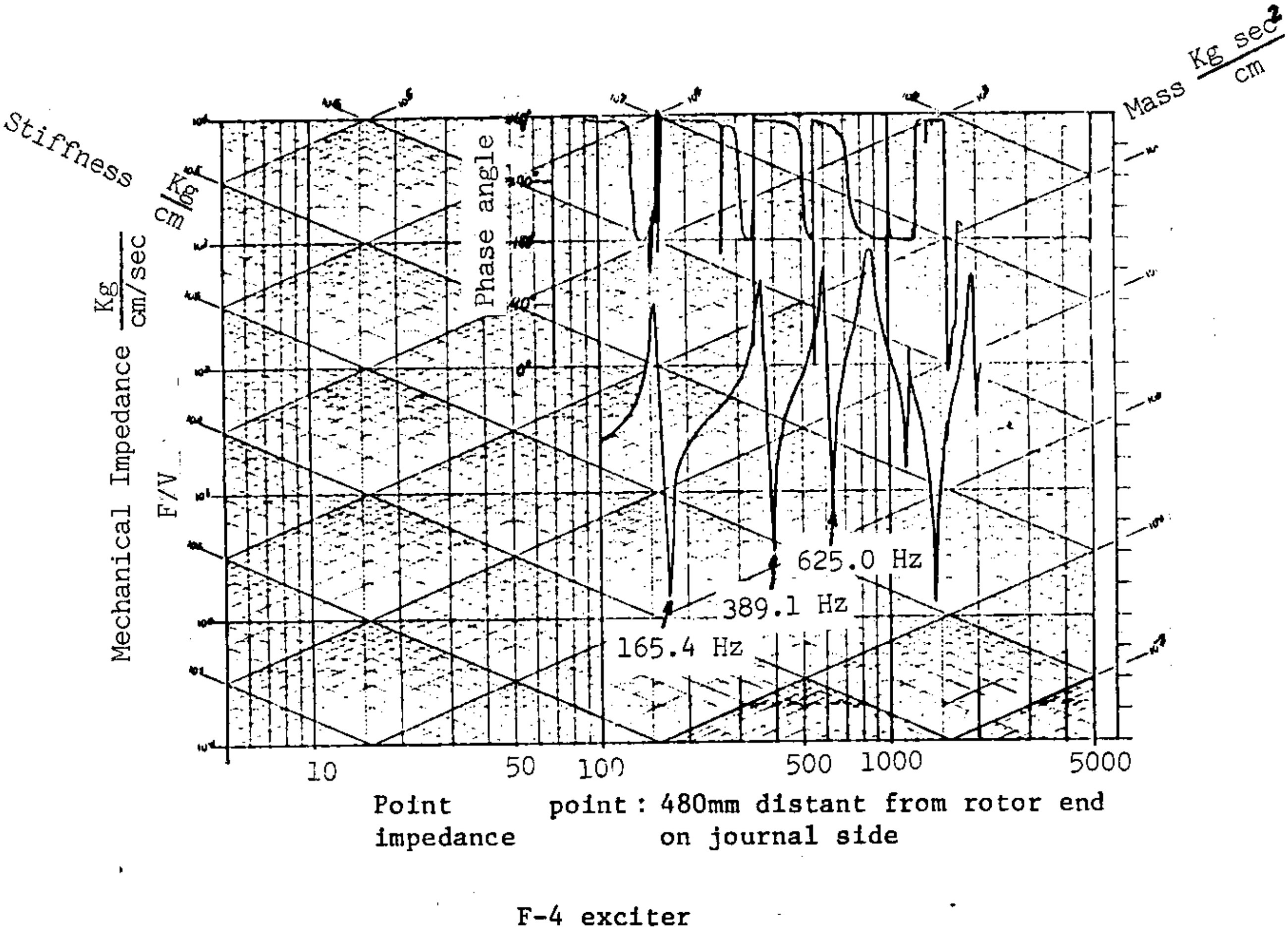


Fig. 5.2 Impedance obtained by point excitation of pump rotor in free-free condition

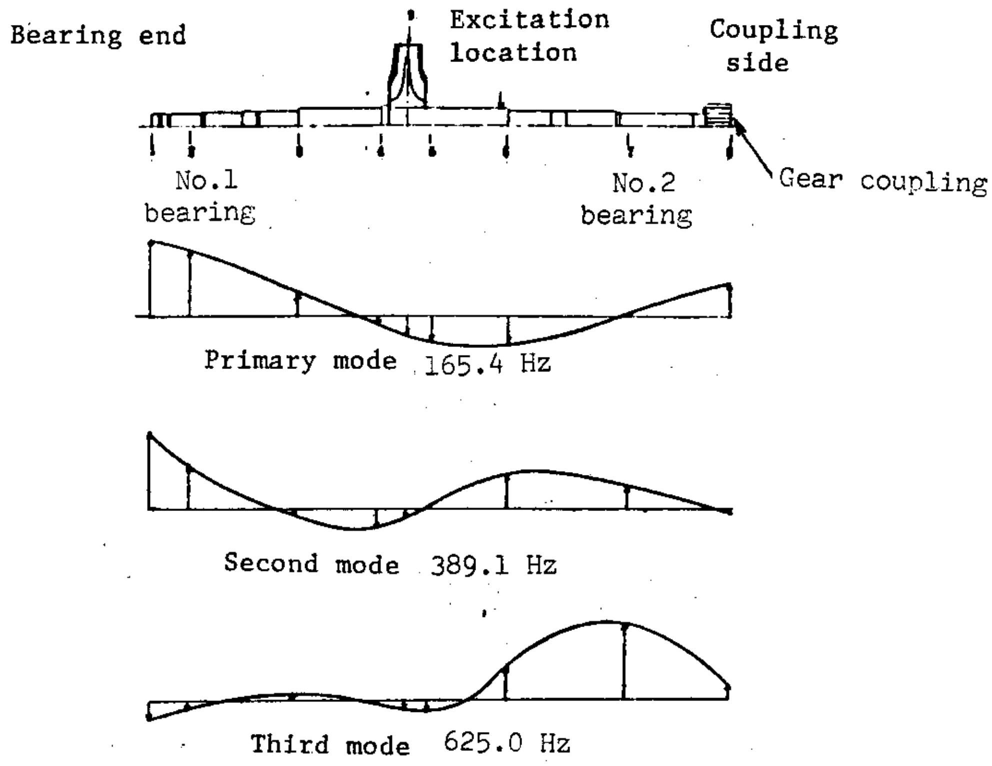


Fig. 5.3 Measured vibration mode of pump rotor in free-free condition

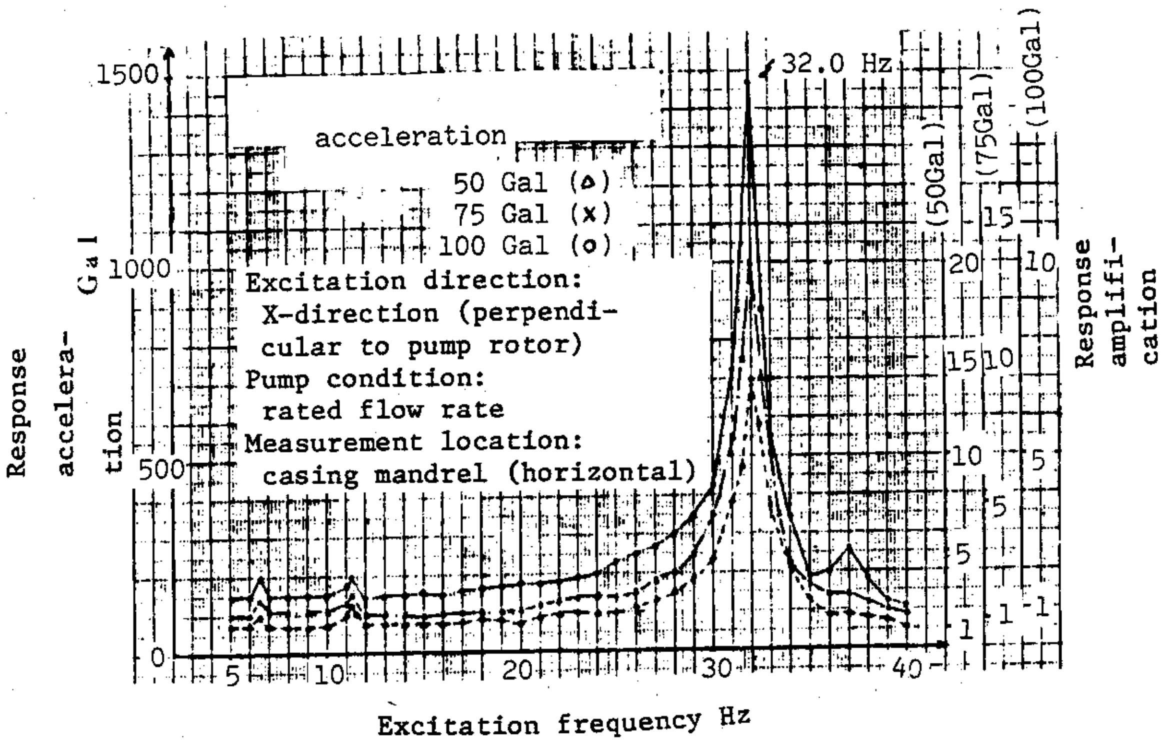


Fig. 5.4 Acceleration response curve of pump casing mandrel due to horizontal excitation in perpendicular direction to pump rotor

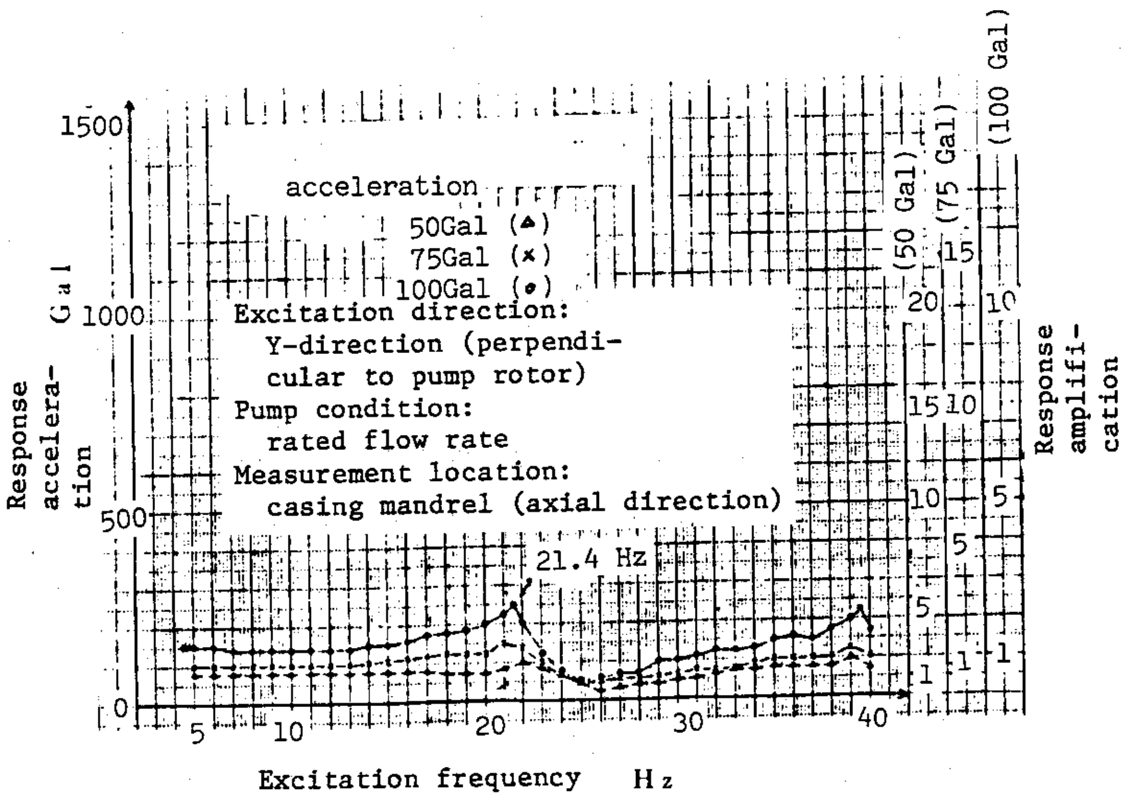


Fig. 5.5 Acceleration response curve of pump casing mandrel due to excitation in pump rotor direction

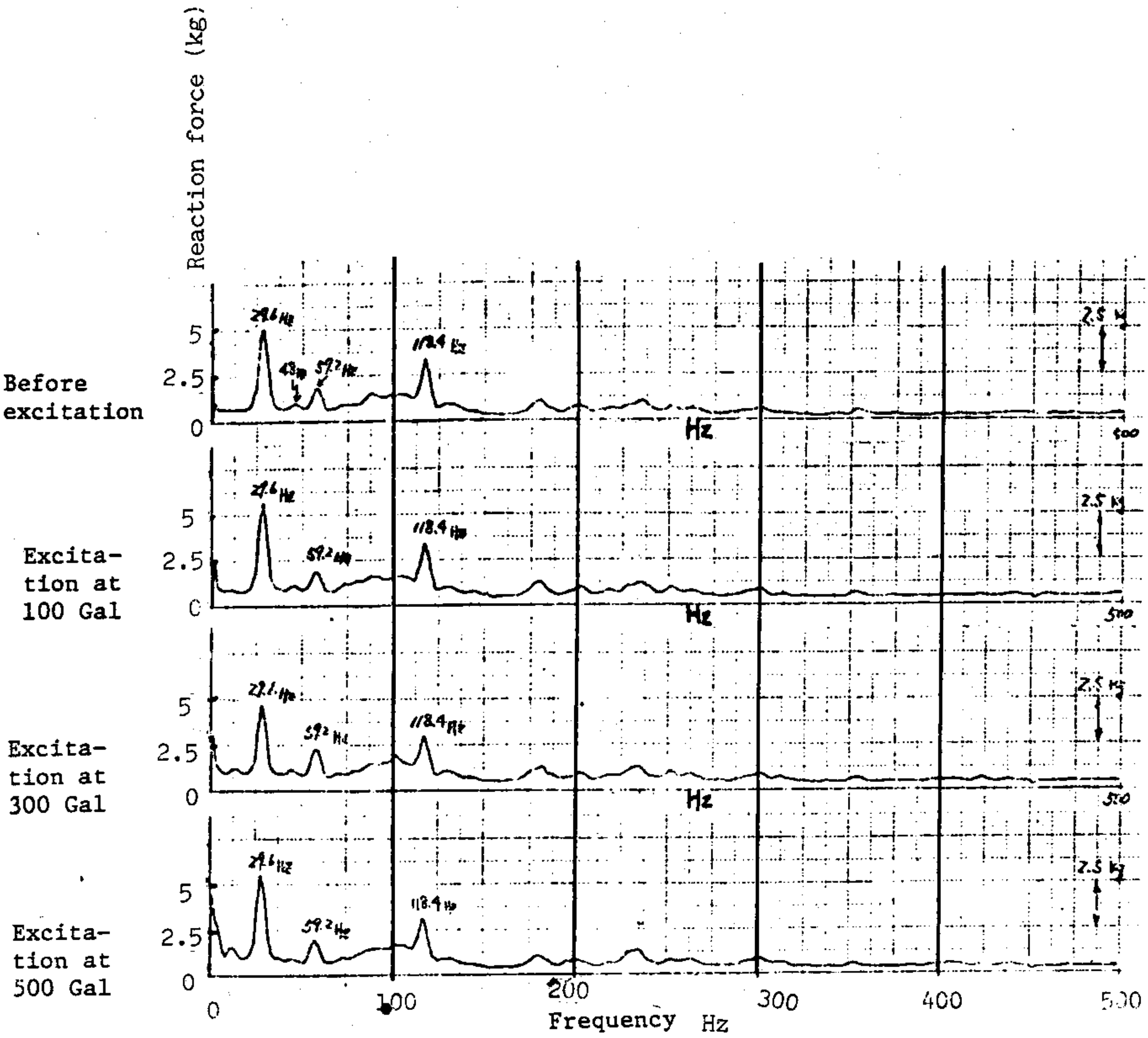


Fig. 5.6 Fourier spectrum of bearing horizontal reaction at rated flow rate and excited in two horizontal directions by El Centro 1940 NS and EW waves

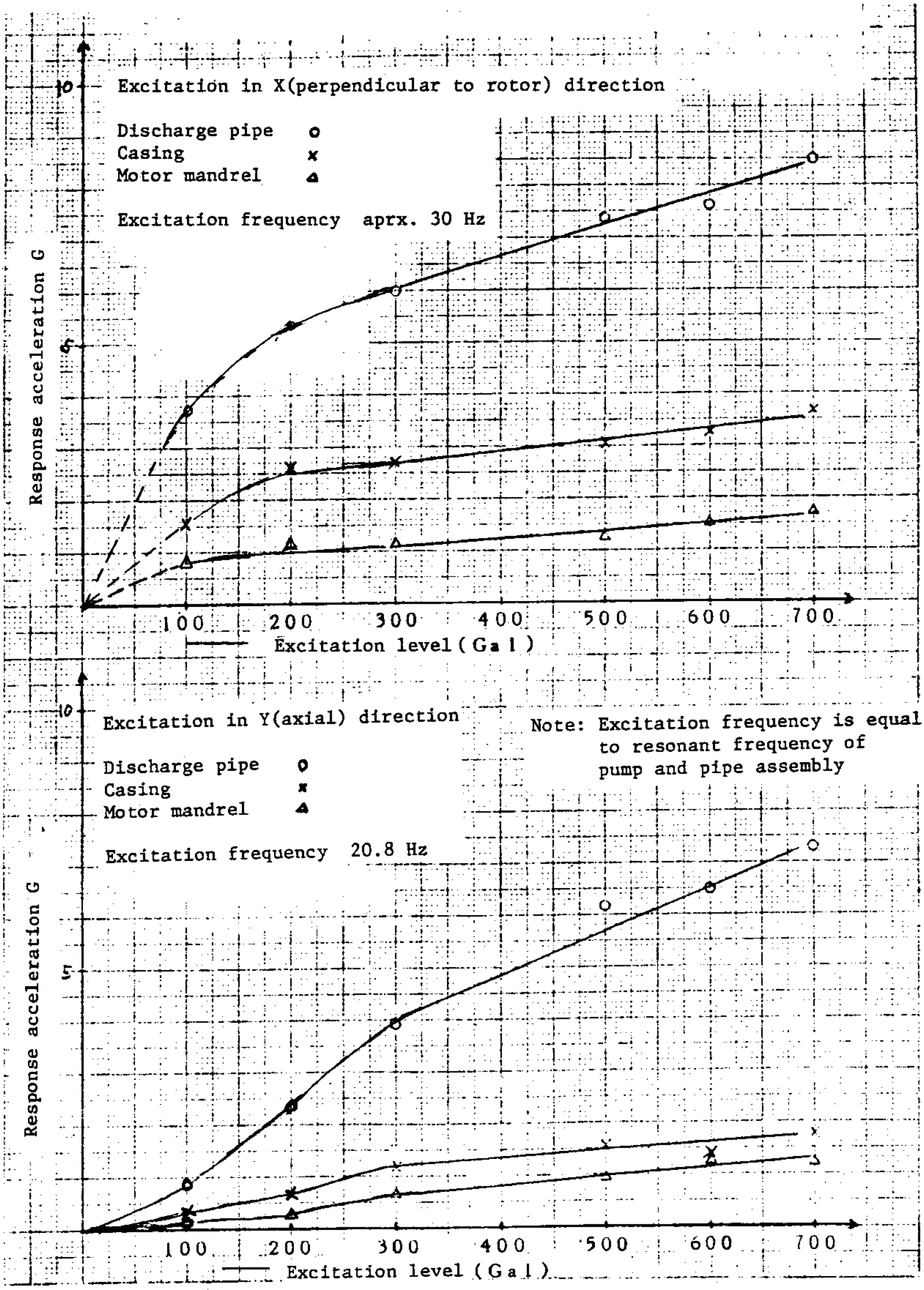


Fig. 5.7 Relationship between excitation level and response acceleration under sinusoidal resonant wave excitation

CUSTOMER	JAERI	PUMP NAME	RHR pump	PUMP MACHINE No.	16077
NOZZLES SIZE	Dis. 150 ϕ, Suc 250 ϕ	PUMP TYPE	MLC-15358	MOTOR MACHINE No.	2H3224A0101

CAPACITY	454 m^3/h	TOTAL HEAD(H)	86 m	PUMP EFF	75 %	REVOLUTION	1770 rpm
LIQUID	Boric acid water	TEMP.	~177° C	SP. GR.	0.89 ~ 1.00	NPSH avail/mg	3.0 / 2.9 m
TEST LIQUID	Fresh water	TEST TEMP.				GEAR RATIO	-
MOTOR TYPE	SB-E	MOTOR OUTPUT	185 kW	VOLT	3300 V	AMP	38 A
CYCLE	60 Hz	PHASE	3 ϕ	REVOLUTION	1770 rpm	MOTOR MR.	MELCO
ORIFICE or V NOTCH	ORIFICE 175 ϕ/250A						

PERFORMANCE TEST

REVOLUTION rpm	WATER TEMP °C	SP. GR	※ mmHg	CAPACITY(Q) m^3/h	CAPACITY(Q)	CAPACITY(Q) m^3/h	CAPACITY(Q) t/h	HEAD(H) DISCH. m	HEAD(H) SUCT. m	HEAD(H) VEL. HEAD m	HEAD(H) GAGE HEIGHT m	HEAD(H) TOTAL HEAD kg/cm^2	HEAD(H) TOTAL HEAD m	THEO. POWER kW	MOTOR VOLT V	MOTOR AMP A	MOTOR INPUT kW	MOTOR EFF %	MOTOR OUTPUT kW	EFF OF TRANS %	PUMP SHP kW	PUMP EFF %
(1774) 1774	(25) 37	1.0	445			630		(90) 90	(22.0) -22.0	4.36	–		(72.4) 72.4	(123.9) 124	(3564) 3390	(32.5) 32.9	(170.1) 165.0	(93.0) 93.0	(158.2) 153		(158.2) 153	(78.3) 81.0
(1774) 1774	(23) 34	1.0	361			567.5		(100) 99	(23.6) 24.0	3.53	–		(79.9) 78.5	(123.2) 121	(3558) 3390	(30.9) 31.9	(164.4) 159.6	(93.0) 93.0	(152.9) 148		(152.9) 148	(80.6) 80.8
(1777) 1776	(26) 34	1.0	231			454		(112) 110	(26.4) 25.8	2.26	–		(87.9) 86.5	(108.4) 107	(3570) 3390	(28.8) 29.4	(150.1) 146.7	(93.0) 93.0	(139.6) 136		(139.6) 136	(77.7) 78.7
(1780) 1780	(27) 38	1.0	130			340.5		(121) 119	(28.8) 27.2	1.27	–		(93.5) 93.1	(86.5) 86.1	(3564) 3450	(25.8) 26.5	(132.3) 132	(92.8) 92.8	(122.8) 122		(122.8) 122	(70.4) 70.6
(1783) 1783	(28) 38	1.0	58			227		(126) 125	(30.4) 28.9	0.57	–		(96.2) 96.7	(59.3) 59.6	(3564) 3426	(22.8) 23.5	(113.7) 113	(92.4) 92.3	(105.1) 104		(105.1) 104	(56.4) 57.3
(1785) 1785	(29) 39	1.0	14			113.5		(130) 127	(31.4) 29.0	0.14	–		(98.7) 98.1	(30.4) 30.2	(3564) 3450	(20.6) 21.4	(101.4) 98	(91.9) 91.7	(93.2) 90		(93.2) 90	(32.6) 33.6
(1789) 1789	(30) 39	1.0	0			0		(135) 129	(32.8) 29.0	0	–		(102.2) 100	(0) 0	(3564) 3450	(19.2) 20.6	(88.5) 94	(91.2) 91.5	(80.7) 86		(80.7) 86	(0) 0

※ Manometer height

Data obtained before vibration test in parenthesis

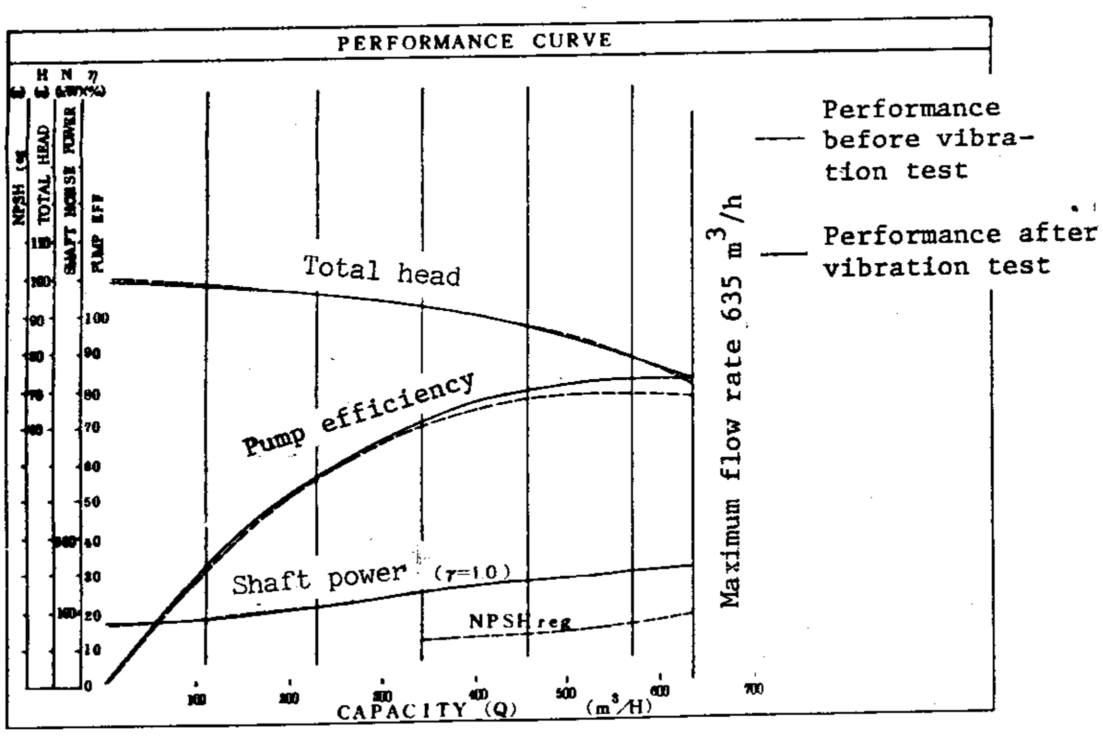


Fig. 5.8 Comparison of performance of RHR pump before and after aseismic design margin test

6. Conclusions

A series of vibration tests were carried out to evaluate the aseismic performance of the RHR pump. This pump, which also acts as the low pressure injection pump, is used in present and will be used in future PWR plants. The test results may be summarized as follows:

(1) In addition to the fundamental structual elements (impeller, shaft and casing), certain additional auxiliary equipments (bearing lubrication system and seal cooling system) are necessary, and this auxiliary equipments require small diameter piping. To insure smooth, long term operation of the fundamental structural elements the auxiliary equipments must not be damaged by the earthquake. Therefore, the stiffener attached to the auxiliary system piping is essential for improving the aseismic performance of this pump.

(2) The pump integrity or the rotor-bearing dynamic system seems to be secure provided that it is not subjected to a transient disturbunce having high frequency content and/or it is not overloaded.

(3) Those parts of the structural system (motor and casing mandrel) which have a resonance frequency which is much higher than the frequency content of a seismic wave have only a small amplification factor. Furthermore, the value of the amplification factor is essentially the same for all of the seismic wave tests, i.e. artificial, El Centro or two axis El Centro.

(4) When the aseismic property of the whole structural system is evaluated on the basis of a resonant vibration test, it is necessary to make clear the relationship between the structure inducing resonance and the whole structure assembly. In this research, the excitation test was conducted at the resonant frequency of the major piping (suction and discharge) and the supporting structure that connects that piping to the shaking table. This excitation was effective in increasing the response amplification of the main body of the pump.

However, since the structure used in these tests to support the piping is different than that used in the actual nuclear power plant this should be investigated further.

(5) The aseismic design margin may be estimated from the experimental results by assuming that the aseismic property of the pump structure can be evaluated by the inertia force criterion of the pump mandrel. It is seen from Table 5.6 that the response amplification of the pump mandrel has a maximum value of 1.3 for the artificial seismic wave and El Centro waves in the axial excitation. The response amplification of the pump mandrel in the axial excitation is 3.0 when the excitation is at the sinusoidal resonant frequency of the major piping, as shown in Table 5.7. The excitation acceleration level of the shaking table, at which the abnormal signal (impulsive wave) was observed in the pump operation, was 500 Gal in the axial excitation. Therefore, we may estimate that the seismic amplitude required to produce the same effect (an impulsive wave) would be 3.0/1.3 x 500 = 1,150 Gal. The RHR pump is installed near the foundation of the reactor building, and it is reasonable to take the dynamic magnitude of the probable strongest earthquake on design basis as 300 Gal and the expected ultimate earthquake on design basis equal to 1.5 times this value, i.e. 300 Gal x 1.5 = 450 Gal. Then it can be concluded that the RHR pump has an aseismic design margin more than 1,150/(300 x 1.5) = 2.6, that is, 2.6 times the expected ultimate earthquake on design basis.

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(1) U.S. AEC Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants", Oct. 1973

(2) H.B. Seed et al., "Characteristics of Rock Motions During Earthquake", EERC, Berkeley, Sept. 1968

(3) P.C. Jennings, G.W. Housner and N.C. Tsai, "Simulated Earthquake Motions", Earth. Engrg. Res. Lab., Calif. Inst. of Tech., Pasadena, April 1968

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