FORCED VIBRATION TEST OF 1/5 SCALE MODEL OF CANDU CORE

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SUMMARY

The CANDU (Canada Deuterium and Uranium) nuclear power reactor system developed in Canada uses heavy water as moderator and natural uranium as fuel. The 600 MWe CANDU core primarily consists of a horizontal cylindrical calandria vessel, a total of 380 fuel channel assemblies and reactivity control mechanisms. The fuel channel assemblies, each of which is made up of calandria tube, pressure tube and fuel elements (hereafter referred to as CT/PT assembly), span the calandria axially on a constant square pitch to form a circular lattice array. In addition the calandria is penetrated by a number of guide tubes for the reactivity mechanisms both in vertical and horizontal directions.

Aiming at introducing CANDU into Japan, EPDC (Electric Power Development Co., Ltd.) has undertaken "CANDU Core Seismic Verification Program" in 1977, which is composed of two stages, STEP I (the test using a 1/5 scale half-cut model of the core) and STEP II (the tests using full scale partial models).

This paper deals with the STEP I test results. The test was intended to clarify the basic characteristics pertinent to the seismic behavior of tube assemblies in water and insertion capability of control shut-off rods during an earthquake. The test model was selected as a half portion of the core and cut vertically so that the actual behavior of the inside components could be visually observed. The tests were conducted using a large shaking table.

Major findings obtained from the testing are given below:

Dynamic characteristics of tube assemblies immersed in water

(1) Added mass coefficient of water for CT/PT assemblies is about 1, while that of guide tubes is about 0.5, where water inside the perforated guide tubes is not considered to be fixed water.

(2) The damping factor of perforated guide tubes is increased by a factor of several times when immersed in water, while a relatively minor increase is observed in CT/PT assemblies.

(3) As for the dynamic behavior of CT/PT assemblies immersed in water, no remarkable effect resulting from grouped tube assemblies was observed. Its behavior is rather dictated by the vibrational characteristics of an individual CT/PT assembly.

(4) Under earthquake wave input conditions, the guide tubes fluctuate in succession with the movement of a shaking table, while the CT/PT assemblies vibrate fractionally with its own natural frequency. Under stronger input conditions, both CT/PT assemblies and guide tubes begin to contact each other and the number of contact amounts to as many as more than ten times.

Insertability of shut-off rods

(1) The drop time of shut-off rods is most influenced by the deformation of guide tubes. However, under dynamic conditions, no stopping of shut-off rods on the way was observed.

(2) From the test results, it is estimated that the drop time of shut-off rods in an actual CANDU (1.5 seconds when at rest) is within the allowable drop time limit of 2 seconds even under severe earthquake conditions.

1. Introduction

This paper describes a forced vibration test of a 1/5 scale half-cut model of the CANDU core (refer to Fig.1) conducted in 1978 by a shaking table to clarify the basic characteristics pertinent to the seismic behavior of tube assemblies in water and insertion capability of control shut-off rods subjected to sinusoidal and random earthquake motions.

The fundamental law of similarity for a 1/5 scale model is shown in Table 1.

2. Test Model

2.1 Model Arrangement

The test model (refer to Fig.2 and Photo 1) is selected as a half portion of the core and cut vertically so that the intricate seismic behavior of the core could be visually observed and reproduced in a movie through a piece of glass fitted onto the cut section.

Therefore, 380 horizontal fuel channel assemblies (hereafter referred to as CT/PT assembly), which are supported at both ends in the prototype, are modelled as cantilevers rigidly supported at the end plate on the opposite side of the glass. A calculation is made of the first natural vibration mode patterns of both cantilever and beam rigidly supported at both ends, and is indicated in Fig.3 based on the assumption that they have the same natural frequency. As can be seen from Fig.3, it is inevitable that the mode pattern of the cantilever is different from that of the beam rigidly supported at both ends. But displacement of the cantilever at the location of guide tubes G1 - G5 accords with that of the beam. Therefore, modelling of a CT/PT assembly into a cantilever is not a major problem, because emphasis is placed on interaction between guide tubes G1 - G5 and their adjacent CT/PT assemblies during an earthquake.

The cylindrical tank is located in the middle of the frame representing a concrete reactor vault. The tank is filled with ordinary light water in place of heavy water. 380 CT/PT assemblies, 13 guide tubes and other reactivity control guide tubes are placed as they would be in the prototype.

Main components of the 1/5 scale model (refer to Table 2) are made to satisfy the law of similarity concerning dimension, weight per unit length and stiffness as far as possible.

2.1.1 CT/PT Assembly (refer to Fig.4)

CT/PT assemblies come as stainless hollow tubes wrapped in leaden tape several times over and finished in rubber. Damping factors of CT/PT assemblies thus fabricated are about 1% in air.

2.1.2 Shut-off Rod Guide Tube (refer to Fig.5)

Altogether 13 guide tubes made of acrylic material are provided and in-core portion of each tube has some 3,000 circular holes as in the prototype. The damping factors of in-core guide tubes are about 5% in air.

2.1.3 Shut-off Rod and Drive Mechanism (refer to Fig.5)

A shut-off rod serving to shut down the reactor under emergency conditions is supported by a stainless steel wire which is wounded on a cable drum in the drive mechanism. This mechanism, consisting of a motor unit, an electromagnetic clutch, a cable drum and a potentiometer to measure a drop curve (refer to Fig.6), is essentially identical to that of the prototype. In response to a signal for the drop (referred to as trip signal), all the shut-off rods fall into the reactor under gravity inside perforated guide tubes, and their arrival at the bottom is observed by electric signals (referred to as arrival signal).

2.2 Shaking Table

Used is an electro-hydraulic shaking table (simultaneous horizontal and vertical vibrations are available, manufactured by M.T.S. Company, U.S.A.) at the Kajima Institute of Construction Technology. The maximum horizontal displacement and acceleration of the table are ±150mm and ±1.2G, respectively. The available frequency range is from 0.01 Hz to 30 Hz.

3. Input Waves to Shaking Table

Sinusoidal waves and recorded strong earthquake motions are used as stationary inputs and random inputs, respectively.

3.1 Sinusoidal Wave

Input frequencies range from 5 to 20 Hz and input acceleration levels from 0.03 to 1.25G.

3.2 Earthquake Motions

Utilized as inputs are response acceleration waves at a reactor vault obtained from the seismic analysis of the reactor building using El Centro 1940 (NS) and Taft 1952 (EW). The input acceleration levels to a shaking table are normalized to 0.3, 0.5, 0.75, 1.0 and 1.2G for both waves. Time scale of input acceleration waves is reduced to $\sqrt{1/5}=0.45$, pursuant to the law of similarity.

4. Measurement

4.1 Measurement of Vibration of Tube (refer to Fig.6)

i) Acceleration of CT/PT Assembly

A pair of small accelerometers (type : piezo-resistive, resonant frequency : 2,000 Hz, weight : 0.5grm) are fixed inside the tip of each tube to measure both horizontal and vertical acceleration for 10 CT/PT assemblies.

ii) Acceleration of Guide Tube

The same accelerometers are fixed onto the middle of guide tubes G1 - G5 to measure horizontal accelerations.

iii) Acceleration of Tank, Frame and Shaking Table

Accelerometers (type : servo, resonant frequency : 300 Hz, weight : 60grm) are installed at the tank, the top of the frame and the shaking table.

iv) Sound of Vibration and Contact

Filtering the measured accelerations of CT/PT assemblies, vibrational motions and contacts between the center guide tube G3 and its adjacent CT/PT assemblies are converted into sounds by a newly-developed electronic device for monitoring purpose, as indicated in Fig.6.

v) Movement of Water

Movement of water is observed and made into a movie film by using powdered brass scattered in the tank.

4.2 Measurement of Insertion of Shut-off Rod (refer to Fig.6)

i) Drop Curve

Drop curves of 13 shut-off rods are measured by potentiometers which are supplemented by a stroboscope.

ii) Drop Time

Drop times of 13 shut-off rods are measured with an accuracy of 1/100 seconds by trip signals of electromagnetic clutches and arrival signals of shut-off rods.

4.3 Measured Record

All the measured data are stored in data recorders and displayed on electro-magnetic oscillographs.

Fig.7 and Fig.8 show examples of measured forced vibration records in case of horizontal inputs of sinusoidal wave of 0.1G, 14 Hz and El Centro of 1.G.

5. Summary of Test Results

5.1 Dynamic Characteristics of Tube Assemblies in Water Free Vibration

5.1.1 Free Vibration

Free vibration tests of CT/PT assemblies and guide tubes are performed by wire-cutting method, prior to forced vibration tests.

i) Ratios of vibration frequencies in water to those in air are 0.90 for CT/PT assemblies and 0.57 for guide tubes. Frequency changes of CT/PT assemblies in water are relatively small, in contrast to those of guide tubes. (refer to Table 1)

ii) Added mass coefficient of water for CT/PT assemblies is about 1, while that of guide tubes is about 0.5, where water inside the perforated guide tubes is not considered to be fixed water contributing to its vibration.

iii) Damping factors of perforated guide tubes in water increase several times compared to that in air, while a relatively minor increase is observed in CT/PT assemblies. (refer to Table 1)

5.1.2 Forced Vibration

a. Case of Sinusoidal Wave

Fig.9 and Fig.10 show examples of resonance curves of a CT/PT assembly and a guide tube in air and in water, respectively. The amplification factor indicates the ratio of the absolute acceleration of the tube to that of the tank.

i) Guide tubes show little amplification of acceleration even at their resonant frequencies because of large damping factors in water.(refer to Fig.10)

ii) CT/PT assemblies in water show distinct resonance phenomena and their average amplification factor amounts to 28. (refer to Fig.9) In this case, regular motion of water such as magnetic flux is locally observed around each CT/PT assembly.

iii) As for the dynamic behavior of CT/PT assemblies in water, no remarkable interaction effect between adjacent tubes are observed. Its behavior is rather dictated by the vibrational characteristics of an individual CT/PT assembly.

iv) As shown in Fig.9, damping factors of CT/PT assemblies in water observed in forced vibrations for sinusoidal waves tend to increase, where the damping factor in water is about 3% in contrast to 1% in air.

b. Case of Earthquake Motions

i) Under 0.5G of El Centro and 0.3G of Taft, CT/PT assemblies and guide tubes make independent vibrations without touching each other. In this case, CT/PT assemblies vibrate fractionally with their own natural frequencies, and the maximum amplification factor is 3 to 4.5. Guide tubes fluctuate in succession with the movement of the shaking table with the amplification factor of 1.

ii) Under stronger input conditions, CT/PT assemblies and guide tubes begin to contact each other, and at 1.G the number of contact amounts to as many as more than ten times.

5.2 Insertability of Shut-off Rod

5.2.1 At Rest

The drop time of the shut-off rod SR3 in G3 is 0.73 seconds, which corresponds to 1.6 seconds in an actual core.

5.2.2 Forced Vibration

a. Case of Sinusoidal Wave

Fig.11 shows relationship between the input acceleration level and drop time in case of sinusoidal wave of 13.7 Hz, which corresponds to the resonant frequency of CT/PT assemblies.

i) In the neighborhood of resonant frequency of CT/PT assemblies, arrival of the shut-off rod delays about 5% at 0.1G as compared to that when at rest, as shown in Fig.11, because vibration of the guide tube is excited due to contact with CT/PT assemblies.

ii) Except at the frequencies described above, no remarkable change of drop time is observed.

iii) According to the supplementary insertion test of a guide tube in air under extreme dynamic deformations exceeding 2cm, which corresponds to 10cm in an actual guide tube, the shut-off rod dropped without stopping on the way.

b. Case of Earthquake Motions

Fig.12 shows relationship between the input acceleration level and drop time in case of El Centro of 1.G (G-level of trip signal : 0.1, 0.2 and 0.3G).

i) As shown in Fig.12, drop time does not differ from that at rest, even when the input acceleration is raised to 1.G.

6. Conclusion

Clarified through this testing are such basic characteristics as added mass coefficient of water, damping factors, interaction effect of adjacent tube assemblies, movement of water and insertability of shut-off rods.

As the most important result among various findings, the drop time of shut-off rods is demonstrated to be within the allowable drop time specified for the standard CANDU 600MWe even under severe earthquake condition.

7. Acknowledgment

The data on an actual CANDU core necessary for the test were furnished from Atomic Energy of Canada, Limited.

The test was planned and conducted by Mr. Hajime Murakami and Mr. Kaoru Mizukoshi of Electric Power Development Co., Ltd., Dr. Kazuyoshi Uchida, Mr. Masamitsu Miyamura, and Mr. Masato Motosaka and other colleagues of Muto Institute of Structural Mechanics, Inc.

The authors are greatly pleased to acknowledge their helpful cooperations.

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Table 1 Law of Similarity for 1/5 Scale Model

Length, Displacement	1/5 = 0.20
Time, Velocity	$\sqrt{1/5} = 0.45$
Frequency	$\sqrt{5/1} = 2.23$
Acceleration	1/1 = 1
Density	1/1 = 1
Stiffness	$(1/5)^2 = 0.04$

Table 2 Data of Main Components of 1/5 Scale Model

CT/PT assembly	Material : Stainless Steel Tube, Leaden Tape, Rubber Diameter : 24.4 mm, Length : 594 mm Weight per Unit Length : 22.9 grm/cm (density : 4.9 grm/cm^3) Resonant Frequency : 15.3 Hz (in air), 13.7 Hz (in water) Damping Factor : about 1% (in air), about 1% (in water) Pitch : 57.2 mm
Guide Tube (in-core)	Material : Acryl, Perforated Ratio : 36% Diameter : 27.5 mm, Length : 1,540 mm (the Longest Tube G3) Weight per Unit Length : 1.2 grm/cm Resonant Frequency : 18.3 Hz (in air), 10.5 Hz (in water) Damping Factor : about 5% (in air), about 30% (in water) Clearance between Guide Tube and CT/PT Assembly : 2.6 mm
Shut-off Rod	Material : Aluminum Diameter : 21.1 mm, Length : 1,080mm (the Longest Rod : SR3) Weight per Unit Length : 4.4 grm/cm Drop Distance : 1,330 mm Total Clearance between Shut-off Rod and Guide Tube : 2.3 mm

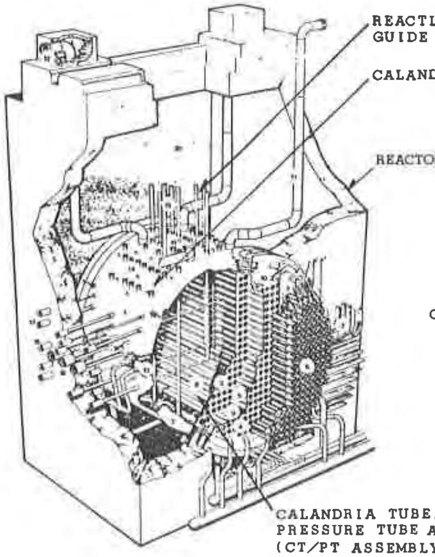


FIG.1 CANDU REACTOR CORE[1)]

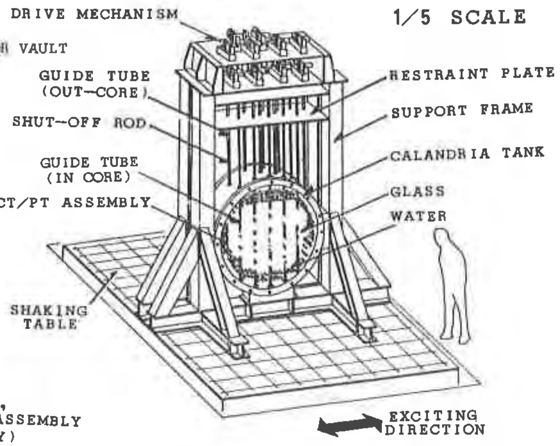


FIG.2 GENERAL VIEW OF MODEL

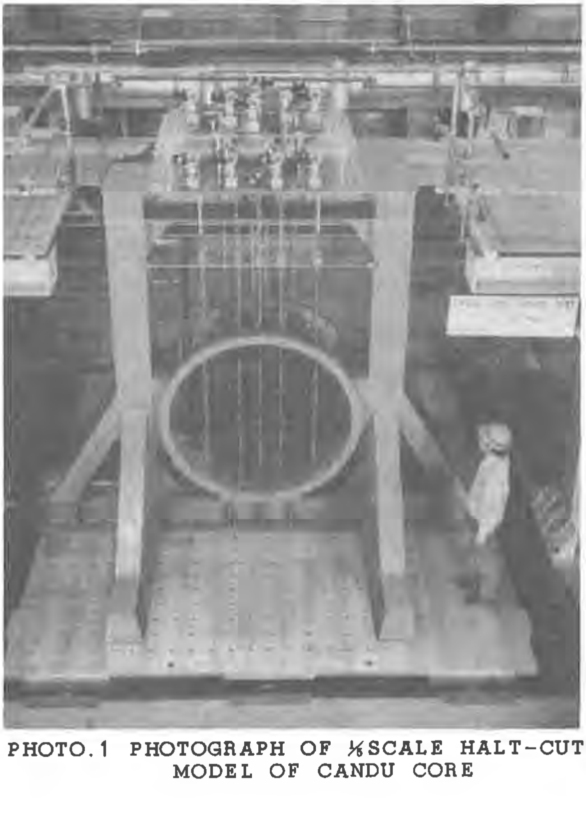


PHOTO.1 PHOTOGRAPH OF ⅕SCALE HALT-CUT MODEL OF CANDU CORE

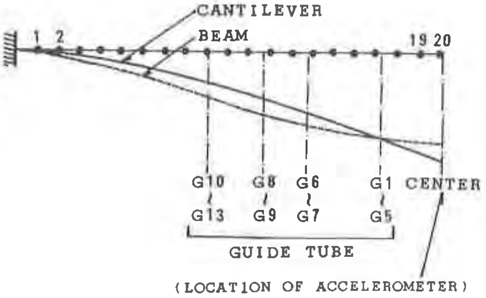


FIG.3 COMPARISON BETWEEN CANTILEVER AND BEAM BASED ON CALCULATION

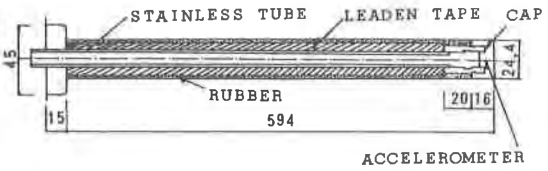
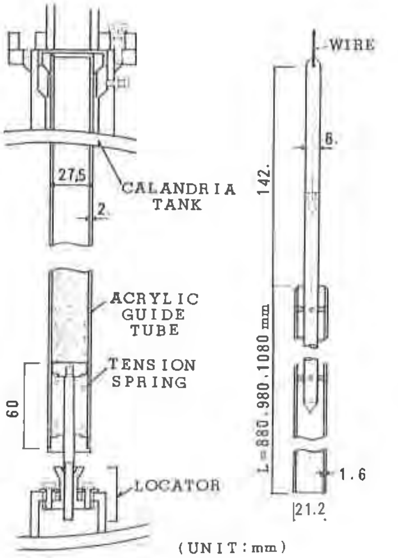


FIG.4 CT/PT ASSEMBLY MODEL



(a) GUIDE TUBE (IN-CORE)

(b) SHUT-OFF ROD

FIG.5 GUIDE TUBE MODEL AND SHUT-OFF ROD MODEL

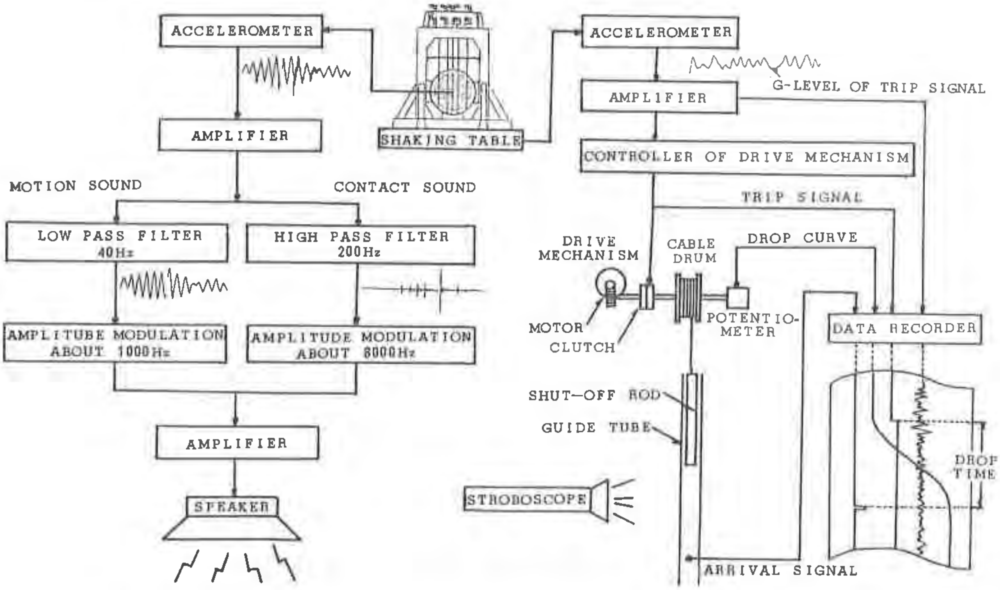


FIG.6 FLOW DIAGRAM OF MEASUREMENT

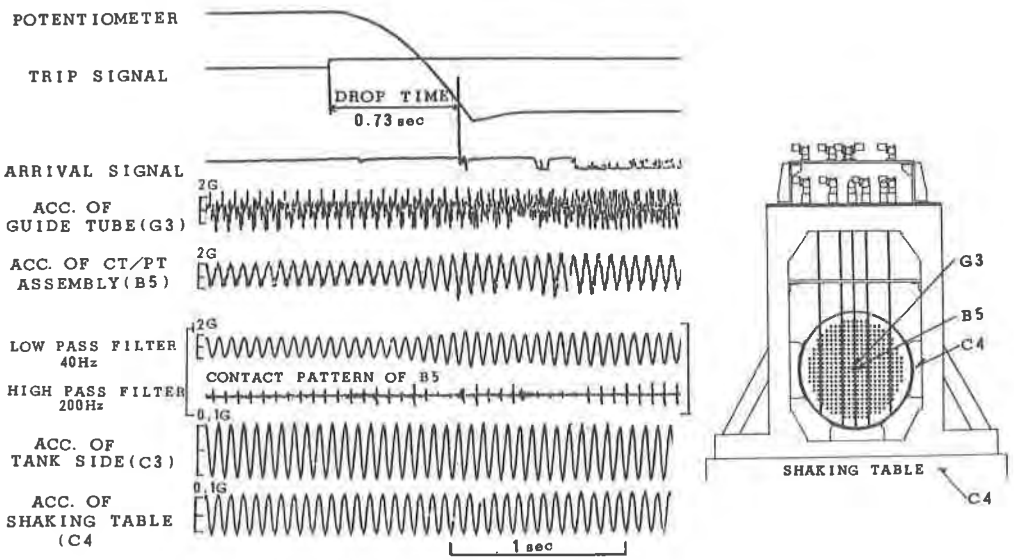


FIG.7 EXAMPLE OF FORCED VIBRATION RECORD (SINUSOIDAL WAVE, 0.1G, 14.Hz)

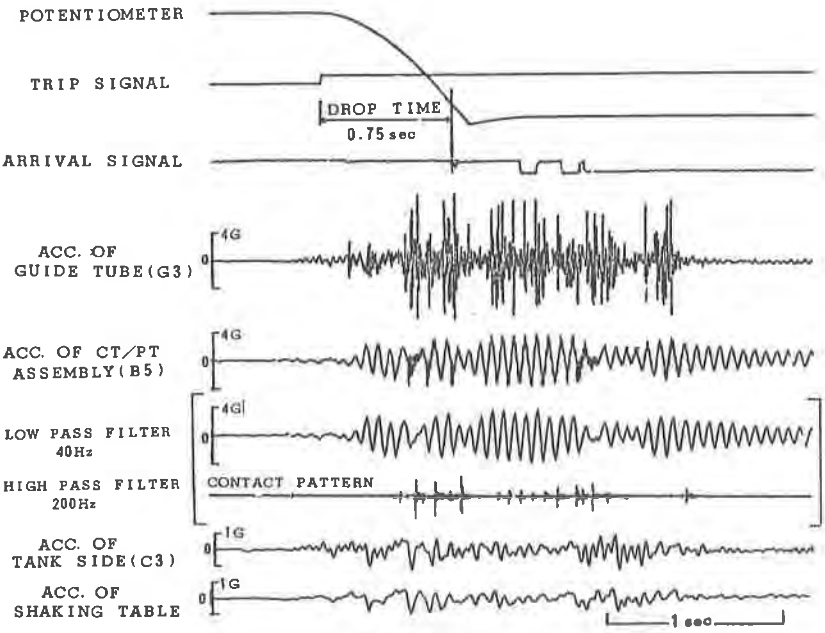


FIG.8 EXAMPLE OF FORCED VIBRATION RECORD (EL CENTRO, 1.G)

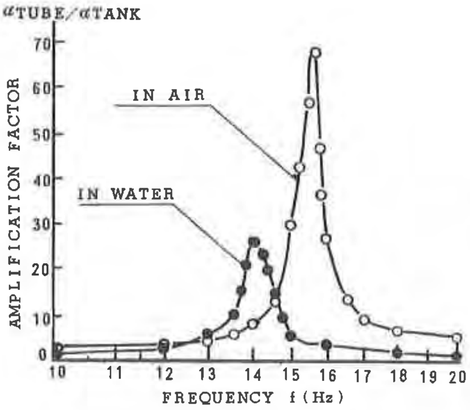


FIG. 9 RESONANCE CURVE OF CT/PT ASSEMBLY MODEL (B5)

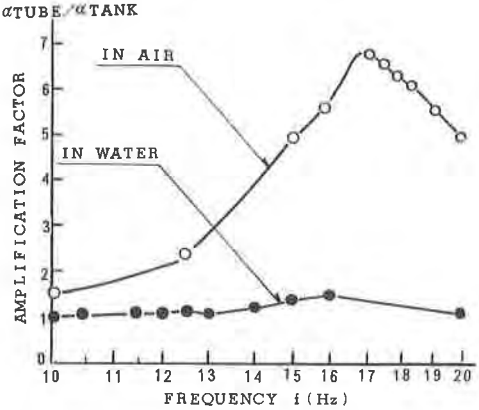


FIG.10 RESONANCE CURVE OF GUIDE TUBE MODEL (G3)

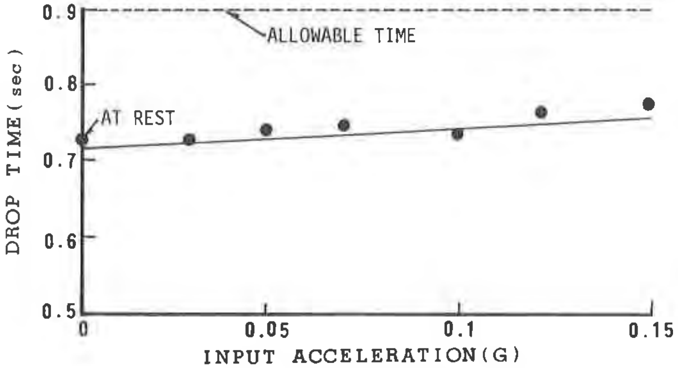


FIG.11 INPUT ACCELERATION VS. DROP TIME AT G3 IN WATER (SINUSOIDAL WAVE, 13.7 Hz)

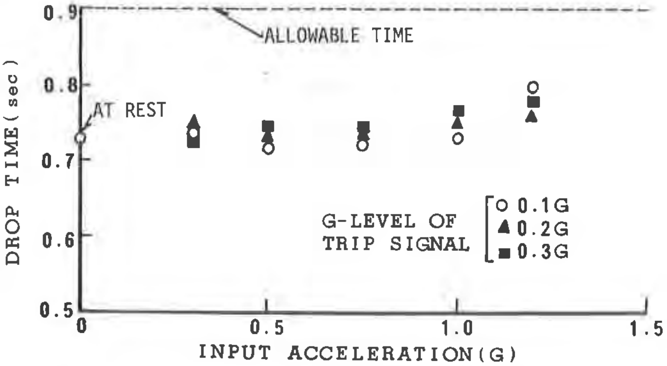


FIG.12 INPUT ACCELERATION VS. DROP TIME AT G3 IN WATER (EL CENTRO)