TWO-DIMENSIONAL VIBRATION TEST AND ITS SIMULATION ANALYSIS FOR A HORIZONTAL SLICE MODEL OF HTGR CORE

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SUMMARY

The forced vibration test and its simulation analysis of the two-dimensional horizontal slice model of the General Atomic Company's High Temperature Gas-Cooled Reactor (HTGR) core were studied subsequent to the vertical slice model test (K7/8 in 4th SMiRT). The purpose is to clarify such dynamic properties as resonant characteristics and vibration modes of the core, lumping phenomena of blocks, and distribution of reflector reactions.

Forced Vibration Test

Selecting a horizontal slice across the middle height of the core, the 577 graphite blocks of 1/5 scale are suspended with a clearance of 0.8 mm by 4-meter steel wires and are placed in the circumference of 18 reflectors. Each reflector is supported by the octagonal frame through two spigots which simulate the actual side support spring. On the spigots, strain gauges are attached to measure reflector reactions in the radial and tangential directions. The forced vibration tests of the 1/5 scale model were performed by using a shaking table (an electric-hydraulic type). As stationary inputs to the shaking table, sinusoidal waves were used. As random inputs, earthquake waves equivalent to El Centro (1940, NS), Taft (1952, EW) and an artificial wave were used. Regarding the random waves, both the time scale and displacement were reduced to $\sqrt{1/5}=0.46$ and $1/5=0.2$ respectively, pursuant to the law of similarity.

1. In the case of the stationary inputs, resonant phenomena as seen in the vertical slice test could not be observed. The block behaviors are much influenced by the input displacement irrespective of input frequency and g-level. The values of the reflector reactions are the largest in the excitation direction of flat-to-flat of hexagonal blocks.
2. In the case of the El Centro input, collision occurrence between the end block and reflector is about 4 times during 3 seconds (about 7 seconds in the actaul core) of the main shock. The distributed pattern of the reflector reaction is similar to the case of sinusoidal wave inputs. The reflector reactions increase with an increase of input g-level.

Simulation Analysis

A computer code called COLLAN 2-H was developed to theoretically simulate the test results. Computation is made as iteration of collisions between two blocks, based on the analytical results coincide fairly with the experimental results.

1. Introduction

This paper describes a two-dimentional forced vibration test and the simulation analysis for a horizontal slice model of the General Atomic Company's High Temperature Gas-Cooled Reactor (HTGR) core (refer to Fig.1), subsequent to the vertical slice model test reported by the authors at 4th SMiRT.

Selecting a horizontal slice (577 hexagonal blocks and 18 reflector blocks) across the middle height of the core, the forced vibration test of a 1/5 scale model was performed by using a shaking table to obtain such dynamic properties as frequency characteristics and vibration modes of the core, lumping and collision patterns of blocks and the response distribution of reflector reactions.

Together with the test, a computer code called COLLAN 2-H was developed to theoretically simulate the test results. It was found that the analytical results coincided fairly with the experimental results.

2. Forced Vibration Test

2.1 Test Apparatus

The 1/5 scale model shown in Photo 1 is used for the experiment. The 577 hexagonal graphite blocks (weight: 0.8 kg per a block and 460 kg in total) are suspended by 4-meter steel wires(the natural period of pendulum: 4 sec.) from the hanger, and are arranged with a clearance of 0.8 mm each other. The 18 reflector blocks are arrayed along the circumference of blocks. Each reflector is supported to the octagonal frame by two steel bars called spigot representing side support spring. On the spigot, strain gauges are attached to measure the reflector reactions in both radial and tangential directions. The spring constant of the spigot is decided by referring to the previous vertical slice test. The octagonal support frame representing the PCRV is a sufficiently rigid steel structure.

2.2 Execution of Test

The experiment was conducted using an electric-hydraulic shaking table installed at the Kajima Institute of Construction Technology in Japan.

Regarding the input waves to the shaking table, sinusoidal waves as stationary waves, and El Centro (1940, NS), Taft (1952, EW) and artificial waves as random waves were used. In case of the random waves, both the time scale and displacement were reduced to $\sqrt{1/5}$ and 1/5, respectively, pursuant to the law of similarity.

The shaking directions were A (flat to flat of hexagonal block), B (corner to corner and C (intermediate between A and B).

The major measuring items were the radial and tangential reactions of 18 reflectors and the acceleration, velocity and displacement of the shaking table. As shown in Fig.2, all data were recorded in the form of an oscillograph and stored in magnetic tapes.

2.3 Summary of Test Results

Main test results are summerized as follows:

(1) Case of Stationary Wave

Fig.5 shows the reflector reaction versus input frequency in A direction with parameters of input g-levels. Outstanding resonant phenomena as seen in the previous vertical slice test are not observed.

Fig.6 shows the block movement patterns in cases of A and B directions. Block behaviors depend on the input amplitude of displacement. If the amplitudes are same, blocks show the same vibration behavior irrespective of the input frequency and acceleration level. For example, at the input amplitude less than 0.8 cm (corresponds to 10 block gaps), blocks in the center part of the core remain still, and blocks in the circumference vibrate partially. On the other hand, at the input amplitudes larger than 0.8 cm, all the blocks vibrate in lumping.

Fig.3 shows the distribution of reflector reactions. In case of A direction, the resultant reflector reactions tend to be parallel to the shaking direction and are largest at both front ends, but gradually decrease towards the sides. In case of B direction, the resultant reflector reactions are not parallel to the shaking direction. The values tend to scatter around the circumference of the core. In case of C direction, reflector reactions have the common characteristics of both A and B directions. Concerning the comparison of reflector reactions between A, B and C directions, the values in A are the largest and those of B and C are fairly smaller than those of A.

(2) Case of Random Wave

Fig.7 shows the reflector reaction versus input g-level in A direction in case of El Centro wave. The reflector reactions increase with an increase of input g-level.

In case of El Centro wave of 0.5g, the entire lumping blocks strike the reflectors 4 or 5 times violently during the 3 seconds (correspond to about 7 seconds in the actual scale according to the law of similarity) of the main shock.

Fig.4 shows the distribution of reflector reactions. They are similar to the case of stationary input. Again, the values of A are the largest.

3. Simulation Analysis

3.1 Outline of Analysis

Together with the test, a computer code called COLLAN 2-H was developed to theoretically simulate the test results. The characteristics and assumptions of its analytical method are as follows:

(1) Each block is assumed to be a rigid body with a circular shape. Both the rotation of each block and the friction between blocks are neglected.

(2) Computation is made as iteration of collisions between two blocks. In the analysis, the collision theory assuming a constant coefficient of restitution is applied.

(3) For the vibration system of the reflector and side support spring, spring constants and damping factors in both the radial and tangential directions are considered.

(4) Input earthquake can be considered in any horizontal direction.

Fig.8 shows the mathematical vibration model. Each block is modeled to have a circular shape and is suspended by a pendulum with a required clearance. Each reflector is supported by side support springs.

3.2 Analytical Theory

(1) Judgement of Block Collision

As shown in Fig.9, the coordinates and the absolute velocities in the centers of the two blocks (mass: m_i, m_j, radius: R_i, R_j) at the time of t are expressed by (x_i, y_i), (x_j, y_j) and $(\dot{x}_i, \dot{y}_i)$, $(\dot{x}_j, \dot{y}_j)$ respectively. When no collision occurs during the time of Δt, the coordinate of i-block is expressed as follows:

$$\begin{cases} \bar{x}_i = x_i + \Delta t \cdot \dot{x}_i \\ \bar{y}_i = y_i + \Delta t \cdot \dot{y}_i \end{cases} \qquad (1)$$

On the other hand when the collision occurs, the following equation is established.

$$\sqrt{(\overline{x}_i - \overline{x}_j)^2 + (\overline{y}_i - \overline{y}_j)^2} - (R_i + R_j) < 0 \tag{2}$$

(2) Velocity of Block after Collision

Velocities $(\dot{x}_i, \dot{y}_i)$ and $(\dot{x}_j, \dot{y}_j)$ of the two blocks before collision are transformed into the velocities of $(\dot{u}_i, \dot{v}_i)$ and $(\dot{u}_j, \dot{v}_j)$ in the local coordinate which consists of both the radial $(|u|)$ and tangential (v) components as shown in Fig.10. The velocities of $(\widetilde{u}_i, \widetilde{v}_i)$, $(\widetilde{u}_j, \widetilde{v}_j)$ after collision are expressed as follows:

$$\begin{cases} \widetilde{u}_i = \dfrac{m_i - e m_j}{m_i + m_j} \dot{u}_i + \dfrac{(1+e) m_j}{m_i + m_j} \dot{u}_j \\ \widetilde{v}_i = \dot{v}_i \end{cases} , \quad \begin{cases} \widetilde{u}_j = \dfrac{(1+e) m_i}{m_i + m_j} \dot{u}_i + \dfrac{-e m_i + m_j}{m_i + m_j} \dot{u}_j \\ \widetilde{v}_j = \dot{v}_j \end{cases} \tag{3}$$

e: coefficient of restitution

The above mentioned velocities after collision are transformed into those in the standard coordinate.

(3) Displacement of Block after Collision

In case that the collision occurs within Δt (the time interval of calculation) as shown in Fig.11, at the time of $t + \Delta t$ the two blocks intrude into each other. Therefore it is necessary to be reset at the rebounded position.

First, the intruding movement δ_1 is expressed as follows:

$$\delta_1 = R_i + R_j - \sqrt{(\overline{x}_i - \overline{x}_j)^2 + (\overline{y}_i - \overline{y}_j)^2} \tag{4}$$

The intrusion time t_1 is expressed as follows:

$$t_1 = \delta_1 / V \tag{5}$$

where V is the relative velocity $(= \dot{u}_j - \dot{u}_i)$. According to the collision theory, the relative velocity after collision is $-eV$.

The rebounded movement δ_2 can be finally obtained as follows:

$$\delta_2 = (-eV) \times t_1 = -e\delta_1 = -e\left(R_i + R_j - \sqrt{\{(x_i - x_j) + \Delta t(\dot{x}_i - \dot{x}_j)\}^2 + \{(y_i - y_j) + \Delta t(\dot{y}_i - \dot{y}_j)\}^2}\right) \tag{6}$$

The above intrusion is checked with respect to all blocks during Δt.

(4) Vibration System of Reflector and Side Support Spring

The equation of motion for the reflector and the side support spring in Fig.12 is expressed by eq.(7) for the radial and tangential directions.

$$\begin{cases} m\ddot{x}_r + C_r \cdot \dot{x}_r + K_r \cdot x_r = -m\ddot{\alpha}\sin\theta \\ m\ddot{y}_t + C_t \cdot \dot{y}_t + K_t \cdot y_t = -m\ddot{\alpha}\cos\theta \end{cases} \tag{7}$$

where

m : mass of reflector

(C_r, C_t), (K_r, K_t) : damping coefficients and spring constants of the side support springs in the radial and tangential directions

$\ddot{\alpha}$, θ : input acceleration and the angle

Concerning the collisions between the reflector and block, the same method for the collisions of blocks as mentioned above is applied. The reflector reactions in the radial and tangential directions are calculated by $K_r \cdot x_r$ and $K_t \cdot y_t$ respectively.

3.3 Comparison between Analytical and Experimental Values

As an example, the analysis was made regarding the 1/5 scale full array model subject to the A directional excitation. Main input data are, radius of block; 7.2 cm, weight of block; 0.8 kg, coefficient of restitution; 0.65, weight of reflector; 15 kg, spring constant of side support spring; 10000 kg/cm, damping factor of side support spring; 0.50 and computation time interval; 1/1000 sec..

Fig.13 shows the comparison between the analytical and experimental results in case of sinusoidal wave of 0.3 g at 1.5 Hz. In the fiture, the time histories and distributions of the reflector reactions are shown. It can be found that the analytical results coincide fairly with the experimental results.

4. Conclusion

The main remarks can be drawn from the test and its simulation analysis as follows:

(1) Case of Stationaly Wave

Outstanding resonant phenomena as seen in the previous vertical slice test are not observed.

The block behaviors depend on the input amplitude of displacement. If the amplitudes are same, blocks show the same behaviors irrespective of input frequency and acceleration level.

In case of A direction, the resultant reflector reactions are parallel to the shaking direction, but in case of B direction, they are not parallel. And the values of A direction are fairly larger than those of B and C directions.

(2) Case of Random Wave

The entire lumping block strikes the reflectors about 4 times violently during main shock in case of El Centro wave of 0.5 g input.

(3) Simulation Analysis

The analytical results by COLLAN 2-H coincide fairly with the experimental values. Therefore, the dynamic behavior of the actual core may be analyzed by use of COLLAN 2-H in conjunction with COLLAN 2-V introduced at the 4th SMiRT.

5. Acknowledgement

The authers are greatly pleased to acknowledge the help of Messrs. H. Murakami, Y. Kasai of Electric Power Development Co., Ltd., Japan and Dr. K. Uchida, Messrs. H. Takase, Y. Goto of Muto Institute of Structural Mechanics, Inc., Japan, and are thankful to the helpful advice of Messrs. A. J. Neylan, B. E. Olsen, T. H. Lee and others of General Atomic Company, U.S.A..

Reference

[1] A. J. Neylan, "Design Development of the HTGR Core and Support Structure - Seismic Considerations", 2nd International Conference on SMiRT, Berlin, September 1973

[2] K. Muto, T. Kuroda, et al, "One Dimensional Vibration Test and Simulation Analysis for HTGR Core", 3rd International Conference on SMiRT, London, September 1975

[3] K. Muto, T. Kuroda, et al, "Two-Dimentional Vibration Test and Simulation Analysis for a Vertical Slice Model of HTGR Core", 4th International Conference on SMiRT, San Francisco, August 1977

[4] K. Muto, T. Kuroda, et al, "Two-Dimentional Vibration Test and Its Simulation Analysis for a Horizontal Slice Model of HTGR Core", Japan-U.S. Seminar on HTGR Safety Technology, Brookhaven National Laboratory, September 1977

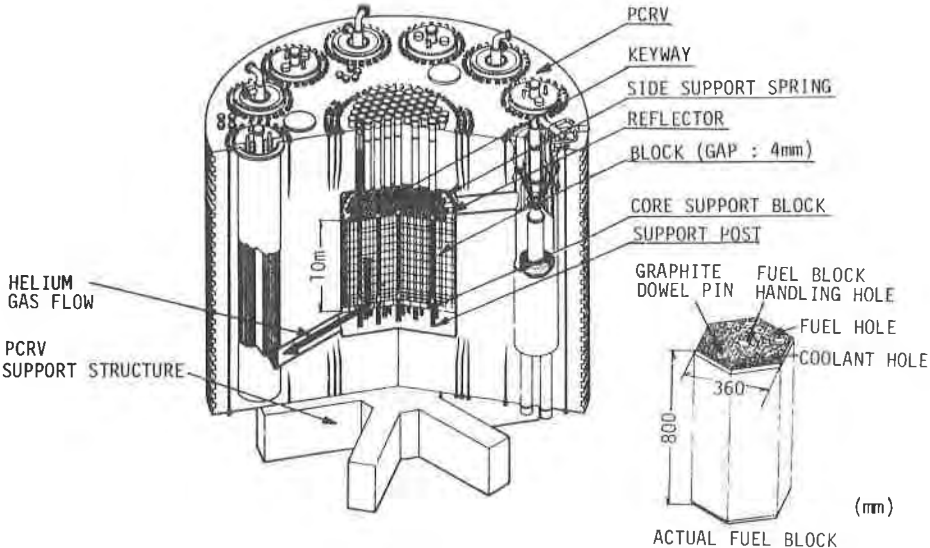


FIG. 1 OUTLINE OF HTGR

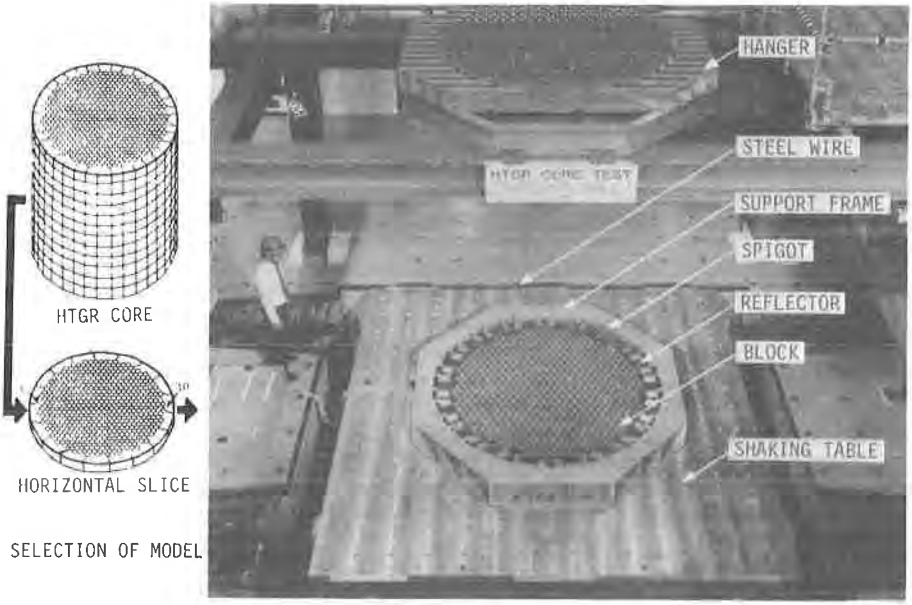
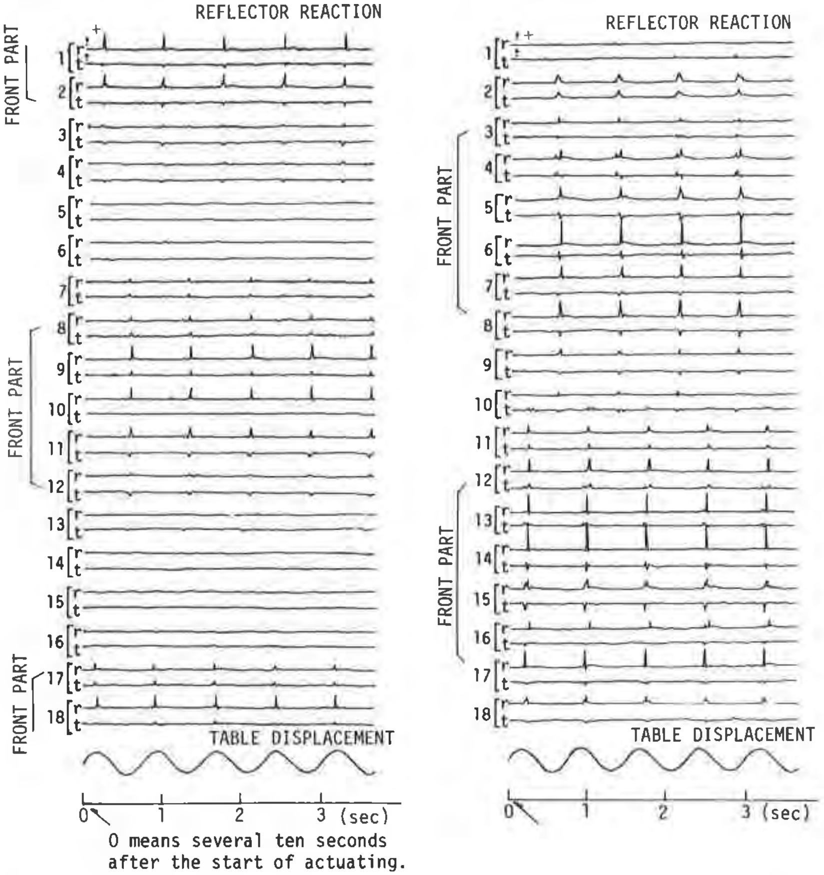


PHOTO 1 1/5 SCALE HORIZONTAL SLICE TEST MODEL

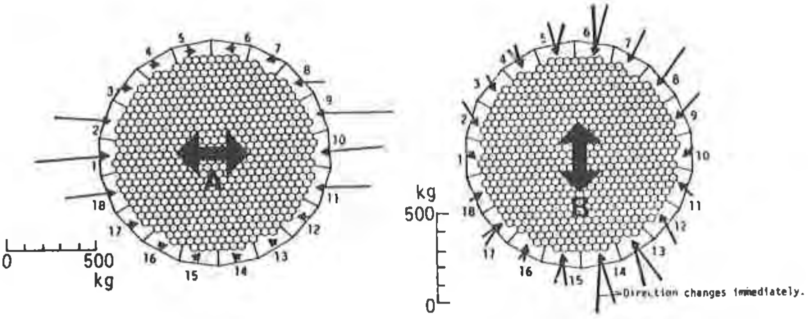


0 means several ten seconds after the start of actuating.

A direction

B direction

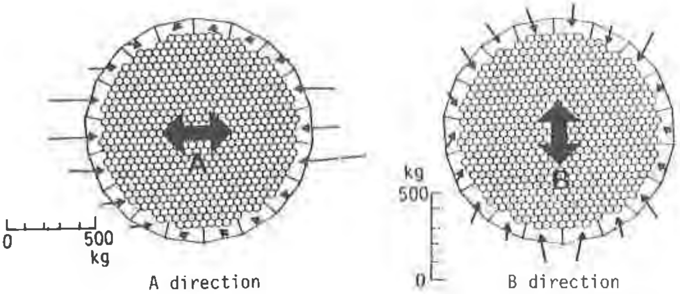
FIG. 2 EXAMPLE OF OSCILLOGRAPH RECORD (0.3G,1.5Hz)



A direction

B direction

FIG. 3 DISTRIBUTION OF REFLECTOR REACTION (0.3G,1.5Hz)



A direction B direction

FIG. 4 DISTRIBUTION OF REFLECTOR REACTION (EL CENTRO,0.5G)

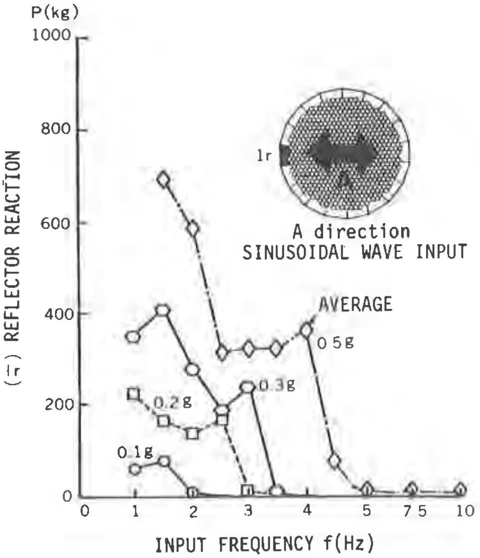


FIG. 5 REFLECTOR REACTION VERSUS INPUT FREQUENCY

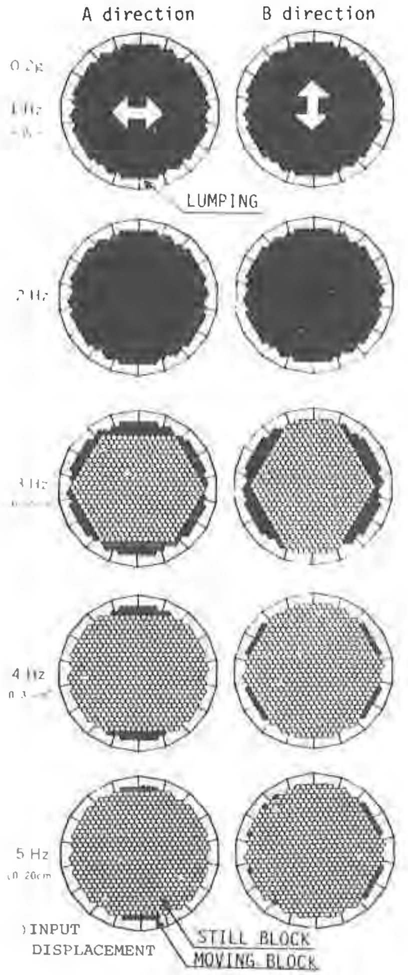


FIG. 6 VIBRATION MODE (BLOCK BEHAVIOR PATTERN)

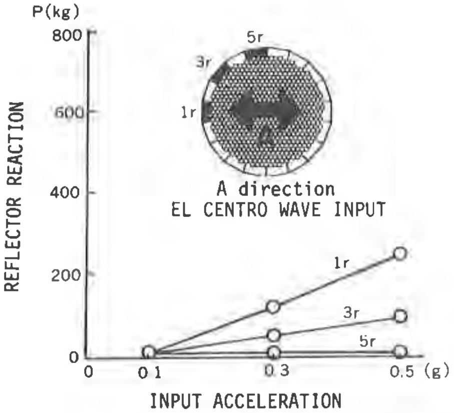
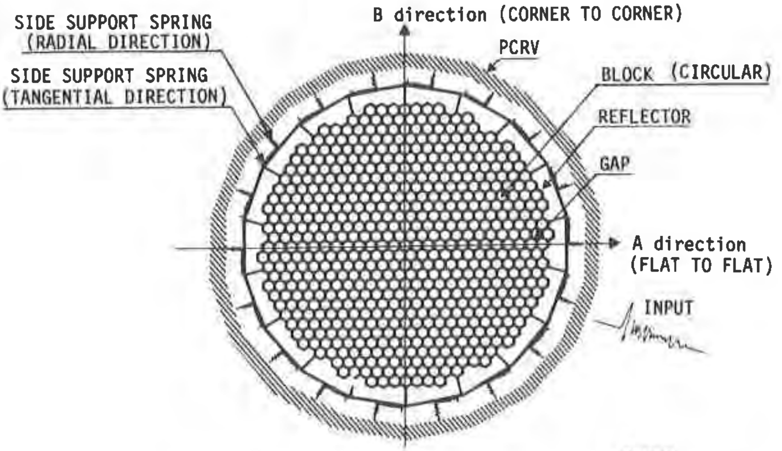
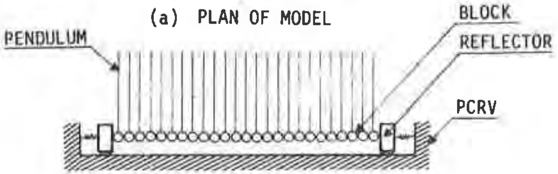


FIG. 7 REFLECTOR REACTION VERSUS INPUT G-LEVEL



(a) PLAN OF MODEL



(b) SECTION OF MODEL

FIG. 8 VIBRATION MODEL FOR HORIZONTAL SLICE

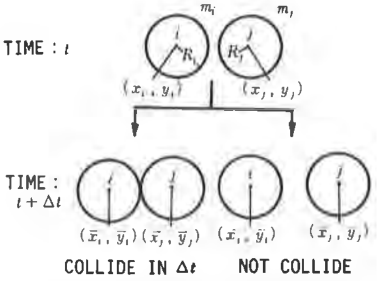


FIG. 9 JUDGEMENT OF COLLISION

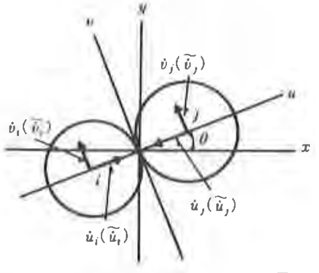


FIG. 10 TRANSFORMATION OF COORDINATE ON VELOCITY

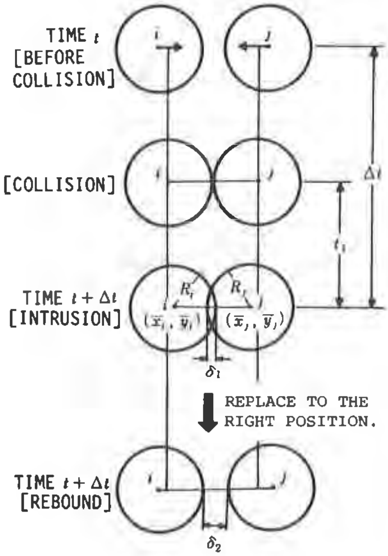


FIG. 11 BLOCK DISPLACEMENT AFTER COLLISION

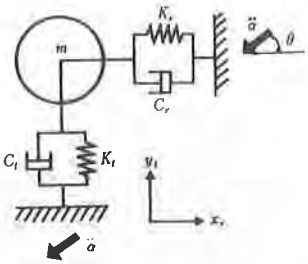


FIG. 12 VIBRATION SYSTEM OF REFLECTOR

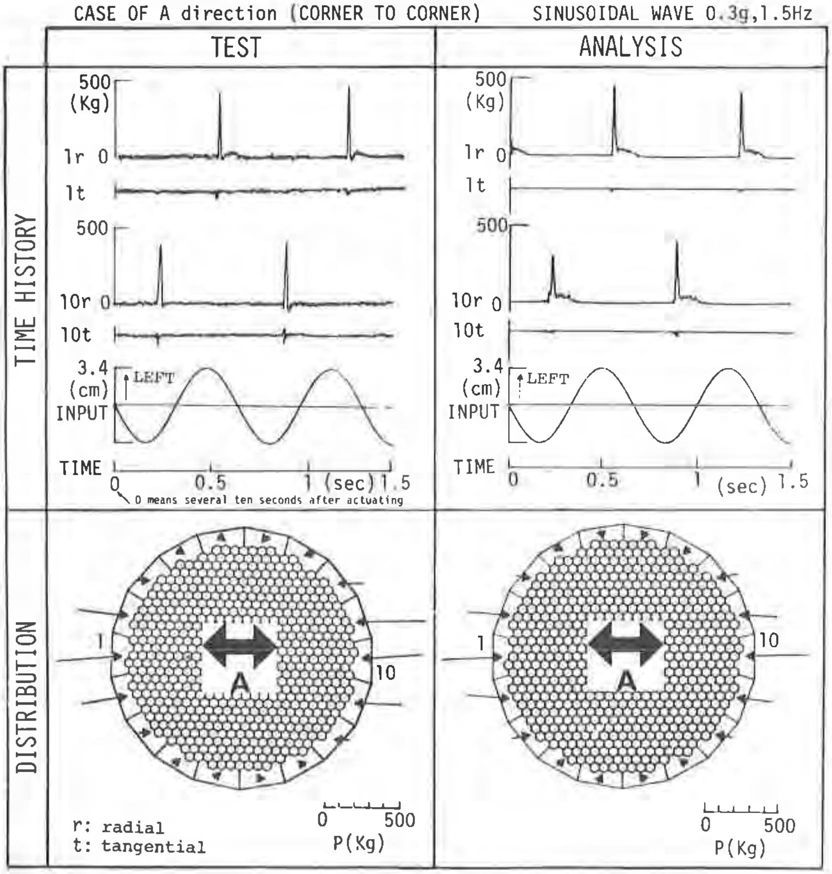


FIG. 13 COMPARISON BETWEEN ANALYZED AND TESTED REFLECTOR REACTION