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SONATINA-2H
A COMPUTER PROGRAM FOR SEISMIC ANALYSIS OF THE TWO-DIMENSIONAL HORIZONTAL SLICE HTGR CORE

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Japan Atomic Energy Research Institute

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SONATINA-2H
A Computer Program for Seismic Analysis of the Two-dimensional Horizontal Slice HTGR Core

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A Computer program SONATINA-2H has been developed for predicting the behavior of a two-dimensional horizontal HTGR core under seismic excitation. SONATINA-2H is a general two-dimensional computer program capable of analyzing the horizontal slice HTGR core with the fixed side reflector blocks and its restraint structures and the core support structure. In the analytical model, each block is treated as a rigid body and represent one column of the reactor core and is connected to the core support structure by mean of column springs and viscous dampers. A single dashpot model is used for the collision process between adjacent blocks. The core support structure is represented by a single block. The computer program SONATINA-2H is capable of analyzing the core behavior for an excitation input applied simultaneously in two mutually perpendicular horizontal directions.

In the present report are given, the theoretical formulation of the analytical model, an user's manual to describe the input and output format and sample problems.

Keywords: Computer Program, Seismic Analysis, HTGR Core, Core Seismic, Seismic Response, Nonlinear Vibration, Impact Vibration, Core Structure

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SONATINA－2H：高温ガス炉水平2次元炉心の地震応答解析プログラム

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（1990年1月5日受理）

ブロック状燃料から構成された高温ガス炉の水平2次元炉心の地震応答解析プログラムSONAINA－2Hを開発した。SONATINA－2Hは，側方固定反射体とその拘束構造物および炉心支持構造物を含めた水平2次元炉心モデルの解析が可能である。解析モデルでは，ブロックは剛体として取り扱い，炉心支持構造物に，コラム等価ばねと粘性ダンパーによって取り付けられたものとする。近接ブロック間の衝突は，スプリングーダッシュポットによってモデル化する。SONATINA－2Hは，水平2軸同時地震入力に対して解析可能である。

SONATINA－2Hの解析結果は実験結果と良く一致しており，本計算プログラムによって，高温ガス炉炉心の地震挙動を解析することができる。

本報告は，解析モデルの数式化，入力と出力データを示したユーザマニュアルおよび計算例について記述したものである。

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Nomenclature

C : damping coefficient

C_n^{CX} : x-component of restoring damping coefficient of the n-th fuel block

C_n^{CY} : y-component of restoring damping coefficient of the n-th fuel block

C_n^{GX} : x-component of support damping coefficient of the n-th side reflector block

C_n^{GY} : y-component of support damping coefficient of the n-th side reflector block

C_n^{R} : damping coefficient associated with the velocity of the n-th block

F : force

F_{bi}^{CX} : x-component of reaction force acting on the core support block by fuel block and side reflector block

F_{bi}^{CY} : y-component of reaction force acting on the core support block by fuel block and side reflector block

F_n^{CX} : x-component of restoring force of the n-th side reflector block

F_n^{CY} : y-component of restoring force of the n-th side reflector block

F_n^{D} : impact damping force

F_b^{GX} : x-component of reaction force acting on the core support block by restraint structure

F_b^{GY} : y-component of reaction force acting on the core support block by restraint structure

F_n^{GX} : x-component of support force of the n-th side reflector block

F_n^{GY} : y-component of support force of the n-th side reflector block

F_{ni}^{KX} : x-component of key reaction force of the n-th side reflector block

F_{ni}^{KY} : y-component of key reaction force of the n-th side reflector block

F_{nij}^{RX} : x-component of impact force caused by the surface ⓙ of the corner ⓘ of the n-th block

F^{RY}_{nij} : y-component of impact force caused by the surface ⓙ of the corner ⓘ of the n-th block

F^{S}_{n} : impact spring force

F^{SX}_{ni} : x-component of impact force caused by impact between the i-th block and the i-th surface of the n-th block

F^{SY}_{ni} : y-component of impact force caused by impact between the i-th block and the i-th surface of the n-th block

I_n : mass moment of inertia of the n-th block

K : spring constant

K^{CX}_{n} : x-component of restoring spring constant of the n-th fuel block

K^{CY}_{n} : y-component of restoring spring constant of the n-th fuel block

K^{GX}_{n} : x-component of support spring constant of the n-th side reflector block

K^{GY}_{n} : y-component of support spring constant of the n-th side reflector block

K^{R}_{n} : spring constant associated with δ_{n1}

M : moment

M^{C}_{n} : moment generated by forces F^{CX}_{n} and F^{CY}_{n}

M^{G}_{ni} : moment generated by forces F^{GX}_{ni} and F^{GY}_{ni}

M^{K}_{ni} : moment generated by forces F^{KX}_{ni} and F^{KY}_{ni}

M^{R}_{nij} : moment generated by forces F^{RX}_{nij} and F^{RY}_{nij}

M^{R}_{ni} : moment generated by forces F^{SX}_{ni} and F^{SY}_{ni}

m_b : mass of the core support block

m_n : mass of the n-th block

NCR : number of possible impact corners of the n-th side reflector block

NH : number of fuel blocks around the n-th side reflector block

NR : number of side reflector blocks around the n-th side reflector block

v : relative velocity between impacting blocks

(v_{kix}, v_{kiy}) : x- and y-component of velocity of the i-th block

(v_{knx}, v_{kny}) : x- and y-component of velocity of the n-th block

x : x coordinate or x-direction displacement

x_b : x-direction displacement of the core support block

x_i : x-direction displacement of the i-th block

x_n : x-direction displacement of the n-th block

x_{oi} : initial x coordinate of the i-th block

x_{on} : initial x coordinate of the n-th block

x_{pn} : x coordinate of the point P of the n-th block

x_{ipi} : x coordinate of the point P of the i-th block (the coordinate origin is at the i-th block's center of gravity)

x_{ipn} : x coordinate of the point P of the i-th block (the coordinate origin is at the n-th block's center of gravity)

x_{kii} : x coordinate of the corner of the i-th reflector block keyway (the coordinate origin is at the i-th reflector block's center of gravity)

x_{kin} : x coordinate of the corner of the i-th reflector block keyway (the coordinate origin is at the n-th reflector block's center of gravity)

x_{knn} : x coordinate of the corner of the n-th reflector block keyway (the coordinate origin is at the n-th reflector block's center of gravity)

x_{npn} : x coordinate of the point P of the n-th block (the coordinate origin is at the n-th block's center of gravity)

x_{pno} : x coordinate of the point P of the n-th block (the coordinate origin is at the n-th block's center of gravity)

$\dot{x}$: x-component of velocity

$\ddot{x}$: x-component of acceleration

$\ddot{x}_0$: x-component of input acceleration

y : y coordinate or y-direction displacement

y_b : y-direction displacement of the core support block

y_i : y-direction displacement of the i-th block

y_n : y-direction displacement of the n-th block

y_{oi} : initial y coordinate of the i-th block

y_{on} : initial y coordinate of the n-th block

y_{pn} : y coordinate of the point P of the n-th block

y_{ipi} : y coordinate of the point P of the i-th block (the coordinate origin is at the i-th block's center of gravity)

y_{ipn} : y coordinate of the point P of the i-th block (the coordinate origin is at the n-th block's center of gravity)

y_{kii} : y coordinate of the corner of the i-th reflector block keyway (the coordinate origin is at the i-th reflector block's center of gravity)

y_{kin} : y coordinate of the corner of the i-th reflector block keyway (the coordinate origin is at the n-th reflector block's center of gravity)

y_{knn} : y coordinate of the corner of the n-th reflector block keyway (the coordinate origin is at the n-th reflector block's center of gravity)

y_{npn} : y coordinate of the point P of the n-th block (the coordinate origin is at the n-th block's center of gravity)

y_{pno} : y coordinate of the point P of the n-th block (the coordinate origin is at the n-th block's center of gravity)

$\dot{y}$: y-component of velocity

$\ddot{y}$: y-component of acceleration

$\ddot{y}_0$: y-component of input acceleration

δ : gap width between blocks

δ_g : gap width between key and keyway

δ_{gx} : x-direction gap width between key and keyway

δ_{gy} : y-direction gap width between key and keyway

δ_{ni} : spring deformation of a spring dashpot unit acting between blocks

θ_n : rotation of the n-th block

$\dot{\theta}_n$: angular velocity of the n-th block

$\ddot{\theta}_n$: angular acceleration of the n-th block

μ : friction factor

1. Introduction

In the HTGR designed by General Atomic and a high-temperature engineering test reactor (HTTR) by Japan Atomic Energy Research Institute, the reactor core consists of hexagonal graphite blocks. These graphite blocks are stacked in several hundred columns. The reactor core is enclosed in a core barrel and the column is restrained horizontally at the top with keyed orifice blocks of a heat-resisting alloy. The column bottoms are restrained with dowel pins placed on the core support blocks. The column bottoms are restrained with dowel pins placed on the core support blocks. On the periphery, fixed reflectors are restrained by the core barrel. Blocks in the core are aligned in the columns by the dowel pins. Each column is separated from adjacent columns by small gaps. The gaps are initially several millimeters. After residence in the core, however, the block diameter is reduced on size due to fast neutron irradiation, so that the gap increases to several millimeters or more.

This large gap together with the large number of columns may result in a large cumulative gap during a seismic excitation. The cumulative gap accross the core diameter is significant since it may affect the capability of insertion of the control and shutdown material into the core. Moreover, because of these gaps, columns may repeatedly impact each other during a seismic excitation. The aseismic design requres the following information from analysis and/or experiments:

(1) deflections and disarrays which could cause disengagement of dowels and affect control rod insertion, and

(2) collision forces of fuel blocks, reflector blocks and core restraint structures which cause integrety of the core.

A HTGR core consists of several thousand or more indivisual graphite blocks of various shapes. It would be most difficult, if not possible, to model such a large array of core blocks in the three dimensions where each block can have up to six degrees of freedom. A three-dimensional analysis would be economically unfeasible in terms of computational cost and computer operating facilities. A two-dimensional analysis would seem to be the best approach if it can adequately describe the major characteristics of the three-dimensional core. Exact modeling of the complete three dimenisonal core arry is not possible because of computational cost. It is realized, therefore that reasonable tools are needed; i.e. analytical methods and computer program, which are conducted in parallel with experiments. The methods and computer programs should be verified and revised, if necessary, by using the experimental data, in order to make them usable for design purposes.

Since such a system of blocks as in the HTGR core does not constitute a structure in the usual sense, existing structural theory and experimental data cannot be applied directly. Several special computer programs have thus been developed for analysis of this system.

Muto et al.(1) prososed a two-dimensional analytical method of a horizontal slice core model using a rigid body to simplify the calculation model and to save the computer time. In the model, impulse momemtum conservation rule are applied. However, the column caracteristics such as the column stiffness and damping, and the column rotation are not considered. Two(2) have developed the analytical method and the computer program using a simplified model.

The author has developed the computer program SONATINA-2H for analyzing the dynamic behavior of the two-dimensional horizontal slice HTGR core under seismic excitation. SONATINA-2H is a relatively general two-dimensional computer program capable of handling a wide range of core blocks, reflector blocks, core restraint structures and the core support structure coupled with a one or two axis horizontal excitation. The HTGR core is modeled as a multi-mass system consisting of an entire horizontal section of the core at a single elevation. Main features of SONATINA-2H are as follows:

(1) each graphite block is modeled as a rigid body,

(2) each graphite block has three degrees-of-freedom, two translational displacements and one rotation around the block center of gravity,

(3) block force are normal to the faces and no firction are allowed,

(4) collision forces are represented by a spring and dashpot model located at the impact points of each graphite block,

(5) permanent side reflector blocks are restrainted with core restraint structures,

(6) Two-dimensional seismic excitation is avaiable for one horizontal direction and two horizontal directions-simultaneously.

(7) Three types of one horizontal and two horizontal excitations can be simulated; these are sinusoidal sweep, sinusoidal dwell and time history excitations.

The remainder of this report is arranged as follows. In Chapter 2, we present the mathmatical model dealing with the dynamic behavior of the HTGR core including two-dimensional effects. Chapte 3 describes the formulism of the analytical model. In Chapter 4 is given a use's manual to describe the input and output format. In addition, the applicabilities are demonstrated through comparison between experimental and analytical values.

2. Mathematical mode

2.1 Structure of HTGR core

The block-type fuel HTGR core consists of several thousand hexagonal graphite elements stacked in column and separated by small gaps. The blocks are aligned in columns by menas of dowel pins which restrict relative horizontal movement but allow vertical and rocking motion between blocks. The hexagonal graphite blocks are surrounded at its outer periphery by irregular shaped permanent side reflector blocks and a series of restraint structures and finally the reactor vessel. The core restraint structures are attached to the core barrel. The core restraint structures transfer lateral core blocks loads from the permanent side reflector blocks to the core barrel. The core structure of an experimental HTGR is illustrated in Fig. 1.

2.2 Analytical model

A horizontal slice across the core is selected and the fuel blocks and permanent side feflector blocks are modeled as shown in Fig. 2. A horizontal layer of the core one high forms a partial SONATINA-2H model as shown in Fig. 2. Each fuel block or reflector block is connected to the core support structure by means of column springs and dashpots. Figures 3 and 4 show the schematic representation of the core support structure and column model. The core support structure is modeled as a single mass. Figures 5 and 6 together form the complete SONATINA-2H mathmatical model. Collisions of blocks are modeled either by using interblock spring and damper alone, or interblock spring and dashpot in parallel with an impulse momentum computation. Input excitation is described by the core barrel. In SONATINA-2H, the following two-dimensional model is considered:

(1) each graphite block is modeled as a rigid body,

(2) each graphite block has three degrees-of-freedom, two translational displacements and one rotation around the block center axis,

(3) block forces are normal to the faces and no friction are allowed,

(4) block forces are represented by a spring and dashpot model located at the impact points of the each graphite block and,

(5) permanent side reflector blocks are restrained with core restraint structures.

2.3 Representation of collision forces

The representation of collision forces provides the spring-dashpot model as shown in Figs. 5, 6 and 7. At the instant of impact, when the interblock gap goes to zero or becomes negative, the inteblock spring and damper engage thus producing a force. The spring and damping forces are calculated as followings. The initial gap between adjacent blocks, the i-th and j-th blocks, is defined by parameter δ_{ij}. The spring and damping forces as a function of relative displacement x_i-x_j, and relative velocity $\dot{x}_k-\dot{x}_j$ of the two impacting bodies are:

Spring force F^S;

$$\left.\begin{array}{ll} F^S = K_{ij}(x_i-x_j+\delta_{ij}), & \text{if } |x_i-x_j| \leqq \delta_{ij} \ , \\ \quad = 0 \ , & \text{if } |x_i-x_j| > \delta_{ij} \ . \end{array}\right\} \tag{1}$$

Damping force F^D;

$$\left.\begin{array}{ll} F^D = C_{ij}(\dot{x}_i-\dot{x}_j), & \text{if } |x_i-x_j| \leqq \delta_{ij} \ , \\ \quad = 0 \ , & \text{if } |x_i-x_j| > \delta_{ij} \ . \end{array}\right\} \tag{2}$$

The impact force is then

$$F = F^S + F^D \ . \tag{3}$$

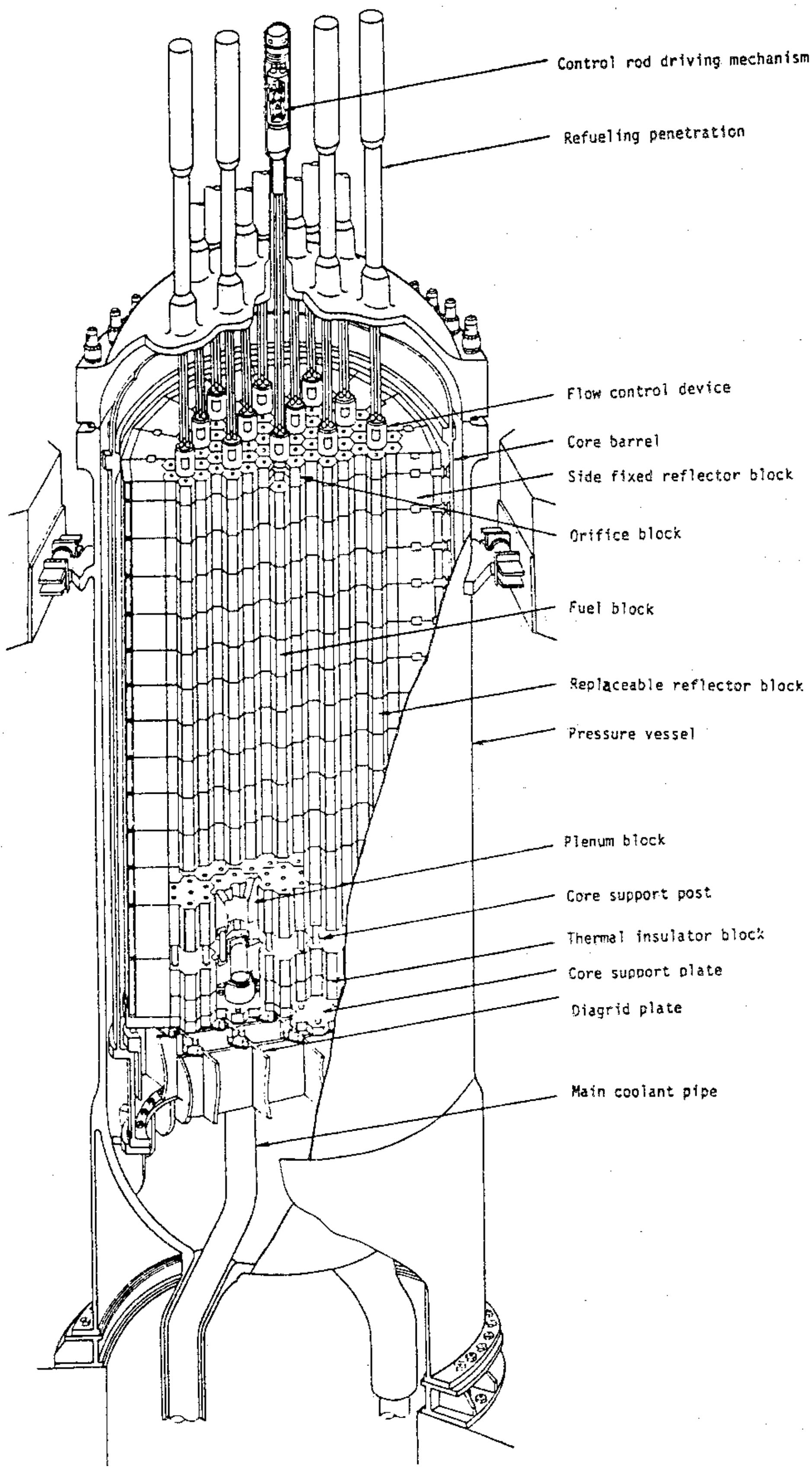


Fig. 1 Reactor vertical view of HTGR

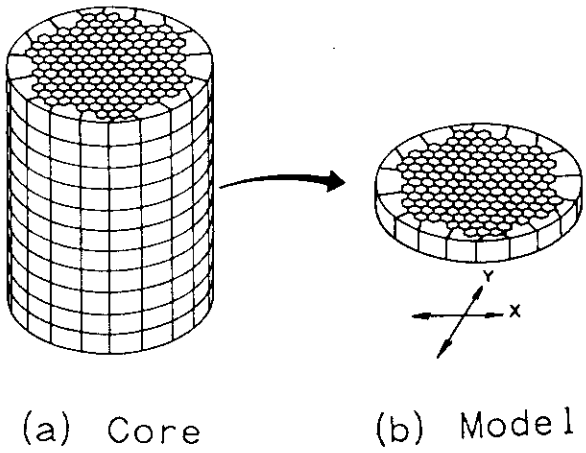


Fig. 2 HTGR core and analytical model

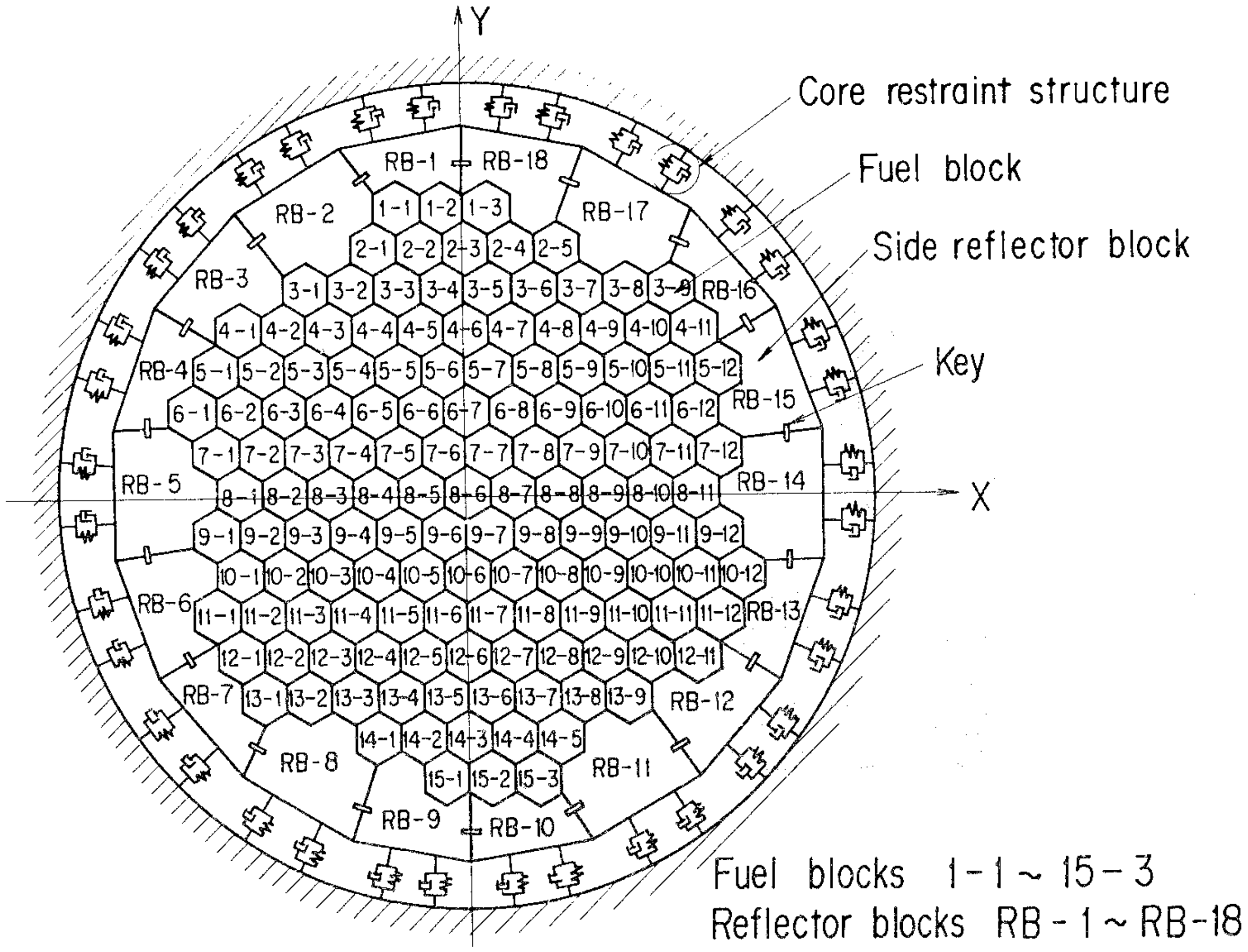


Fig. 3 Analytical model of two-dimensional horizontal core (I)

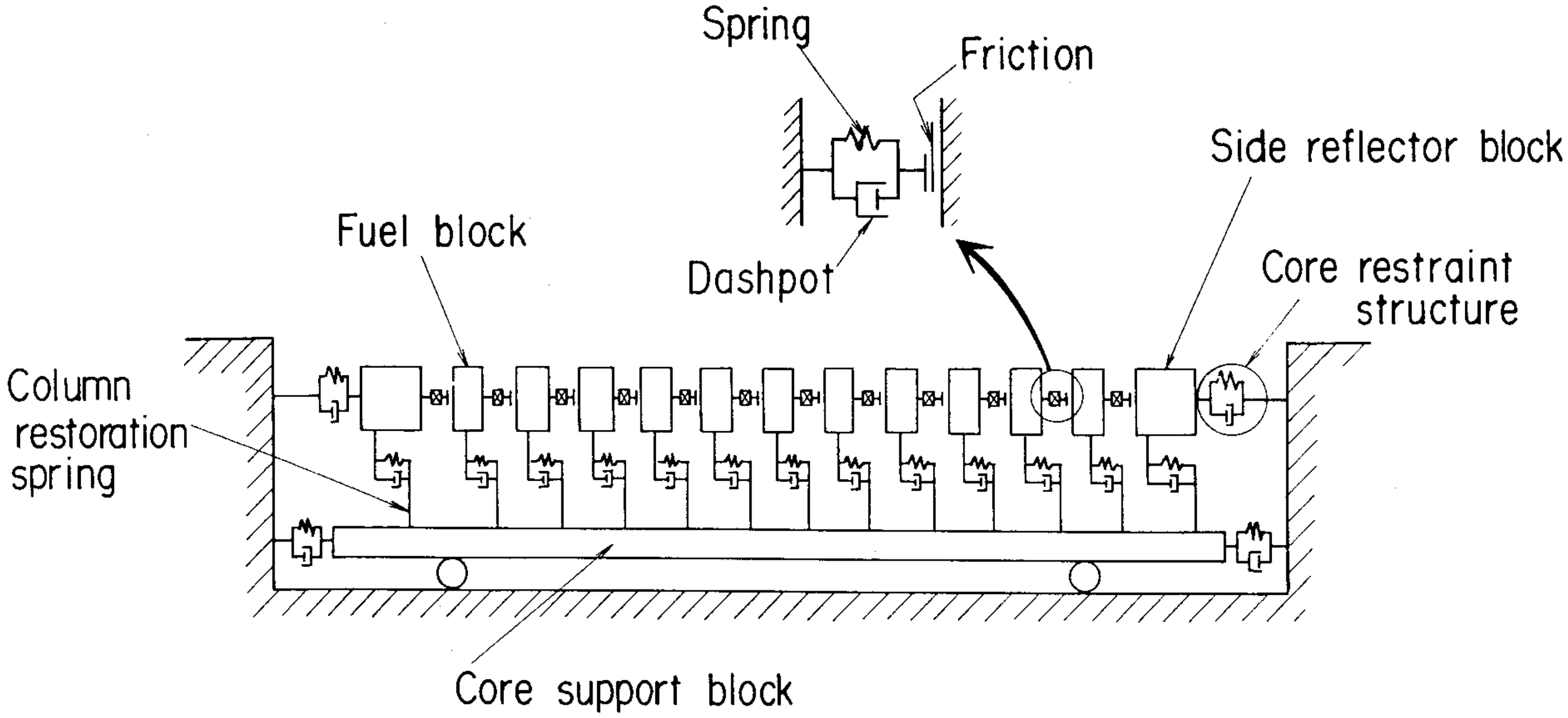


Fig. 4 Analytical model of two-dimensional horizontal core (II)

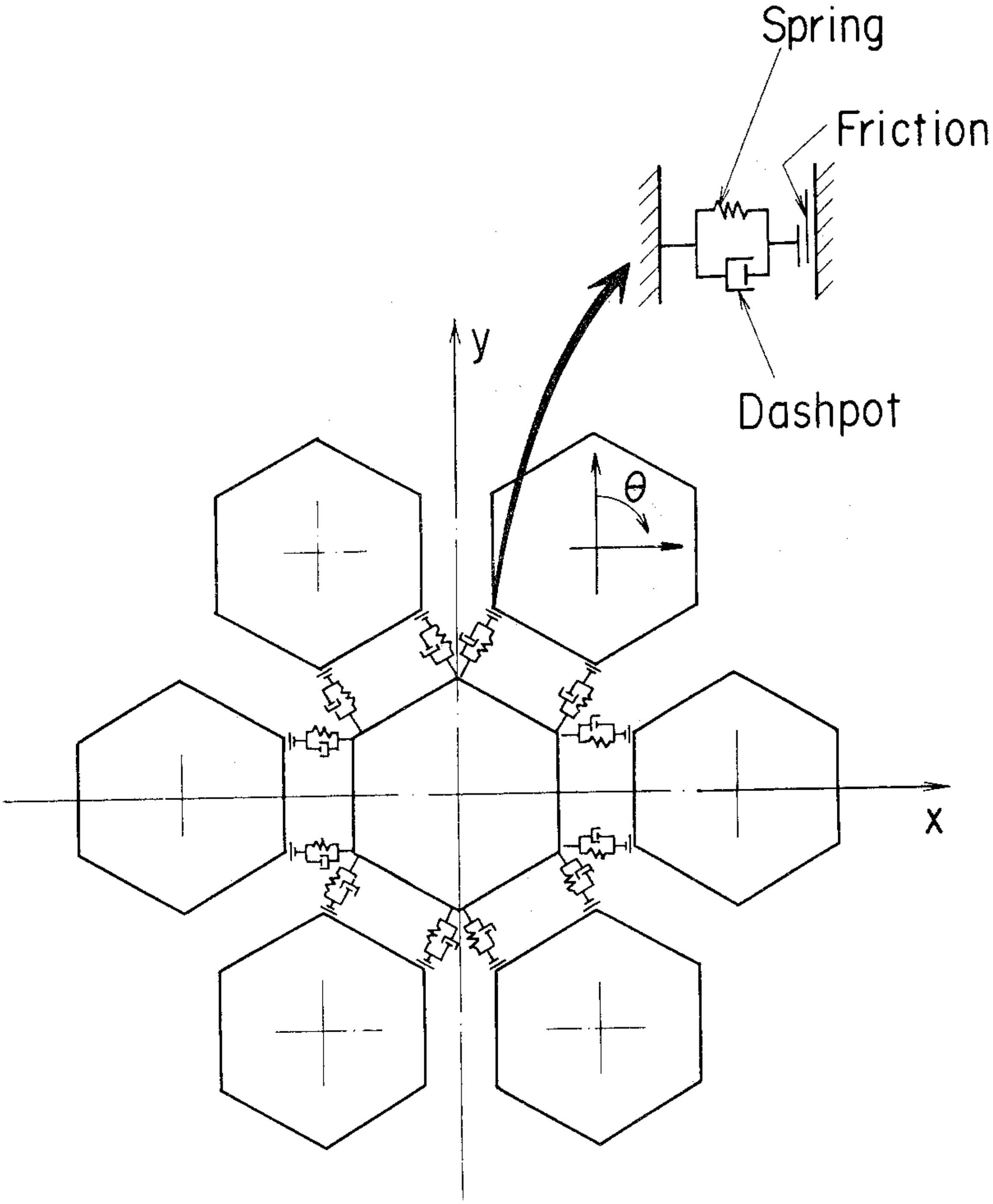
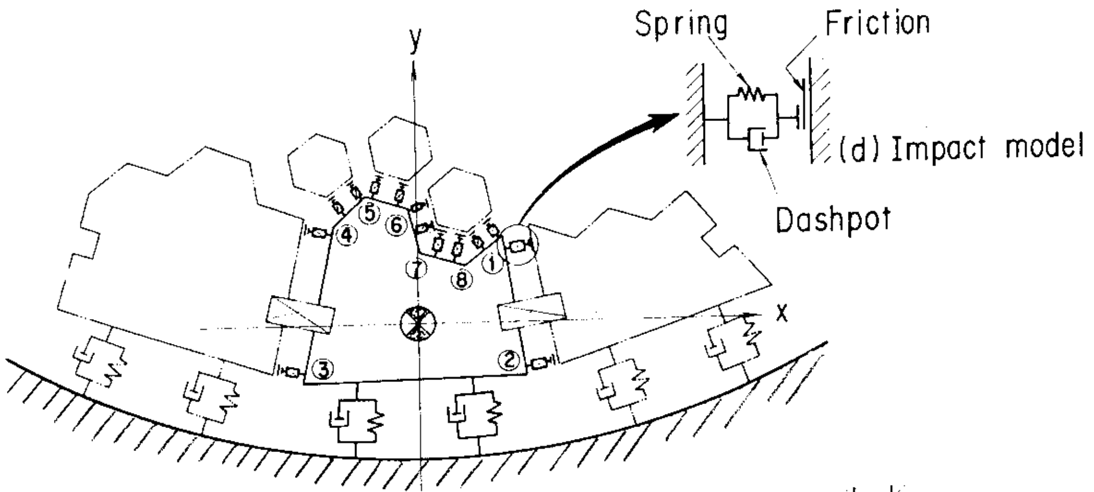
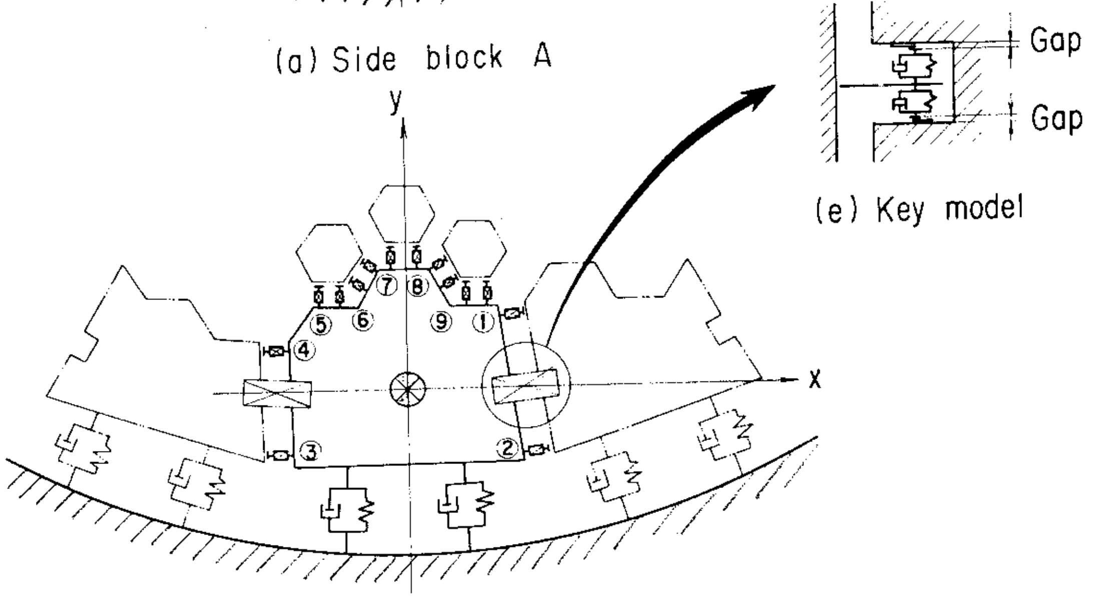


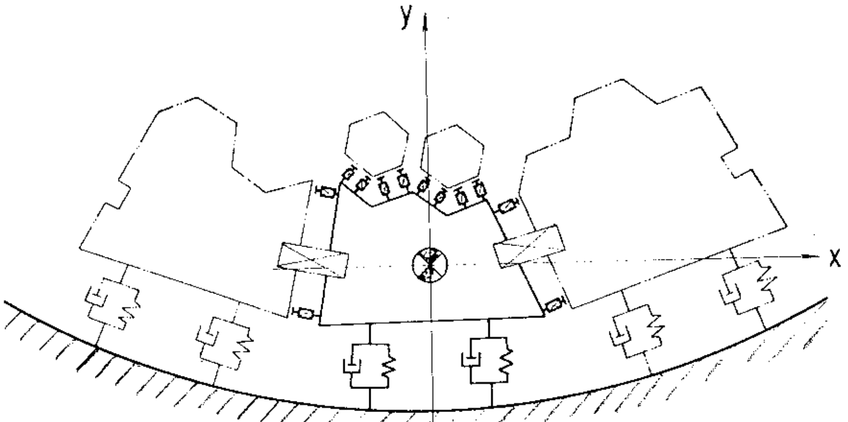
Fig. 5 Block arrangement and impact model



(a) Side block A

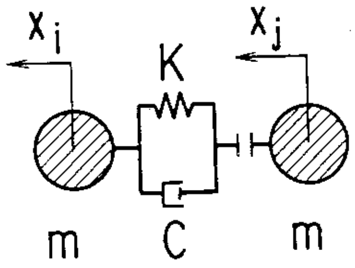


(b) Side block B

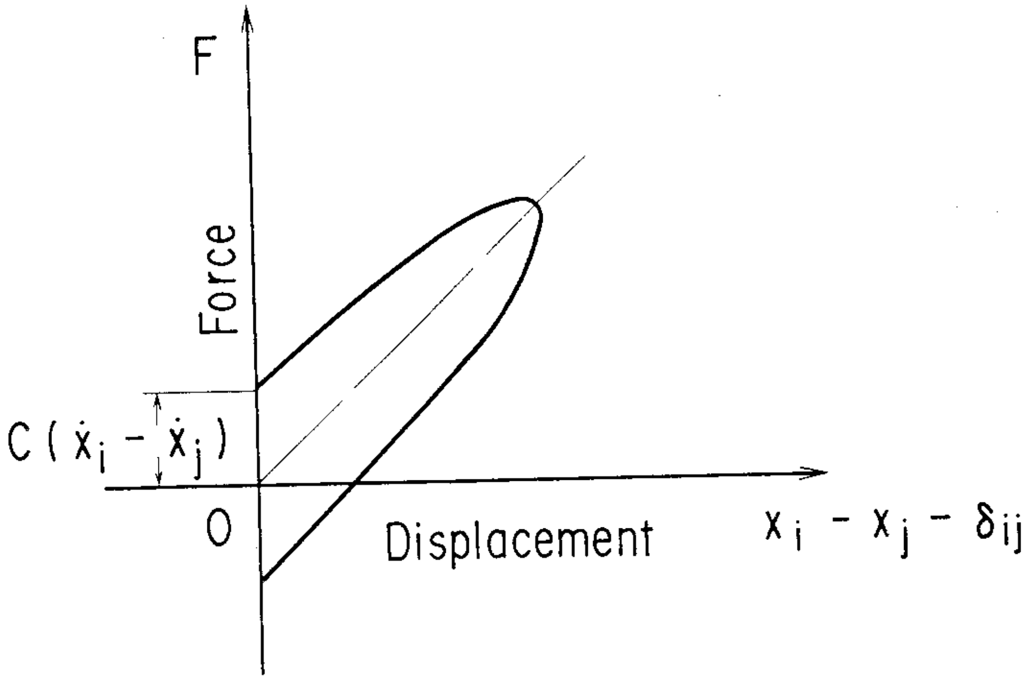


(c) Side block C

Fig. 6　Side reflector block model



(a) Mass impacting model



(b) Hysteresis loop for impact

Fig. 7 Viscoelastic model with two impacting bodies

3. Calculation equations

3.1 Global and local coordinate systems

One global coordinate system and three local coordinate systems are used for the convenience of the formulations. The coordinate systems of this analytical model are:

(1) global coordinate system with the origin (x,y) at the core center,

(2) local coordinate systems with the origin at the block center of gravity,

(a) initial coordinate system (x^L, y^L),

(b) coordinate system after displacement (x^Q, y^Q), and

(3) local coordinate system for rotation (x^S, y^S).

3.2 Equations of motion of fuel block

Let the coordinate system be chosen as shown in Fig. 8. The equations of motion for the n-th fuel block may be written as

$$\left.\begin{aligned} m_n\ddot{x}_n + \sum_{i=1}^{6}\sum_{j=1}^{2} F_{nij}^{RX} + \sum_{i=1}^{6} F_{ni}^{SX} + F_n^{CX} &= -m_n\ddot{x}_o \,, \\ m_n\ddot{y}_n + \sum_{i=1}^{6}\sum_{j=1}^{2} F_{nij}^{RY} + \sum_{i=1}^{6} F_{ni}^{SY} + F_n^{CY} &= -m_n\ddot{y}_o \,, \\ I_n\ddot{\theta}_n + \sum_{i=1}^{6}\sum_{j=1}^{2} M_{nij}^{R} + \sum_{i=1}^{6} M_{ni}^{S} &= 0 \,. \end{aligned}\right\} \qquad (4)$$

3.3 Displacement and velocity of blocks

The displacements and velocities of the points on the surfaces of a hexagonal block and a fixed side reflector block are similar. Therefore, the case of the hexagonal block alone will be shown. As indicated in Fig. 9, when the center of gravity of the n-th block moves from O_2 to O_3

(displacement x_n, y_n) and the block rotates by an angle of θ_n, the surface point P of the n-th block in the global coordinate system is expressed by the following equations,

$$\left.\begin{aligned} x^S_{pn} &= x_n + y^L_{pn} \sin\theta_n - x^L_{pn}(1 - \cos\theta_n) \ , \\ y^S_{pn} &= y_n - x^L_{pn} \sin\theta_n - y^L_{pn}(1 - \cos\theta_n) \ . \end{aligned}\right\} \tag{5}$$

The velocity of the point P of the block is derived from equation (5) and expressed as follows

$$\left.\begin{aligned} \dot{x}^S_{pn} &= \dot{x}_n + (y^L_{pn} \cos\theta_n - x^L_{pn} \sin\theta_n)\, \dot{\theta}_n \ , \\ \dot{y}^S_{pn} &= \dot{y}_n - (x^L_{pn} \cos\theta_n + y^L_{pn} \sin\theta_n)\, \dot{\theta}_n \ . \end{aligned}\right\} \tag{6}$$

The coordinates of the point P are expressed by the equations below

$$\left.\begin{aligned} x^Q_{npn} &= x^S_{pn} + x^L_{pn} - x_n \ , \\ y^Q_{npn} &= y^S_{pn} + y^L_{pn} - y_n \ . \end{aligned}\right\} \tag{7}$$

Substituting equation (5) into equation (7)

$$\left.\begin{aligned} x^Q_{npn} &= y^L_{pn} \sin\theta_n + x^L_{pn} \cos\theta_n \ , \\ y^Q_{npn} &= -x^L_{pn} \sin\theta_n + y^L_{pn} \cos\theta_n \ . \end{aligned}\right\} \tag{8}$$

The coordinates of the point P in the rotated local coordinate system can be expressed by the global coordinate system. Solving equation (8) for the coordinates (x^L_{pn}, y^L_{pn})

$$\left.\begin{aligned} x^L_{pn} &= x^Q_{npn} \cos\theta_n - y^Q_{npn} \sin\theta_n \ , \\ y^L_{pn} &= x^Q_{npn} \sin\theta_n + y^Q_{npn} \cos\theta_n \ , \end{aligned}\right\} \tag{9}$$

or

$$\left.\begin{aligned} x^L_{pn} &= x^L_{pno}\cos\theta_n - y^L_{pno}\sin\theta_n - x_n\cos\theta_n + y_n\sin\theta_n\ , \\ y^L_{pn} &= x^L_{pno}\sin\theta_n + y^L_{pno}\cos\theta_n - x_n\sin\theta_n - y_n\cos\theta_n\ . \end{aligned}\right\} \qquad (10)$$

where

$$\left.\begin{aligned} x^Q_{npn} &= x^L_{pno} - x_n\ , \\ y^Q_{npn} &= y^L_{pno} - y_n\ . \end{aligned}\right\} \qquad (11)$$

3.4 Gap between blocks

The calculation of the gap between hexagonal blocks, a hexagonal and a side reflector block, and side reflector blocks are done in a similar way. We will show only the metod of calculation for the gap between hexagonal blocks. The gap between a corner ① of the n-th block and the side ④ - ⑤ of the i-th block is shown in Fig. 10.

(1) Displacement coordinates of corners ① and ② of the n-th block

The coordinates of corners ① and ② of the displaced n-th block are expressed by the following equations.

(a) For the corner ①,

$$\left.\begin{aligned} x^Q_{n1n} &= x^L_{1n} + x^S_{1n} - x_n\ , \\ y^Q_{n1n} &= y^L_{1n} + y^S_{1n} - y_n\ . \end{aligned}\right\} \qquad (12)$$

(b) For the corner ②,

$$\left.\begin{aligned} x^Q_{n2n} &= x^L_{2n} + x^S_{2n} - x_n\ , \\ y^Q_{n2n} &= y^L_{2n} + y^S_{2n} - y_n\ . \end{aligned}\right\} \qquad (13)$$

(2) Displacement coordinates of corners ④ and ⑤ of the i-th block

The coordinates of corners ④ and ⑤ of the displaced i-th block are expressed by the following equations.

(a) For the corner ④,

$$\left.\begin{aligned} x^Q_{i4n} &= x^L_{4i} + x^S_{4i} - x_n + (x_{oi} - x_{on}) \ , \\ y^Q_{i4n} &= y^L_{4i} + y^S_{4i} - y_n + (y_{oi} - y_{on}) \ , \end{aligned}\right\} \tag{14}$$

(b) For the corner ⑤,

$$\left.\begin{aligned} x^Q_{i5n} &= x^L_{5i} + x^S_{5i} - x_n + (x_{oi} - x_{on}) \ , \\ y^Q_{i5n} &= y^L_{5i} + y^S_{5i} - y_n + (y_{oi} - y_{on}) \ . \end{aligned}\right\} \tag{15}$$

(c) Equation of the straight line of the side ① - ② of the n-th block

Equation of the straight line of the side ① - ② of the n-th block is the following.

$$y = a_1 x + b_1 \ , \tag{16}$$

where

$$a_1 = \frac{A_2}{A_4} \ ,$$

$$b_1 = y^Q_{n1n} - x^Q_{n1n} \frac{A_2}{A_4} \ ,$$

$$\left.\begin{aligned} A_1 &= x^Q_{i4n} - x^Q_{i5n} \ , \\ A_2 &= y^Q_{n1n} - y^Q_{n2n} \ , \\ A_3 &= y^Q_{i4n} - y^Q_{i5n} \ , \\ A_4 &= x^Q_{n1n} - x^Q_{n2n} \ . \end{aligned}\right\} \tag{17}$$

(d) Equation of the straight line of the side ④ - ⑤ of the i-th block

$$y = a_2 x + b_2 \ , \tag{18}$$

where

$$a_2 = \frac{A_3}{A_1} ,$$

$$b_2 = y^Q_{i4n} - x^Q_{i4n} \frac{A_3}{A_1} .$$

(e) Coordinates of block impact point

The coordinates of the point of intersection between a straight line passing through corner ① of the n-th block and perpendicular to the side ① - ② and the side ④ - ⑤ of the i-th block are given by the following.

Assuming that the side ① - ② of the n-th block intersects the side ④ - ⑤ of the i-th block at a 90° angle, the condition under which a straight line passing through the corner ① of the n-th block and perpendicular to the side ① - ② does not intersect the side ④ - ⑤ of the i-th block, i.e., the corner ① of the n-th block does not impact the side ④ - ⑤ of the i-th block, is expressed by the equations below.

$$\left.\begin{array}{ll} \text{i)} & A_4 \neq 0 , \quad A_2 \neq 0 \text{ and } -\frac{A_4}{A_2} = \frac{A_3}{A_1} , \\ \text{ii)} & A_4 \neq 0 , \quad A_2 = 0 \text{ and } A_1 = 0 , \\ \text{iii)} & A_4 = 0 , \quad A_2 \neq 0 , \quad A_1 \neq 0 \text{ and } A_3 = 0 , \end{array}\right\} \tag{19}$$

where, A_1, A_2, A_3 and A_4 are given in equation (17).

(f) Impact point coordinates under conditions $A_4 \neq 0$ and $A_2 \neq 0$

i) Equation of the straight line of the side ① - ② passing through the corner ①

The equation of a straight line passing through the corner ① of the n-th block and perpendicalar to the side ① - ②, which passes through the coordinates of the corner ① at a slope a_3, is given as follows.

$$y = a_3 x + b_3 \ , \tag{20}$$

where

$$a_3 = -\frac{A_4}{A_2} \ ,$$

$$b_3 = y^Q_{n1n} + x^Q_{n1n} \frac{A_4}{A_2} \ .$$

ii) Coordinates of intersection point

The coordinates of the intersection point (d^Q_{d1n}, y^Q_{d1n}) between the n-th block and the i-th block are obtained from equations (18) and (20).

ii-a) If $A_1 \neq 0$,

$$\left.\begin{aligned} x^Q_{d1n} &= (-b_3 + y^Q_{i4n} - x^Q_{i4n} \frac{A_3}{A_1})/(a_3 - \frac{A_3}{A_1}) \ , \\ y^Q_{d1n} &= (a_3 \ x^Q_{d1n} + b_3) \ . \end{aligned}\right\} \tag{21}$$

ii-b) If $A_1 = 0$,

$$\left.\begin{aligned} x^Q_{d1n} &= x^Q_{i4n} \ , \\ y^Q_{d1n} &= a_3 \ x^Q_{i4n} + b_3 \ . \end{aligned}\right\} \tag{22}$$

(g) Impact point coordinate under the conditions $A_4 \neq 0$ and $A_2 = 0$

i) Equation of the straight line passing through the corner ① of the n-th block at right angle to the side ① - ②.

Since the straight line of the side ① - ② is parallel to the x axis, a straight line perpendicular to the straight line is given by the equation below.

$$x = x^Q_{n1n} \ . \tag{23}$$

ii) Coordinates of intersection point

The coordinates of the intersection point is obtained from equations (20), (21) and (22).

ii-a) If $A_1 \neq 0$,

$$\left.\begin{aligned} x^Q_{d1n} &= x^Q_{n1n} , \\ y^Q_{d1n} &= \frac{A_3}{A_1} x^Q_{d1n} + \{y^Q_{i4n} - x^Q_{i4n} \frac{A_3}{A_1}\} . \end{aligned}\right\} \tag{24}$$

ii-b) If $A_1 = 0$, there is no intersection under the condition ii) of equation (19).

(h) Impact point coordinates under the conditions $A_4 = 0$ and $A_2 \neq 0$

i) Equation of the straight line passing through the corner ① of the n-th block at right angles to the side ① - ②.

Since the straight line of the side ① - ② is parallel to the y axis, a straight line perpendicular to the straight line is given by the equation below.

$$y = y^Q_{n1n} . \tag{25}$$

ii) Coordinates of intersection point

The coordinates of the intersection point are obtained from equations (18) and (25).

ii-a) If $A_1 \neq 0$ and $A_3 \neq 0$,

$$\left.\begin{aligned} x^Q_{d1n} &= \frac{A_1}{A_3} \{y^Q_{d1n} - y^Q_{i4n} + x^Q_{i4n} \frac{A_3}{A_1}\} , \\ y^Q_{d1n} &= y^Q_{n1n} . \end{aligned}\right\} \tag{26}$$

ii-b) If $A_1 = 0$,

$$\left.\begin{aligned} x^Q_{d1n} &= x^Q_{i4n} , \\ y^Q_{d1n} &= y^Q_{i4n} . \end{aligned}\right\} \tag{27}$$

(i) Gap between the corner ① of the n-th block and the side ④ - ⑤ of the i-th block.

The gap between the corner ① of the n-th block and the side ④ - ⑤ of the i-th block is given as follows.

$$\delta_{n1} = \{(x^Q_{n1n} - x^Q_{d1n})^2 + (y^Q_{n1n} - y^Q_{d1n})^2\}^{\frac{1}{2}} . \tag{28}$$

3.5 Judgment of impact between blocks

(1) Judgment of impact from geometrical arrangement of blocks

The judgment on the possibility of block impact is made by whether a corner of the block is facing a side of the adjacent block, or a straight line perpendicular to the side having a corner of the block intersects the side of its adjacent block. The condition under which this intersection does not exist is that, by reference to Fig. 11, there is no intersection between a corner ① of the n-th block and the side ④ - ⑤ of the i-th block, which is expressed by equations (17) and (19). Under other conditions than the above, there is a possibility of block impact.

(2) Judgment of hexagonal block impact

When the conditions below are satisfied, block impact will occur.

(a) A corner ① of the n-th block is in between the side ④ - ⑤ of the i-th block (see Fig. 10)

$$\left.\begin{array}{l} (x^Q_{d1n} - x^Q_{i4n})(x^Q_{d1n} - x^Q_{i5n}) < 0 , \\ (y^Q_{d1n} - y^Q_{i4n})(y^Q_{d1n} - y^Q_{i5n}) < 0 , \end{array}\right\} \tag{29}$$

(b) The position of the intersection described above is within the hexagonal contours of the impacting n-th block (see Fig. 11), i.e. $R_2 \leqq R_1$,

where

$$\left.\begin{aligned} R_1 &= \{(x^Q_{d1n})^2 + (y^Q_{d1n})^2\}^{\frac{1}{2}} , \\ R_2 &= \{(x^Q_{n1n})^2 + (y^Q_{n1n})^2\}^{\frac{1}{2}} . \end{aligned}\right\} \tag{30}$$

(3) Judgment of side reflector block impact

Additional judgment rules of block impact are applied as illustrated in Fig. 12. In the figure, the side ① - ⑦ of the impact corner ① of the n-th block is on the line of passing point 0_{n1} and if the following condition holds, impact occurs between blocks.

$$y^Q_{n1n}\, x^Q_{n7n} - x^Q_{n1n}\, y^Q_{n7n} = 0 . \tag{31}$$

If it is not determined to judge impact under the condition as defined by the above equation, the following judgment rule is required for impact occurrence.

(a) Straight line of the side ① - ⑦ of the n-th block

$$y = ax + b , \tag{32}$$

where

$$a = \frac{y^Q_{n1n}}{x^Q_{n1n}} ,$$

$$b = 0 .$$

(b) Distance between the center of gravity and the corner ① of the n-th side reflector block is represented in equation (30).

(c) Judgment rule for impact is as follows.

$$\left.\begin{aligned} |\theta_1| &= \tan^{-1}\left|\frac{y^Q_{dln}}{x^Q_{dln}}\right| \ , \\ |\theta_2| &= \tan^{-1}\left|\frac{y^Q_{nln}}{x^Q_{nln}}\right| \ , \\ |\theta^R_1| &= \tan^{-1}\left|\frac{y^R_{dln}}{x^R_{dln}}\right| \ . \end{aligned}\right\} \tag{33}$$

i) If no-impact occurs between the n-th side reflector block and the i-th hexagonal block, the following equation exists.

$$\left|\frac{y^Q_{nln}}{x^Q_{nln}}\right| < \left|\frac{y^R_{dln}}{x^R_{dln}}\right| \quad \text{or} \quad |\theta_2| < |\theta_1{}^R| \ . \tag{34}$$

ii) If impact occurs between the n-th side reflector block and the i-th hexagonal block, the following equation exists.

$$\left|\frac{y^Q_{nln}}{x^Q_{nln}}\right| \geqq \left|\frac{y^R_{dln}}{x^R_{dln}}\right| \quad \text{or} \quad |\theta_2| \geqq |\theta_1{}^R| \ . \tag{35}$$

3.6 Impact forces and their associated moments of fuel blocks

(1) Inclination angle of impacting blocks

The inclination angle $\theta_{\ell n}$ at the corner of the n-th block in Fig. 13 is obtained. If the coordinate of the corner ⓘ of the block and of the corner $\boxed{i+1}$ after the displacement of the block are (x^Q_i, y^Q_i) and (x^Q_{i+1}, y^Q_{i+1}) respectively, the equation of the straight line ⓘ - $\boxed{i+1}$ becomes as follows.

(a) If $x^Q_i - x^Q_{i+1} \neq 0$,

$$y = a_i x + b_i \ , \tag{36}$$

where

$$a_i = \frac{y_i^Q - y_{i+1}^Q}{x_i^Q - x_{i+1}^Q} \; ; \quad (i \neq 6) \; ,$$

$$a_6 = \frac{y_1^Q - y_6^Q}{x_1^Q - x_6^Q} \quad ; \quad (i = 6) \; .$$

(b) If $x_i^Q - x_{i+1}^Q = 0$,

$$x = x_i^Q \; . \tag{37}$$

The inclination angle $\theta_{\ell n}$ is as follows.

(a) If $x_i^Q - x_{i+1}^Q \neq 0$,

$$\theta_{\ell n} = \tan^{-1} a_i \; . \tag{38}$$

(b) If $x_i^Q - x_{i+1}^Q = 0$,

$$\left.\begin{aligned} \theta_{\ell n} &= -\frac{\pi}{2} \; ; \quad (y_i^Q - y_{i+1}^Q > 0) \; , \\ \theta_{\ell n} &= \frac{\pi}{2} \quad ; \quad (y_i^Q - y_{i+1}^Q < 0) \; . \end{aligned}\right\} \tag{39}$$

(2) Relative velocity between impacting blocks

The velocity components, v_x and v_y, in the direction perdendicular to the impacting side having the impacting corner of the n-th block (the side ⑥ - ① of the n-th block in Fig. 13) are given by the following equations.

(a) velocity vector generated by x-direction velocity

$$\left.\begin{aligned} v_x &= |\dot{x}_p| \, |\sin(\theta_{\ell n} + \theta_n)| \frac{B}{|B|} \; ; & (y_1^Q - y_6^Q \neq 0) \; , \\ v_x &= 0 \; ; & (y_1^Q - y_6^Q = 0) \; . \end{aligned}\right\} \tag{40}$$

(b) velocity vector generated by y-direction velocity

$$\left.\begin{aligned} v_y &= |\dot{y}_p| \, |\cos(\theta_{\ell n} + \theta_n)| \frac{b}{|b|} \; ; & (x_1^Q - x_6^Q \neq 0) \; , \\ v_y &= 0 \; ; & (x_1^Q - x_6^Q = 0) \; . \end{aligned}\right\} \tag{41}$$

where

$$\dot{x}_p = \dot{x}_{pn} - \dot{x}_{pi} \; ,$$

$$\dot{y}_p = \dot{y}_{pn} - \dot{y}_{pi} ,$$

$$B = x_6^Q - y_6^Q \frac{x_1^Q - x_6^Q}{y_1^Q - y_6^Q} ,$$

$$b = y_6^Q - x_6^Q \frac{y_1^Q - y_6^Q}{x_1^Q - x_6^Q} .$$

The relative velocity in the direction perpendicular to the impacting side having the corner of the n-th block thus becomes the following.

$$v = v_x + v_y . \tag{42}$$

(3) Impact force of the n-th block

The impact force directed inward to the block is taken as positive. Impact force F_n^R of the n-th block is as follows.

$$F_n^R = F_n^S + F_n^D , \tag{43}$$

where

$$F_n^S = K_n^R \delta_{n1} ,$$

$$F_n^D = C_n^R v .$$

The judgment of block impact is carried out as in previous section 3.5, but due to the viscoelastic model employed, it is necessary to consider also the following conditions.

$$\left.\begin{aligned} F_{n1}^R &\geqq 0 ; \quad \text{(impact case)} , \\ F_{n1}^R &= 0 ; \quad \text{(no-impact case)} . \end{aligned}\right\} \tag{44}$$

(4) Perpendicular force and parallel force to the impacting surface of the i-th block

As in Fig. 11 the force applied to the i-th block by the impact is divided into two components i.e., the force F_{i10}^R in the direction perpendicular to the impacting surface and the force F_{i10}^T in the direction along the impacting surface, which are given by the equations below respectively.

$$\left.\begin{aligned} F^R_{i10} &= F^R_{n1} \cos \theta_{io} , \\ F^T_{i10} &= F^R_{n1} \sin \theta_{io} . \end{aligned}\right\} \tag{45}$$

where

$$\begin{aligned} \theta_{io} &= \theta_{n1} - \theta_{i1} , \\ \theta_{i1} &= \theta_{\ell i} + \theta_i , \\ \theta_{n1} &= \theta_{\ell n} + \theta_n . \end{aligned}$$

(5) Parallel force to the impacting surface and friction force

The friction force F^F_{i10} of the impacting surface of the i-th block is

$$F^F_{i10} = \mu F^R_{i10} . \tag{46}$$

where μ is the coefficient of static friction. The force F^{TD}_{i10}, parallel to the impacting surface, which exceeds the friction force F^F_{i10}, does not become larger than this friction force due to the slip. The following conditions are, thus satisfied.

$$\left.\begin{aligned} F^{TD}_{i10} &= F^F_{i10} \ ; \quad (|F^T_{i10}| \geqq F^F_{i10}) , \\ F^{TD}_{i10} &= F^T_{i10} \ ; \quad (|F^T_{i10}| < F^F_{i10}) . \end{aligned}\right\} \tag{47}$$

The impact force of the n-th block, F^{RD}_{ni}, is modified as in the following,

$$F^{RD}_{ni} = F^R_{i10} \cos \theta_{io} + F^{TD}_{i10} \sin \theta_{io} . \tag{48}$$

(6) x- and y-direction force components and their associated moments due to modified impact force

(a) Impact force component in x- and y-direction for the n-th block

i) x-component force

$$\left.\begin{array}{ll} R^{RX}_{ni} = F^{RD}_{ni} \left|\sin(\theta_{\ell n} + \theta_{n})\right| \frac{B}{|B|} \; ; & (y^{Q}_{1} - y^{Q}_{6} \neq 0) \; , \\ F^{RX}_{ni} = 0 \; ; & (y^{Q}_{1} - y^{Q}_{6} = 0) \; . \end{array}\right\} \tag{49}$$

ii) y-component force

$$\left.\begin{array}{ll} F^{RY}_{ni} = F^{RD}_{ni} \left|\cos(\theta_{\ell n} + \theta_{n})\right| \frac{b}{|b|} \; ; & (x^{Q}_{1} - x^{Q}_{6} \neq 0) \; , \\ F^{RY}_{ni} = 0 \; ; & (x^{Q}_{1} - x^{Q}_{6} = 0) \; . \end{array}\right\} \tag{50}$$

(b) Moment around the n-th block center of gravity for the n-th block

$$M^{R}_{ni} = - x^{Q}_{npn} \, F^{RY}_{ni} + y^{Q}_{npn} \, F^{RX}_{ni} \; . \tag{51}$$

(c) x- and y-direction force component due to the modified impact force F^{RD}_{ni} for the i-th block

i) x-component force

$$\left.\begin{array}{ll} F^{RX}_{i10} = F^{RD}_{ni} \left|\sin(\theta_{io} + \theta_{i1})\right| \frac{B}{|B|} \; ; & (y^{Q}_{3} - y^{Q}_{4} \neq 0) \; , \\ F^{RX}_{i10} = 0 \; ; & (y^{Q}_{3} - y^{Q}_{4} = 0) \; . \end{array}\right\} \tag{52}$$

ii) y-component force

$$\left.\begin{array}{ll} F^{RY}_{i10} = F^{RD}_{ni} \left|\cos(\theta_{io} + \theta_{i1})\right| \frac{b}{|b|} \; ; & (x^{Q}_{3} - x^{Q}_{4} \neq 0) \; , \\ F^{RY}_{i10} = 0 \; ; & (x^{Q}_{3} - x^{Q}_{4} = 0) \; . \end{array}\right\} \tag{53}$$

(d) Moment due to the modified impact force for the i-th block

$$M^{R}_{i10} = - x^{Q}_{ipi} \, F^{RY}_{i10} + y^{Q}_{ipi} \, F^{RX}_{i10} \; . \tag{54}$$

3.7 Restoring forces of fuel block

Restoring forces of the n-th fuel block are given by

$$\left.\begin{aligned} F_n^{CX} &= K_n^{CX}\, x_n^Q + C_n^{CX}\, \dot{x}_n \,, \\ F_n^{CY} &= K_n^{CY}\, y_n^Q + C_n^{CY}\, \dot{y}_n \,. \end{aligned}\right\} \tag{55}$$

3.8 Restraint forces of side reflector block and their associated moment

Restraint forces of the side reflector block are written as

$$\left.\begin{aligned} F_n^{GX} &= K_n^{GX}\, x_n^Q + C_n^{GX}\, \dot{x}_n \,, \\ F_n^{GY} &= K_n^{GY}\, y_n^Q + C_n^{GY}\, \dot{y}_n \,. \end{aligned}\right\} \tag{56}$$

Moment M_n acting the n-th side reflector block caused by restraint forces is written as follows,

$$M_n^G = F_n^{GX}\,(y_{ng1}^Q + y_{ng2}^Q) - F_n^{GY}\,(x_{ng1}^Q + x_{ng2}^Q) \,. \tag{57}$$

where, x_{ng1}^Q, x_{ng2}^Q, y_{ng1}^Q and y_{ng2}^Q are shown in Fig. 14.

3.9 Key reaction force between side reflector block

The formulation of the reaction force due to shearing force in the key installed between two adjacent blocks is as follows. To simplify, the friction force between the key and the keyway is ignored. Setting the origin of the coordinate system of the n-th block after displacement of the block to the center of gravity, the coordinates of the key corner are as follows (see Fig. 15).

$$\left.\begin{aligned} x^Q_{n1n} &= x^L_{n1n} + x^S_{n1n} - x_n , \\ y^Q_{n1n} &= y^L_{n1n} + y^S_{n1n} - y_n , \\ x^Q_{n2n} &= x^L_{n2n} + x^S_{n2n} - x_n , \\ y^Q_{n2n} &= y^L_{n2n} + y^S_{n2n} - y_n . \end{aligned}\right\} \tag{58}$$

(1) Coordinates of key after its displacement

Setting the origin of the coordinate system of the n-th block after its displacement as the center of gravity of the keyway are as follows.

i) For the n-th block,

$$\left.\begin{aligned} x^Q_{knn} &= x^L_{knn} + x^S_{knn} - x_n , \\ y^Q_{knn} &= y^L_{knn} + y^S_{knn} - y_n . \end{aligned}\right\} \tag{59}$$

ii) For the i-th block,

$$\left.\begin{aligned} x^Q_{kin} &= x^L_{kii} + x^S_{kii} - x_n + (x_{oi} - x_{on}) , \\ y^Q_{kin} &= y^L_{kii} + y^S_{kii} - y_n + (y_{oi} - y_{on}) . \end{aligned}\right\} \tag{60}$$

(2) Inclination angles of a side having the key

The inclination angles of the side having the key are as follows.

(a) For the n-th block,

$$\left.\begin{aligned} \theta_{pn} &= \tan^{-1}\frac{y^Q_{n1n} - y^Q_{n2n}}{x^Q_{n1n} - x^Q_{n2n}} \; ; \quad (x^Q_{n1n} - x^Q_{n2n} \neq 0) , \\ \theta_{pn} &= \frac{\pi}{2}\,\frac{y^Q_{n1n} - y^Q_{n2n}}{|y^Q_{n1n} - y^Q_{n2n}|} \; ; \quad (x^Q_{n1n} - x^Q_{n2n} = 0) . \end{aligned}\right\} \tag{61}$$

(b) For the i-th block,

$$\left.\begin{aligned}\theta_{pi} &= \tan^{-1}\frac{y^Q_{i1n} - y^Q_{i2n}}{x^Q_{i1n} - x^Q_{i2n}} \;; \quad (x^Q_{i1n} - x^Q_{i2n} \neq 0)\,, \\ \theta_{pi} &= \frac{\pi}{2}\,\frac{y^Q_{i1n} - y^Q_{i2n}}{|y^Q_{i1n} - y^Q_{i2n}|} \;; \quad (x^Q_{i1n} - x^Q_{i2n} = 0)\,.\end{aligned}\right\} \tag{62}$$

(3) x- and y-components of gap, δ_{gx} and δ_{gy}

$$\left.\begin{aligned}\delta_{gx} &= \frac{\delta_g}{|\cos\theta_{pi}|}\,, \\ \delta_{gy} &= \frac{\delta_g}{|\sin\theta_{pi}|}\,.\end{aligned}\right\} \tag{63}$$

where δ_g is gap between the key and the keyway.

(4) x- and y-components of spring constant K^{KX}_n and K^{KY}_n

$$\left.\begin{aligned}K^{KX}_n &= |\,K^K_n \cos\theta_{pn}\,|\,, \\ K^{KY}_n &= |\,K^K_n \sin\theta_{pn}\,|\,.\end{aligned}\right\} \tag{64}$$

where K^K_n is spring constant of the key.

(5) x- and y-components of damping coefficient C^{KX}_n and C^{KY}_n

$$\left.\begin{aligned}C^{KX}_n &= |\,C^K_n \cos\theta_{pn}\,|\,, \\ C^{KY}_n &= |\,C^K_n \sin\theta_{pn}\,|\,.\end{aligned}\right\} \tag{65}$$

where C^K_n is damping coefficient of the key.

(6) x- and y-components of key reaction force F^{KX}_n and F^{KY}_n

(a) If $|x^Q_{knn} - x^Q_{kin}| \geq \delta_{gx}$,

$$F^{KX}_n = \left\{(x^Q_{knn} - x^Q_{kin}) - \frac{x^Q_{knn} - x^Q_{kin}}{|x^Q_{knn} - x^Q_{kin}|}\delta_{gx}\right\} K^{KX}_n + (v_{knx} - v_{kix})\,C^{KX}_n \;, \tag{66}$$

(b) If $|y_{knn}^Q - y_{kin}^Q| \geqq \delta_{gy}$,

$$F_n^{KY} = \left\{ (y_{knn}^Q - y_{kin}^Q) - \frac{y_{knn}^Q - y_{kin}^Q}{|y_{knn}^Q - y_{kin}^Q|} \delta_{gy} \right\} K_n^{KY} + (v_{kny} - v_{kiy}) C_n^{KY} , \tag{67}$$

(c) If $|x_{knn}^Q - x_{kin}^Q| < \delta_{gx}$,

$$F_n^{KX} = 0 . \tag{68}$$

(d) If $|y_{knn}^Q - y_{kin}^Q| < \delta_{gy}$,

$$F_n^{KY} = 0 . \tag{69}$$

(7) Key reaction forces

The shearing force in the key reaction is divided into two. One component is parallel to the side having the key, F_n^{KT}, and the other component is in the direction perpendicular to it, F_n^{KR}. These are given as follows.

$$\left.\begin{aligned} F_n^{KT} &= F_n^{KX} \cos \theta_{pn} + F_n^{KY} \sin \theta_{pn} , \\ F_n^{KR} &= -F_n^{KX} \sin \theta_{pn} + F_n^{KY} \cos \theta_{pn} . \end{aligned}\right\} \tag{70}$$

(8) Moment due to key reaction force

The moment around the center of gravity of the n-th side reflector block, due to the key reaction force, M_n^K is written as

$$M_n^K = F_n^{KX} y_{knn}^Q - F_n^{KY} x_{knn}^Q . \tag{71}$$

3.10 Equations of motion for side reflector block

The equations of motion for the n-th side reflector block may be written as

$$\left.\begin{aligned}
&m_n \ddot{x}_n + \sum_{i=1}^{NCR} \sum_{j=1}^{2} F_{nij}^{RX} + \sum_{i=1}^{NCR} F_{ni}^{SX} + F_n^{CX} + \sum_{i=1}^{2} F_{ni}^{GX} + \sum_{i=1}^{2} F_{ni}^{KX} \\
&\qquad = -m_n \ddot{x}_o \ , \\
&m_n \ddot{y}_n + \sum_{i=1}^{NCR} \sum_{j=1}^{2} F_{nij}^{RY} + \sum_{i=1}^{NCR} F_{ni}^{SY} + F_n^{CY} + \sum_{i=1}^{2} F_{ni}^{GY} + \sum_{i=1}^{2} F_{ni}^{KY} \\
&\qquad = -m_n \ddot{y}_o \ , \\
&I_n \ddot{\theta}_n + \sum_{i=1}^{NCR} \sum_{j=1}^{2} M_{nij}^{R} + \sum_{i=1}^{NCR} M_{ni}^{S} + M_n^{C} + \sum_{i=1}^{2} M_{ni}^{G} + \sum_{i=1}^{2} M_{ni}^{K} = 0 \ .
\end{aligned}\right\} \qquad (72)$$

3.11 Equations of motion for core support block

The equations of motion of the core support block may be written as

$$\left.\begin{aligned}
&m_b \ddot{x}_b - \sum_{i=1}^{NH} F_i^{CX} - \sum_{i=1}^{NR} F_i^{CX} + F_b^{GX} = -m_b \ddot{x}_o \ , \\
&m_b \ddot{y}_b - \sum_{i=1}^{NH} F_i^{CY} - \sum_{i=1}^{NR} F_i^{CY} + F_b^{GY} = -m_b \ddot{y}_o \ .
\end{aligned}\right\} \qquad (73)$$

3.12 Numerical integration method

A number of direct numerical integration methods have been considered for the calculation. Both implicit and explicit time integration methods and convergent characteristics as a function of integration time step size and numerical stability have been investigated. The fouth-order Runge-Kutta-Gills method was then selected for our calculation.

The integration time step used in the calculation should be large enough to reduce excessive computer run time but small enough to obtain an accurate convergent solution. In general, the recommended integration time step is based on the smaller value of 1/10 of the interblock contact time or 1/10 of the natural period of the highest natural frequency of the model.

The numerical integration time step is automatically adjusted in the calculation.

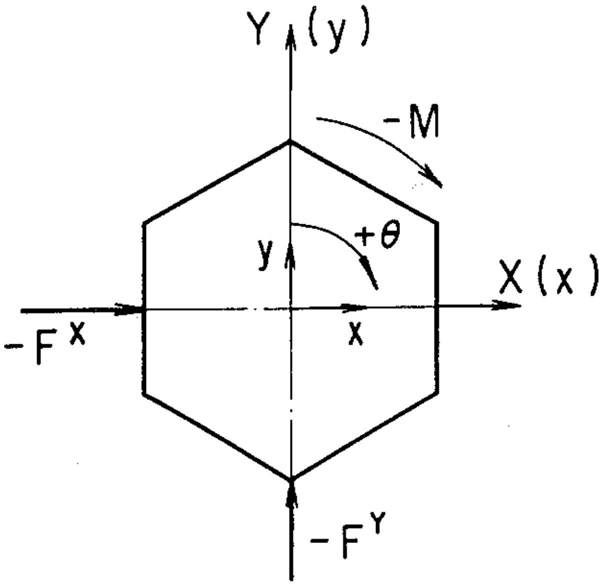


Fig. 8 Sign of displacement, force and moment

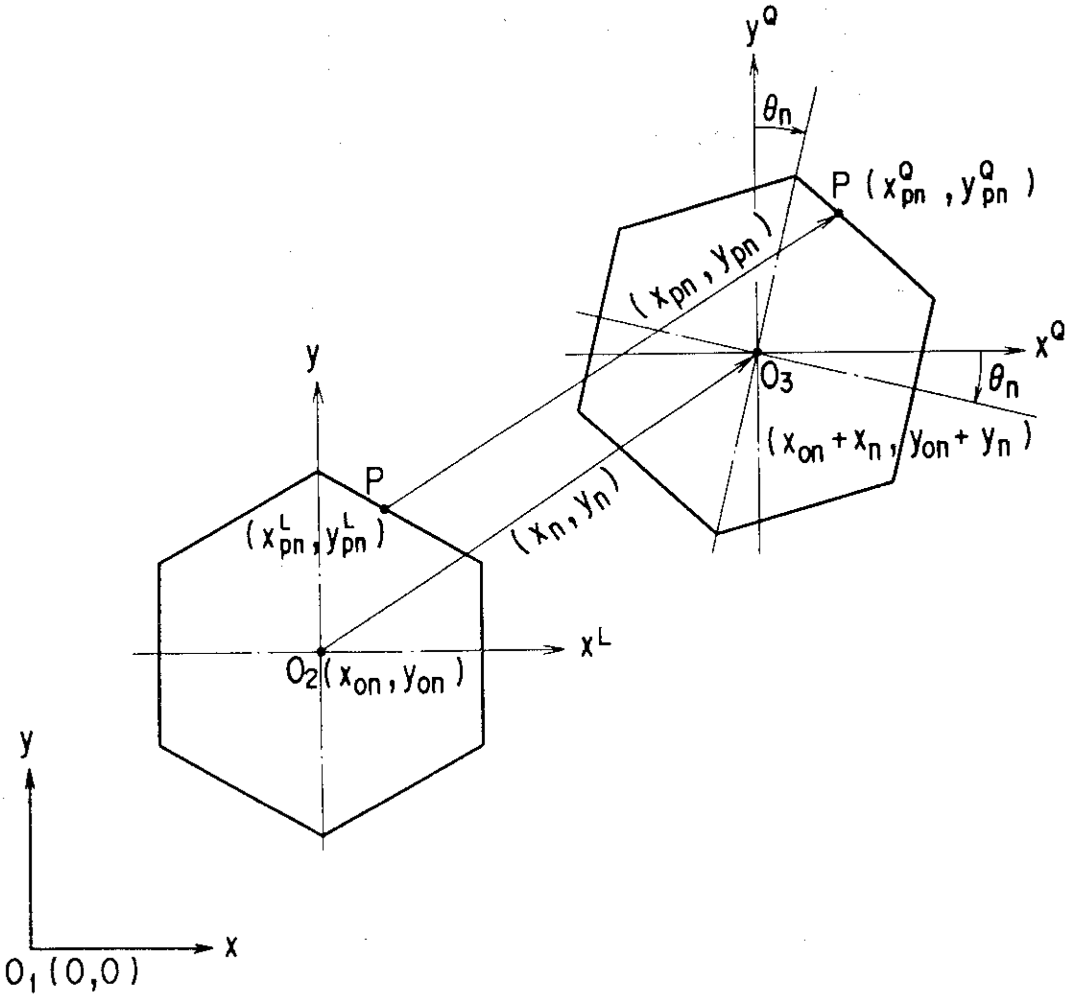


Fig. 9 Block displacement

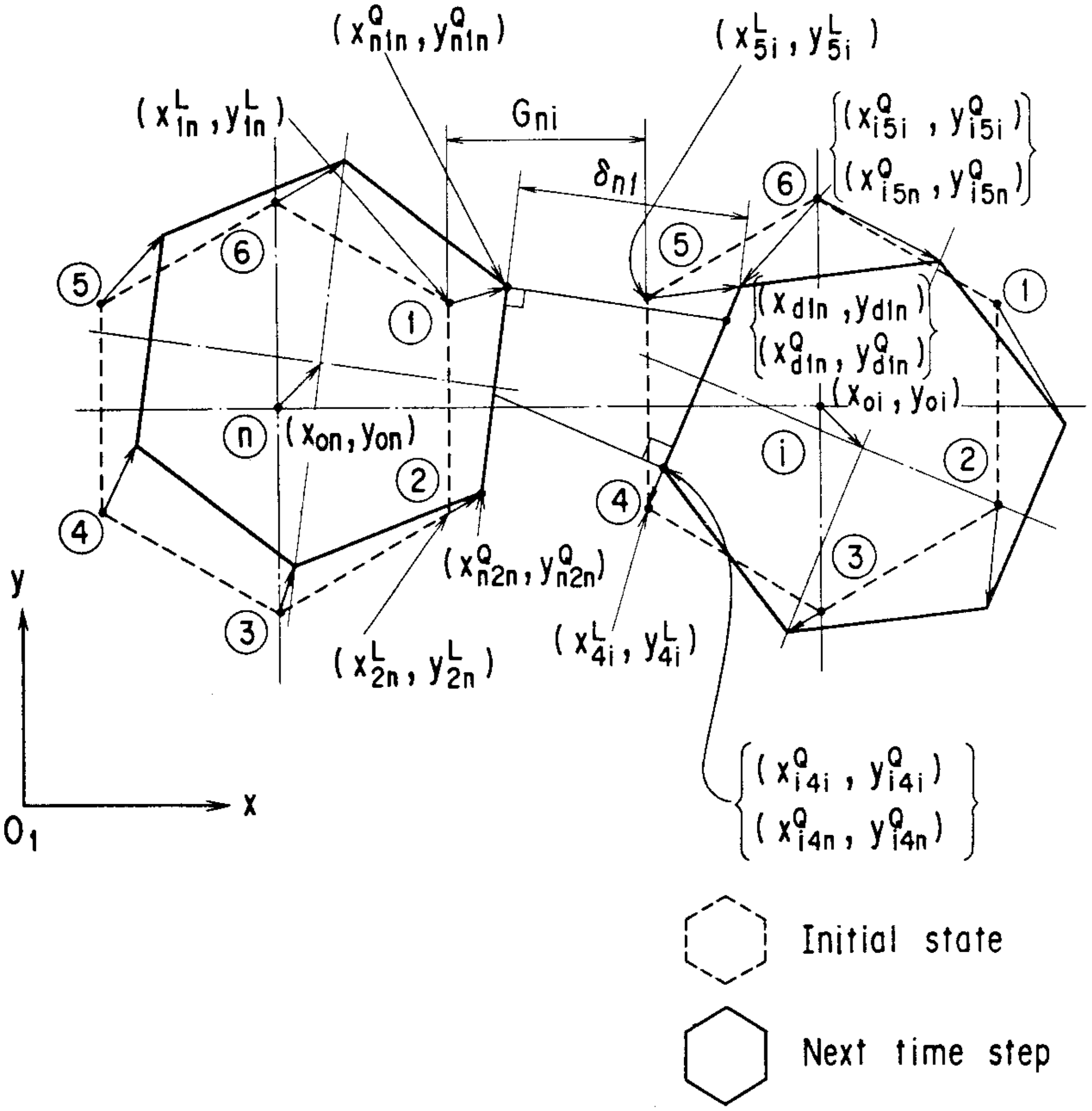


Fig. 10 Gap between blocks

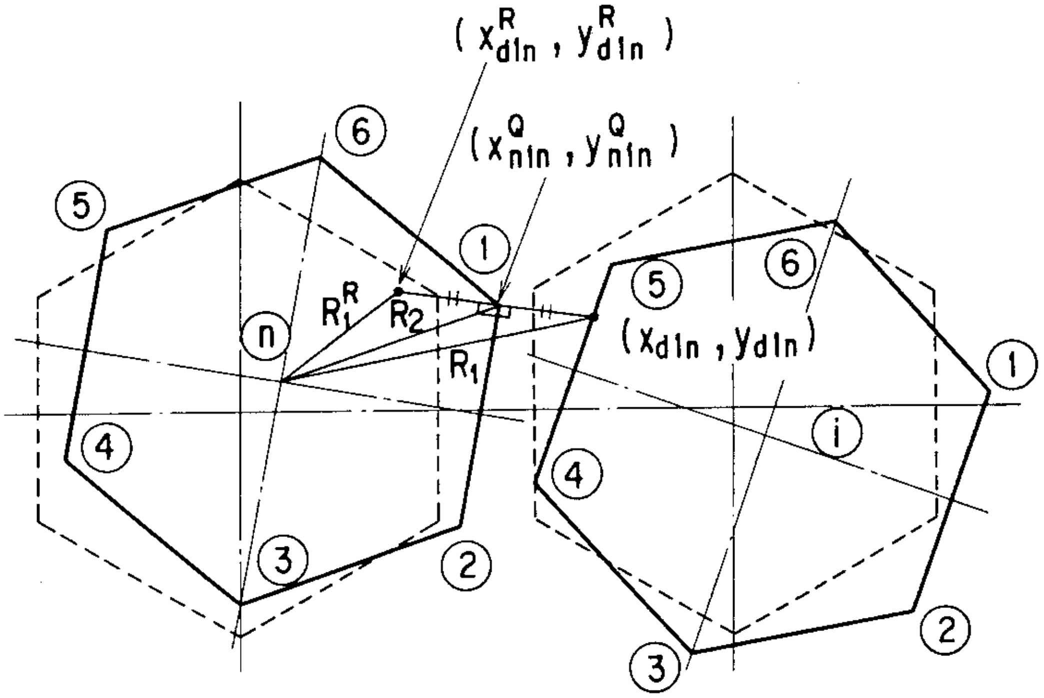


Fig. 11 Judgment of block impact

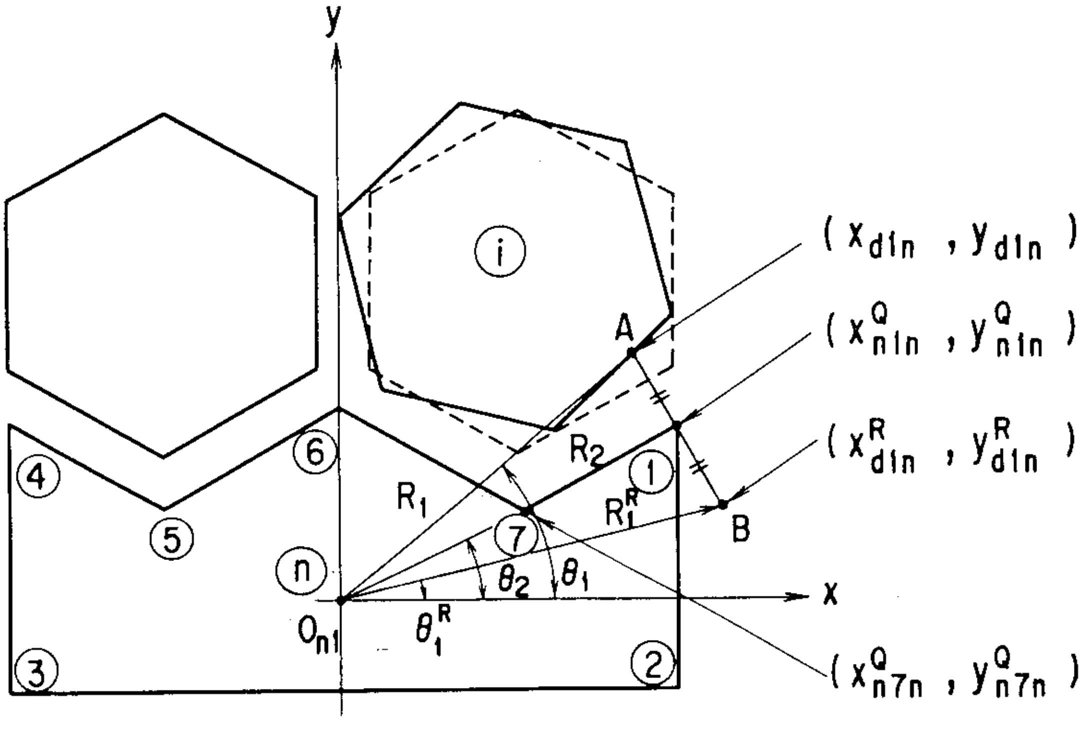


Fig. 12 Undefined case of block impact

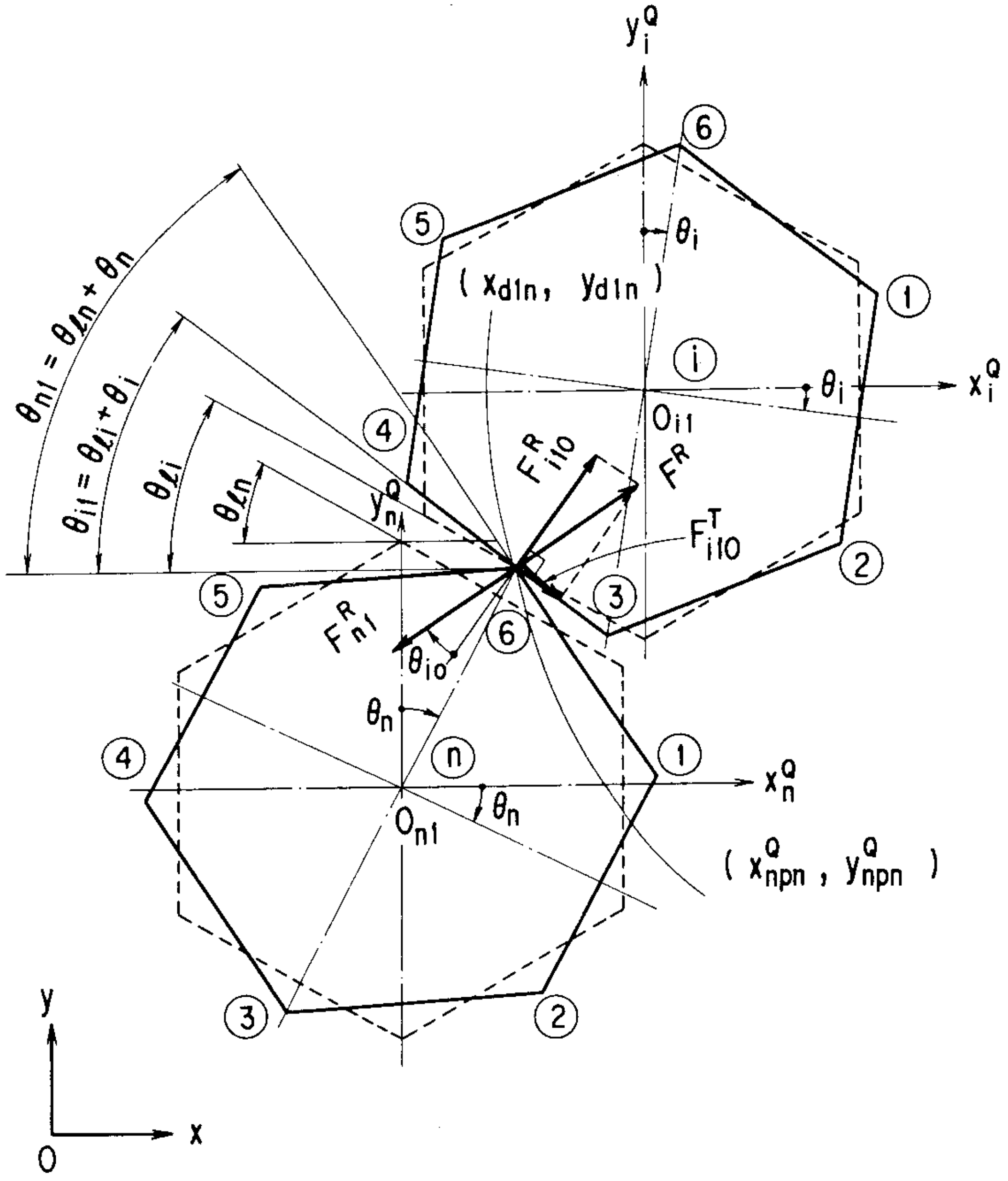


Fig. 13 Impact force components

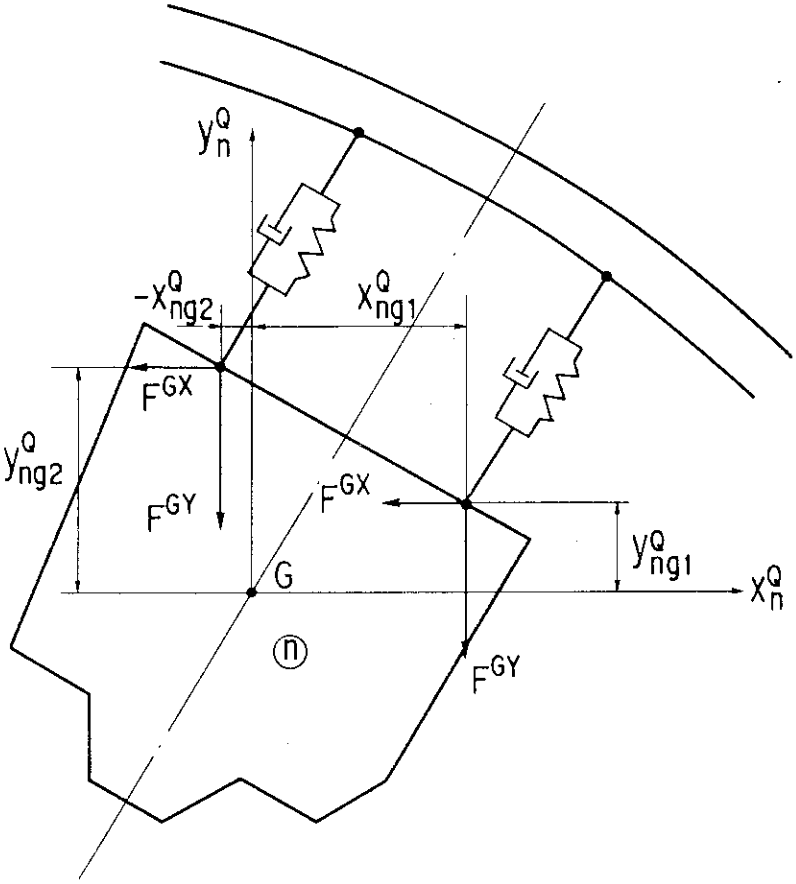


Fig. 14 Restraint forces of side reflector block

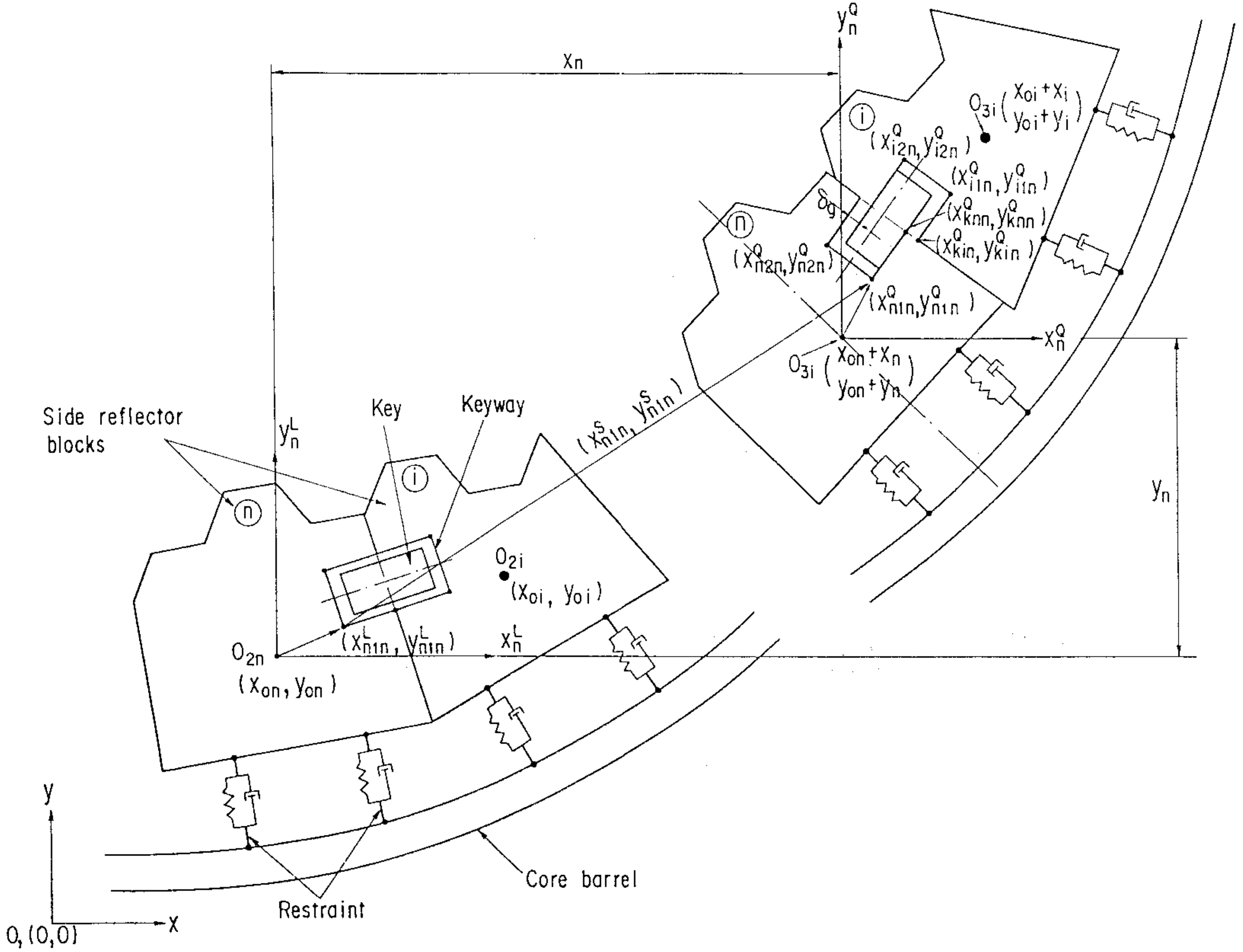


Fig. 15 Key and keyway displacement

4. Computer program

The computer program SONATINA-2H performs the dynamic analysis for a two-dimensional horizontal slice HTGR core subjected to seismic excitation. The program is capable of solving nonlinear impact problems.

4.1 Program description

The computer program SONATIONA-2H consists of 28 subroutines that are MAIN, INP, ZAHYOU, MAIN1, MAIN2, FINDM, FCT, ICOUT, OUTDVA, RKGST, FUN, BPLATE, PICT, ZAFIX, SEIWAV, FOUT, FUEL, XYCOL, FCOL, BFACE, XYBINF, XYBINP, FIXED1, FIXED2, FRSCOL, FKEY, VELDIS, DELTA and DELTA2. Overall structure of SONATINA-2H is shown in Fig. 16. In the figure, the line from one subroutine to another indicates that the right subroutine is called by the left one. Functions of subroutines are as follows:

MAIN : initializes the start run and sets memory core size,
INP : reads input data,
ZAHYOU : initializes the coordinates of blocks,
MAIN1 : controls the processing of program,
MAIN2 : controls the processing of program,
FINDM : searchs maximum displacement, velocity, acceleration and force and its times,
FCT : sets up equations for given time,
ICOUT : prints out input data,
OUTDVA : prints out displacement, velocity, acceleration and force at each print step,
RKGST : integrates system of differential equations using the Runge-Kutta-Gills method,
FUN : sums up all forces acting on the block and calculates acceleration,

BPLATE : determines force acting on the base plate,

PICT : stores the output data for plotting of block displacement and impact force,

ZAFIX : calculates the coordinates of block edge points,

SEIWAV : determines base horizontal displacement and velocity as simulating seismic excitation at given time step,

FOUT : stores the output data for plotting of time histories of displacement, velocity, acceleration and force,

FUEL : determines fuel block impact force,

XYCOL : determines coordinates of impact point,

FCOL : determines fuel block impact force and its asociated moment,

BFACE : searchs impact surfaces,

XYBINF : determines impact point coordinates,

XYBINP : determines impact point coordinates of block surface,

FIXED1 : determines impact force of reflector block due to impact between fuel blocks and reflector block,

FIXED2 : determines impact force of the reflector block due to impact between reflector blocks,

FRSCOL : determines reflector block impact force and its associated moment,

FKEY : determines reflector key force,

VELDIS : computes velocity and displacement of blocks,

DELTA : searchs impact point of the reflector blocks,

DELTA2 : searchs impact point of the reflector blocks,

A macroscopic flow chart of SONATINA-2H is shown in Fig. 17.

4.2 Description of input data

This section describes the input data required by SONATINA-2H. The input data consists of the job description, number of blocks, block weight and geometry, gaps between blocks, spring constant, damping coefficient, integral time step and options for printting and plotting. The input istructions are simple and easy to follow. The computer progran SONATINA-2H contains a number of options which are available to the user.

For the restart options, the user is required to assign a catalogue File No. 17. File No. 17 will save all required data prior to the termination of Run No. 1 as File No. 16 and will use these stored data for the restart of Run No. 2.

The input data forms are presented in Table 1;

Data set No. 1

Problem title.

Data set No. 2

Problem size parameters and control options.

Data set No. 3

Input data options for coordinates and geometry data for fixed reflector blocks.

Data set No. 4

Calculation control data (I).

Data set No. 5

Calculation control data (II).

Data set No. 6

Block diameter and gap between block data.

Data set No. 7

Option data for irregular blocks.

Data set No. 8

Fuel block properties.

Data set No. 9

Fixed reflector block properties.

Data set No. 10

Edge number data of impact triangle for decision of fixed reflector block impact.

Data set No. 11

Apex number of fixed reflector block, probable to impact between fuel block and fixed reflector block.

Data set No. 12

Core support block properties.

Data set No. 13

Fuel block number and adjacent fuel block numbers.

Data set No. 14

Fixed reflector block number and adjacent fuel block numbers.

Data set No. 15

Initial condition data.

Data set No. 16

Seismic data.

Data set No. 17

Block number for plotting.

Data set No. 18

Corner coordinates of fixed reflector block

Data set No. 19

Coordinates of fixed reflector block key

Data set No. 20

Coordinate of fixed reflector block restraint structure

A sample input is presented in the Appendix A.

4.3 Description of output data

This section describes the output data from SONATINA-2H. SONATINA-2H prints out all of the input data as well as various time history response values. To minimize the amount of output produced by the program, the user choose options to select the output data. The contents of these various output quantities are described in the followings.

(1) Input data

Input data are printed in two formats. The first print format is exactly the same as they read. Second, the program lists the data as interpreted by the code.

(2) Time history response value

Time history response values are printed at every print interval steps, which describe the response history as a function of time. The title of the analysis is printed at the top of the various output quantities for an easy identification to the problem.

A sample output is presented in the Appendix B. The block direction and notation on computer output is shown in Fig. 22.

4.4 Post-processor

The computer program has a post-processor that are SONATINA2H-PLOT as shown in Fig. 23. SONATINA2H-PLOT is to provide the users with graphical display output of the time history response curves, vibration modes and maps of maximum response values and its time of the fuel blocks and fixed reflector blocks. Maps of maximum response values are presented for each block together with their times. The illustration of this graphical display output is presented in a sample problem in the Appendix C.

The input data for SONATINA2H-PLOT is summarized in Table 2.

Table 1 Input data for SONATINA-2H

Column	Format	Variable	Description
Data set No. 1; Problem title.			
1-80	20A4	NAME	Title or job description.
Data set No. 2; Problem size parameters and control options.			
1- 5	I5	NFB	Number of fuel blocks.
6-10	I5	NFB1	Number of fuel block types.
11-15	I5	NFRB	Number of fixed reflector blocks.
16-20	I5	NFRB1	Number of fixed reflector block types.
21-25	I5	NR	Maximum number of fixed reflector block faces to contact with fuel blocks.
26-30	I5	NIBMAX	Number of reflector block types.
31-35	I5	ICLCKW	Numbering direction of blocks. = -1; Clockwize. = 1; Counter clockwise.
36-40	I5	INITCO	Option for restart. = 0; Initial run. = 1; restart run.
41-45	I5	IKEYFR	Option for calculation of key force. = 0; No calculation. = 1; Calculation.
46-50	I5	IGM	Not use.
51-55	I5	NPBMAX	Maximum block numbers for response values plotting. If NPBMAX is less than zero, NPBMAX is total number of blocks.
56-60	I5	NPMI	Print option. = 0; Input data are printed out. = 1; Not print out.
61-65	I5	ISOLV	Not use.
66-70	I5	NPMA	Option for maximum value printing.
71-75	I5	ICBT	Option for presence of fixed reflector blocks. = 0; No reflector blocks exist. = 1; Reflector blocks exist.

Table 1 (Continued)

Column	Format	Variable	Description
76-80	I5	NPIT	Option for output data printing. = 0; All data are printed out. ≠ 0; Selected data are printed out.
Data set No. 3; Input data options for coordinates and geometry data for fixed reflector blocks.			
1- 5	I5	NFRBCG	Input data option for reflector block coordinates.
6-10	I5	NFRBCP	Input data option for reflector block corner coordinates (If NFRBCP is not zero).
11-15	I5	NFRBKO	Input data option for reflector block key position (If NFRBKC is not zero).
16-20	I5	NFRBSO	Input data option for fixed reflector restraint position (If NFRBSO is not zero).
21-30	F10.0	THETAO	Location angle of fixed reflector block type No. 1 (NFRB1=1).
31-40	F10.0	RMAX	Outside radius of fixed reflector blocks.
Data set No. 4; Calculation control data (I).			
1-10	F10.0	TSTART	Starting time.
11-20	F10.0	TEND	Ending time.
21-30	F10.0	DT	Initial integration time step.
31-40	F10.0	DTPRNT	Print internal time.
41-50	F10.0	DTWAVE	Time interval for time history plotting data.
51-60	F10.0	DTMODE	Time interval for vibration mode plotting data.
61-70	F10.0	DTDUMP	Time inteval for restart dumps.
71-80	F10.0	CPSTOP	Maximum computer time (CPU seconds).

Table 1 (Continued)

Column	Format	Variable	Description
Data set No. 5; Calculation control data (II).			
1-10	F10.0	ULE	Upper value of truncation error.
11-20	F10.0	EPS	Truncation value of zero judgement of block gaps.
21-30	F10.0	DELLIM	Upper limitation value of overlap vector for impact between blocks.
Data set No. 6; Block diameter and gap between block data.			
1-10	F10.0	GAP	Gap width between block.
11-20	F10.0	DG	Gap width between fixed reflector block and fixed reflector key.
21-30	F10.0	WG	Distance of across to flat of fuel block.
31-40	F10.0	BLKF	Friction factor between blocks.
41-75	—	—	Blank
76-80	I5	IROTAT	Flag for degree-of-freedom. =0: Two degrees-of-freedom (x,y). =1: Three degrees-of-freedom (x,y,θ).
Data set No. 7; Option data for irregular blocks.			
1- 5	I5	NBT(I)	Number of irregular block.
6-10	I5	IIBT(I)	Number of block type.
11-15	I5	NBT(I)	} Same as above data.
16-20	I5	IIBT(I) (I=1,NIBMAX)	If ICBT is zero, these data set are omitted.
Data set No. 8A; Fuel block properties (1).			
1- 5	I5	N	Number of fuel block.
6-15	F10.0	MASS(N)	Mass of fuel block.
16-25	F10.0	KR(N,1)	Column restoring stiffness for X-direction.
26-35	F10.0	KR(N,2)	Column restoring stiffness for Y-direction.
36-45	F10.0	CR(N,1)	Column restoring damping coefficient for X-direction.

Table 1 (Continued)

Column	Format	Variable	Description
46-55	F10.0	CR(N,2)	Column restoring damping coefficient for Y-direction.
56-65	F10.0	KB(N,1)	Gap interface spring stiffness for X-direction.
66-75	F10.0	KB(N,2)	Gap interface spring stiffness for Y-direction.
Data set No. 8B; Fuel block properties (2).			
1- 5	5X		Blank.
6-15	F10.0	AI(N)	Mass moment of inertia of block.
16-25	F10.0	CB(N,2)	Gap interface damping coefficient for X-direction.
26-35	F10.0	CB(N,2)	Gap interface damping coefficient for Y-direction.
36-45	F10.0	CC(N,1)	Damping coefficient of detector for X-direction.
46-55	F10.0	CC(N,2)	Damping coefficient of detector for Y-direction.
56-65	F10.0	FFIN(N,1)	Friction between fuel block and core base plate for X-direction.
66-75	F10.0	FFIN(N,2)	Friction between fuel block and core base plate for Y-direction.
Data set No. 8C; Fuel block properties (3).			
1- 5	5X		Blank.
6-15	F10.0	AKTHT(N)	Artificial spring stiffness for rotation angle.
16-25	F10.0	ACTHT(N)	Artificial damping coefficient for angular velocity.
Data set No. 9A; Fixed reflector block properties (1) (see Fig.18).			
1- 5	I5	I	Number of fixed reflector type.
6-15	F10.0	MASS(I)	Mass of fixed reflector block.

Table 1 (Continued)

Column	Format	Variable	Description
16-25	F10.0	AI(I)	Mass moment of inertia of fixed reflector block.
26-30	I5	NJIR(I)	Number of fixed reflector block face to contact with fuel blocks.
31-35	I5	JIR1(I,1)	Face number 1 of fixed reflector block (counter clockwise).
36-40	I5	JIR1(I,2)	Face number 2 of fixed reflector block.
41-45	I5	JIR1(I,3)	Face number 3 of fixed reflector block.
46-50	I5	JIR1(I,4)	Face number 4 of fixed reflector block.
51-55	I5	JIR1(I,5)	Face number 5 of fixed reflector block.
56-60	I5	JIR1(I,6)	Face number 6 of fixed reflector block.
61-65	I5	JIR1(I,7)	Face number 7 of fixed reflector block.
66-70	I5	JIR1(I,8)	Face number 8 of fixed reflector block.
71-75	I5	JIR1(I,9)	Face number 9 of fixed reflector block.
76-80	I5	JIR1(I,10)	Face number 10 of fixed reflector block.
Data set No. 9B; Fixed reflector block properties (2).			
1-10	F10.0	KR(I,1)	Column restoring stiffness for X-direction.
11-20	F10.0	KR(I,2)	Column restoring stiffness for Y-direction.
21-30	F10.0	CR(I,1)	Column restoring damping coefficient for X-direction.
31-40	F10.0	CR(I,2)	Column restoring damping coefficient for Y-direction.
41-50	F10.0	KB(I,1)	Gap interface spring stiffness for X-direction.
51-60	F10.0	KB(I,2)	Gap interface spring stiffness for Y-direction.
61-70	F10.0	CB(I,1)	Gap interface damping coefficient for X-direction.

Table 1 (Continued)

Column	Format	Variable	Description
71-80	F10.0	CB(I,2)	Gap interface damping coefficient for Y-direction.
Data set No. 9C; Fixed reflector block properties (3).			
1-10	F10.0	CC(I,1)	Damping coefficient of detector for X-direction.
11-20	F10.0	CC(I,2)	Damping coefficient of detector for Y-direction.
21-30	F10.0	FFIN(I,1)	Friction factor for X-direction.
31-40	F10.0	FFIN(I,2)	Friction factor for Y-direction.
41-50	F10.0	KRR(I,1)	Support sfiffness of core barrel for radial direction.
51-60	F10.0	CRR(I,2)	Support damping coefficient of core barrel for radial direction.
61-70	F10.0	KKEY	Stiffness of key between fixed reflector blocks.
71-80	F10.0	CKEY	Damping coefficient of key between fixed reflector blocks.
Data set No. 9D; Fixed reflector block properties (4).			
1-10	F10.0	AKTHT(I)	Artificial spring stiffness for rotation angle.
11-20	F10.0	ACTHT(I)	Artificial damping coefficient for angular velocity.
Data set No. 9E; Fixed reflector block properties (5) (see Fig. 19).			
1- 5	I5	NAP(I)	Total number of corner points of fixed reflector block.
6-10	I5	NPP(I)	Number of corner points of fixed reflector block.
11-15	I5	NFP(I)	Number of corner points of fixed reflector block for impact between fuel block and fixed reflector block.

Table 1 (Continued)

Column	Format	Variable	Description
Data set No. 10; Edge number data of impact triangle for decision of fixed reflector block impact (see Fig. 20).			
1- 5	I5	LAB(1,I)	Two-pairs of edge number data of impact triangle decision of fixed reflector block impact.
6-10	I5	LAB(2,I)	Same as above data.
11-15	I5	LAB(3,I)	....
16-20	I5	LAB(1,I+1)	....
21-25	I5	LAB(2,I+1)	....
26-30	I5	LAB(3,I+1) (I=1,NR6,2)	.... NR6 = NR * 2 * NFBR1
Data set No. 11; Apex number of fixed reflector block, probable to impact between fuel block and fixed reflector block (see Fig. 21).			
1- 5	I5	IP2(I,1)	Apex number of fixed reflector block, probable to impact between fuel block and fixed reflector block.
6-10	I5	IP2(I,2)	Same as above data.
11-15	I5	IP2(I,3)	....
16-20	I5	IP2(I,4)	....
21-25	I5	IP2(I,5)	....
26-30	I5	IP2(I,6) (I=1,NFRB1)	....
Data set No. 12; Core support block properties.			
1-10	F10.0	MASBP	Mass of core support block.
11-20	F10.0	KRBP(1)	X-direction restraint stiffness of core support block.
21-30	F10.0	KRBP(2)	Y-direction restraint stiffness of core support block.
31-40	F10.0	CRBP(1)	X-direction restraint damping coefficient of core support block.
41-50	F10.0	CRBP(2)	Y-direction restraint damping coefficient of core support block.

Table 1 (Continued)

Column	Format	Variable	Description
Data set No. 13; Fuel block number and adjacent fuel block numbers.			
1- 5	I5	N	Fuel block number.
6-10	I5	FBN(N,1)	Number of fuel block to right of fuel block N.
11-15	I5	FBN(N,2)	Number of fuel block to right of fuel block N.
16-20	I5	FBN(N,3)	Number of fuel block above and left of fuel block N.
21-25	I5	FBN(N,4)	Number of fuel block to left of fuel block N.
26-30	I5	FBN(N,5)	Number of fuel block and left of fuel block N.
31-35	I5	FBN(N,6)	Number of fuel block and right of fuel block N.
Data set No. 14; Fixed reflector block number and adjacent fuel block numbers.			
1- 5	5X		Blank.
6-10	I5	FBNR(N,1)	Number of adjacent fuel block No. 1.
11-15	I5	FBNR(N,2)	Number of adjacent fuel block No. 2.
16-20	I5	FBNR(N,3)	Number of adjacent fuel block No. 3.
21-25	I5	FBNR(N,4)	Number of adjacent fuel block No. 4.
26-30	I5	FBNR(N,5)	Number of adjacent fuel block No. 5.
31-35	I5	FBNR(N,6)	Number of adjacent fuel block No. 6.
36-40	I5	FBNR(N,7)	Number of adjacent fuel block No. 7.
41-45	I5	FBNR(N,8)	Number of adjacent fuel block No. 8.
46-50	I5	FBNR(N,9)	Number of adjacent fuel block No. 9.
51-55	I5	FBNR(N,10)	Number of adjacent fuel block No. 10.
56-60	I5	FBNR(N,11)	Number of adjacent fuel block No. 11.

Table 1 (Continued)

Column	Format	Variable	Description
61-65	I5	FBNR(N,12)	Number of adjacent fuel block No. 12.
66-70	I5	FBNR(N,13)	Number of adjacent fuel block No. 13.
71-75	I5	FBNR(N,14)	Number of adjacent fuel block No. 14.
76-80	I5	FBNR(N,15) (N=1,NFBR)	Number of adjacent fuel block No. 15.
Data set No. 15; Initial condition data.			
1- 5	I5	N	Number of block.
6-15	F10.0	U(I,1)	Initial displacement of X-direction.
16-25	F10.0	U(I,2)	Initial displacement of Y-direction.
26-35	F10.0	U(I,3)	Initial velocity of X-direction.
36-45	F10.0	U(I,4) (N=1,NFB)	Initial velocity of Y-direction.
If INITCO is zero or two, these data are omitted.			
Data set No. 16; Seismic data.			
Data set No. 16A; Sinusoidal excitation data.			
1-10	F10.0	COF1	Amplitude of X-direction input wave. KIK = 0; COF1 is displacement. KIK = 1; COF1 is acceleration. KIK = 2; COF1 is acceleration. KIK = 3; COF1 is displacement. KIK = 4; COF1 is dummy data.
11-20	F10.0	COF2	Angular velocity or frequency of X-direction input wave. KIK = 0; COF2 is angular velocity (Rad./s). KIK = 1; COF2 is circular frequency (Hertz). KIK = 2; COF2 is circular frequency (Hertz). KIK = 3; COF2 is circular frequency (Hertz). KIK = 4; COF2 is dummy data.
21-30	F10.0	COF3	Phase shift of X-direction input wave (radian).

Table 1 (Continued)

Column	Format	Variable	Description
31-40	F10.0	COF4	Amplitude of Y-direction input wave. COF4 is same as COF1.
41-50	F10.0	COF5	Angular velocity or frequency of Y-direction input wave. COF5 is same as COF2.
51-60	F10.0	COF6	Phase shift of Y-direction input wave (radian).

X-direction input displacement;

KIK = 0: (t=time)

$$U_0 = COF1 * \sin(COF2*t-COF3)$$

KIK = 1:

$$U_0 = \frac{COF1}{(2\pi COF)^2} * \sin(2\pi*COF*t-COF3)$$

$$COF = Z1 + Z2*t + Z3*t^2 + Z4*t^3 + Z5*t^4 + Z6*t^5$$

Frequency COF is sweeping up or down from Z1 to COF2.

KIK = 2:

$$U_0 = \frac{COF1}{(2\pi*COF)^2} * \sin(2\pi*COF2*t-COF3)$$

KIK = 3:

$$U_0 = COF1 * \sin(2\ *COF*t-COF3)$$

$$COF = Z1 + Z2*t + Z3*t^2 + Z4*t^3 + Z5*t^4 + Z6*t^5$$

Frequency COF is sweeping up or down from Z1 to COF2.

Y-direction input displacement;

KIK = 0: (t=time)

$$U_0 = COF4 * \sin(COF5*t-COF6)$$

Table 1 (Continued)

<table>
<tr><th>Column</th><th>Format</th><th>Variable</th><th>Description</th></tr>
<tr><td colspan="4">KIK = 1:
$$U_0 = \frac{COF4}{(2\pi*COF)^2} * \sin(2\pi*COF*t-COF6)$$
$COF = Z1 + Z2*t + Z3*t^2 + Z4*t^3 + Z5*t^4 + Z6*t^5$
Frequency COF is sweeping up or down from Z1 to COF5.
KIK = 2:
$$U_0 = \frac{COF4}{(2\pi*COF5)^2} * \sin(2\pi*COF5*t-COF6)$$
KIK = 3:
$U_0 = COF4 * \sin(2\pi*COF*t-COF6)$
$COF = Z1 + Z2*t + Z3*t^2 + Z4*t^3 + Z5*t^4 + Z6*t^5$
Frequency COF is sweeping up or down from Z1 to COF5.</td></tr>
<tr><td colspan="4">Data set No. 16B; Option for input wave data.</td></tr>
<tr><td>1- 5</td><td>I5</td><td>KIK</td><td>Option for input wave data (See data set No. 16A)</td></tr>
<tr><td>6-10</td><td>5X</td><td></td><td>Blank</td></tr>
<tr><td>11-20</td><td>F10.0</td><td>Z1</td><td>Coefficient of polynominal function (See data set No. 16A).</td></tr>
<tr><td>21-30</td><td>F10.0</td><td>Z2</td><td>Same as above data.</td></tr>
<tr><td>31-40</td><td>F10.0</td><td>Z3</td><td>....................</td></tr>
<tr><td>41-50</td><td>F10.0</td><td>Z4</td><td>....................</td></tr>
<tr><td>51-60</td><td>F10.0</td><td>Z5</td><td>....................</td></tr>
<tr><td>61-70</td><td>F10.0</td><td>Z6</td><td>....................</td></tr>
<tr><td colspan="4">Data set No. 16C; Seismic data (Random wave).</td></tr>
<tr><td>1- 5</td><td>I5</td><td>KXK(1)</td><td>Option for X-direction data input.
= 0; No data input.
= 1; Data input.</td></tr>
<tr><td>6-10</td><td>I5</td><td>KXK(2)</td><td>Option for Y-direction data input.
= 0; No data input.
= 1; Data input.</td></tr>
<tr><td>11-15</td><td>5X</td><td>——</td><td>Dummy</td></tr>
</table>

Table 1 (Continued)

Column	Fromat	Variable	Description
15-20	5X	—	Blank.
21-30	F10.0	ALP	Maltiplication factor for X-direction input data.
31-40	F10.0	BET	Multiplication factor for Y-direction input data.
Data set No. 16D; Number of displacement data and time step of data for X-direction.			
1- 4	I5	KXN11	Number of X-direction displacement data.
21-30	F10.0	DOT11	Time step.
Data set No. 16E; X-direction displacement data.			
21-60	5F10.0	VX(1,1,J) (J=1,KXK11)	X-direction displacement data.
Data set No. 16F; Number of velocity data and time step of data for X-direction.			
1- 4	I5	KXN12	Number of X-direction velocity data.
21-30	F10.0	DDT12	Time step.
Data set No. 16G; X-direction velocity data.			
21-60	5F10.0	VS(1,2,J) (J=1,KXK12)	X-direction velocity data.
Data set No. 16H; Number of displacement data and time step of data for Y-direction.			
1- 4	I5	KNX21	Number of Y-direction displacement data.
21-30	F10.0	DDT21	Time step.
Data set No. 16I; Y-direction displacement data.			
21-60	5F10.0	VX(2,1,J) (J=1,KXK21)	Y-direction displacement data.

Table 1 (Continued)

Column	Format	Variable	Description
Data set No. 16J; Number of velocity data and time step of data for Y-direction.			
1- 4	I5	KXN22	Number of Y-direction velocity data.
21-30	F10.0	DDT22	Time step.
Data set No. 16K; Y-direction velocity data.			
21-60	5F10.0	VS(2,2J) (J=1,KXK22)	Y-direction velocity data
Data set No. 17; Block number for plotting.			
1- 5	I5	NPB(1)	Block number for plotting.
6-10	I5	NPB(2)	Same as above data.
---	---	------	--------------------
		NPB(1) (I=1,NPBMAX)	
Data set No. 18; Corner coordinates of fixed reflector block (Skip this data if NFRBCP is zero. This coordinate system is block gravity center).			
1-10	F10.0	CP(1,1,I)	X-coordinate of corner No. 1 of fixed reflector block.
11-20	F10.0	CP(2,1,I)	Y-coordinate of corner No. 2 of fixed reflector block.
21-30	F10.0	CP(1,2,I)	X-coordinate of corner No. 3 of fixed reflector block.
31-40	F10.0	CP(2,2,I) (I=1,NFRB1)	Y-coordinate of corner No. 4 of fixed reflector block.
Data set No. 19; Coordinates of fixed reflector block key (Skip this data if NFRBKO is zero. This coordinate system is block gravity center.).			
1-10	F10.0	XYKO(1,1,I)	X-coordinate of one end of fixed reflector block key.
11-20	F10.0	XYKO(2,1,I)	Y-coordinate of one end of fixed reflector block key.

Table 1 (Continued)

Column	Format	Variable	Description
21-30	F10.0	XYKO(1,2,I)	X-coordinate of another end of fixed reflector block key.
31-40	F10.0	XYKO(2,2,I) (I=1,NFRB1)	Y-coordinate of another end of fixed reflector block key.
Data set No. 20; Coordinate of fixed reflector block restraint structure (Skip this data if NFRBSO is zero. Coordinate system is block center gravity.).			
1-20	F10.0	XYSO(1,1,I)	X-coordinate of one end of fixed reflector block restraint structure.
11-20	F10.0	XYSO(2,1,I)	Y-coordinate of one end of fixed reflector block restraint structure.
21-30	F10.0	XYSO(1,2,I)	X-coordinate of another end of fixed reflector block restraint structure.
31-40	F10.0	XYSO(2,2,I) (I=1,NFRB1)	Y-coordinate of another end of fixed reflector block restraint structure.

Table 2 Input data for SONATINA-2H-PLOT

Column	Format	Variable	Description
Data set No. 1; Title or job description.			
1-80	20A4	NAME(20)	Title or job description.
Data set No. 2; Data for controls and options.			
1- 5	I5	IOPT1	Option for time history curve plotting. = 1; Plotting. = 0; No plotting.
6-10	I5	IOPT2	Option for maximum value plotting. = 1; Plotting. = 0; No plotting.
11-15	I5	IOPT3	Option for vibration mode plotting. = 1; Plotting. = 0; No plotting.
16-20	I5	IOPT4	Dummy
21-25	I5	NFILE	Number of computed result stored files with SONATINA-2H.
Data set No. 3; Data for scaling.			
1-10	F10.0	FACT	Scale factor of figures for maximum value plotting (IOPT2=1) or core vibration mode plotting (IOPT3=1). Skip this data IOPT2 or IOPT3 is 0. FACT = 0.0: Auto scaling.
Data set No. 4; Title for time history curve plothing.			
1-80	20A4	MTITL1	Title for time history curve plotting.
Data set No. 5; Option for figure.			
1- 5	I5	NPFK	Option for number of history curves in a one figure. Skip this data if IOPT1 is 0.

Table 2 (Continued)

Column	Format	Variable	Description
Data set No. 6; Number of block, coordinate option and plot classification option.			
1- 5	I5	NPLTBK(J,I)	Number of block for response curve plotting.
6-10	I5	IFORCE(J,I,1)	Option for coordinate. = 2; Catesian coordinare. = -2; Axisymmetry coordinate.
11-15	I5	IFORCE(J,I,2)	Option for plot classification. = 1; Displacement. = 2; Velocity. = 3; Acceleration. = 8; Impact force. = 9; Restraint force of fixed reflector block. Repeat NPFK times. Repeat Data set No. 4 ~ No. 6, until '*END' data is appear.
Data set No. 7; X and Y axes data for response curve plotting. Skip this data if IOPT1 is 0.			
1-10	F10.0	XLENG	Length of time axis (X axis) in millimeter. = 0.0; default value is 200 mm.
11-20	F10.0	YLENG	Length of response values (Y axis) is millimeter. = 0.0; default value is 20 mm.
Data set No. 8; Title for maximum value plotting.			
1-40	10A4	MTITL2	Title for maximum vlaue plotting.
Data set No. 9; Maximum number of response curve plotting in a one figure and character size of figure.			
1- 5	I5	NVMAX	Maximum number of response curve plotting in a one figure.
6-15	F10.0	VSIZE	Character size in figure in millimeter.

Table 2 (Continued)

Column	Forma	Variable	Description
Data set No. 10; Classification of maximum value plotting.			
	1X		Dummy.
2- 4	I3	KMAX(I)	Classification of maximum value plotting. = 1; Displacement. = 2; Velocity. = 3; Acceleration. = 8; Impact force. = 13; Restraint force of fixed reflector block. = 14; Key force.
5	A1	IKFRC(I)	Classification of component. = X; Component of X direction. = Y; Component of Y direction. = R; Component radial direction. = T; Component of tangential direction.
Data set No. 11; Title for vibration mode plotting.			
1-40	10A4	MTITL3	Title for maximum value plotting.
Data set No. 12; Option for vibration mode plotting. Skip this data IOPT3 is 0.			
1- 5	I5	JPIC	Number of plotting steps.
6-10	I5	INUM	Plot option for block numbering. = 0; Numbering. ≠ 0; No numbering.
Data set No. 13; Last data.			
1- 3	A3	LAST	'END'

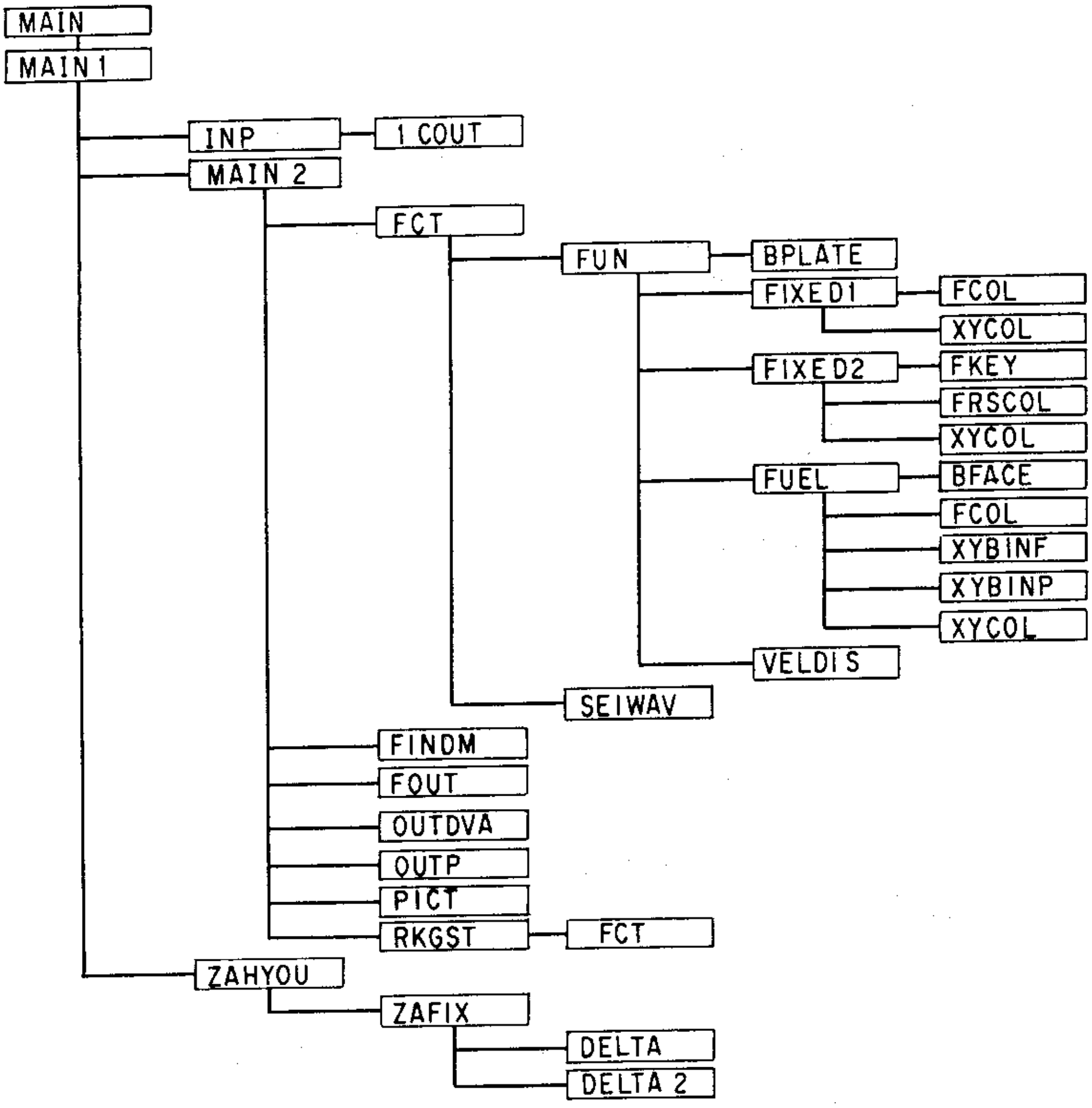


Fig. 16 Structure of computer program SONATINA-2H

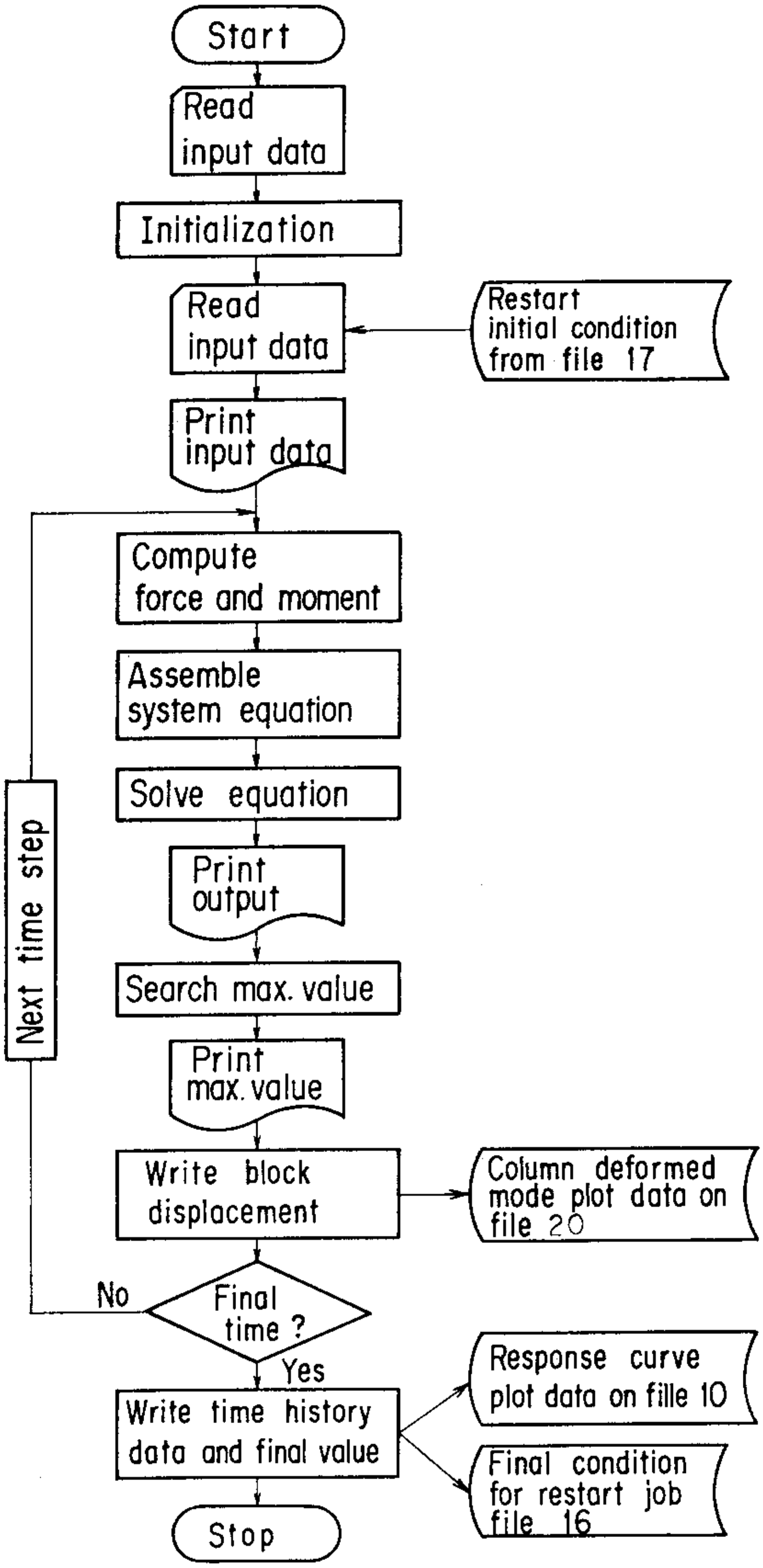


Fig. 17 Program flow

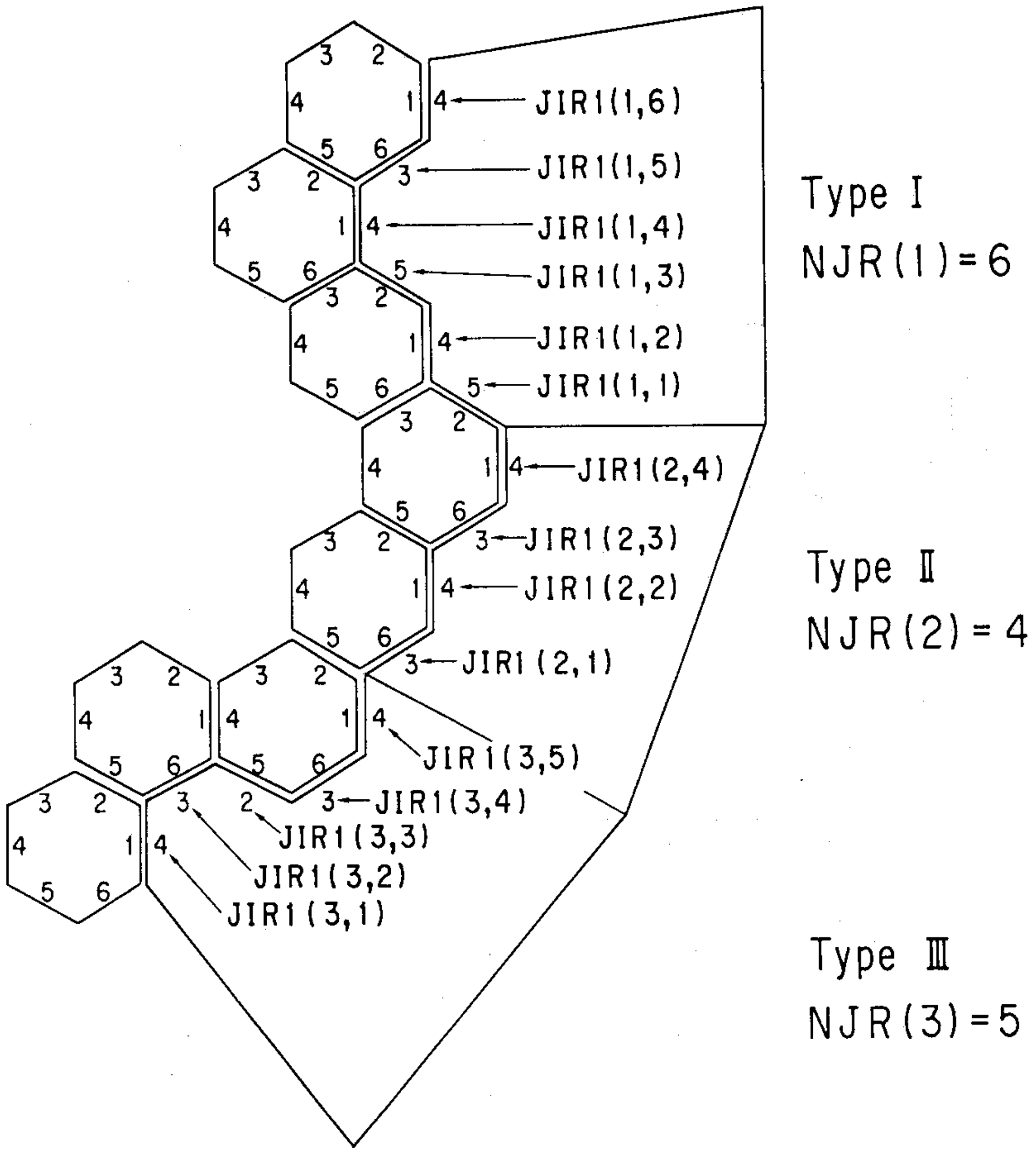
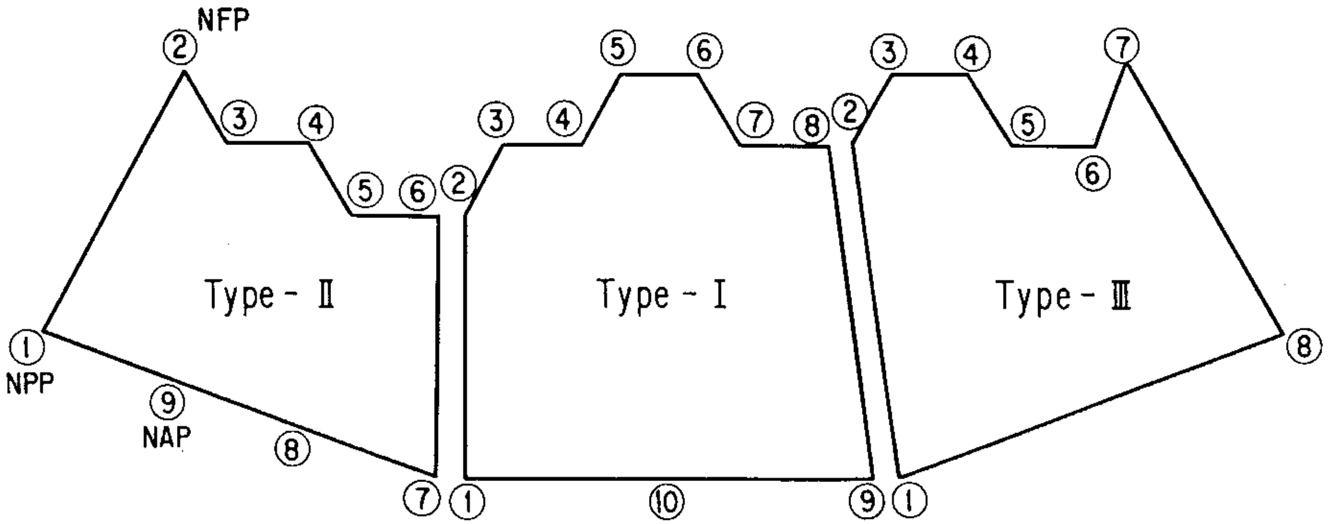
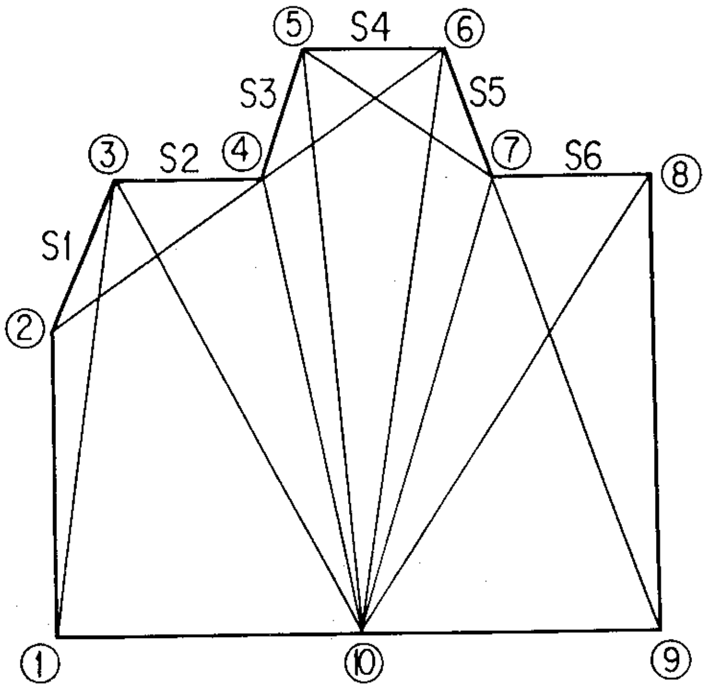


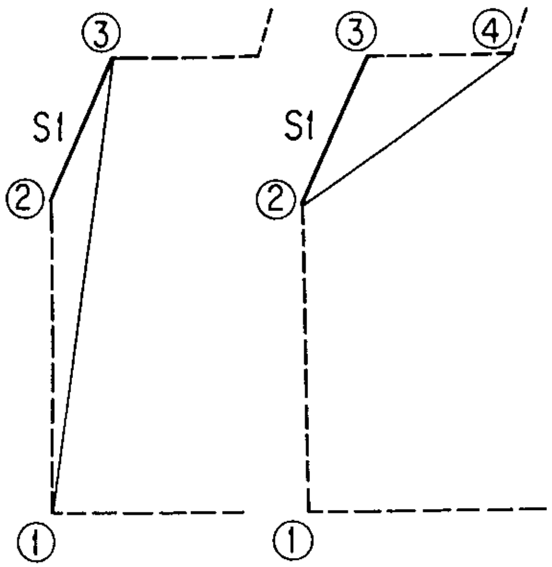
Fig. 18 Face number of reflector block



Fixed reflector block type	Number of triangle point NAP	Number of block corner NPP	Number of block apex NFP
type - Ⅰ	NAP = 10 ; ①②③④⑤⑥⑦⑧⑨⑩	NPP = 9 ; ①②③④⑤⑥⑦⑧⑨	NFP = 5 ; ②③⑤⑥⑧
type - Ⅱ	NAP = 9 ; ①②③④⑤⑥⑦⑧⑨	NPP = 7 ; ①②③④⑤⑥⑦	NFP = 3 ; ②④⑥
type - Ⅲ	NAP = 8 ; ①②③④⑤⑥⑦⑧	NPP = 8 ; ①②③④⑤⑥⑦⑧	NFP = 4 ; ②③④⑦

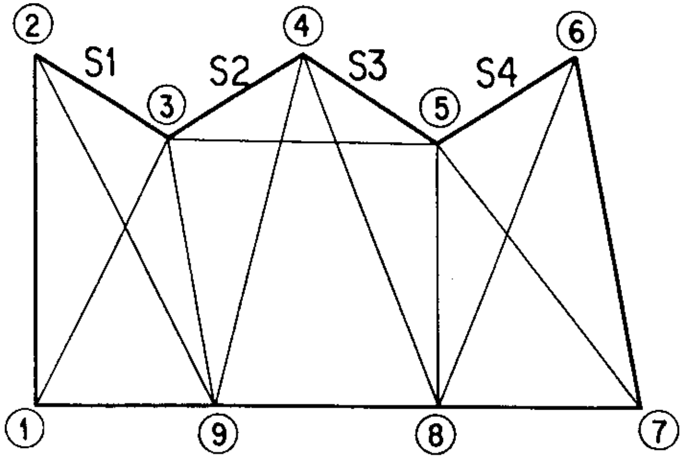
Fig. 19 Various number for fixed reflector block

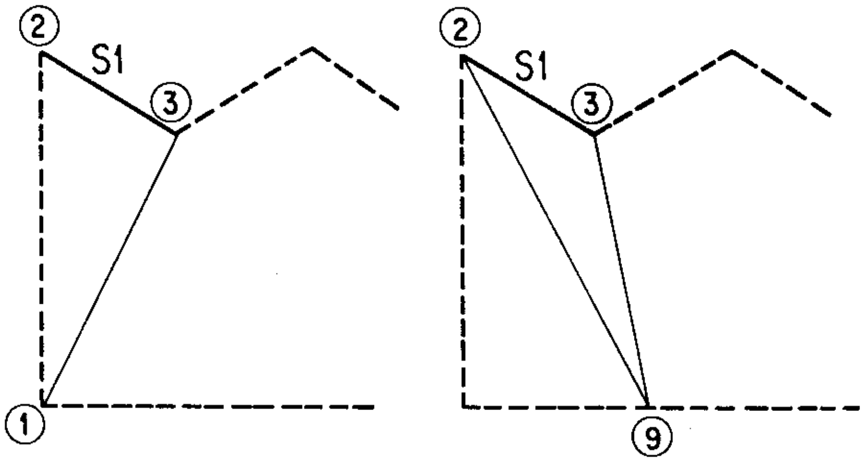




Impact surface	Two-pairs of impact triangle
S 1	△ ② ③ ①, △ ② ③ ④
S 2	△ ③ ④ ②, △ ③ ④ ⑩
S 3	△ ④ ⑤ ⑩, △ ④ ⑤ ⑥
S 4	△ ⑤ ⑥ ④, △ ⑤ ⑥ ⑦
S 5	△ ⑥ ⑦ ⑤, △ ⑥ ⑦ ⑩
S 6	△ ⑦ ⑧ ⑩, △ ⑦ ⑧ ⑨

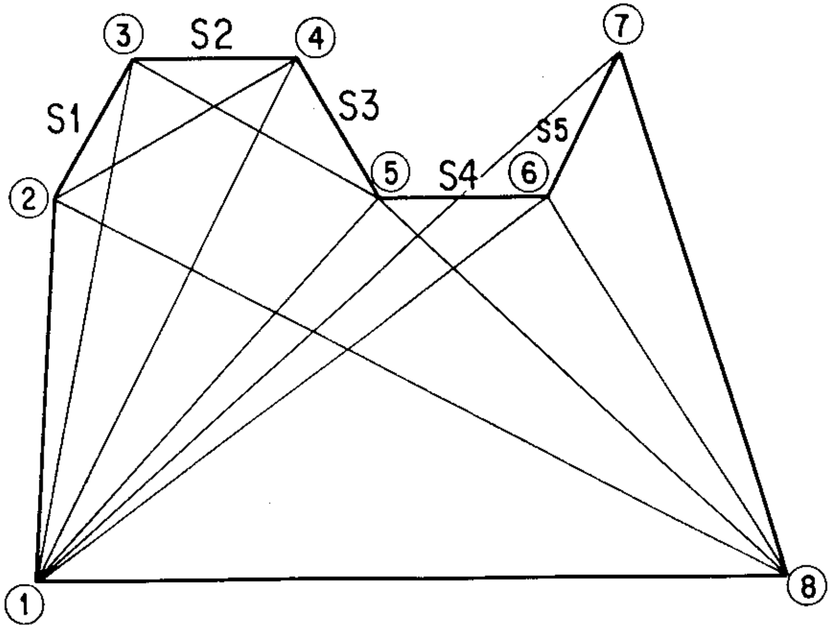
Fig. 20(a) Example of two-pairs of impact surface triangle (in the case of fixed reflector block type - I)

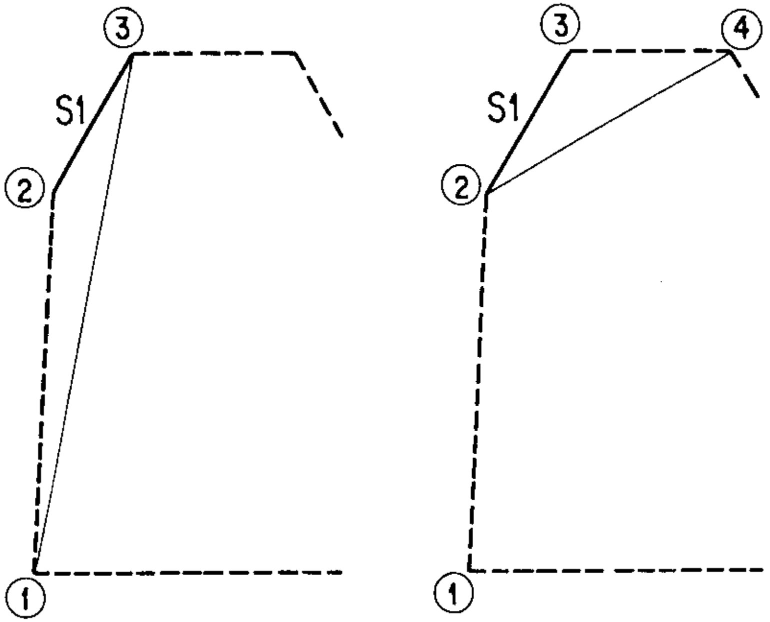




Impact surface	Two−poirs of impact triangle
S 1	△ ② ③ ① , △ ② ③ ⑨
S 2	△ ③ ④ ⑨ , △ ③ ④ ⑤
S 3	△ ④ ⑤ ③ , △ ④ ⑤ ⑧
S 4	△ ⑤ ⑥ ⑧ , △ ⑤ ⑥ ⑦

Fig. 20(b) Example of two-pairs of impact surface triangle
(in the case of fixed reflector block type - II)





Impact surface	Two-pairs of impact triangle
S1	△ ② ③ ①, △ ② ③ ④
S2	△ ③ ④ ②, △ ③ ④ ⑤
S3	△ ④ ⑤ ③, △ ④ ⑤ ①
S4	△ ⑤ ⑥ ①, △ ⑤ ⑥ ⑧
S5	△ ⑥ ⑦ ⑧, △ ⑥ ⑦ ⑧

Fig. 20(c) Example of two-pairs of impact surface triangle
(in the case of fixed reflector block type - III)

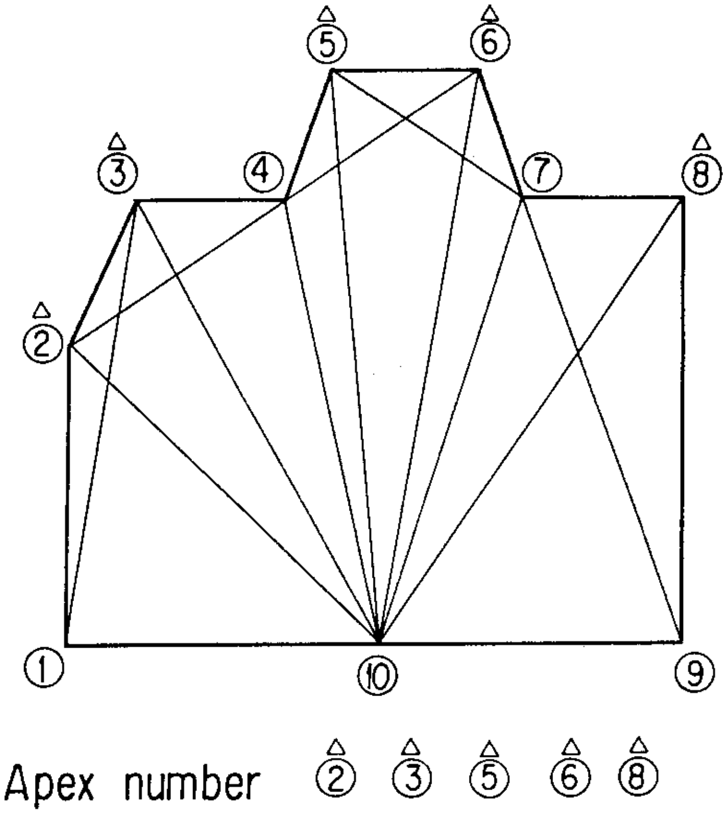


Fig. 21(a) Example of apex number of fixed reflector block, probable to impact between block surface (in the case of fixed reflector block type - I)

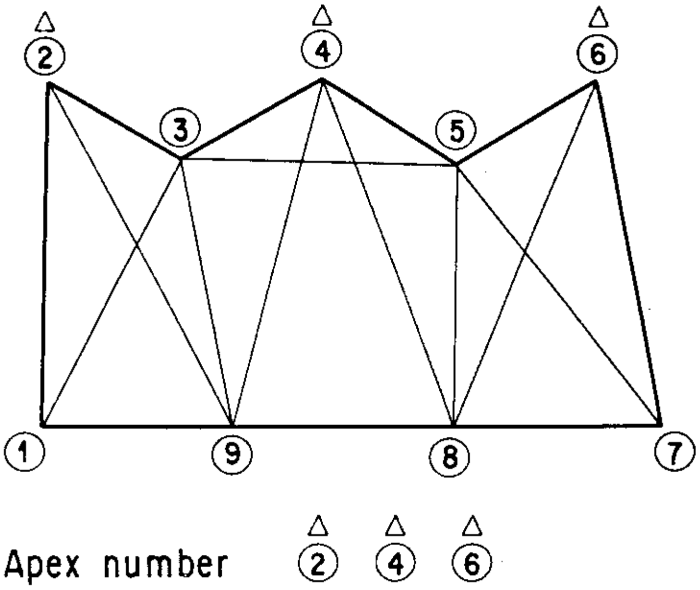


Fig. 21(b) Example of apex number of fixed reflector block, probable to impact between block surface (in the case of fixed reflector block type - II)

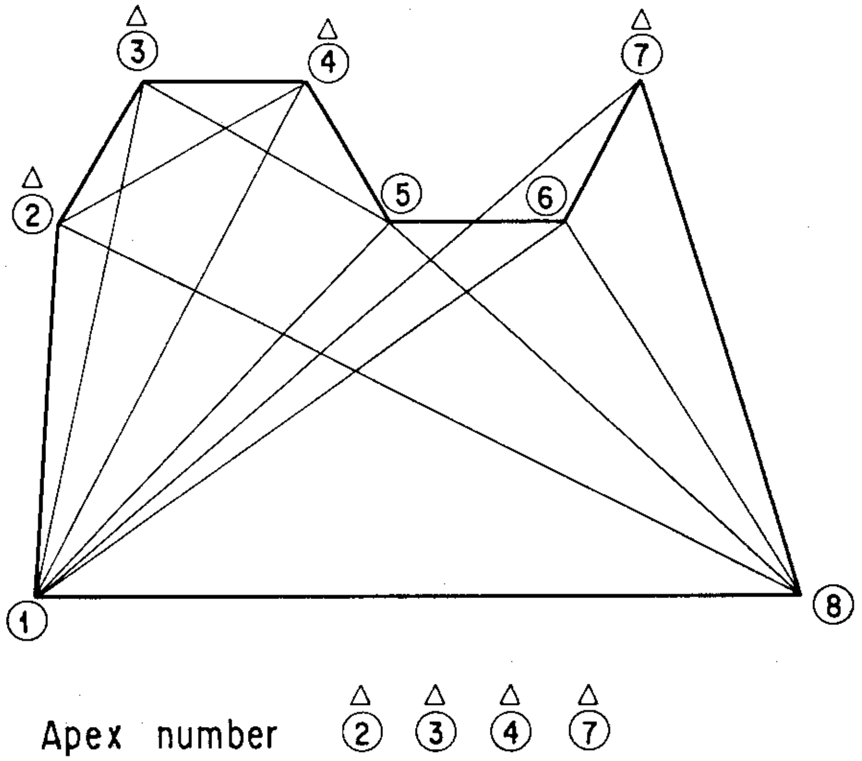
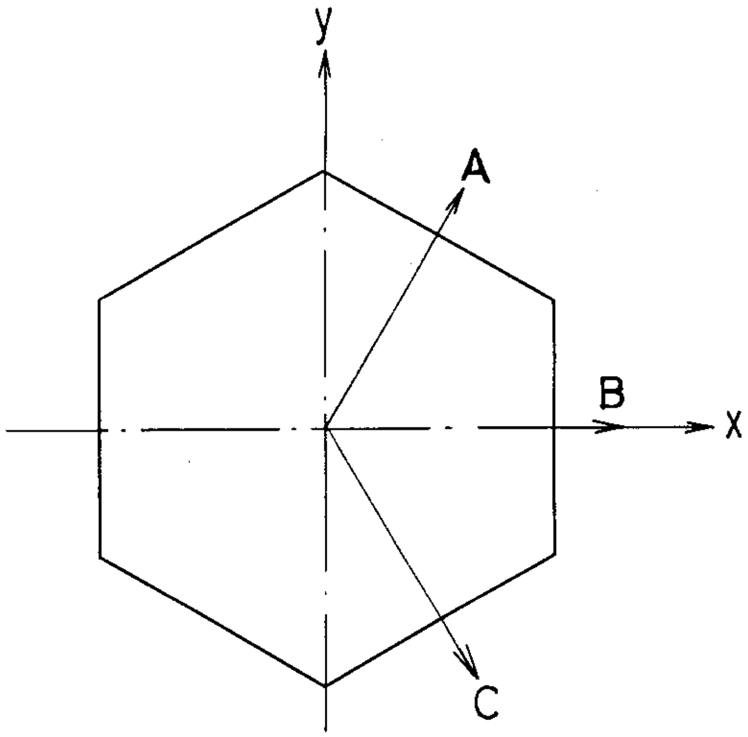


Fig. 21(c) Example of apex number of fixed reflector block, probable to impact between block surface (in the case of fixed reflector block type - III)



Item	Direction	Notation on computer output
Displacement	A B C	UA UB UC
Velocity	A B C	UDA UDB UDC

Fig. 22 Block direction and notation on computer output

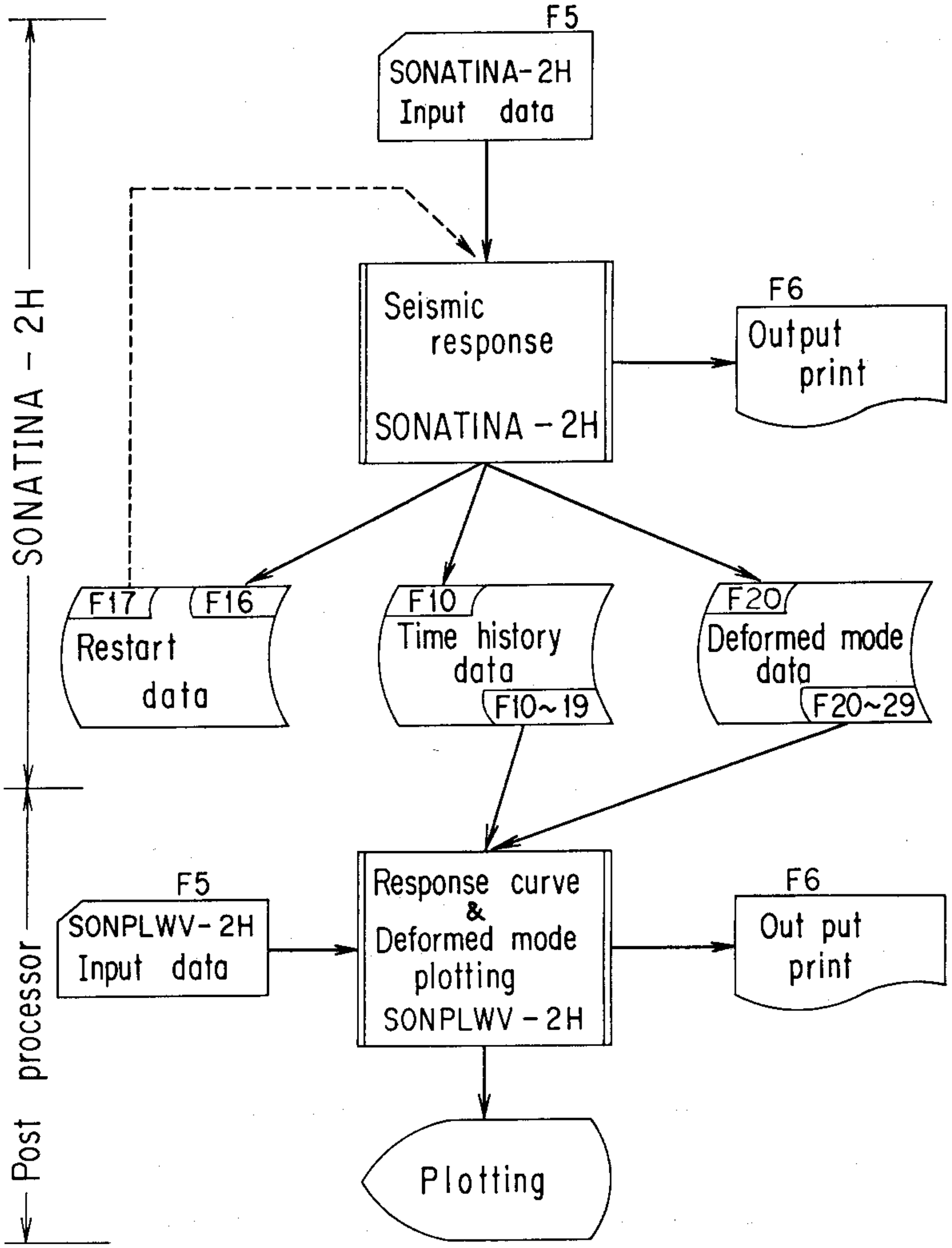


Fig. 23 Computer program SONATINA-2H and post-processor

5. Example and discussions

The governing equation given in Chapter 3 can be numerically solved by using Runge-Kutta-Gill integration schemes. The geometry and weight of the block elements shown in Table 3 are chosen in such a way that the analyzed system corresponds to an experimental HTGR core(3),(4) with dimension scaled by 1/2 and weight scaled by 1/4 (shown in Photo. 1 and Fig. 24). The computation time interval is 1×10^{-4} seconds. The numerical results are compared with experimental results. In the calculation input acceleration wave is 4.1 Hz frequency sinusoidal wave of maximum peak acceleration 250 Gal.

5.1 Displacement response

Figure 25 shows displacement of fuel blocks and side reflectors motion at 4.1 Hz frequency sinusoidal peak acceleration 250 Gal, uni-axis excitation. Fuel blocks move not only in X direction (same as excitation direction) but also Y direction perdendicular to excitation direction. The displacement locus of fuel blocks center have elliptic shape.

Figure 26 shows the comparison between analysis and experiment of the displacement of fuel blocks and side reflector blocks on the X-axis. The analytical results show a favorable correlation with the experimental ones.

Figure 27 shows the comparison between analysis and experiment of the displacement of fuel blocks and side reflector blocks on the Y-axis. In the figure, it can be seen that the analytical results are in good agreement with the experimental ones.

5.2 Impact acceleration response

Figure 28 shows the comparison between analysis and experiment of the acceleration of fuel blocks and side reflector blocks on the X-axis. The analytical results show a favorable correlation with the experimental ones.

Figure 29 shows the comparison between analysis experiment of the impact acceleration of fuel blocks and side reflector blocks on the Y-axis. In the figure, it can be seen that the analytical results are fairly agreement with the experimental ones.

5.3 Impact reaction force response

Figure 30 shows the comparison between analysis and experiment of the impact reaction force of side reflectors. In the figure, two kinds of reaction forces such as radial and tangential forces were shown. The analytical results show a favorable correlation with the experimental ones.

Table 3 Calculation constant

Item		Unit	Fuel block	Fixed side reflector block			Core base plate
				Type A	Type B	Type C	
Mass		$kg \cdot s^2/cm$	0.0195	0.0992	0.1178	0.146	
Spring constant	Impact	kg/cm	12600	12600			——
	Support		4.8	7760			7760
Damping coefficient	Impact	kg•s/cm	7.84	7.84			——
	Support		0.061	2.8	3.0	3.4	6.8
Spring constant of reflector key		kg/cm		12600			
Damping coefficient of reflector key		kg•s/cm		7.84			

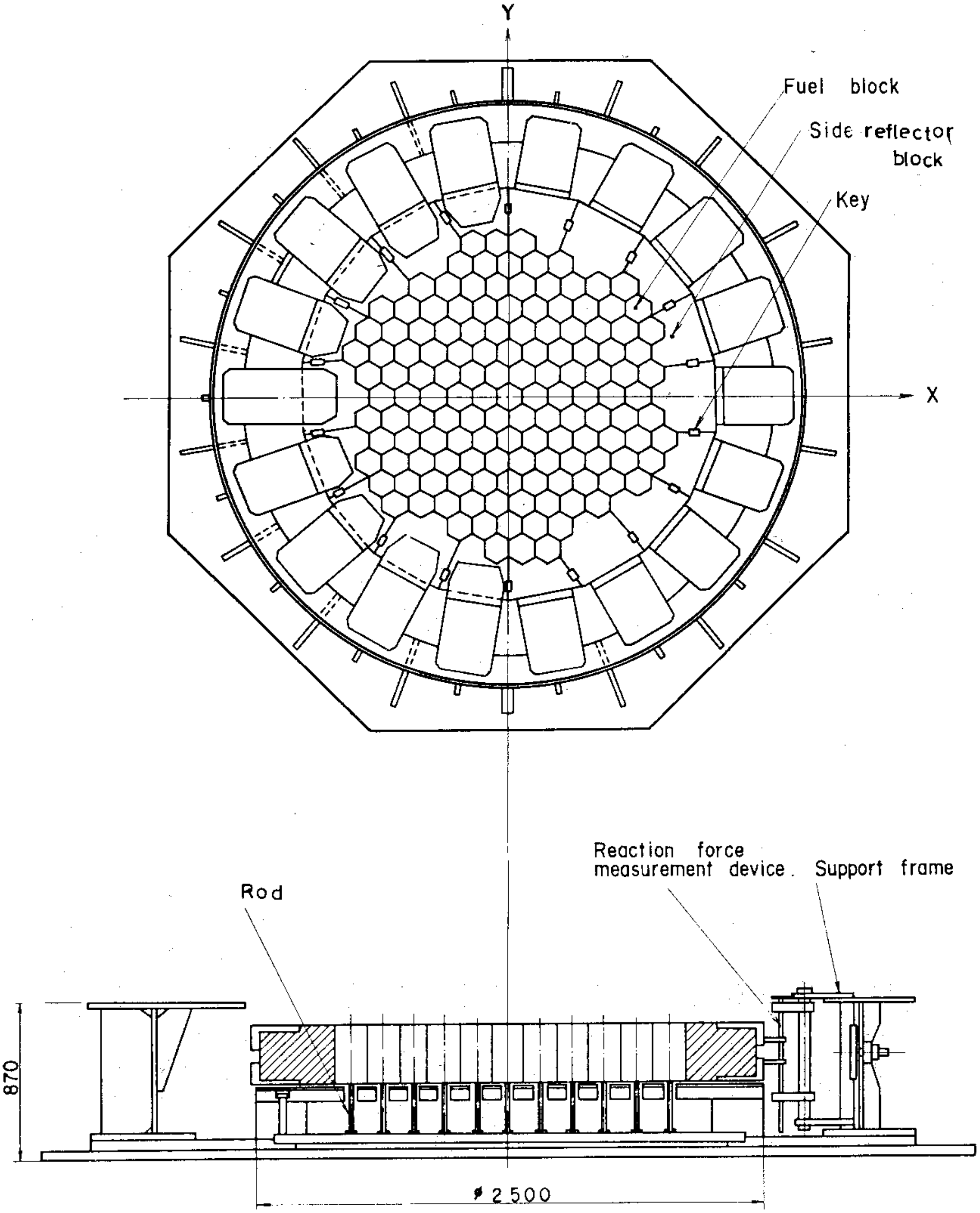


Fig. 24 Test rig and core model

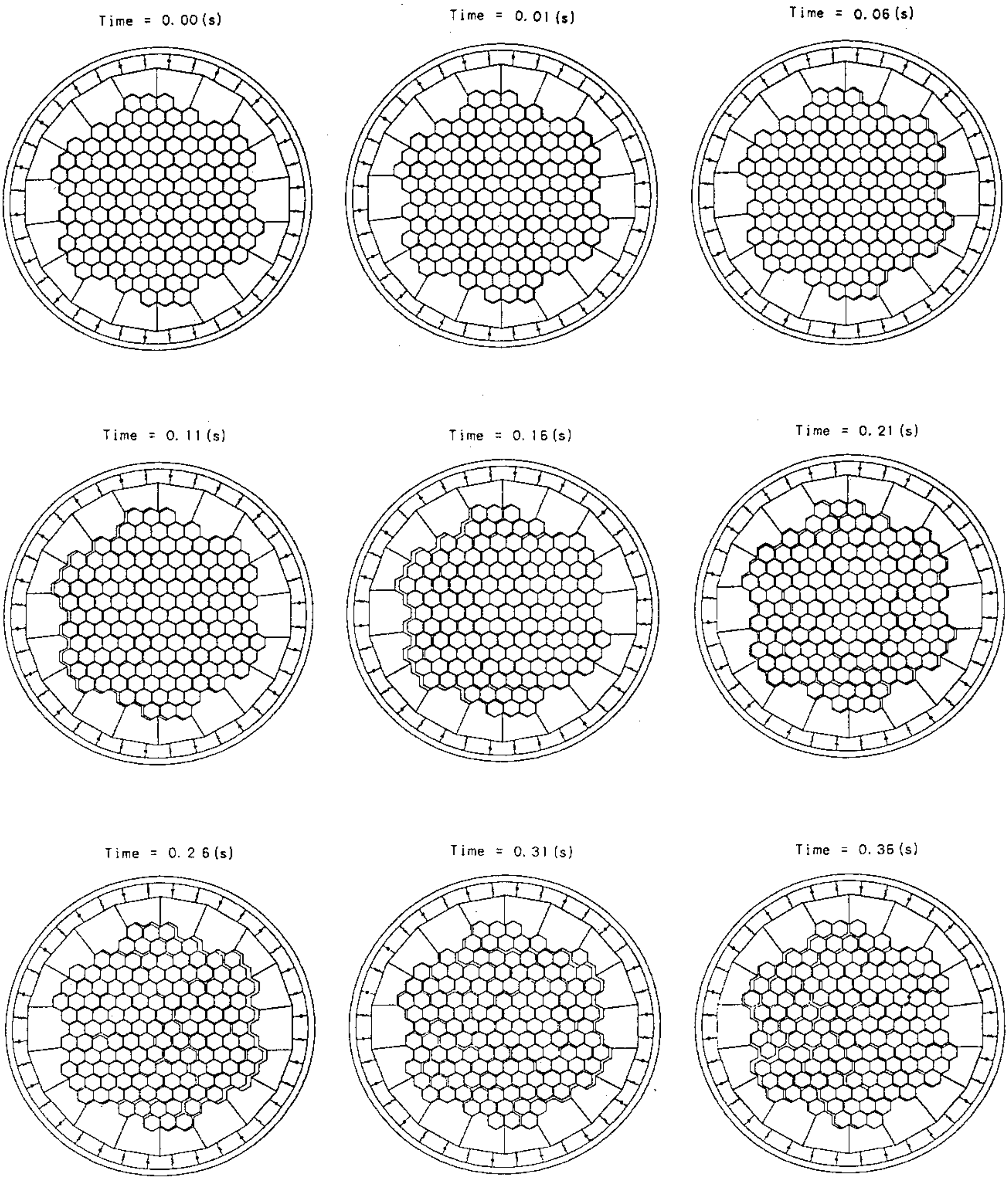


Fig. 25 Seismic behavior of two-dimensional horizontal slice core model (Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

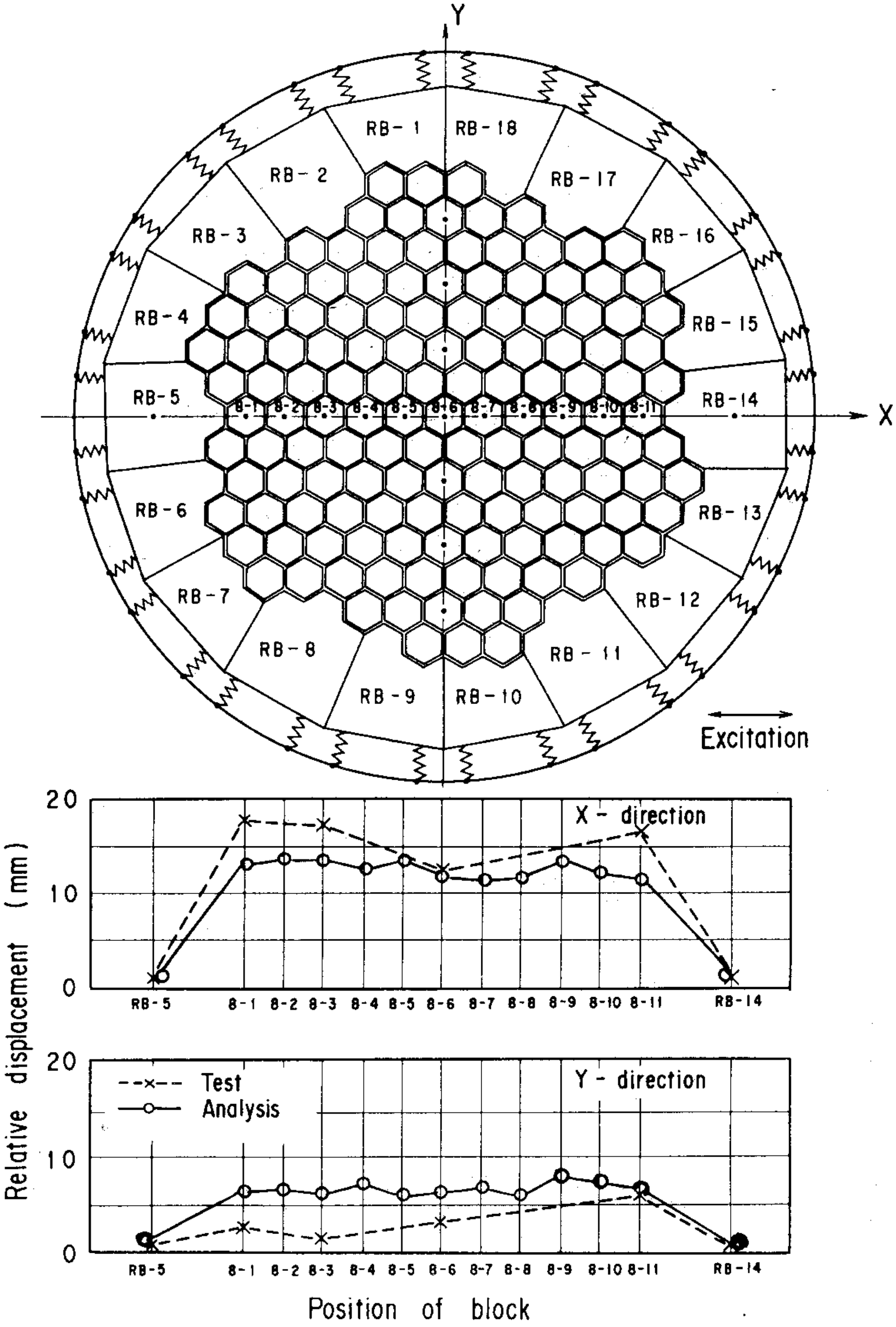


Fig. 26 Displacement of block on X-axis position
(Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

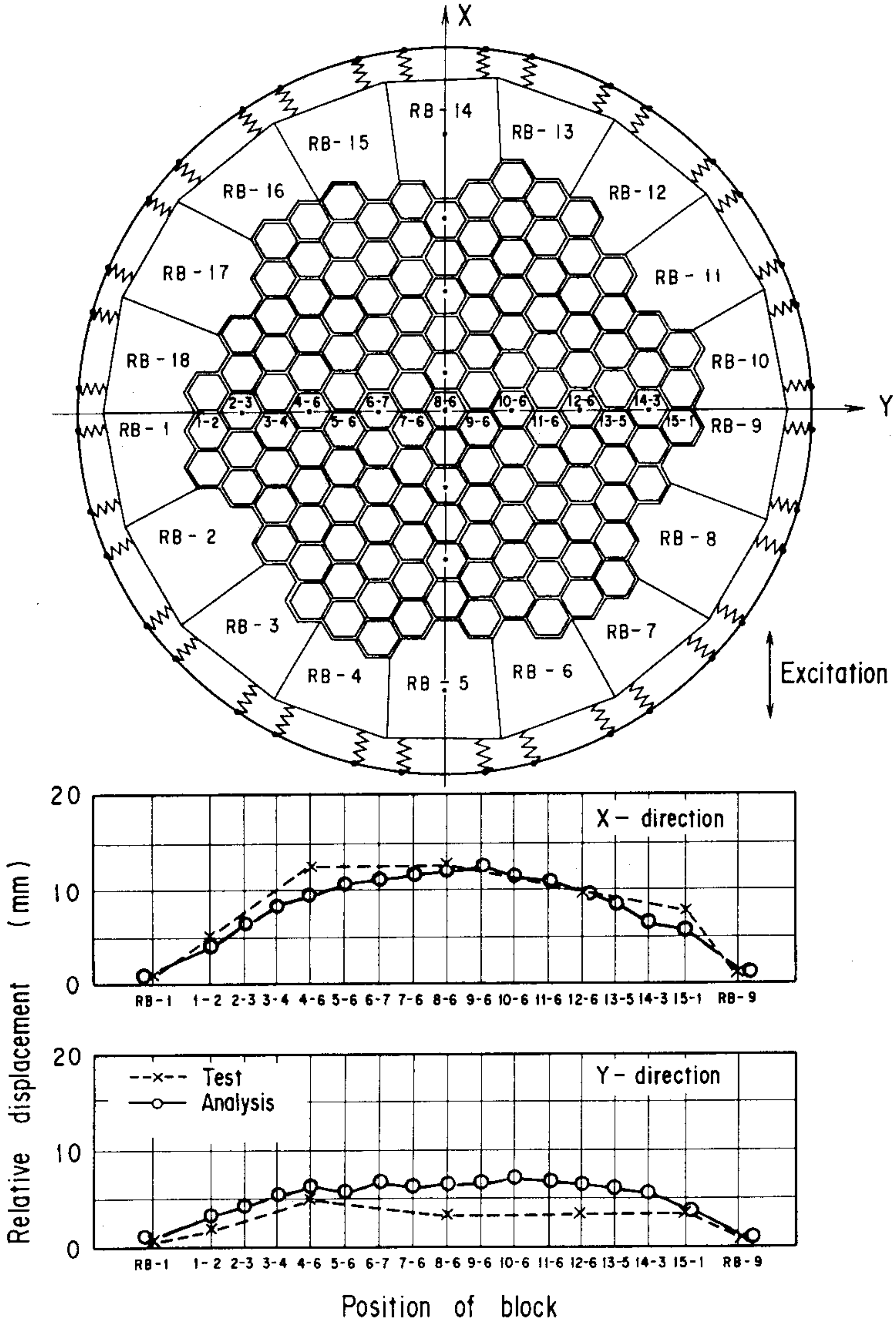


Fig. 27 Displacement of block on Y-axis position
(Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

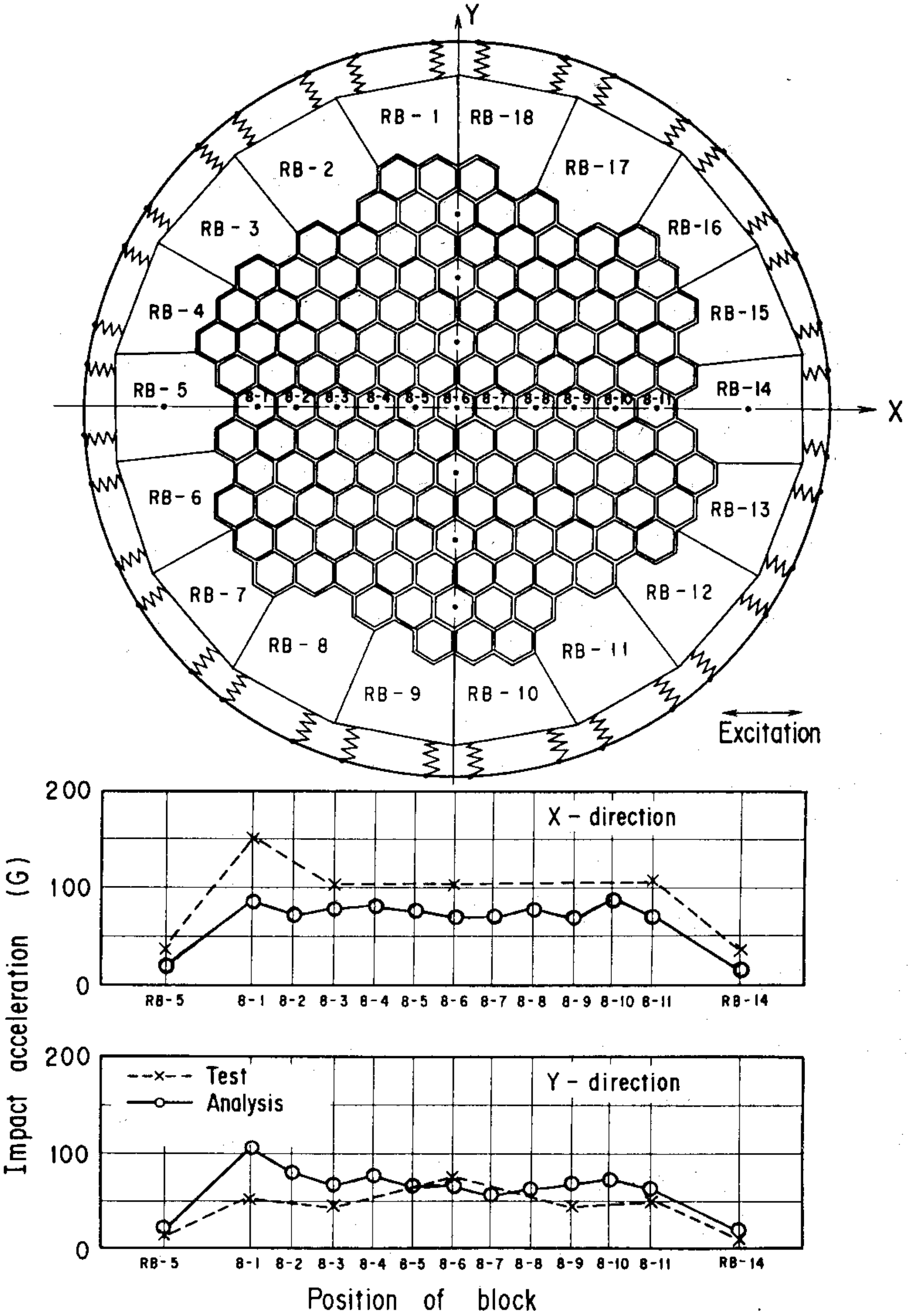


Fig. 28 Impact acceleration of block on X-axis position
(Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

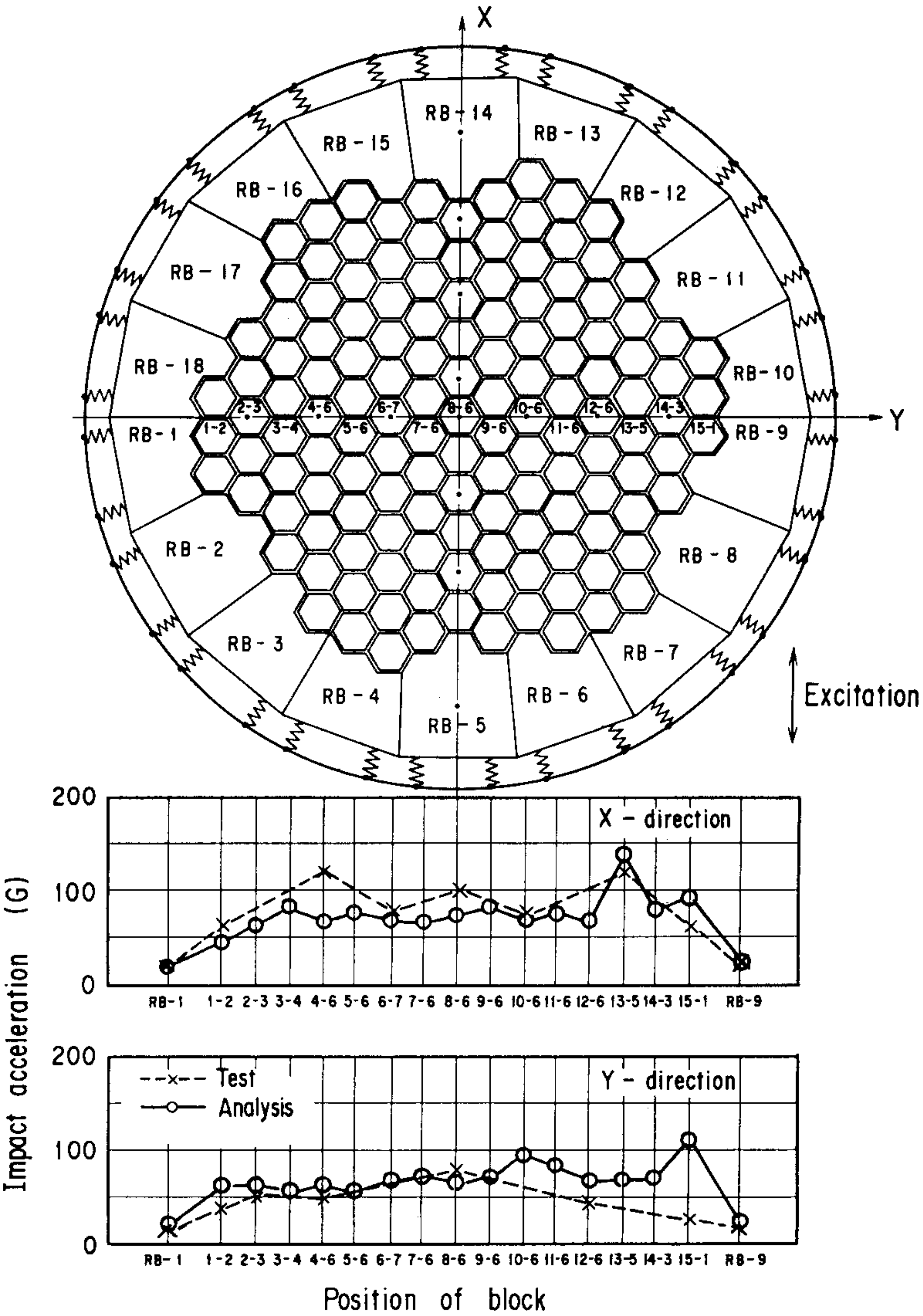


Fig. 29 Impact acceleration of block on Y-axis position
(Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

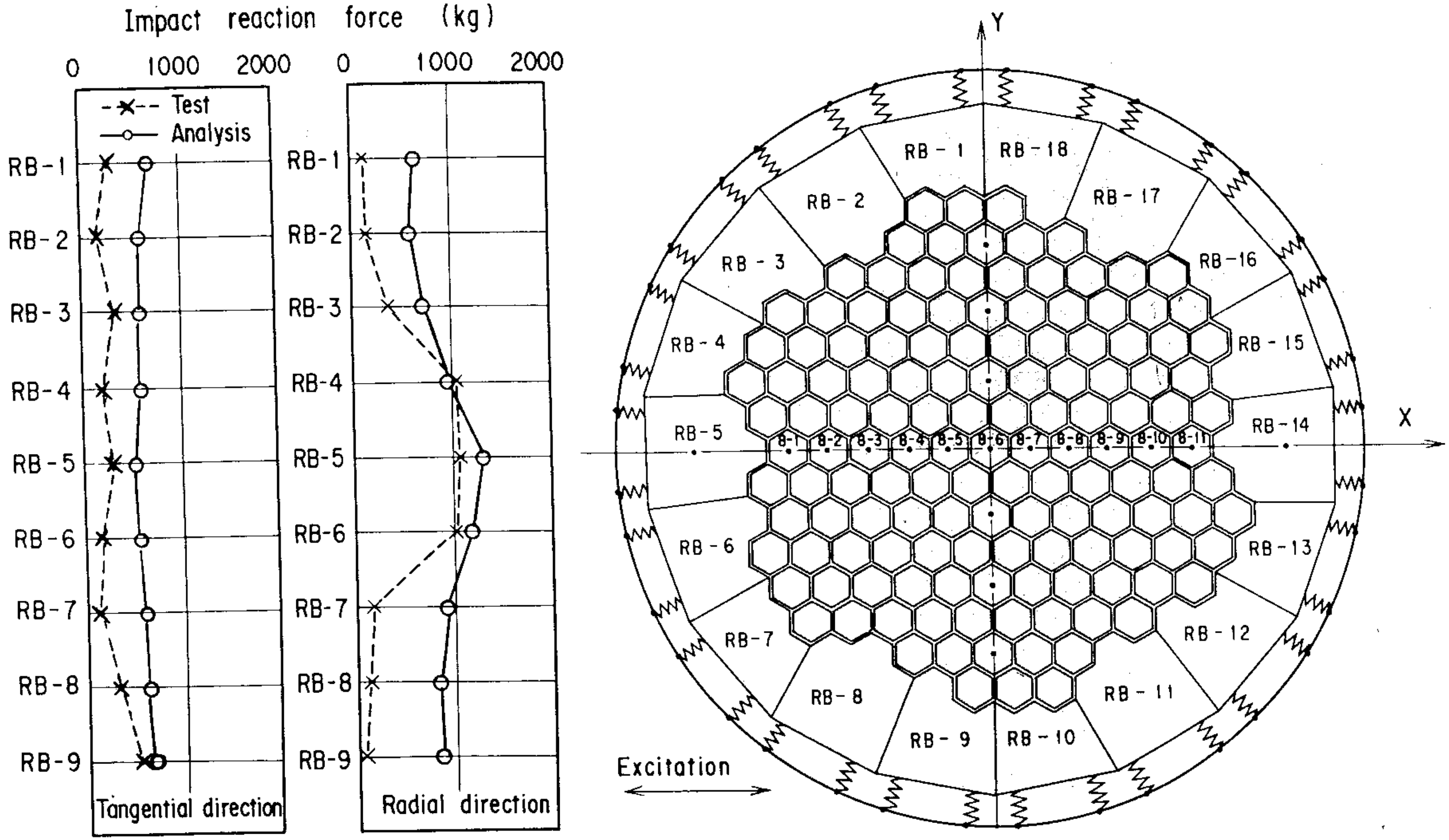


Fig. 30 Impact reaction force distribution of reflector block
(Excitation X-direction, 4.1 Hz, Max. acceleration 250 Gal)

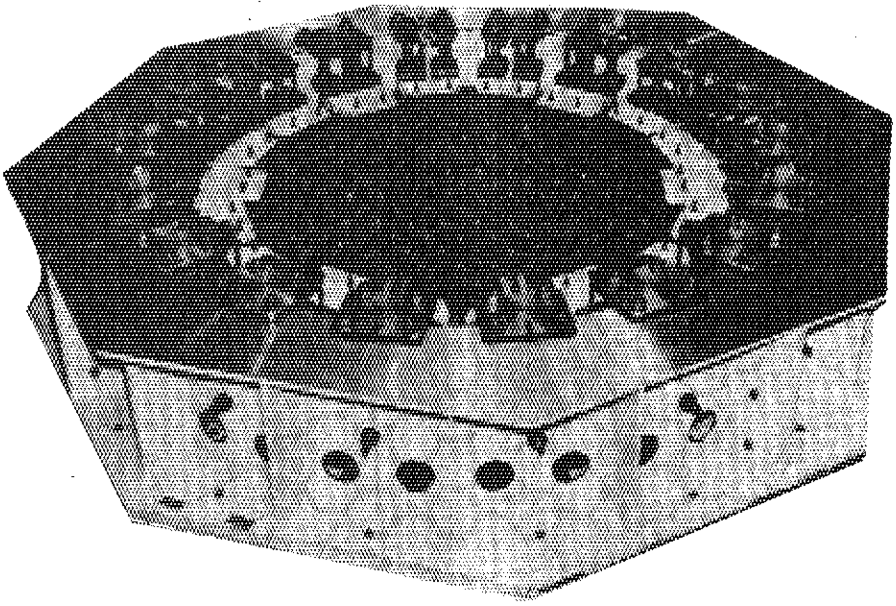


Photo. 1 Two-dimensional horizontal core test model

6. Conclusions

The author has developed a computer pgogram SONATINA-2H for dynamic analysis of a two-dimensional horizontal slice core of HTGR core. The calculation equations have been presented and the numerical results were compared with the results of the experiments. The following conclusions have been drawn:

(1) The analytical results agree well with experimental data.

(2) The present method can be used for HTGR seismic design analysis.

Acknowledgements

The author wish to express his appreciation to Drs. S. Saito and T. Tanaka of Department of HTTR Development Projects in JAERI for their support of the study.

References

(1) Muto K., et al.: "Two-dimensional Vibration Test and Its Simulation Analysis for A Horizontal Slice Model of HTGR Core", Proc. 5th Int. Conf. SMiRT, K 12/2, Paris (1979).

(2) Tow D.,: "CRUNCH-2D A Two-dimensional Computer Program for Seismic Analysis of the HTGR Core", GA-A14765 (1978).

(3) Ikushima T. and Honma T.: "Aseismic Study of High Temperature Gas-cooled Reactor Core with Block-type Fuel (3rd Report, Difference of Excitation Directions and Core Support Stiffness)", Bull. JSME(Tokyo) 28-246, 2986 (1985).

(4) Ikushima T. and Honma T.: "Seismic Response of High Temperature

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(2) Tow D.,: "CRUNCH-2D A Two-dimensional Computer Program for Seismic Analysis of the HTGR Core", GA-A14765 (1978).

(3) Ikushima T. and Honma T.: "Aseismic Study of High Temperature Gas-cooled Reactor Core with Block-type Fuel (3rd Report, Difference of Excitation Directions and Core Support Stiffness)", Bull. JSME(Tokyo) 28-246, 2986 (1985).

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The author wish to express his appreciation to Drs. S. Saito and T. Tanaka of Department of HTTR Development Projects in JAERI for their support of the study.

References

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Appendix A Sample problem input for SONATINA-2H

```
   DATA              1         2         3         4         5         6         7         8
SEQ. NO.    ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0

      1     SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))
      2         7    1    4    2    6    1   -1    0    0    0   -1    0    0    0    0    1
      3         0    0    0    0    0.0      50.0
      4       0.0       2.0       0.0001    1.0       0.01      0.1       1.0      1000.0
      5       0.1       0.0001    0.3
      6       0.2       0.1      10.0      0.0
      7         1 0.0195    4.6       4.6       0.05      0.05      12600.    12600.0
      8           0.365     8.0       8.0       0.0       0.0       0.0       0.0
      9           0.0       0.0
     10         2 0.5      700.          5    4    3    4    5    4
     11      8160.0    8160.0    6.0       6.0       12600.0   12600.0   8.0       8.0
     12      0.0       0.0       0.0       0.0       8160.0    6.0       12600.    8.0
     13      0.0       0.0
     14         9    8    4
     15         3 0.4      560.          4    2    3    2    3
     16      8160.0    8160.0    6.0       6.0       12600.0   12600.0   8.0       8.0
     17      0.0       0.0       0.0       0.0       8160.0    6.0       12600.    8.0
     18      0.0       0.0
     19         9    7    3
     20         2    3    1    2    3    4
     21         3    4    2    3    4    9
     22         4    5    9    4    5    9
     23         5    6    9    5    6    7
     24         6    7    5    6    7    8
     25         0    0    0    0    0    0
     26         2    3    1    2    3    9
     27         3    4    9    3    4    5
     28         4    5    3    4    5    8
     29         5    6    8    5    6    7
     30         0    0    0    0    0    0
     31         0    0    0    0    0    0
     32         2    3    6    7    0    0
     33         0    2    4    6    0    0
     34      1.0       100000.0  100000.0  0.0       0.0       0.0       0.0
     35         1    2    7    6    5    4    3
     36         2    8    8    7    1    3    8
     37         3    8    2    1    4    9    9
     38         4    3    1    5   10    9    9
     39         5    1    6   10   10   10    4
     40         6    7   11   11   10    5    1
     41         7    8   11   11    6    1    2
     42         8    3    2    2    2    7
     43         9    4    4    3    3
     44        10    6    5    5    5    4
     45        11    7    7    6    6
     46       250.0    3.0       0.0       0.0       0.0       0.0
     47         2
     48         0    0           1.0       1.0

            ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0
                     1         2         3         4         5         6         7         8
```

Appendix B Sample problem output for SONATINA-2H

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))


****** CONTROL OPTION ******



NUMBER OF FUEL BLOCKS                             =          7
NUMBER OF FUEL BLOCK TYPES                        =          1
NUMBER OF FIXED REFLECTOR BLOCKS                  =          4
NUMBER OF FIXED REFLECTOR BLOCK TYPES             =          2
NUMBER OF SURFACES OF AROUND REFLECTOR BLOCK      =          6
NUMBER OF IRREGULAR FIXED REFLECTOR BLOCKS        =          1
OPTION FOR BLOCK NUMBERING DIRECTION              =         -1
               CLOCKWISE = -1
       COUNTER CLOCKWISE =  1
OPTION FOR RESTART RUN                            =          0
 INITIAL RUN(DISPLACEMENT=0,VELOCITY=0)     = 0
 INITIAL RUN(DISPLACEMENT,VELOCITY: INPUT)  = 1
 RESTART RUN(PREVIOUS RUN DATA)             = 2
OPTION FOR REFLECTOR KEY FORCE CALCULATION        =          0
        NO KEY FORCE          =  0
        KEY FORCE CALCULATION =  1


OPTION FOR INPUT EXCITATION WAVE                  =          0
        SINUSOIDAL DWELL  =  0
        SINUSOIDAL DWELL  =  1
        SEISMIC WAVE DATA =  2
NUMBER OF PLOTTING BLOCK FOR DATA SAVE            =         11
OPTION FOR INPUT DATA PRINTOUT                    =          0
        INPUT DATA PRINT  =  0
        NO PRINTOUT       =  1
OPTION FOR SOLVER FOR TIME INTEGRATION            =          0
        RUNGE KUTTA GILLS     =  0
        NEWMARK THETA METHOD  =  1


OPTION FOR CENTER COORDINATES OF FIXED BLOCK =               0
        NO INPUT DATA     =  0
        INPUT DATA        =  1
OPTION FOR CORNER COORDINATES OF FIXED BLOCK =               0
        NO INPUT DATA     =  0
        INPUT DATA        =  1
OPTION FOR KEY COORDINATES OF FIXED BLOCK         =          0
        NO INPUT DATA     =  0
        INPUT DATA        =  1
OPTION FOR RESTRAINT COORDINATES OF FIXED BLOCK =            0
        NO INPUT DATA     =  0
        INPUT DATA        =  1
ANGLE OF INITIAL FIXED REFLECTOR BLOCK(DEGREE)  =           0.0
RADIUS OF OUTER FIXED REFLECTOR BLOCK           =        50.000



CORE USED     =       2242

MAXIMUM CORE =      75000
```

Appendix B (Continued)

```
*** PARAMETER FOR FIXED REFLECTOR BLOCK ***


   NAP        NPP        NFP
     9          8          4
     9          7          3

 LAB
     2          3         1,         2          3          4
     3          4         2,         3          4          9
     4          5         9,         4          5          9
     5          6         9,         5          6          7
     6          7         5,         6          7          8
     0          0         0,         0          0          0
     2          3         1,         2          3          9
     3          4         9,         3          4          5
     4          5         3,         4          5          8
     5          6         8,         5          6          7
     0          0         0,         0          0          0
     0          0         0,         0          0          0

 IP2
     2          3          6          7          0          0
     0          2          4          6          0          0



SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))
          P R O B L E M     I N P U T     P A R A M E T E R S

SOLUTION START TIME                             =       0.0
SOLUTION END TIME                               =       2.00000
SOLUTION INTEGRATION TIME STEP                  =       0.00010
RESPONSE DATA PRINTOUT TIME STEP                =       1.00000
STORE TIME STEP FOR RESPONSE WAVE PLOT          =       0.01000
STORE TIME STEP FOR CORE DEFOMATION PLOT        =       0.10000
STORE TIME STEP FOR RESTART                     =       1.00000
COMPUTER STOP TIME                              =    1000.00000


SOLVER IS RUNGR KUTTA GILLS
MAXIMUM ALLOWED ERROR                           =       0.10000
TRUNCATION ERROR                                =       0.00010
TRUNCATION VALUE OF OVERLAPPIG VECTOR           =       0.30000
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

                            F U E L   B L O C K   P A R A M E T E R S

   TYPE     MASS       GAP      GAP      GAP           COEFFICIENT OF RESTORING            COEFFICIENT OF           METER
                                SPRING   SPRING             KR                  CR         FRICTION                  CC
                                STIFF.   DAMPING      X          Y          X          Y          X          Y          X          Y
            (KG)       (CM)      KB       CB

     1    0.0195    0.20000   12600.0    8.000      4.600      4.600      0.050      0.050      0.0        0.0        0.0        0.0

   TYPE    MOMENT OF  COEFFICIENT OF FRICTION
           INERTIA    BETWEEN BLOKS
           (KG*CM**2)
     1      0.365     0.0
------------------------------------------------------------------------------------------------------------------------------

         F I X E D    R E F L E C T O R    B L O C K    P A R A M E T E R S

   TYPE     MASS     MOMENT OF    GAP      GAP       GAP         COEFFICIENT OF RESTORING           COEFFICIENT OF FRICTION
                     INERTIA               SPRING    SPRING             KR                 CR          BETWEEN BLOCKS
                                           STIFF.    DAMPING      X          Y          X          Y
            (KG)    (KG*CM**2)    (CM)      KB        CB

     2    0.5000    700.000    0.20000    12600.0     8.000   8160.000   8160.000     6.000      6.000          0.0
     3    0.4000    560.000    0.20000    12600.0     8.000   8160.000   8160.000     6.000      6.000          0.0

   TYPE    COEFFICIENT OF RESTRAINT        COEFFICIENT OF                     METER                   COEFFICIENT OF KEY
           FOR CORE BARREL                 FRICTION                             CC                    REACTION FORCE
                 KRR             CRR        X             Y              X             Y            KKEY          CKEY

     2          8160.0          6.000       0.0           0.0            0.0           0.0         12600.0        8.000
     3          8160.0          6.000       0.0           0.0            0.0           0.0         12600.0        8.000

  GAP BETWEEN BLOCK AND KEY

           1.0000D-01
------------------------------------------------------------------------------------------------------------------------------

                      B A S E    P L A T E    P A R A M E T E R S

          MASS                          COEFFICIENT OF RESTRAINT
           (G)                        KR                                 CR
                          X                       Y              X                 Y

          1.0000    100000.0000    100000.0000         0.0               0.0
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

                       F U E L    B L O C K    D A T A    A N D    I N I T I A L    C O N D I T I O N S

       BLOCK         SURROUNDING BLOCK NO.          BLOCK       UA          UB          UC         UDA         UDB         UDC          GAP
      NO. TYPE    R    UR    UL     L    LL    LR    MASS      (CM)        (CM)        (CM)    (CM/SEC)    (CM/SEC)    (CM/SEC)        (CM)

        1     1    2     7     6     5     4     3  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        2     1    8     8     7     1     3     8  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        3     1    8     2     1     4     9     9  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        4     1    3     1     5    10     9     9  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        5     1    1     6    10    10    10     4  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        6     1    7    11    11    10     5     1  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01
        7     1    8    11    11     6     1     2  1.95D-02  0.0         0.0         0.0         0.0         0.0         0.0          2.000D-01



SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

              F I X E D    R E F L E C T O R    B L O C K    D A T A    A N D    I N I T I A L    C O N D I T I O N S

      BLOCK   SIDE BK NO      FACE BLOCK NO.             MASS    ANG LOC        UR          UT         UDR         UDT    FACE GAP   SIDE GAP
     NO. TYPE   N-1   N+1    1    2    3    4    5    6                (DEG)        (CM)        (CM)    (CM/SEC)    (CM/SEC)       (CM)       (CM)

       8     2    11     9    3    2    2    2    7    0  5.000D-01  0.0        0.0         0.0         0.0         0.0         2.000D-01
       9     3     8    10    4    4    3    3    0    0  4.000D-01 -9.000D+01  0.0         0.0         0.0         0.0         2.000D-01
      10     2     9    11    6    5    5    5    4    0  5.000D-01 -1.800D+02  0.0         0.0         0.0         0.0         2.000D-01
      11     3    10     8    7    7    6    6    0    0  4.000D-01 -2.700D+02  0.0         0.0         0.0         0.0         2.000D-01
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))
                   S E I S M I C    W A V E    D A T A
          X AXIS EXCITATION FREQUENCY   =                      3.0000  (  HZ   )
          Y AXIS EXCITATION FREQUENCY   =                      0.0     (  HZ   )
          X AXIS EXCITATION PHASE ANGLE =                      0.0     (  DEG  )
          Y AXIS EXCITATION PHASE ANGLE =                      0.0     (  DEG  )
          X AXIS EXCITATION AMPLITUDE   =                    250.0000  (       )
          Y AXIS EXCITATION AMPLITUDE   =                      0.0     (       )
          X AXIS MULTIPLICATION FACTOR  =                      1.0000  (   -   )
          Y AXIS MULTIPLICATION FACTOR  =                      1.0000  (   -   )
```

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))
               P L O T    B L O C K    N U M B E R
                    1         2         3         4         5         6         7         8         9        10
                   11
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

                    I N I T I A L    C O O R D I N A T E S    O F    B L O C K

   I NO.       X           Y       I NO.       X           Y       I NO.       X           Y       I NO.       X           Y
   I    1  0.0         0.0         I    2  1.020D+01  0.0         I    3  5.100D+00 -8.833D+00 I    4 -5.100D+00 -8.833D+00 I
   I    5 -1.020D+01 -4.184D-09 I    6 -5.100D+00  8.833D+00 I    7  5.100D+00  8.833D+00 I    8  3.980D+01  0.0         I
   I    9 -8.163D-09 -3.980D+01 I   10 -3.980D+01  1.633D-08 I   11  2.449D-08  3.980D+01 I
```

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

                    I N I T I A L    C O O R D I N A T E S    O F    K E Y

B-NO. I P-NO.      X           Y       I P-NO.      X           Y       I
    1 I      1 -1.697D+01  2.360D+01 I      2 -1.697D+01 -2.360D+01 I
    2 I      1  2.283D+01  1.620D+01 I      2 -2.283D+01  1.620D+01 I
    3 I      1  1.697D+01 -2.360D+01 I      2  1.697D+01  2.360D+01 I
    4 I      1 -2.283D+01 -1.620D+01 I      2  2.283D+01 -1.620D+01 I
```

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

                    I N I T I A L    C O O R D I N A T E S    O F    R E S T R A I N T    F O R    C O R E    B A R R E L

B-NO. I P-NO.      X           Y       I P-NO.      X           Y       I
    1 I      1 -4.445D+00 -1.768D+01 I      2 -4.445D+00  1.768D+01 I
    2 I      1 -1.768D+01  4.445D+00 I      2  1.768D+01  4.445D+00 I
    3 I      1  4.445D+00  1.768D+01 I      2  4.445D+00 -1.768D+01 I
    4 I      1  1.768D+01 -4.445D+00 I      2 -1.768D+01 -4.445D+00 I


      CORE USED    =     6246

      MAXIMUM CORE =    75000
```

Appendix B (Continued)

```
RESTART DATA STORE ON FILE NO. 16
NUMBER OF STEP =    10001
CURRENT TIME   =    0.100010000D+01
TIME STEP SIZE =    0.100000000D-03

RESPONSE DATA PRINTOUT
CURRENT TIME =    1.0001000D+00




SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

      F U E L   B L O C K   D I S P L A C E M E N T   ( M A X I M U M )

BLK I        MAX  X - DISPLACEMENT                           I        MAX  Y - DISPLACEMENT                          I
NO. I                                                        I                                                       I
    I  DISP.-X(CM)      DISP.-Y(CM)       TIME (SEC)         I  DISP.-X(CM)      DISP.-Y(CM)       TIME (SEC)        I
    I                                                        I                                                       I
  1 I  -0.41059         -0.18180          1.2689             I   0.01072         -0.33759          0.3301            I
  2 I  -0.56859          0.08477          1.2635             I  -0.23601         -0.31710          0.9945            I
  3 I  -0.41502          0.02523          1.9401             I   0.15584          0.28363          0.3796            I
  4 I   0.39865         -0.00481          1.4167             I  -0.05851          0.36309          1.2006            I
  5 I   0.53047         -0.05171          1.4351             I   0.20392         -0.33091          1.1434            I
  6 I   0.40736         -0.13489          1.4441             I  -0.15084         -0.24120          1.5718            I
  7 I  -0.39637          0.00392          1.9007             I  -0.00996          0.23420          0.3974            I



SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

      F U E L   B L O C K   A C C E L E R A T I O N   ( M A X I M U M )

BLK I        MAX  X - ACCELERATION                           I        MAX  Y - ACCELERATION                          I
NO. I                                                        I                                                       I
    I ACCEL.-X(CM/S**2) ACCEL.-Y(CM/S**2) TIME (SEC)         I ACCEL.-X(CM/S**2) ACCEL.-Y(CM/S**2) TIME (SEC)        I
    I                                                        I                                                       I
  1 I  -2.8876D+04       1.5811D-01        0.0674            I  -1.0700D+04       1.8331D+04        0.1417           I
  2 I  -3.0084D+04       8.6248D-03        0.0841            I  -1.3413D+04       2.3296D+04        0.1561           I
  3 I   2.7708D+04       5.1600D-03        0.0227            I   1.6529D+04       2.8646D+04        0.3489           I
  4 I   3.3850D+04       4.4308D+02        0.2098            I  -1.1431D+04       1.9713D+04        0.2206           I
  5 I   4.2255D+04      -3.6815D-02        0.1164            I   1.3230D+04       2.2823D+04        1.2405           I
  6 I   4.1258D+04       2.1674D-02        0.0170            I   1.0783D+04      -1.8686D+04        0.2150           I
  7 I   2.7722D+04       5.1600D-03        0.0227            I  -1.0037D+04      -1.7275D+04        0.1542           I
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

     F I X E D    R E F L E C T O R    B L O C K    D I S P L A C E M E N T    ( M A X I M U M )

     B Y    C A R T E S I A N    C O O R D I N A T E S

BLK I        MAX  X - DISPLACEMENT                    I        MAX  Y - DISPLACEMENT                    I
NO. I                                                 I                                                 I
    I  X-DISP.(CM)     Y-DISP.(CM)     TIME (SEC)     I  X-DISP.(CM)     Y-DISP.(CM)     TIME (SEC)     I
    I                                                 I                                                 I
  8 I  -0.06185         0.00033        0.0075         I   0.00887         0.00501        0.3950         I
  9 I  -0.05748        -0.00082        0.0071         I  -0.01774        -0.00951        0.0640         I
 10 I  -0.06312        -0.00000        0.0077         I  -0.01021         0.00546        0.2709         I
 11 I  -0.05716         0.00048        0.0071         I   0.00765         0.00755        0.1635         I
```

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

     F I X E D    R E F L E C T O R    B L O C K    A C C L E R A T I O N    ( M A X I M U M )

     B Y    C A R T E S I A N    C O O R D I N A T E S

BLK I        MAX  X - ACCELERATION                         I        MAX  Y - ACCELERATION                         I
NO. I                                                      I                                                      I
    I X-ACCEL.(CM/S**2) Y-ACCEL.(CM/S**2) TIME (SEC)       I X-ACCEL.(CM/S**2) Y-ACCEL.(CM/S**2) TIME (SEC)       I
    I                                                      I                                                      I
  8 I   3.8886D+03        4.4672D+01       0.0370          I   9.3225D+02       -6.5141D+02        0.1561          I
  9 I  -3.0581D+03        1.7852D+01       0.0201          I  -8.7796D+02       -1.3591D+03        0.3489          I
 10 I  -5.5078D+03        3.4644D-01       0.0170          I  -1.7355D+02       -8.8311D+02        1.2405          I
 11 I  -2.9934D+03       -8.5336D+01       0.0201          I   6.2637D+02        8.6602D+02        0.1542          I
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

      B A S E   P L A T E   D I S P L A C E M E N T   ( M A X I M U M )

     I        MAX  X - DISPLACEMENT                  I        MAX  Y - DISPLACEMENT                  I
     I                                               I                                               I
     I  X-DISP.(CM)     Y-DISP.(CM)     TIME (SEC)   I  X-DISP.(CM)     Y-DISP.(CM)     TIME (SEC)   I
     I                                               I                                               I
     I  -0.04250        -0.00000        0.0051       I  -0.00423         0.00150        0.2724       I


      B A S E   P L A T E   V E L O C I T Y   ( M A X I M U M )

     I          MAX  X - VELOCITY                    I          MAX  Y - VELOCITY                    I
     I                                               I                                               I
     I X-VEL.(CM/SEC)   Y-VEL.(CM/SEC)    TIME (SEC) I X-VEL.(CM/SEC)   Y-VEL.(CM/SEC)    TIME (SEC) I
     I                                               I                                               I
     I -13.25622        -0.00000        0.0001       I  0.28486         -0.45135        0.2774       I


      B A S E   P L A T E   A C C E L E R A T I O N   ( M A X I M U M )

     I        MAX  X - ACCELERATION                  I        MAX  Y - ACCELERATION                  I
     I                                               I                                               I
     I X-ACCEL.(CM/S**2) Y-ACCEL.(CM/S**2) TIME (SEC) I X-ACCEL.(CM/S**2) Y-ACCEL.(CM/S**2) TIME (SEC) I
     I                                               I                                               I
     I  3.8163D+03  -1.5211D-01       0.0046         I  3.0849D+02  -1.3817D+02        0.2728        I


SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

      F I X E D   R E F L E C T O R   B L O C K   F O R C E   O F   R E S T R A I N T

      B Y   C A R T E S I A N   C O O R D I N A T E S
                                                         ( M A X I M U M )
BLK I                 RESTRAINT FOR CORE BARREL                          I                 RESTRAINT FOR BASE PLATE                          I
NO. I          MAX X-COMP.               I          MAX Y-COMP.          I          MAX X-COMP.              I           MAX Y-COMP.         I
    I    FRSM-X      FRSM-Y    TIME      I    FRSM-X      FRSM-Y    TIME I    FRM-X       FRM-Y     TIME      I    FRM-X       FRM-Y     TIME  I
    I                                    I                               I                                   I                               I
  8 I  8.533D+00  1.281D-02 2.0000 I  0.0        0.0        2.0000 I -4.687D+02  8.011D+00 0.0212 I -4.672D+01 -3.883D+01 0.3941 I
  9 I -6.675D+00  3.710D+01 1.9969 I  0.0        0.0        2.0000 I -3.776D+02  3.078D-01 0.0204 I  1.562D+02  7.711D+01 0.0633 I
 10 I  1.174D+01  1.410D-01 1.9970 I  0.0        0.0        2.0000 I  4.023D+02 -5.997D-02 0.0104 I  2.338D+01 -3.962D+01 1.2608 I
 11 I  3.919D+00 -2.647D+00 2.0000 I  0.0        0.0        2.0000 I -3.688D+02 -9.019D+00 0.0204 I -3.936D+01 -6.543D+01 0.1629 I
```

Appendix B (Continued)

```
SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

      F I X E D     R E F L E C T O R     B L O C K     F O R C E     O F     R E S T R A I N T

      B Y     P O L A R     C O O R D I N A T E S
                                                  ( M A X I M U M )
BLK I                 RESTRAINT FOR CORE BARREL                   I                 RESTRAINT FOR BASE PLATE                    I
NO. I         MAX R-COMP.          I          MAX T-COMP.         I          MAX R-COMP.         I          MAX T-COMP.         I
    I    FRSM-R     FRSM-T   TIME  I    FRSM-R     FRSM-T   TIME  I    FRM-R      FRM-T     TIME  I    FRM-R      FRM-T     TIME  I
    I                              I                              I                              I                              I
  8 I  1.022D+03 -5.206D+00 0.0067 I -1.460D+02 -8.279D+01 0.3943 I -4.687D+02  8.001D+00 0.0212 I -4.673D+01 -3.882D+01 0.3941 I
  9 I -1.575D+02  2.958D+02 0.0633 I -1.446D+01  9.501D+02 0.0064 I -7.717D+01  1.562D+02 0.0633 I -7.932D-01 -3.776D+02 0.0204 I
 10 I -1.042D+03 -9.450D-04 0.0069 I -1.678D+02  9.018D+01 0.2701 I -4.023D+02  5.998D-02 0.0104 I -2.338D+01  3.961D+01 1.2608 I
 11 I -1.253D+02  1.268D+02 0.1628 I -8.532D+00 -9.450D+02 0.0063 I -6.544D+01  3.935D+01 0.1629 I -9.484D+00  3.688D+02 0.0204 I

         RESTART DATA STORE ON FILE NO. 16
         NUMBER OF STEP =   20000
         CURRENT TIME   =   0.2000000000D+01
         TIME STEP SIZE =   0.1000000000D-03



        ******** SUMMARY OF SONATINA-2H ********

        PROBLEM TITLE      SONATINA-2H SAMPLE PROBLEM NO.1 (SINE. WAVE 3.0(HZ), MAX. 250(GAL))

        CPU TIME (SEC)                            =    741.00000

        CPU TIME LIMIT (SEC)                      =   1000.00000

        CALCULATION STOP TIME (SEC)               =      2.00000

        NUMBER OF TOTAL CALCULATION TIME HISTORY  =   20000

        NUMBER OF TOTAL TIME STEP                 =   20000

        NUMBER OF TIME HISTORY DATA  (FILE NO.10) =     191

        NUMBER OF CORE DEFORMED DATA (FILE NO.20) =      21

        NUMBER OF DATA DUMP          (FILE NO.16) =       2

        NUMBER OF TIME STEP DATA PRINTOUT         =       1

        NUMBER OF MAXIMUM VALUE PRINTOUT          =       2
```

Appendix C Sample problem input for SONATINA-2H-PLOT

```
  DATA                 1         2         3         4         5         6         7         8
SEQ. NO.    ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0

    1       SONATINA-2H-PLOT SAMPLE PROBLEM NO.1
    2           1    1    1    0    1
    3        0.0
    4       SONATINA-2H SAMPLE PROBLEM NO.1
    5           1
    6           1    2    1
    7       SONATINA-2H SAMPLE PROBLEM NO.1
    8           1
    9           1    2    3
   10       SONATINA-2H SAMPLE PROBLEM NO.1
   11           2
   12          10    2    1
   13          11    2    1
   14       SONATINA-2H SAMPLE PROBLEM NO.1
   15           2
   16          10    2    3
   17          11    2    3
   18       SONATINA-2H SAMPLE PROBLEM NO.1
   19           2
   20          10    2    9
   21          11    2    9
   22       *END
   23        150.0     20.0
   24       SONATINA-2H SAMPLE PROBLEM
   25           8
   26          1X   1Y   3X   3Y   8X   8Y  13R  13T
   27       SONATINA-2H SAMPLE PROBLEM
   28           5    1
   29       END

            ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0
                     1         2         3         4         5         6         7         8
```

Appendix D Graphical output of SONATINA-2H-PLOT

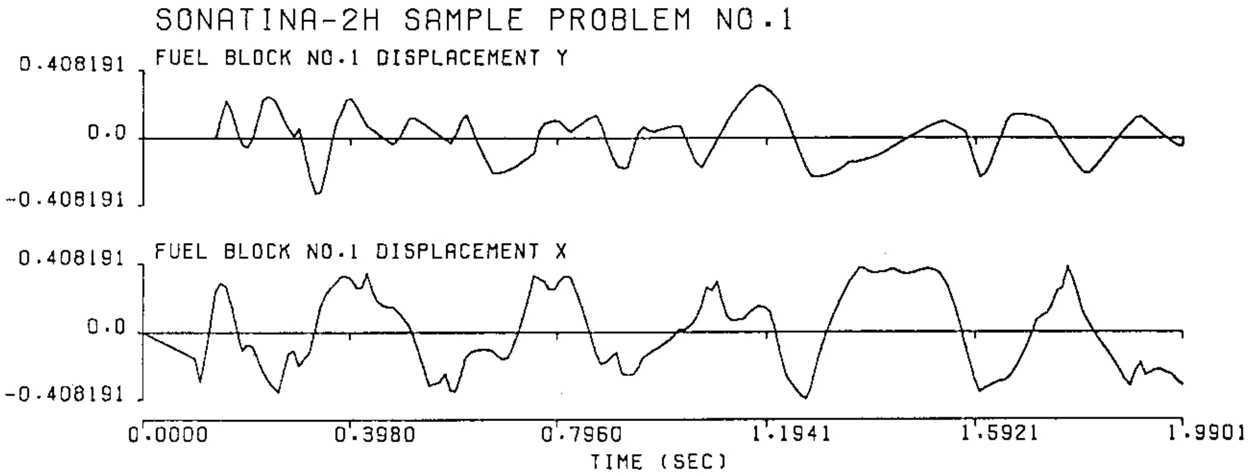

Fig. D. 1 Output of SONATINA-2H-PLOT(1)

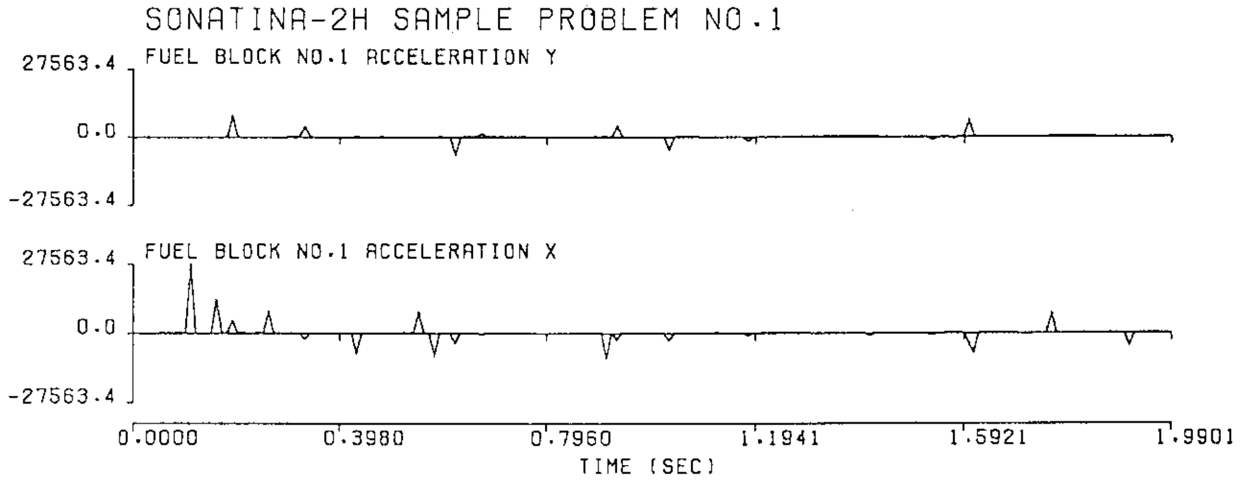

Fig. D. 2 Output of SONATINA-2H-PLOT(2)

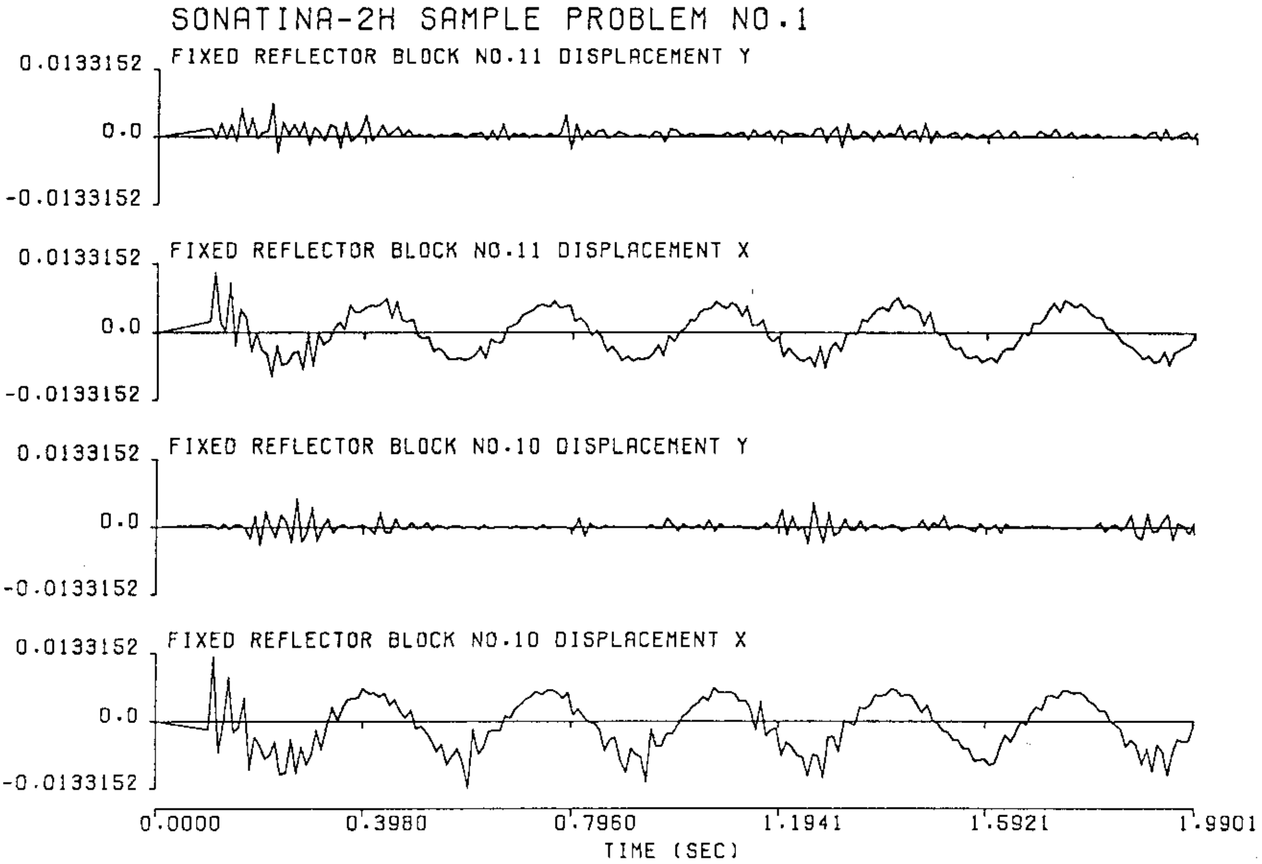

Fig. D. 3 Output of SONATINA-2H-PLOT(3)

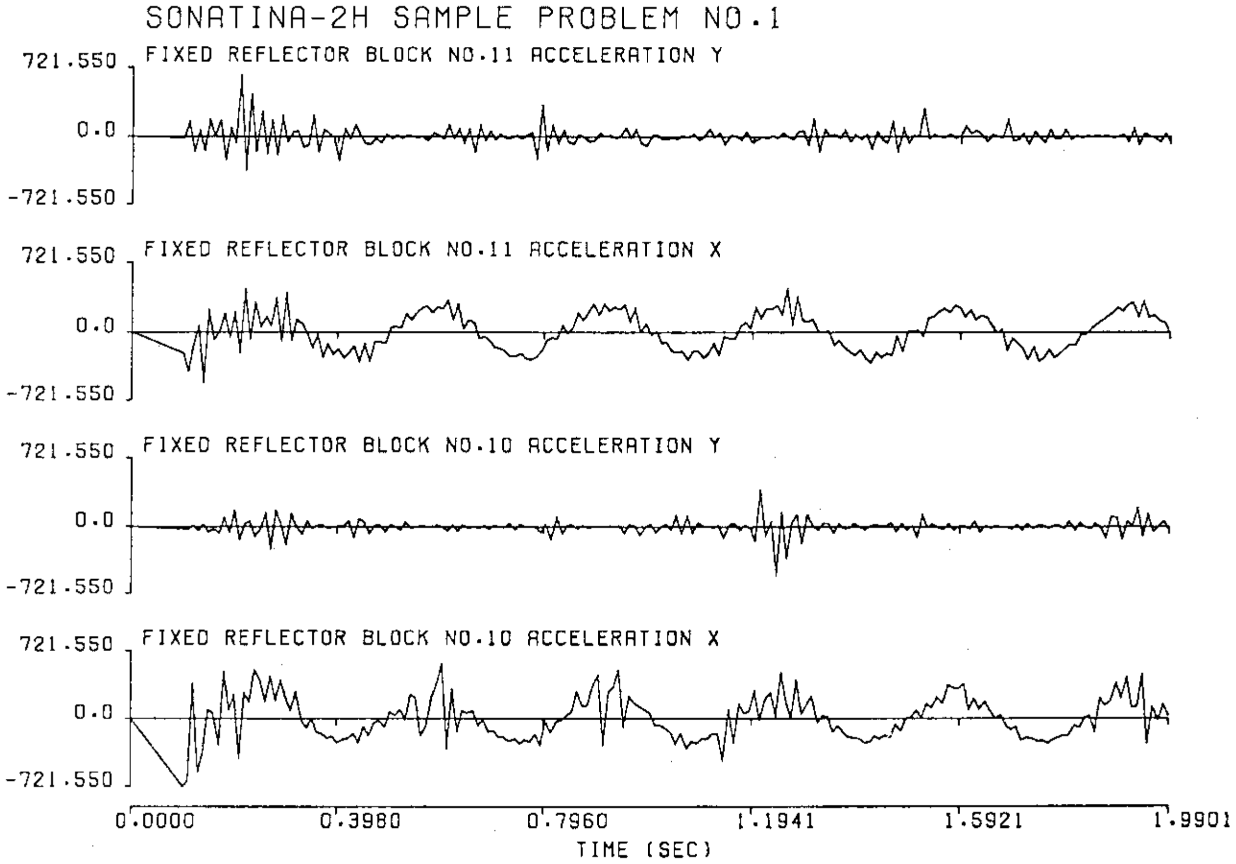

Fig. D. 4 Output of SONATINA-2H-PLOT (4)

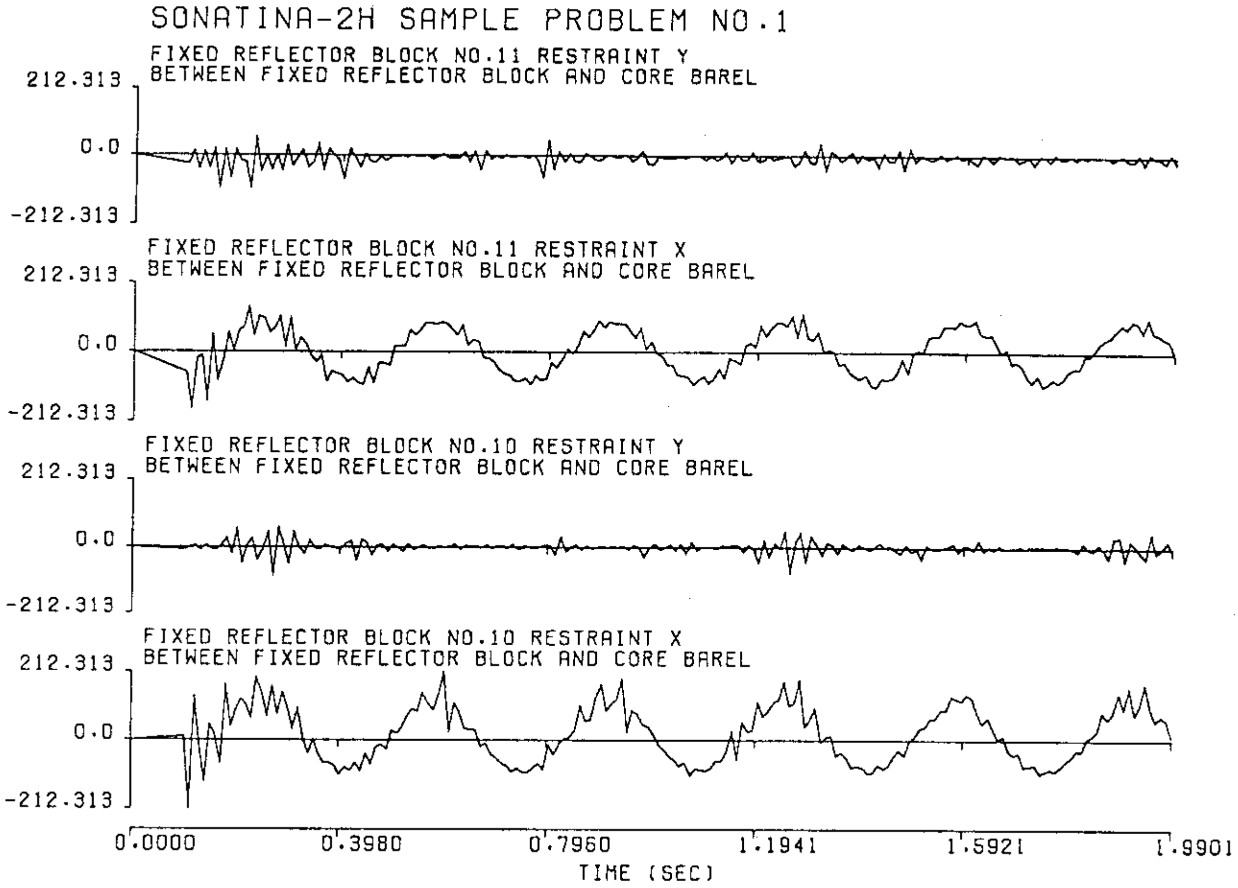

Fig. D. 5 Output of SONATINA-2H-PLOT (5)

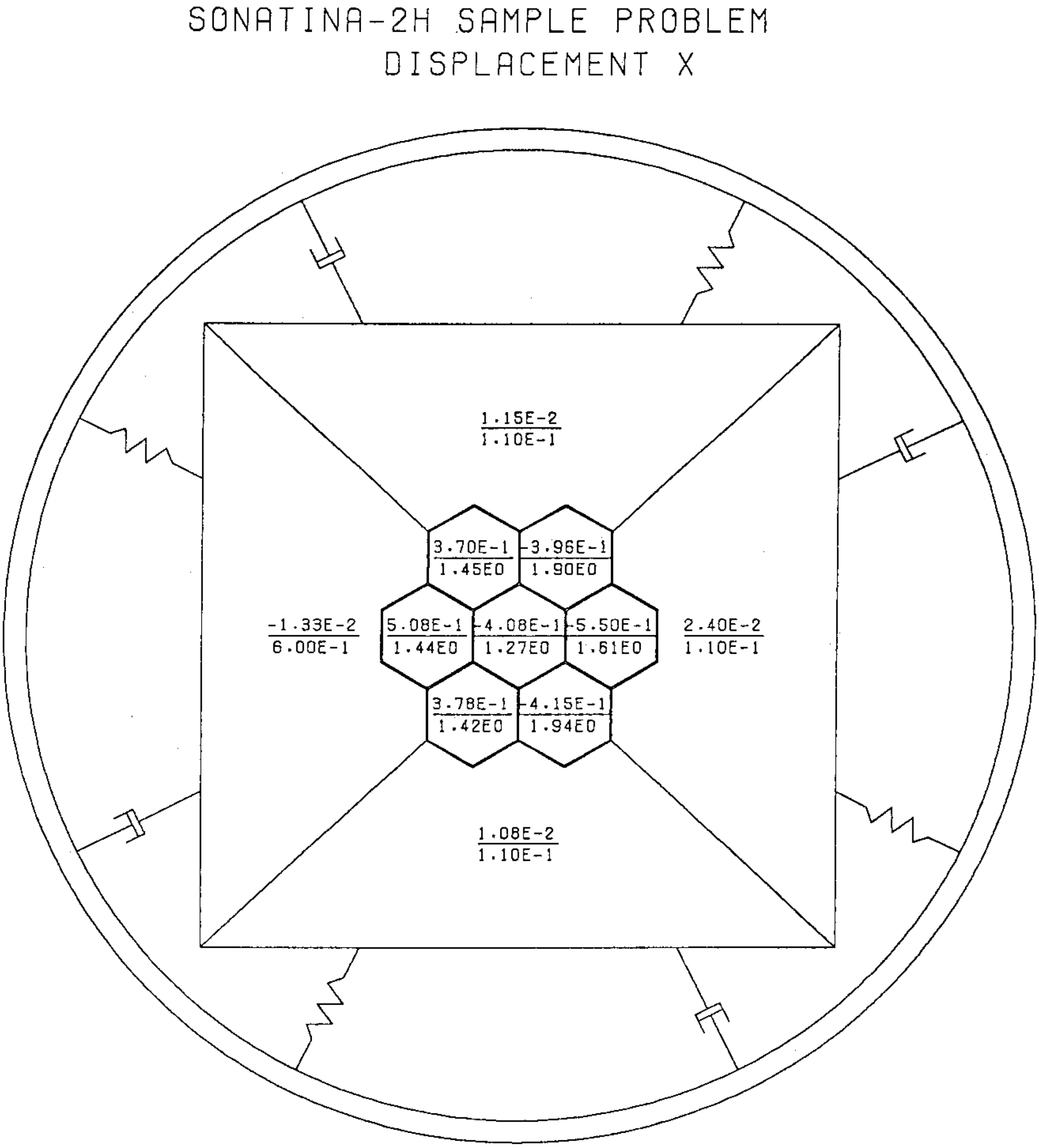

Fig. D. 6 Output of SONATINA-2H-PLOT(6)

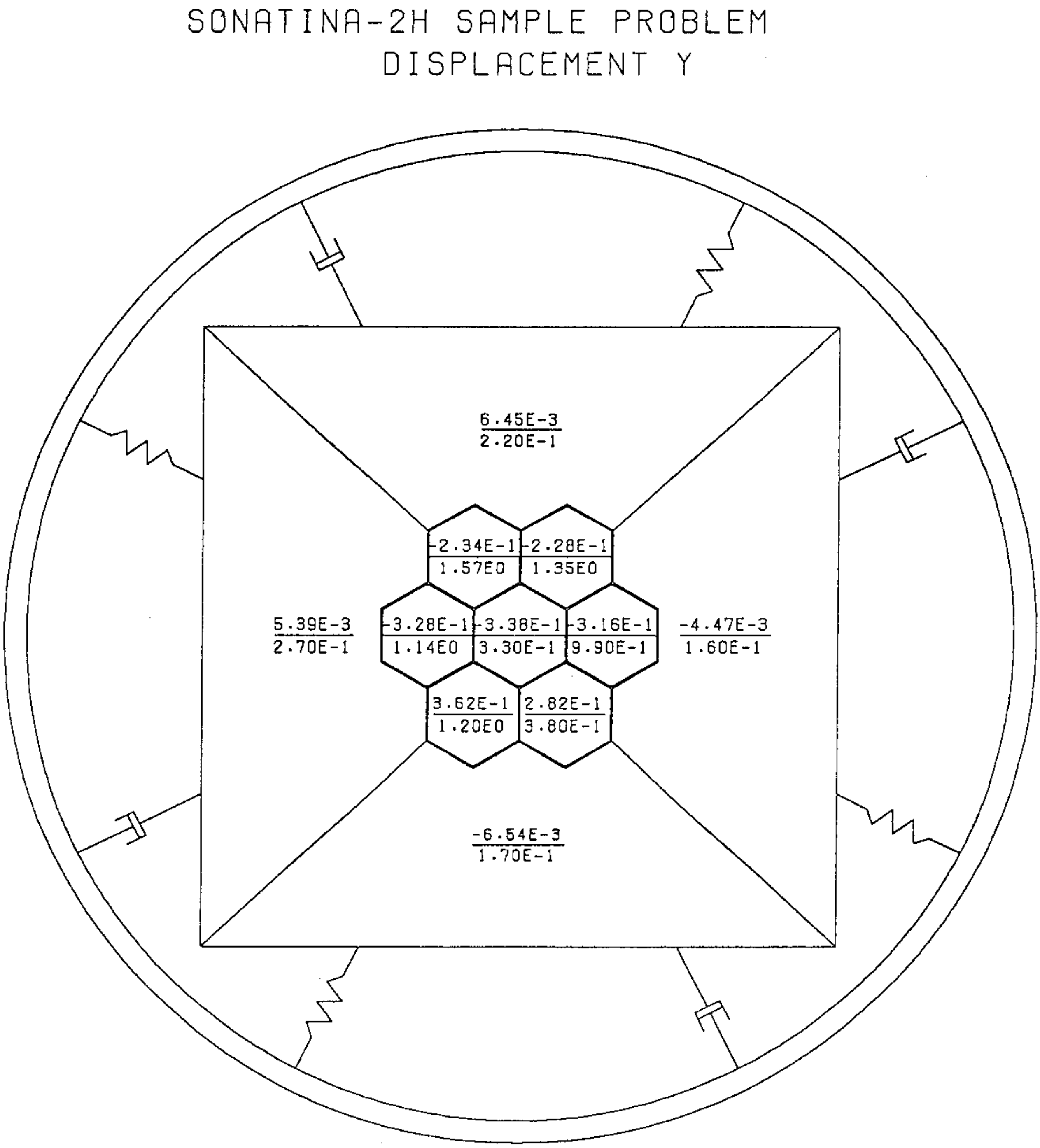

Fig. D. 7 Output of SONATINA-2H-PLOT(7)

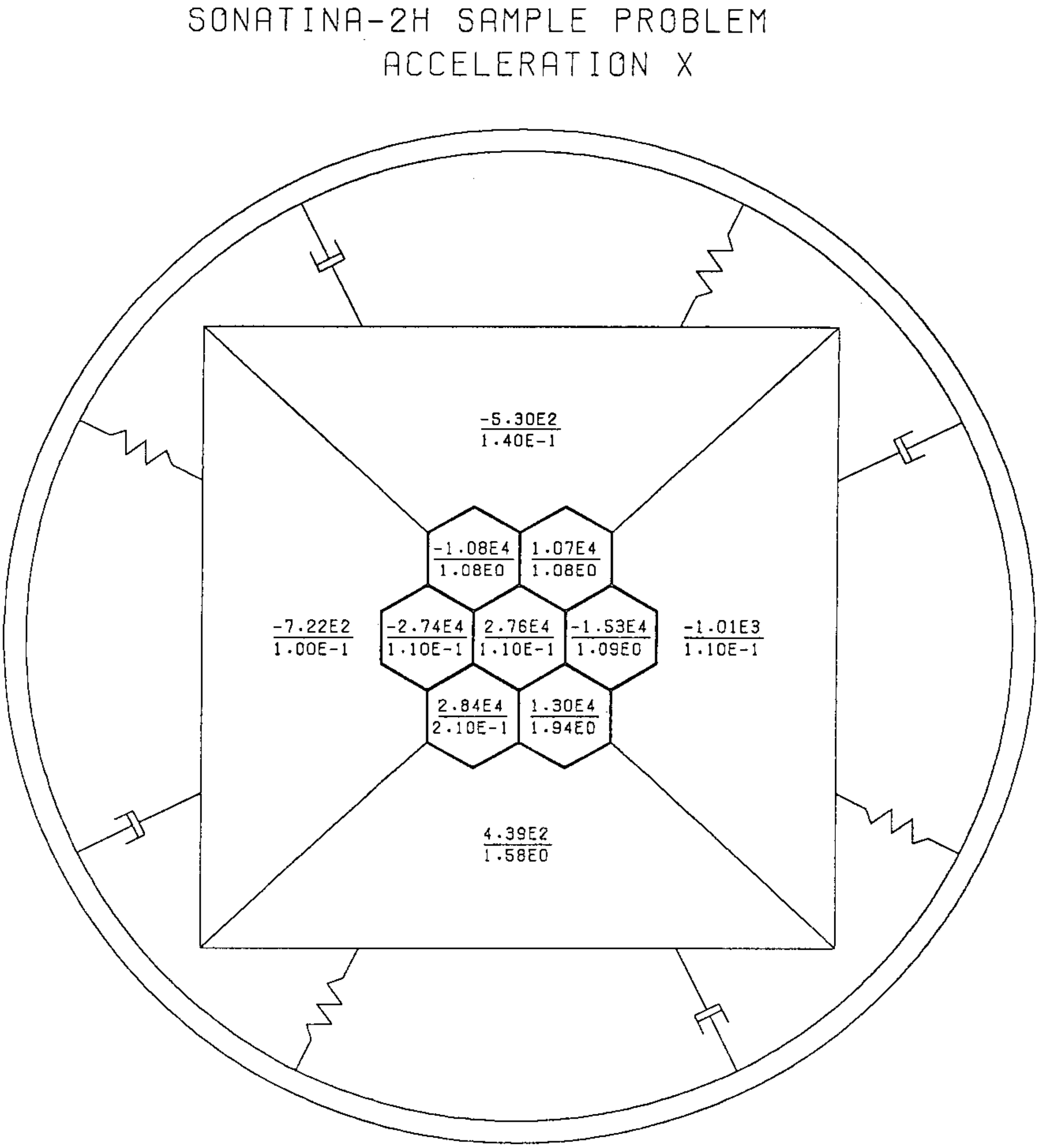

Fig. D.8 Output of SONATINA-2H-PLOT (8)

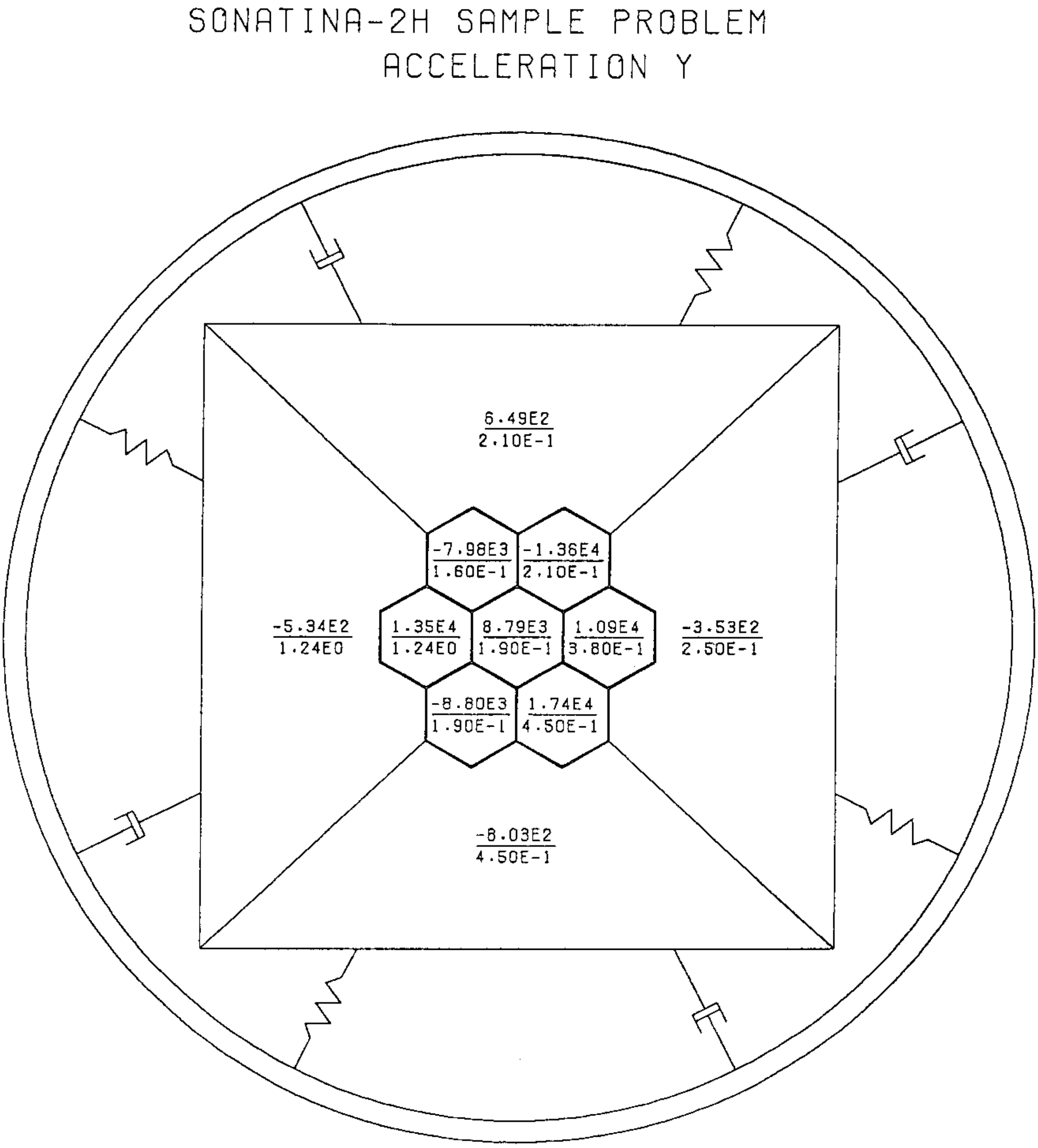

Fig. D. 9 Output of SONATINA-2H-PLOT (9)

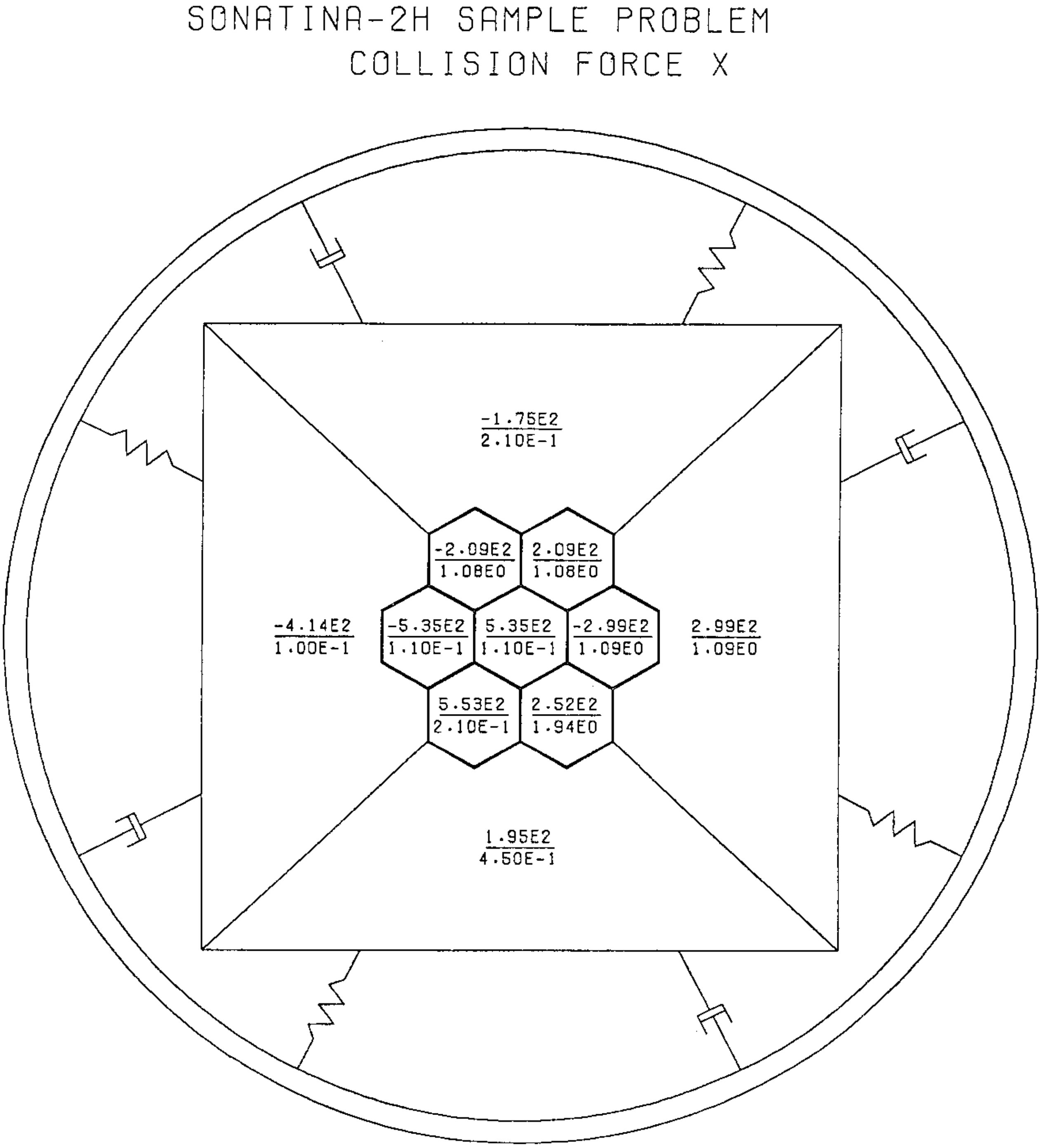

Fig. D.10 Output of SONATINA-2H-PLOT(10)

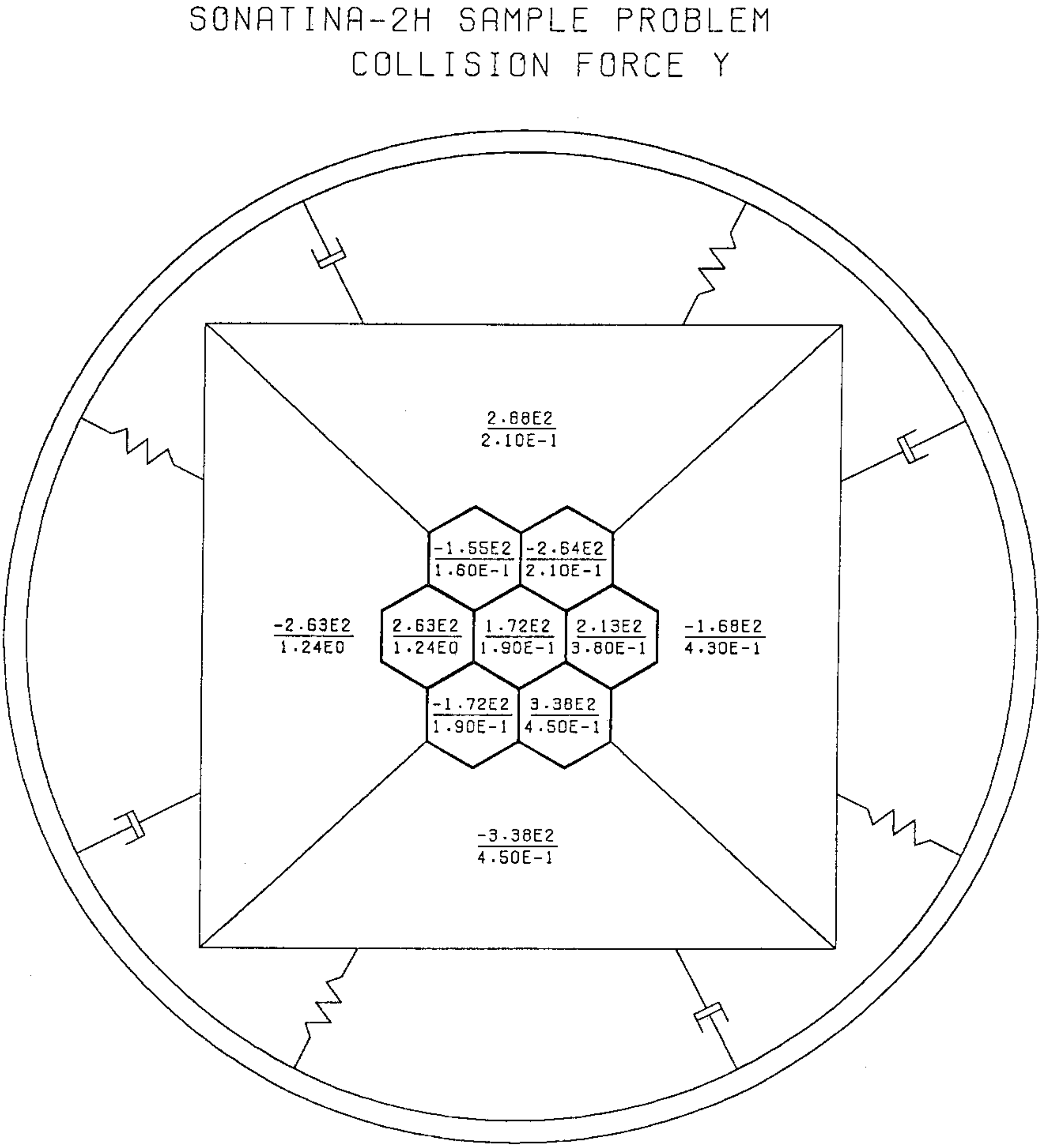

Fig. D. 11 Output of SONATINA-2H-PLOT(11)

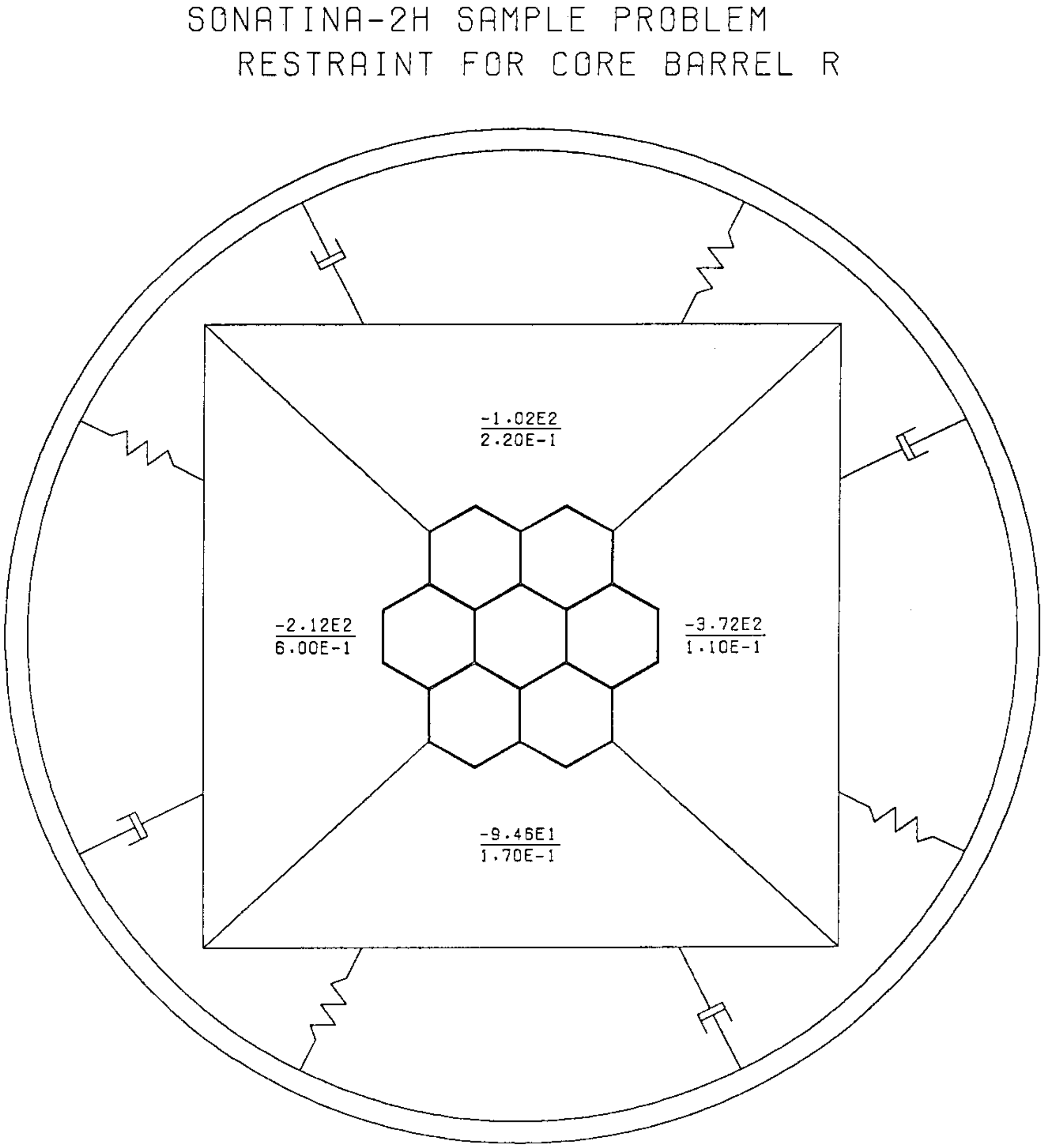

Fig. D. 12 Output of SONATINA-2H-PLOT (12)

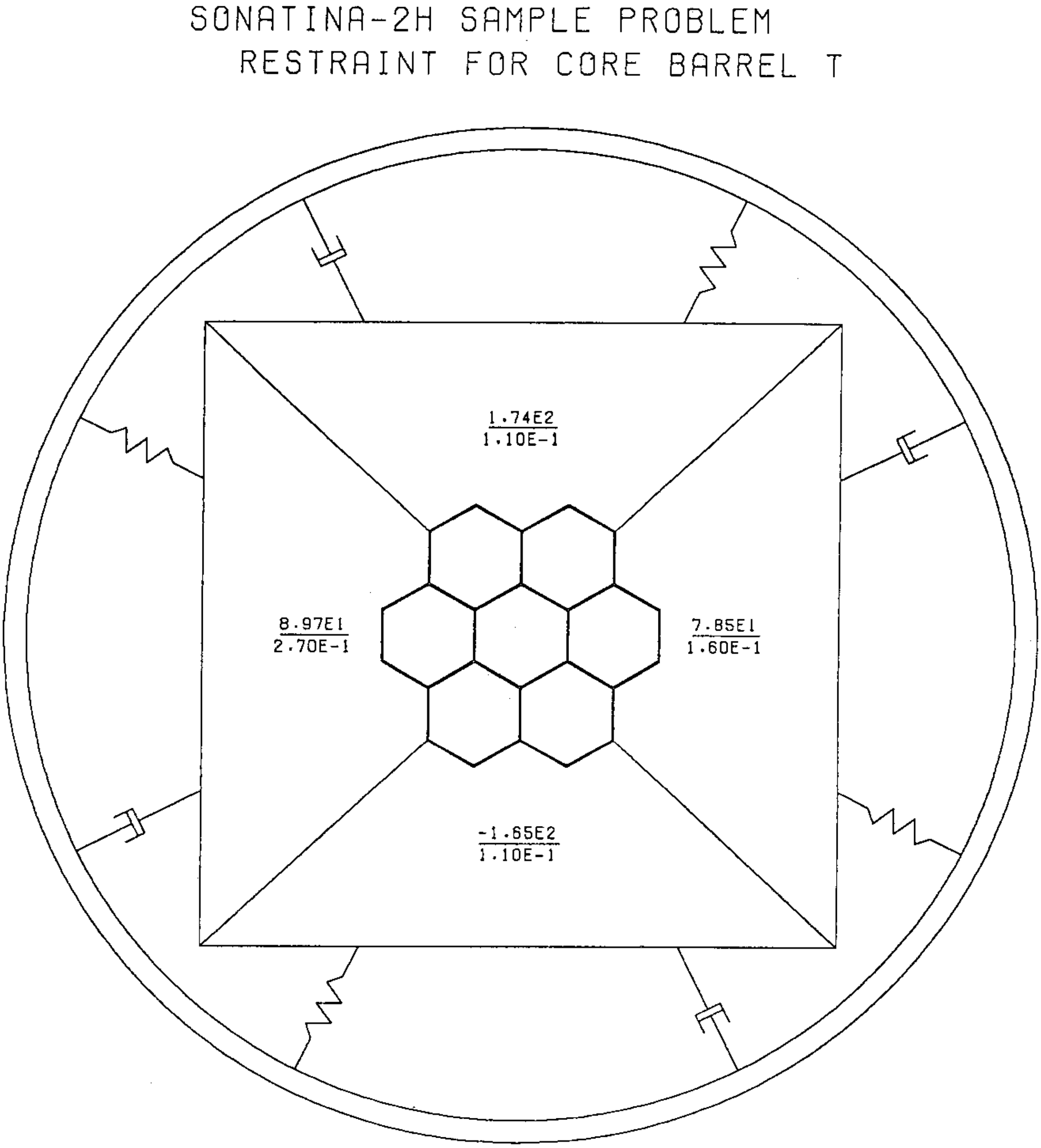

Fig. D. 13 Output of SONATINA-2H-PLOT(13)

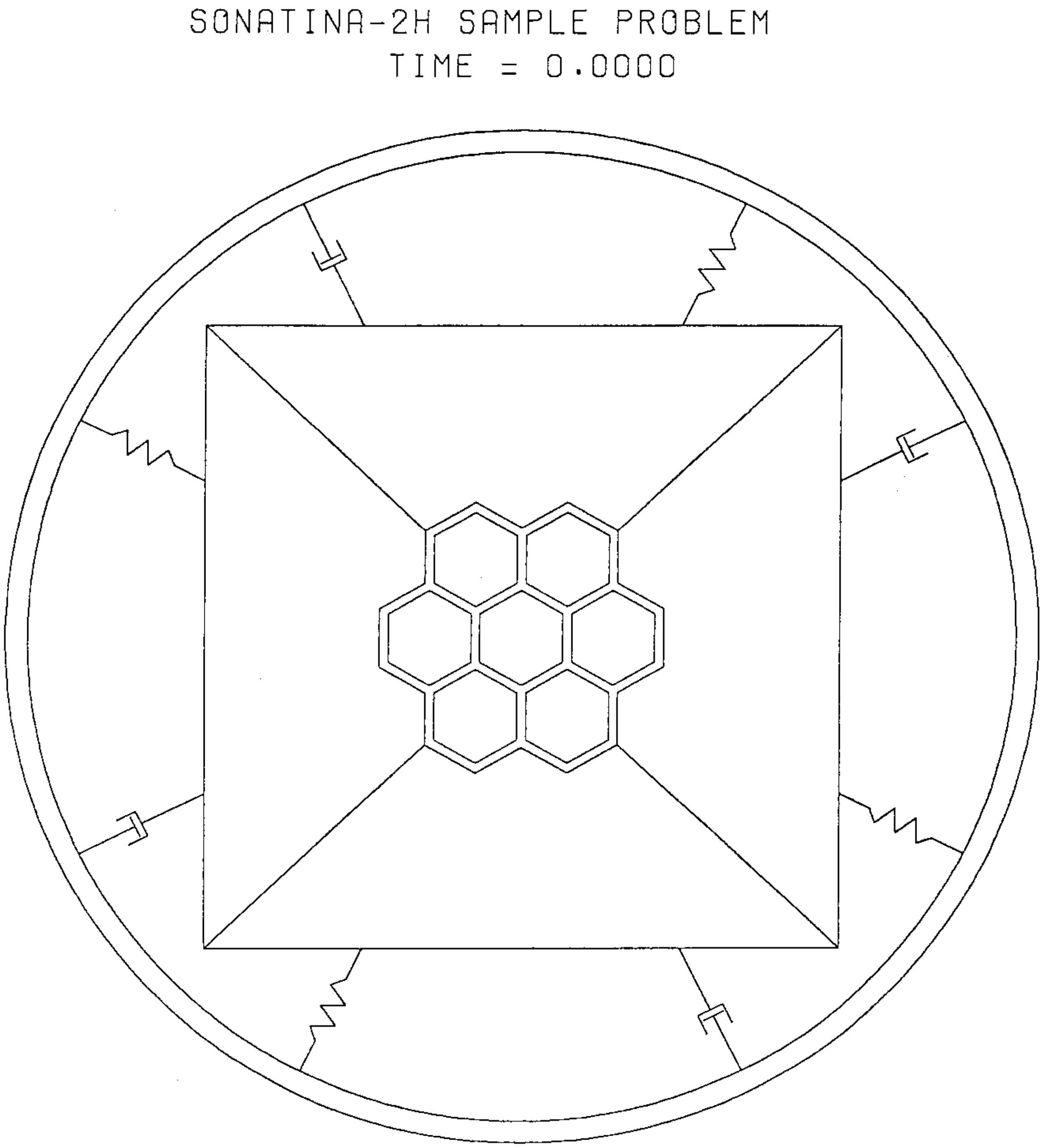

Fig. D.14 Output of SONATINA-2H-PLOT(14)

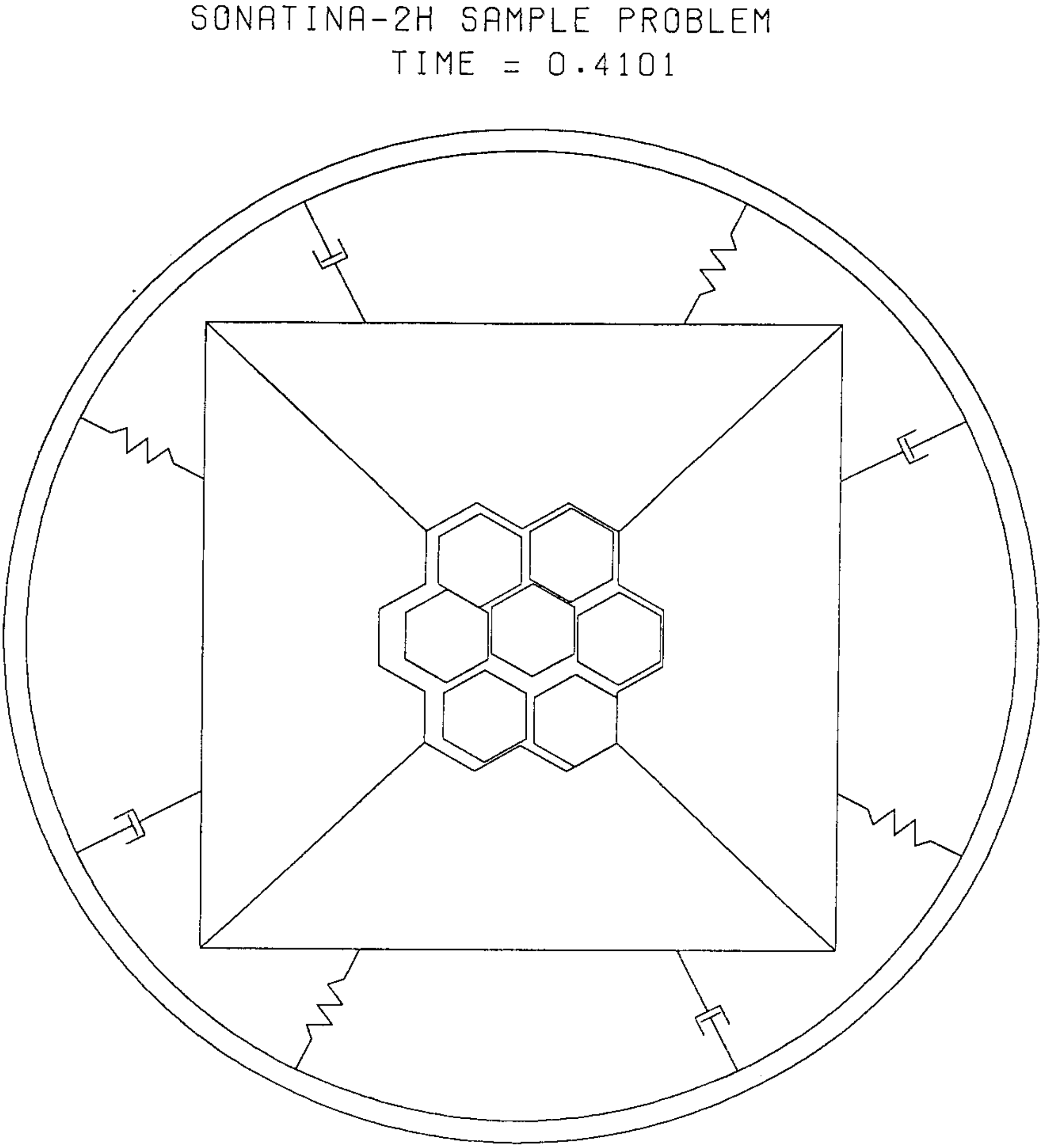

Fig. D. 15 Output of SONATINA-2H-PLOT (15)

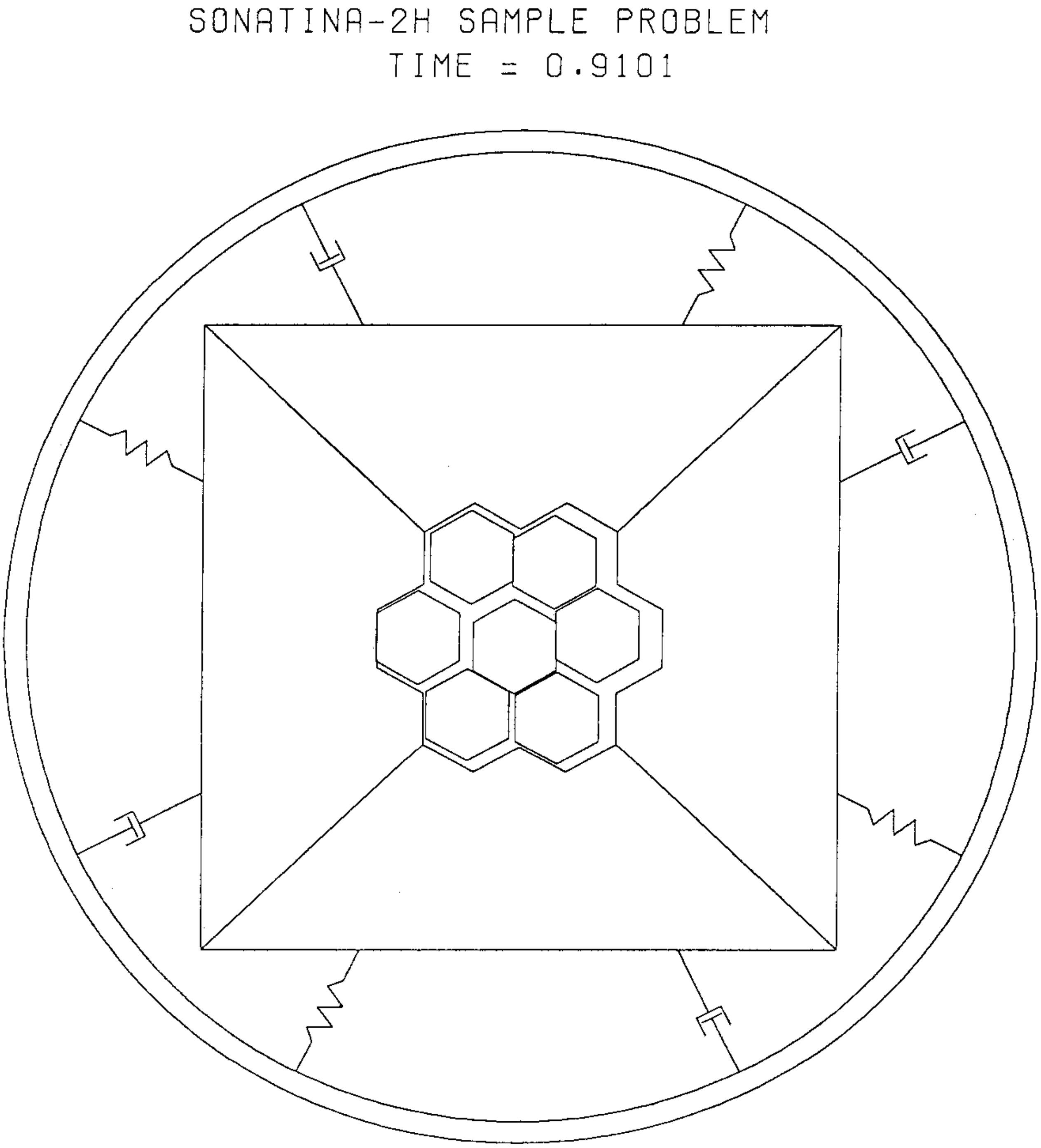

Fig. D. 16 Output of SONATINA-2H-PLOT(16)

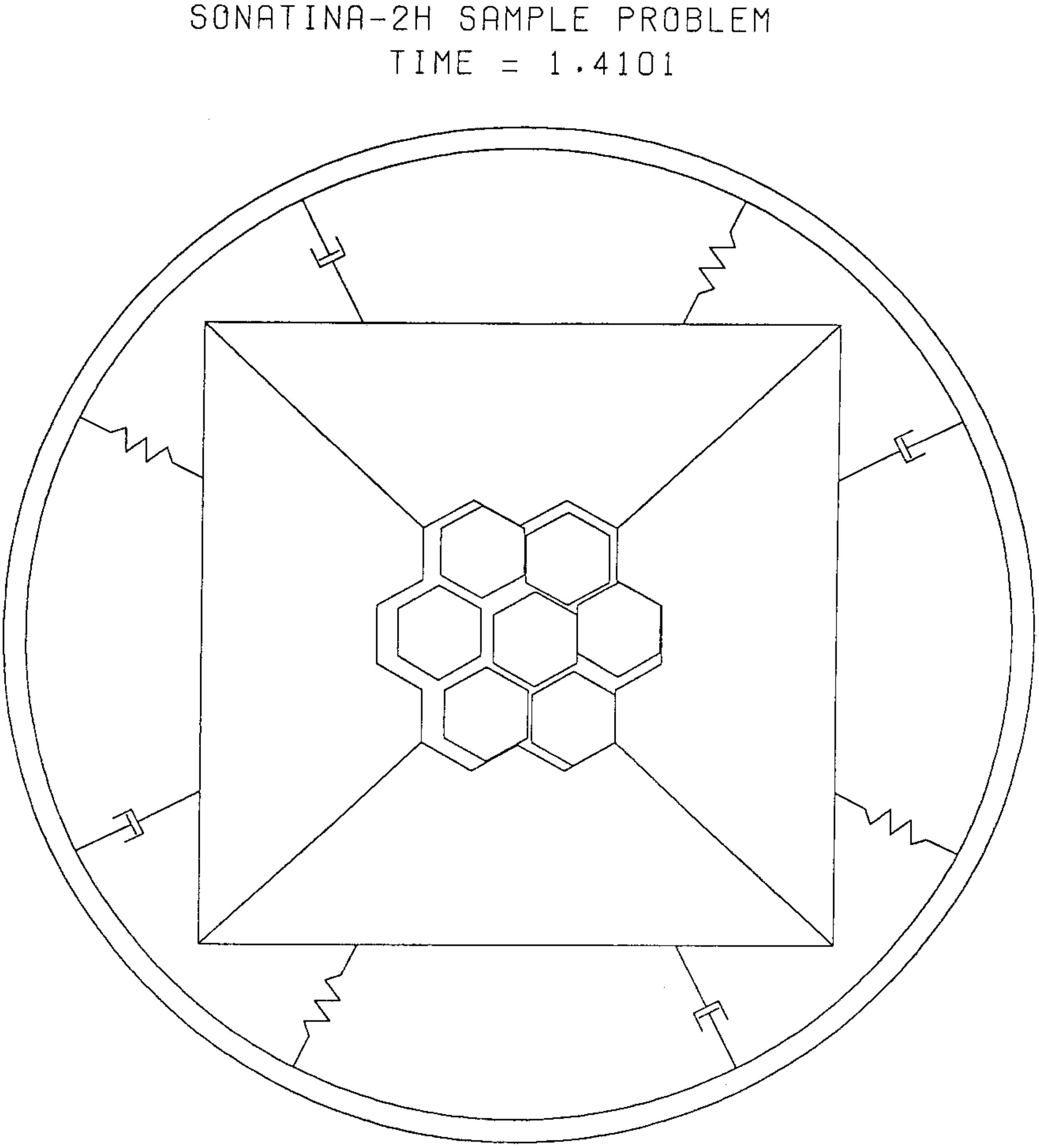

Fig. D. 17 Output of SONATINA-2H-PLOT(17)

SONATINA-2H SAMPLE PROBLEM
TIME = 1.9101

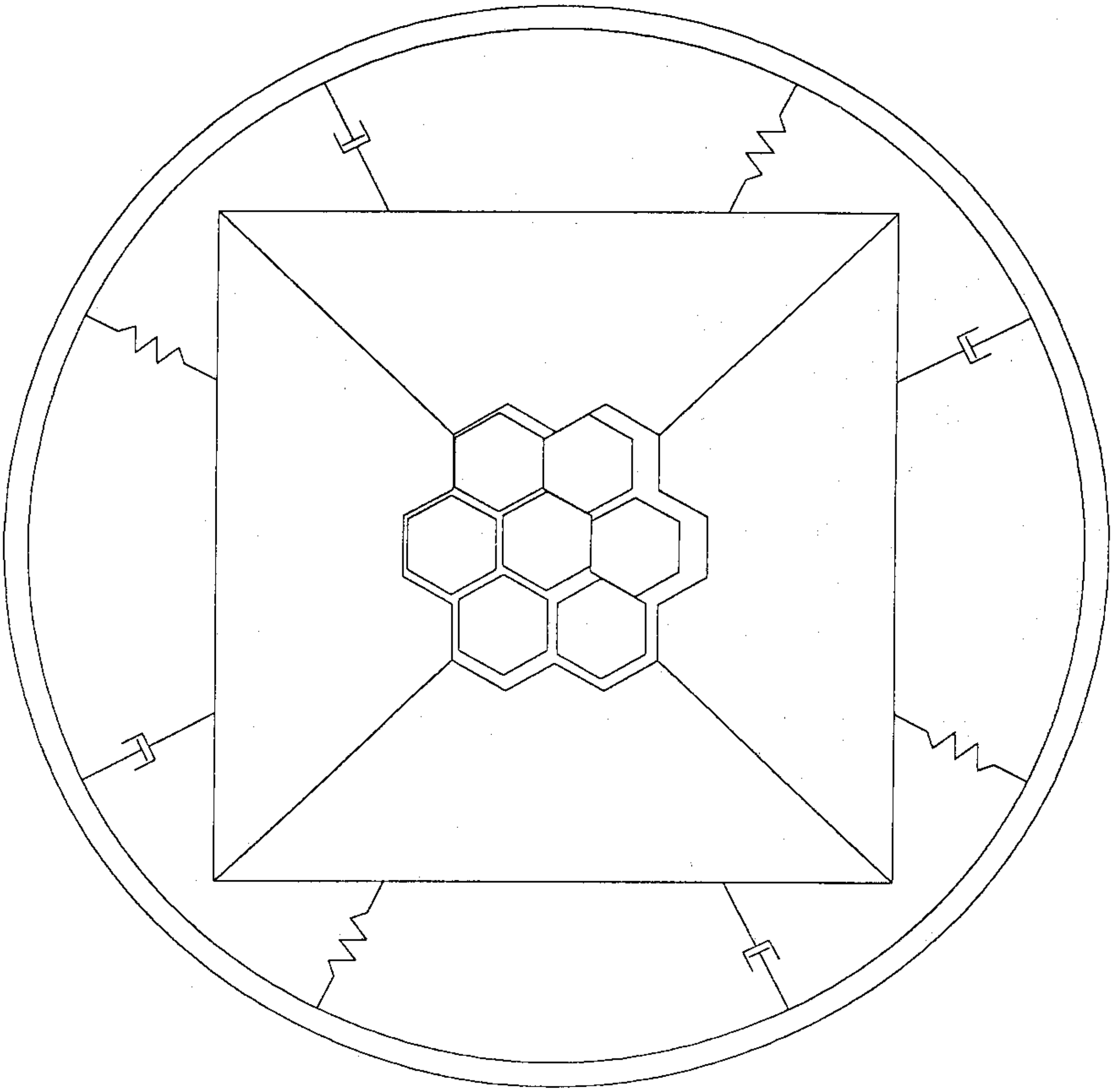

Fig. D.18 Output of SONATINA-2H-PLOT(18)

SONATINA-2H SAMPLE PROBLEM
DISPLACEMENT X

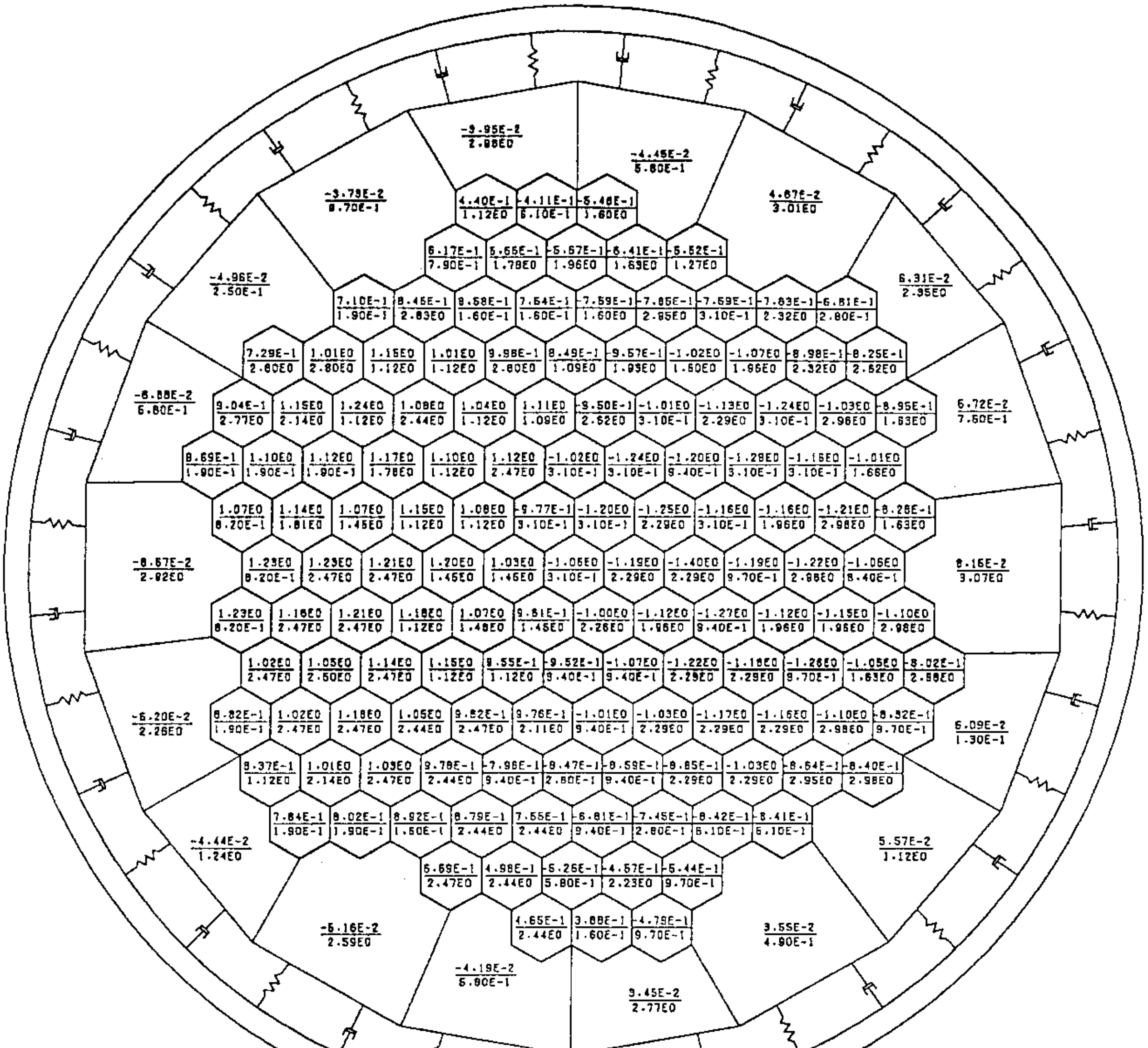

Fig. D. 19 Output of SONATINA-2H-PLOT (19)

SONATINA-2H SAMPLE PROBLEM
DISPLACEMENT Y

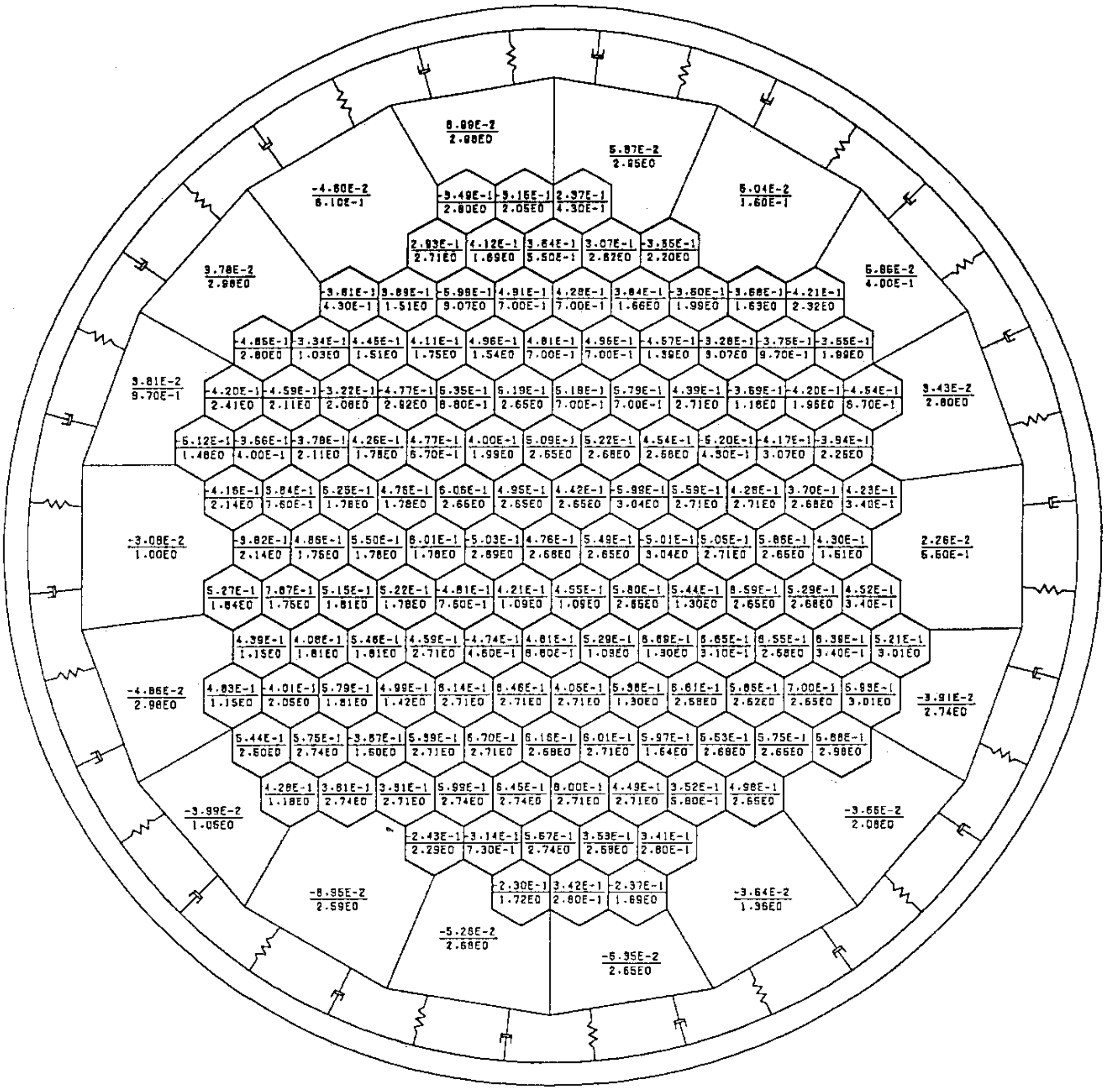

Fig. D. 20 Output of SONATINA-2H-PLOT (20)

SONATINA-2H SAMPLE PROBLEM
ACCELERATION X

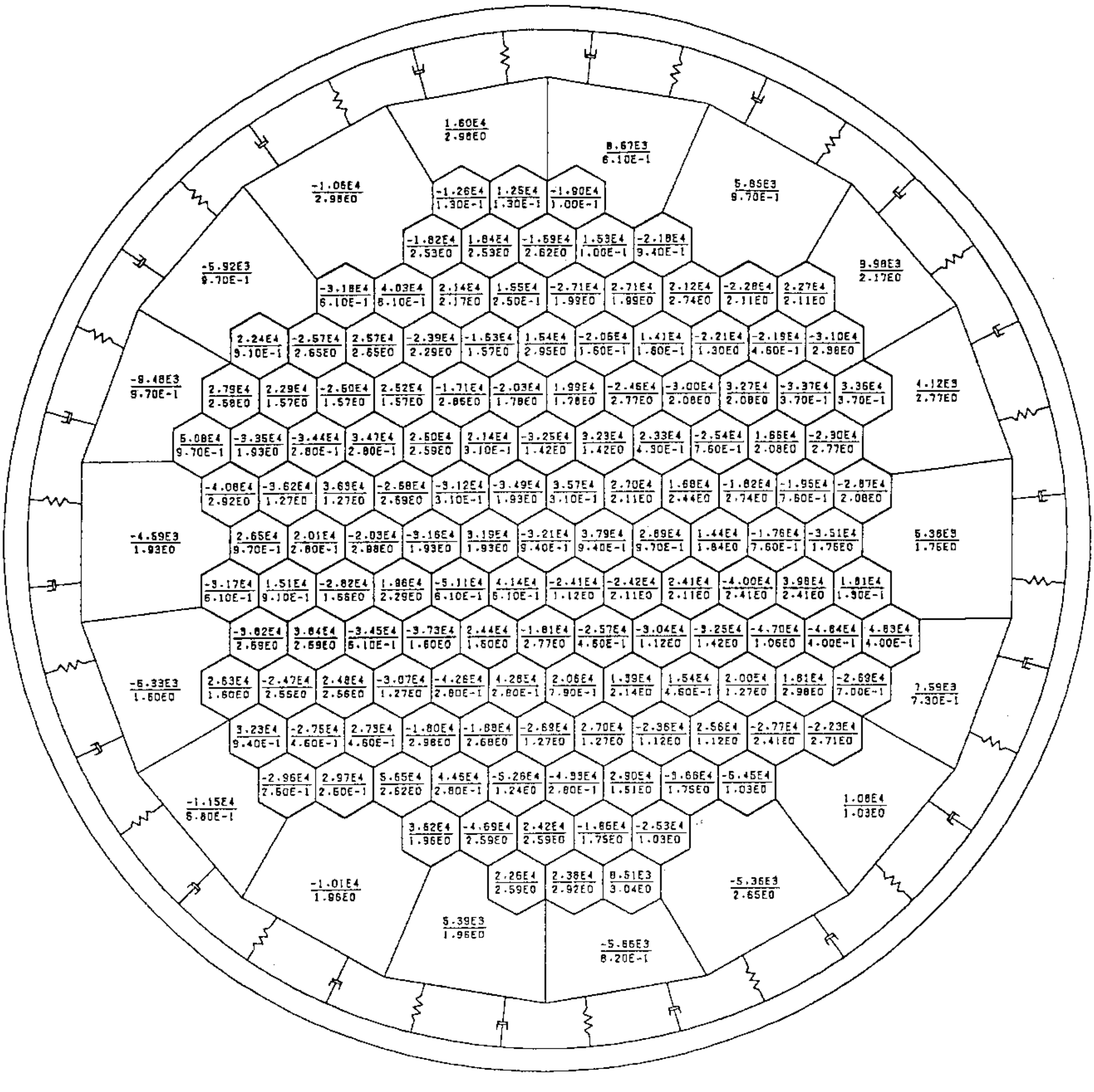

Fig. D.21 Output of SONATINA-2H-PLOT(21)

SONATINA-2H SAMPLE PROBLEM
ACCELERATION Y

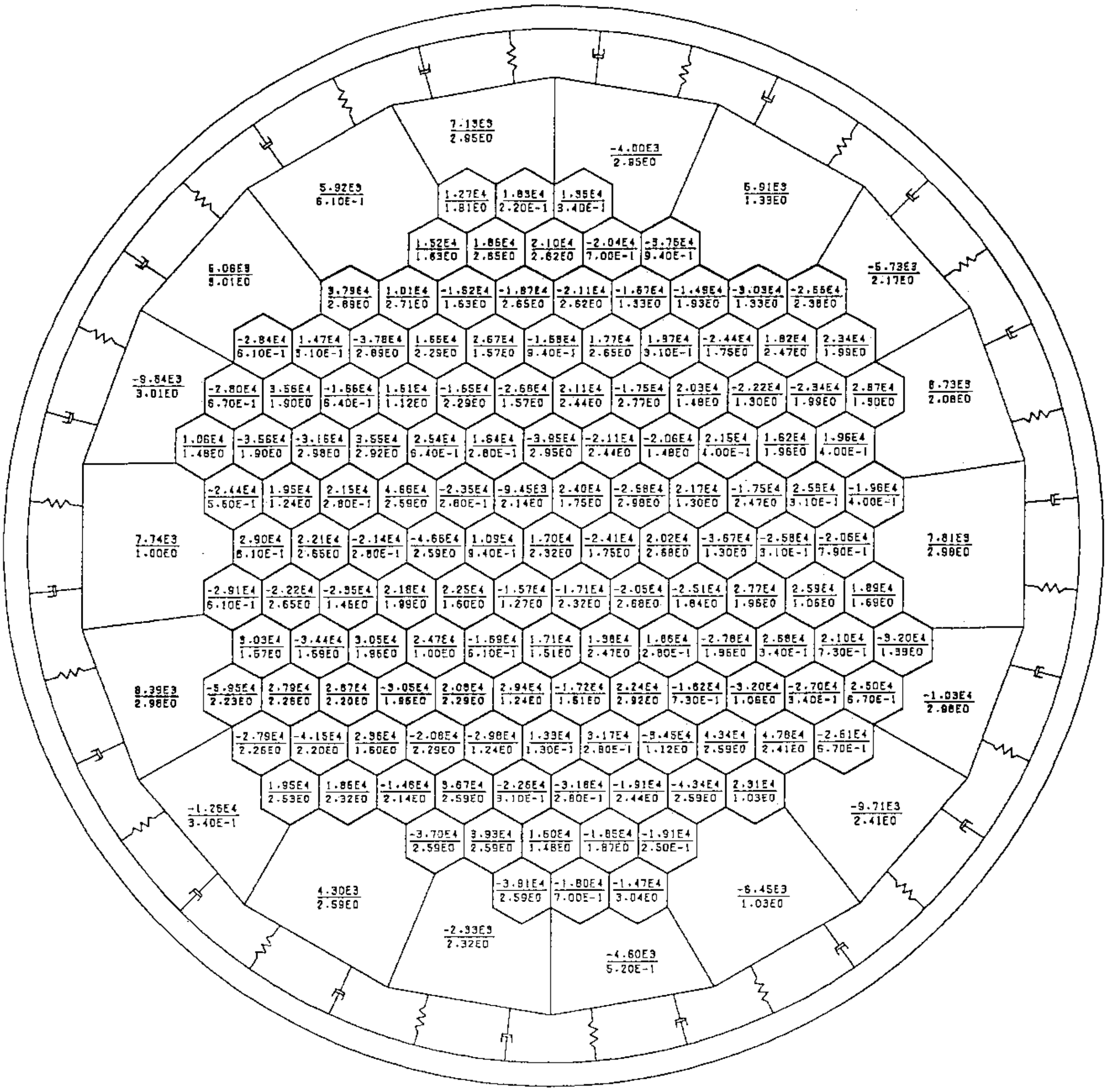

Fig. D. 22 Output of SONATINA-2H-PLOT (22)

SONATINA-2H SAMPLE PROBLEM
COLLISION FORCE X

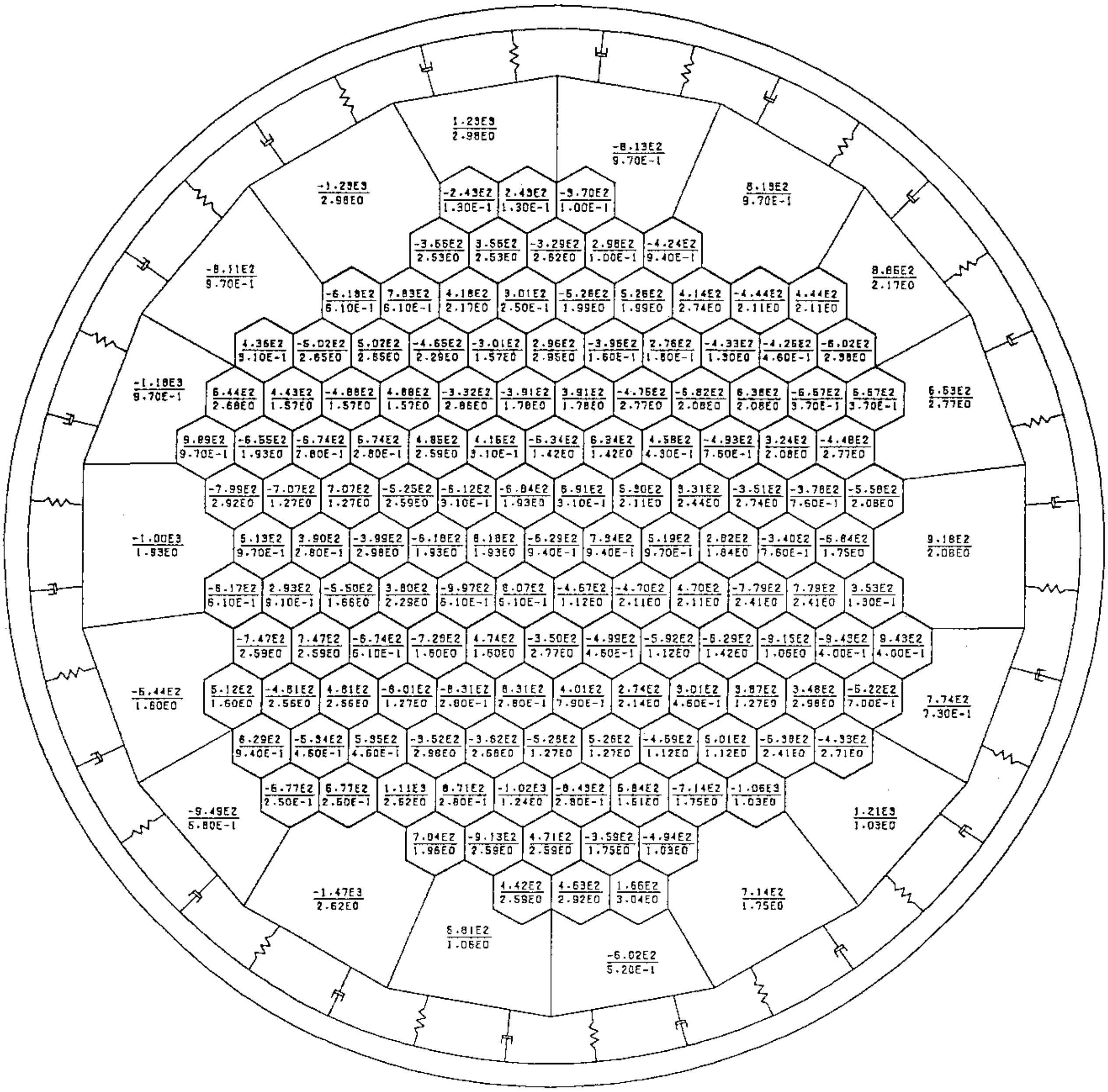

Fig. D. 23 Output of SONATINA-2H-PLOT (23)

SONATINA-2H SAMPLE PROBLEM
COLLISION FORCE Y

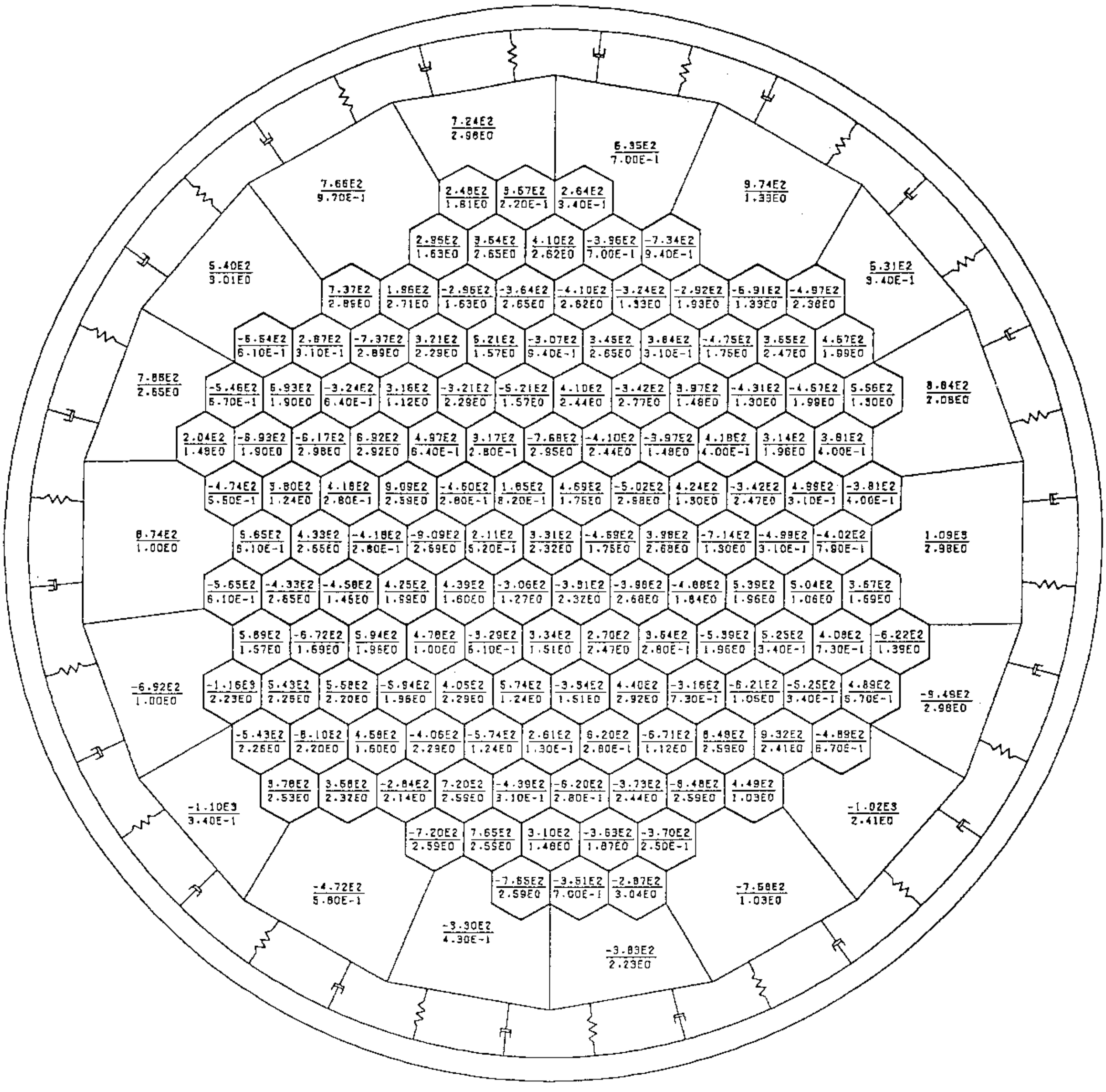

Fig. D. 24 Output of SONATINA-2H-PLOT (24)

SONATINA-2H SAMPLE PROBLEM
RESTRAINT FOR CORE BARREL R

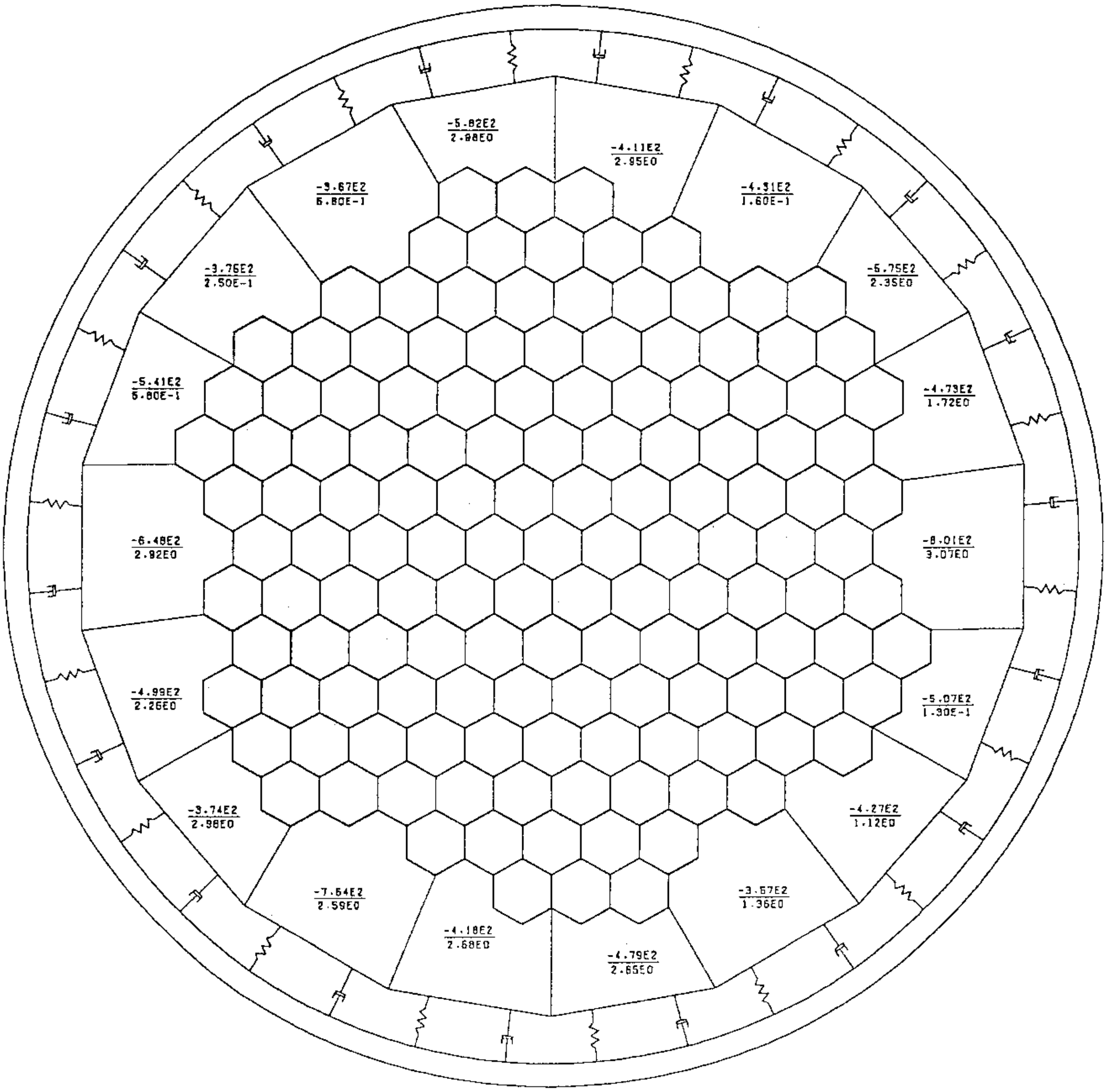

Fig. D. 25 Output of SONATINA-2H-PLOT(25)

SONATINA-2H SAMPLE PROBLEM
RESTRAINT FOR CORE BARREL T

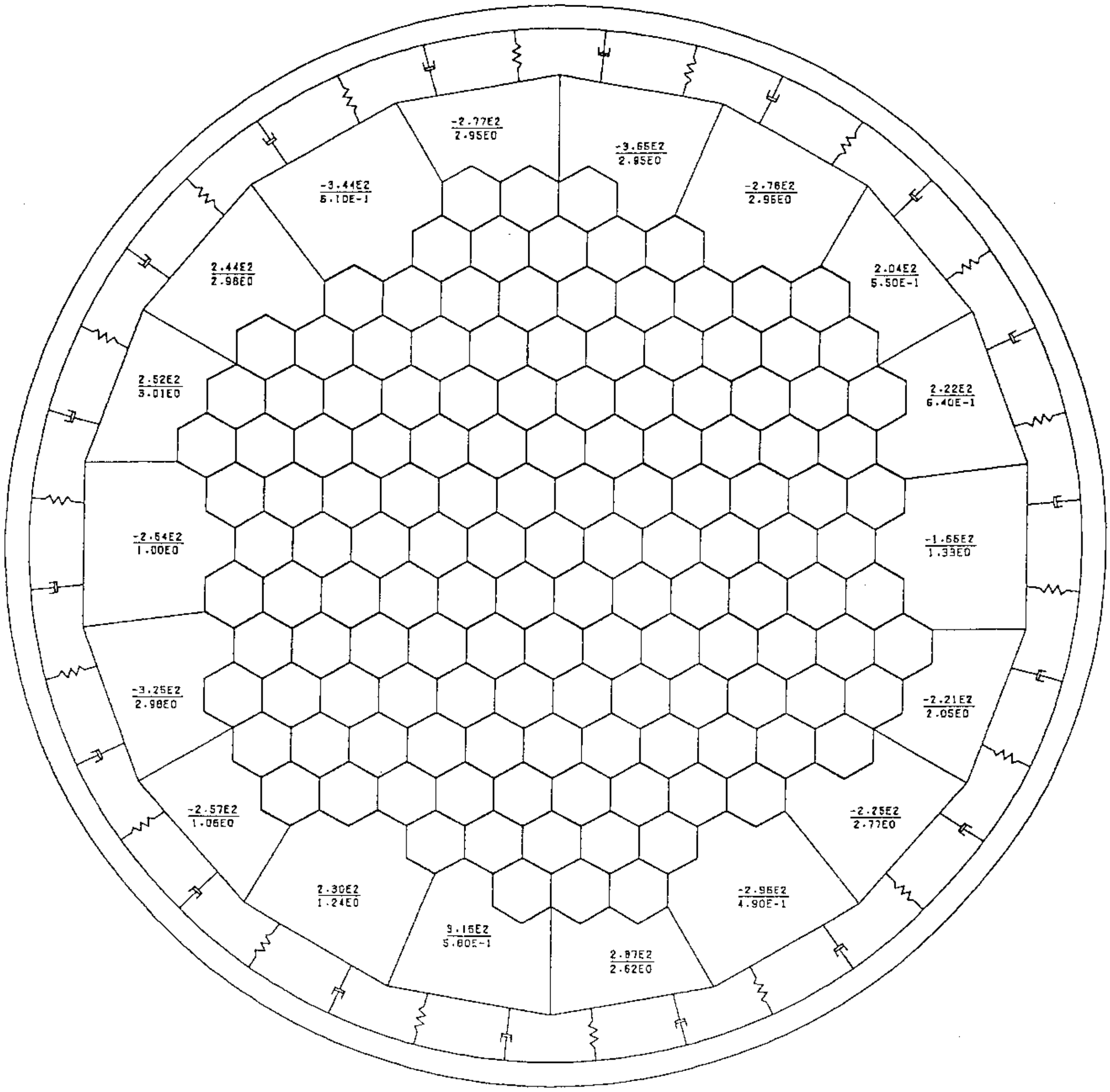

Fig. D. 26 Output of SONATINA-2H-PLOT (26)

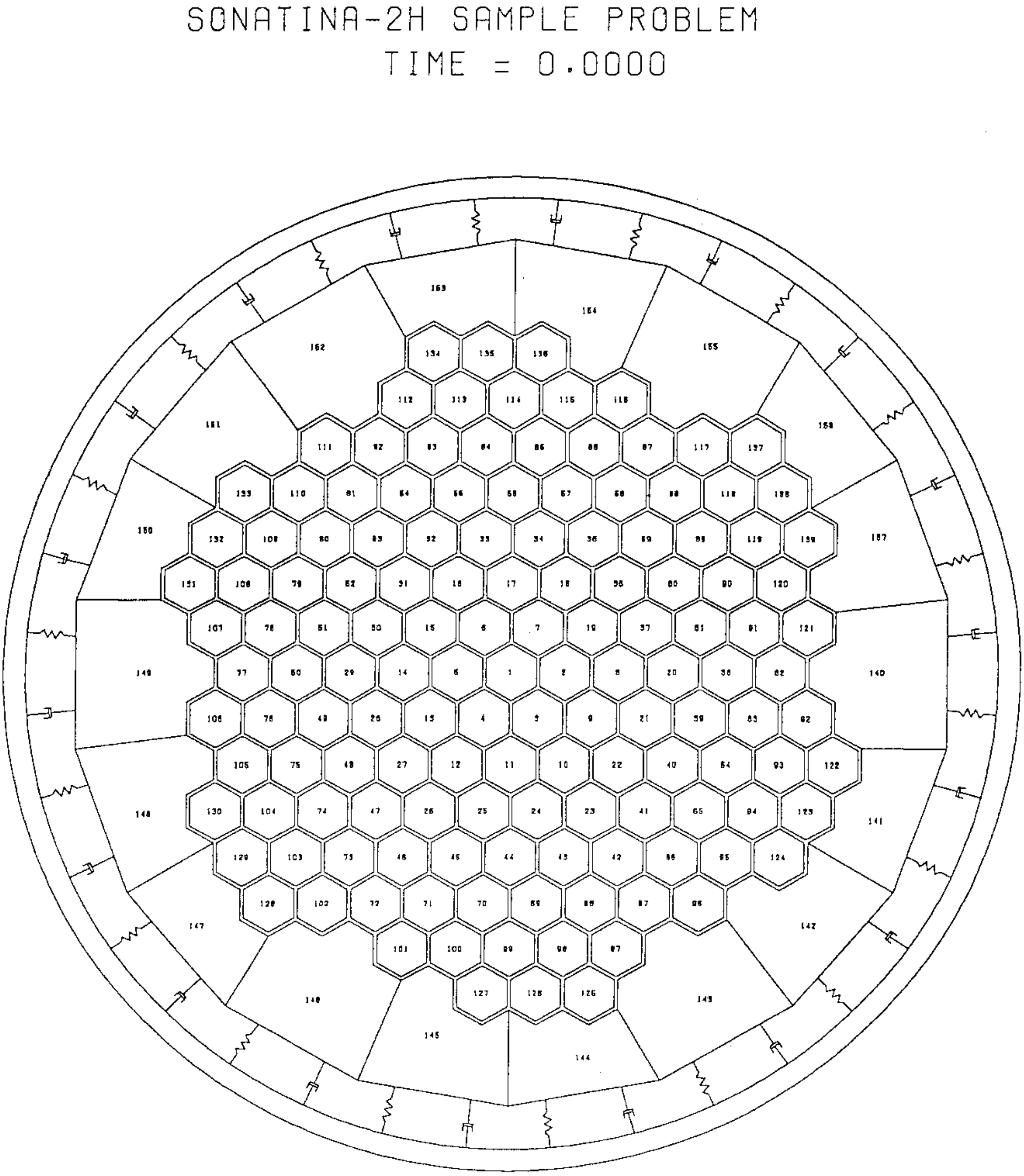

Fig. D. 27 Output of SONATINA-2H-PLOT (27)

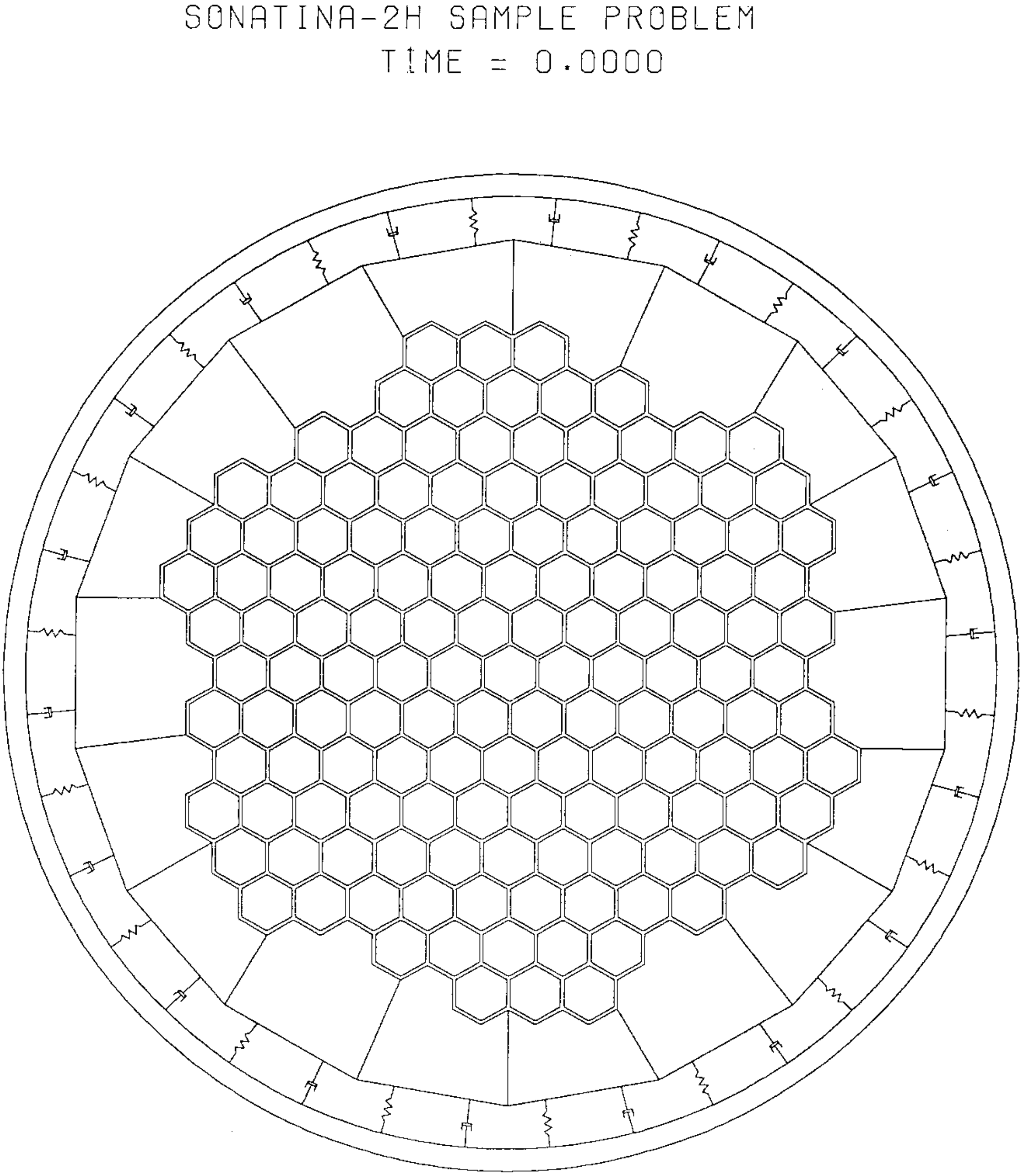

Fig. D. 28 Output of SONATINA-2H-PLOT (28)

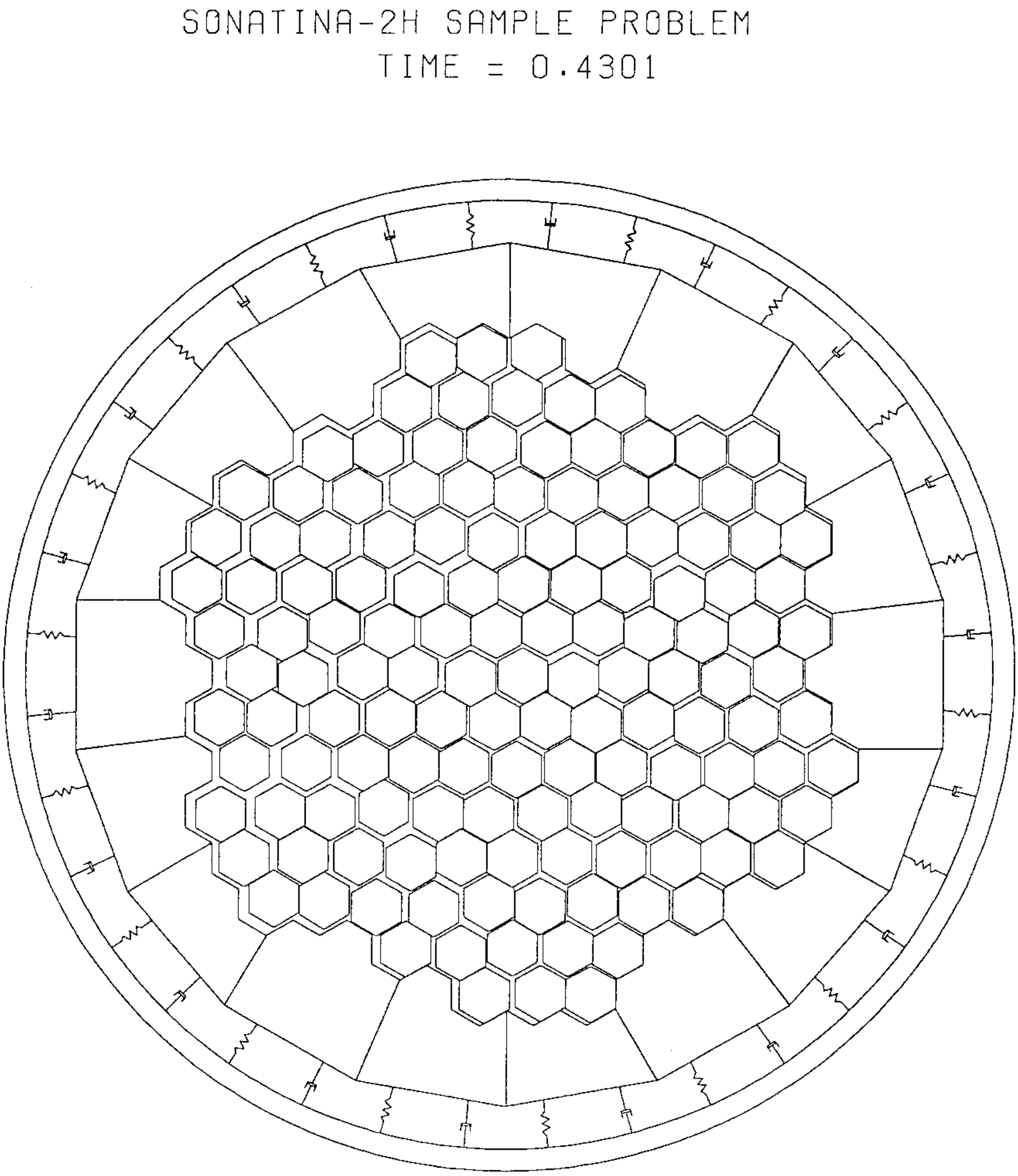

Fig. D. 29 Output of SONATINA-2H-PLOT (29)

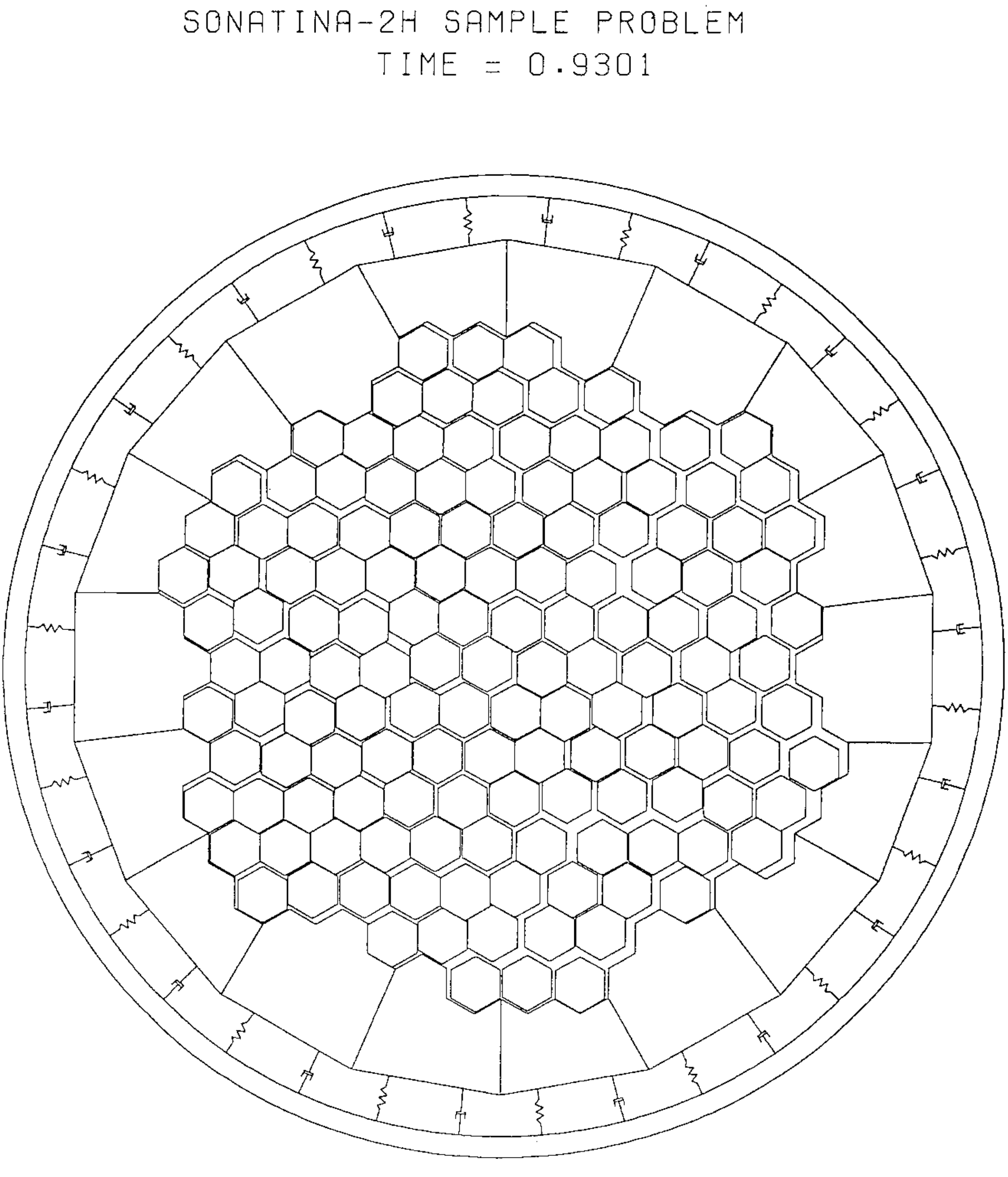

Fig. D.30 Output of SONATINA-2H-PLOT(30)

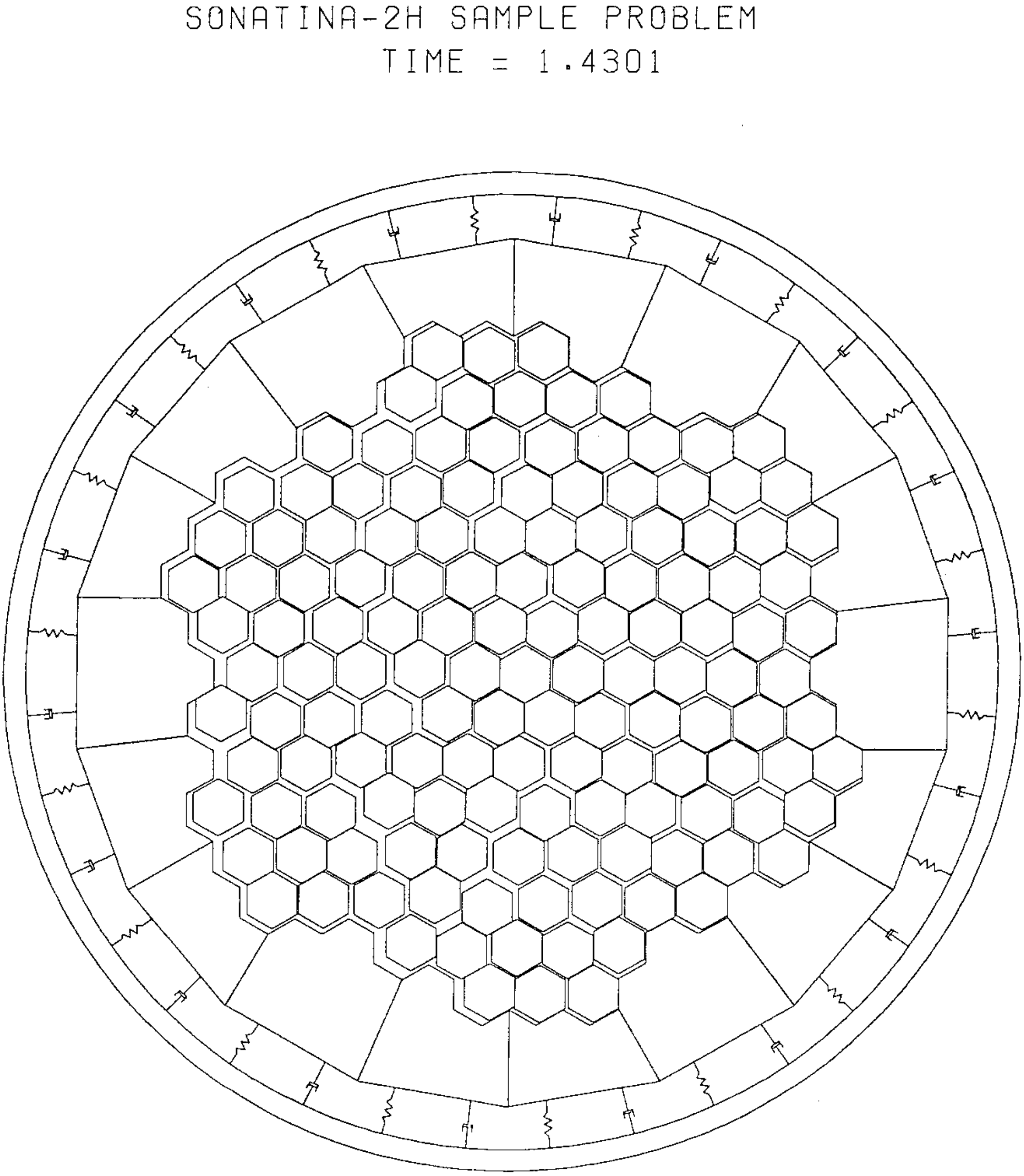

Fig. D.31 Output of SONATINA-2H-PLOT(31)

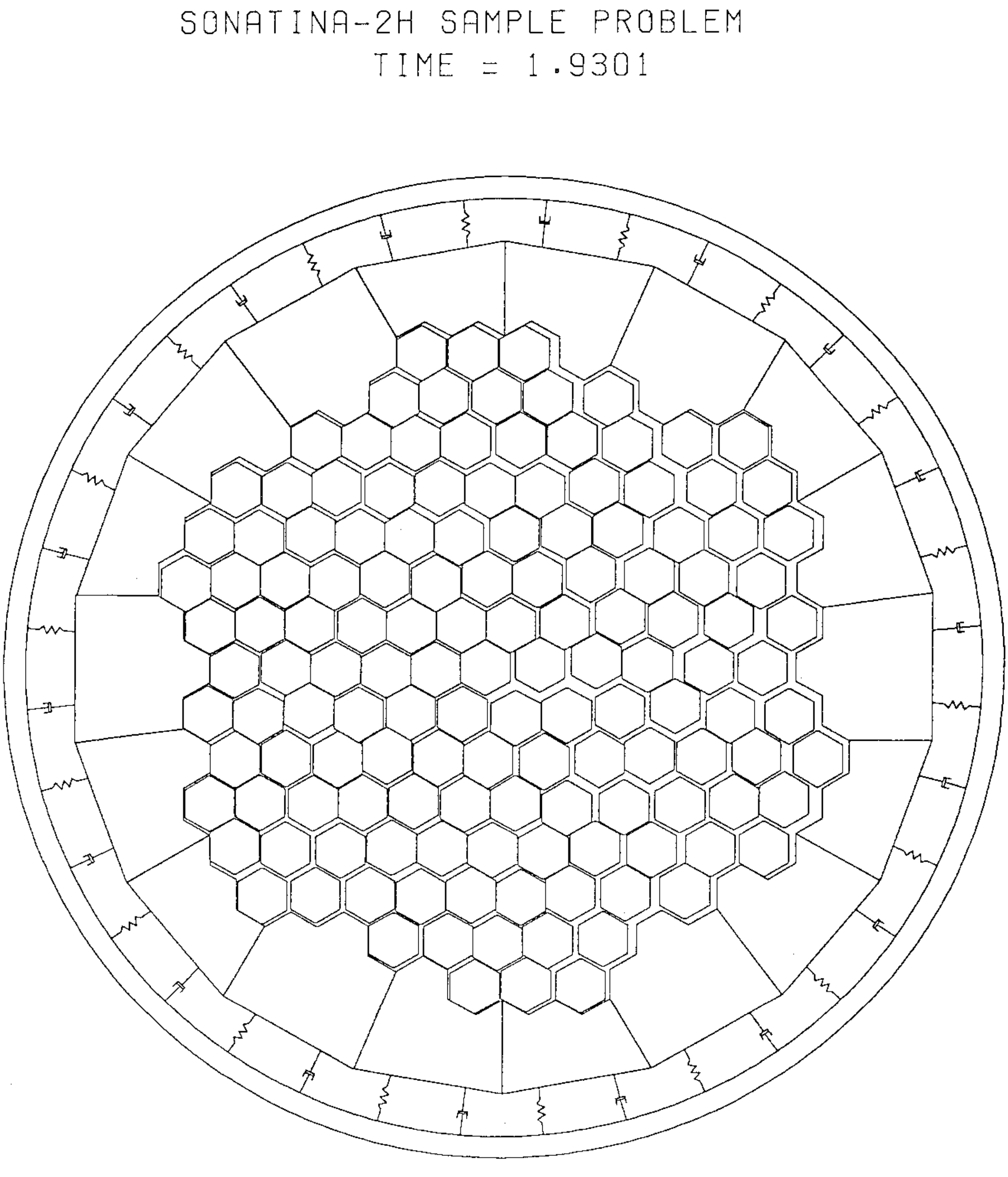

Fig. D.32 Output of SONATINA-2H-PLOT(32)

SONATINA-2H SAMPLE PROBLEM
TIME = 2.4300

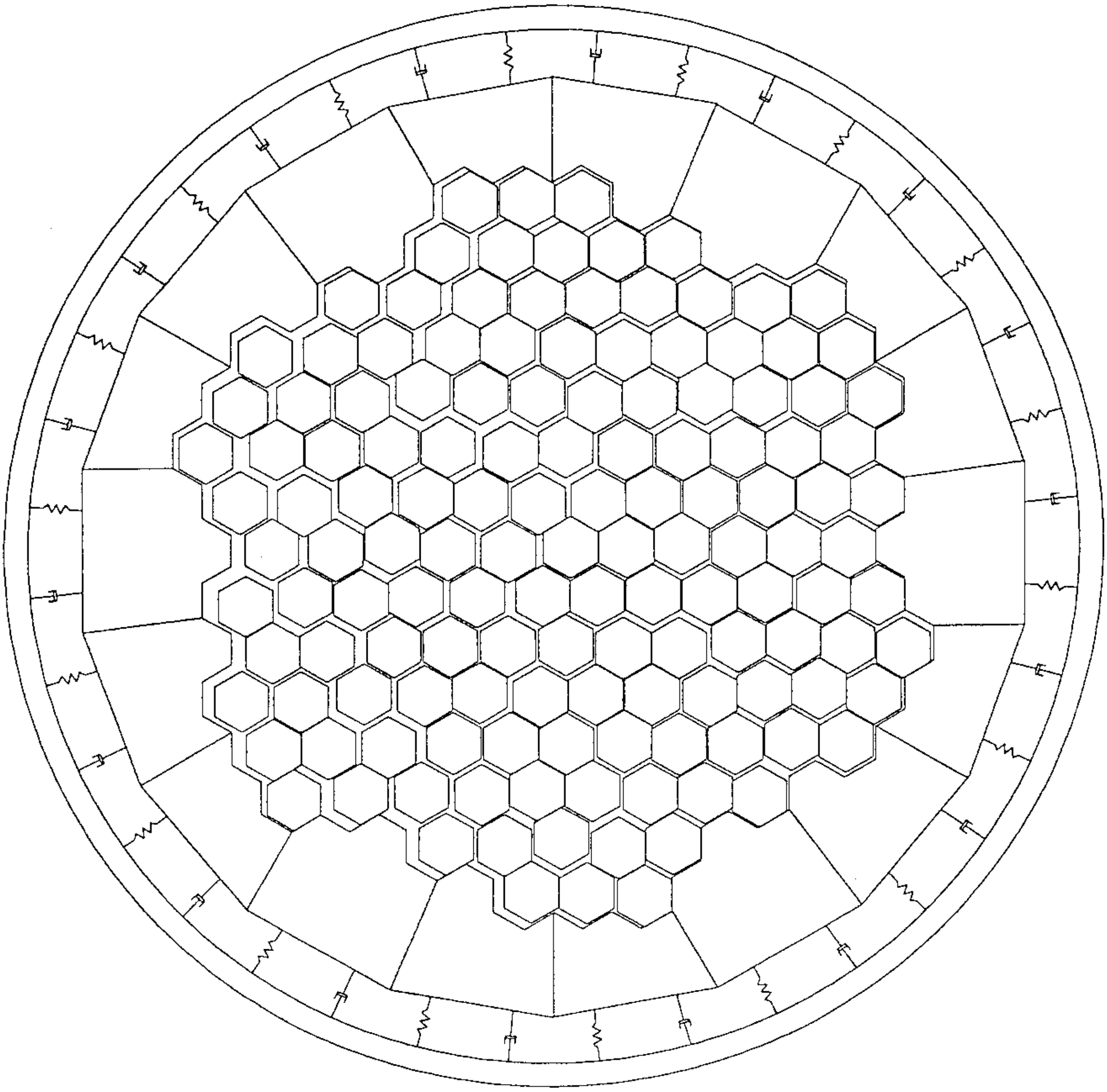

Fig. D.33 Output of SONATINA-2H-PLOT(33)

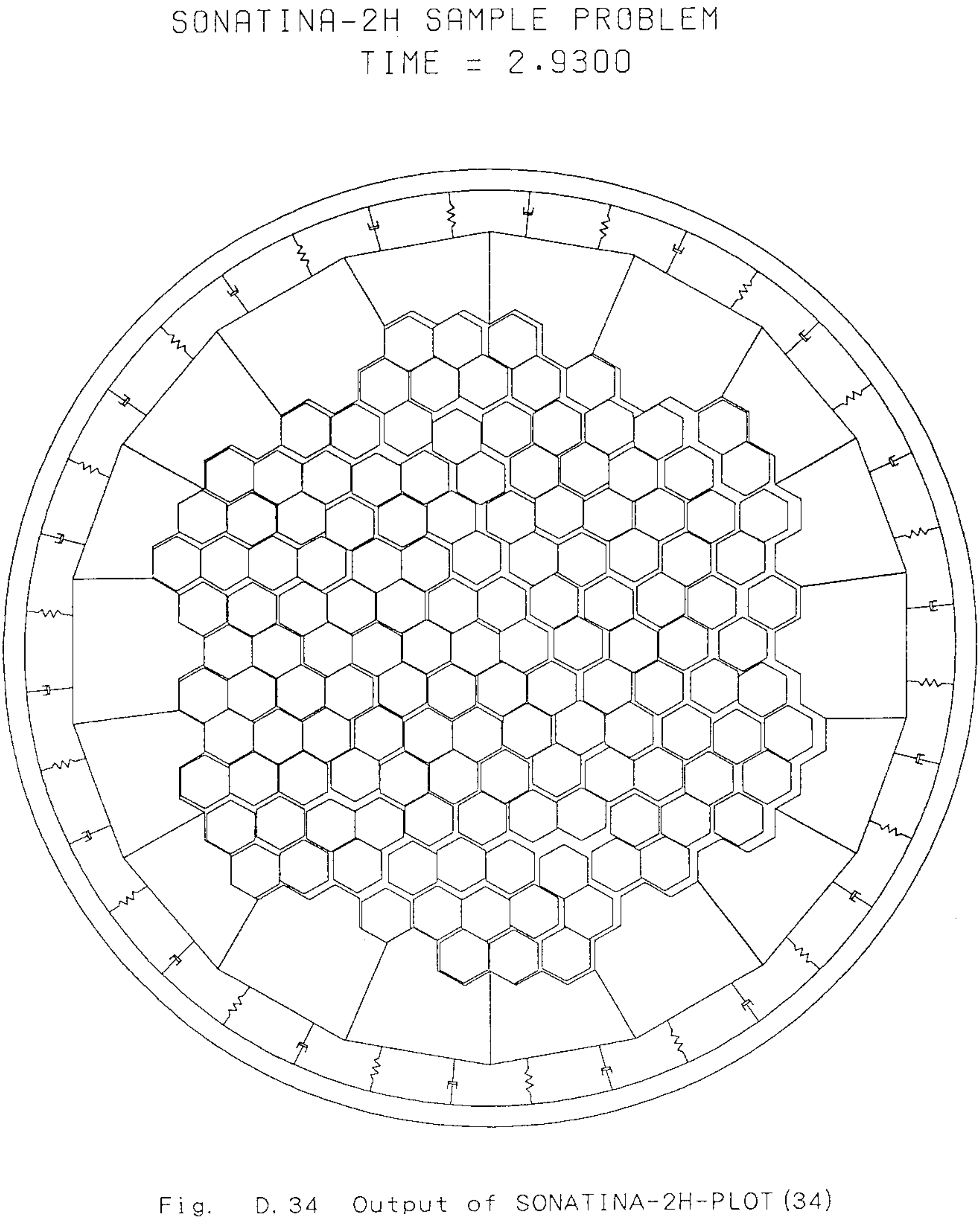

Fig. D. 34 Output of SONATINA-2H-PLOT (34)