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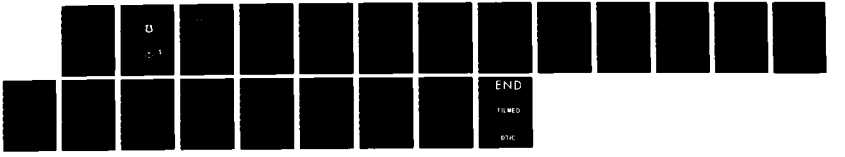

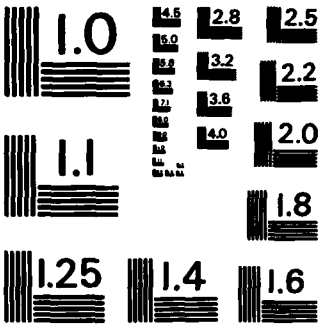

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SOFTWARE FOR NUMERICAL CALCULATION OF TWO-DIMENSIONAL NONSTATIONARY FLUID ELASTICITY AND PLASTICITY PROBLEMS

by

Qin Meng-zhao, Xie Chung-sheng, et al.

EDITED TRANSLATION

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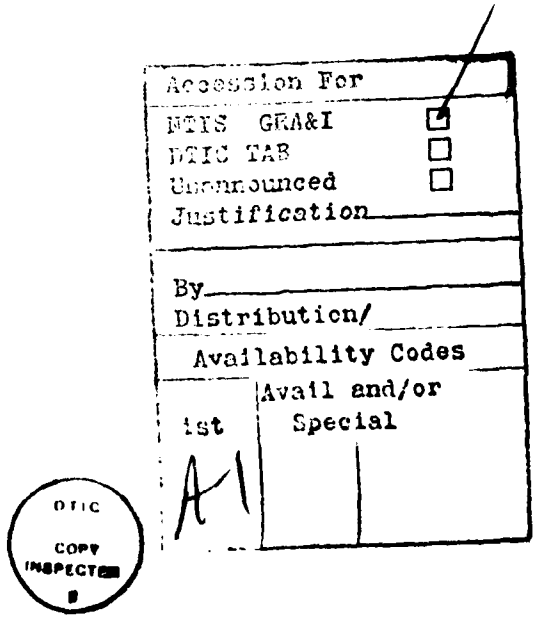

Software for Numerical Calculation of Two-dimensional Nonstationary Fluid Elasticity and Plasticity Problems

/129

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Abstract

It is very difficult to standardize programs in mathematical physics.

*received on August 18, 1981

1) In addition, comrades Liu Zhiping and Li Yingtao of the computing center, Gu Peizi, Wu Zhiyuan, Xiao Zuoshi and Xu Feng of the third chemical engineering institute, and Zhou Xiaowei of Shanxi Qinghua Electrical Machine Institute also participated in this work.

However, it is not possible to compile an application software or /130 program for a specific type of problem. We primarily referred to the "HELP Code"[1] to compile a LTDL program[4] in BCY language. It is capable of solving plasticity and elasticity problems of a two dimensional nonstationary fluid (planar or axisymmetry problems), including multi-materials (metals and non-metals). A great deal of calculation was performed to solve problems such as metal projectile penetration into steel target, high speed collision, surface explosion of high energy explosive, spherical explosion, collision of two rods, etc. Very useful results were obtained.

This paper describes the capabilities and focal points of this software. In the first section, we will introduce the fundamentals of this software, i.e. program modulation based on

split operator method. In the second section, the key of software design - calculation of mixed cell flow - is described. The third section describes the determination of the problem, i.e. setting up the region and boundary. The fourth section discusses techniques to divide meshes. Energy verification is introduced in section five. Several examples and figures are shown in section six.

§1. Split Operator Method - Modulation of Numerical Calculation

In order to compile a software for a specific type of physical problem which is affected by many factors, the split operator method may be used in approximation. The effect of several factors is split into the superposition of effects of several single factors. A numerical calculation program based on the split factor method is modular. A new physical problem may be calculated by suitably selecting the relevant operators (corresponding to several modules) and to match them with boundary conditions and region of interest.

The split operator method was initially used to lower the number of dimensions. For example, it can reduce a three-dimensional problem to three one-dimensional problems, i.e.

$$u_t = L(x_1, x_2, x_3) \cdot u = L_{x_3} \cdot L_{x_2} \cdot L_{x_1} \cdot u.$$

Moreover, the split operator-method can be applied to different physical effects. For instance, the N-S equation can be considered as the superposition of the inviscous operator L_1 and viscous operator L_2, i.e.

$$u_t = L_2 \cdot L_1 \cdot u.$$

Similarly, the plasticity and elasticity operator of a fluid may be split into the pressure effect operator L_1, stress effect operator L_3, and the transport effect operator L_3, i.e.

$$u_t = L_3 \cdot L_2 \cdot L_1 \cdot u.$$

Each operator is separated to become independent modules when the numerical calculation program is compiled. For instance, the LTDL program was compiled based on this principle. This

program is very flexible. For example, a fluid can be calculated by shutting off program modules corresponding to L_3 in LTDL. If there is only one fluid material and it includes a free boundary, i.e. the FLIC method[2,3], then all modules corresponding to L_1, L_2 and L_3 are used, which is the so-called HELP[1] method.

§2. Key of Software Design - Mixed Cell Flow Calculation

The most complex portion of the software to calculate plasticity and elasticity of two dimensional nonstationary fluids is mixed cell flow calculation (cells at the interface of materials). The key is to determine the rules to calculate the area of material interface which cuts the Euler mesh. Obviously, the direction of flow, the shape of interface, the number of interfaces in a section cell can vary widely. To use a set of rules to calculate the area where the interface cuts into a cell, the density of the transport mesh and the transport rate at the interface will enable us to calculate the mass, momentum and energy transport between a mixed cell and its neighbors. Then, the mechanical parameters of a mixed cell at any time can be calculated by using laws of conservation of mass, momentum and energy. The logic is very complicated and includes the following steps: /131

1. First, the interface of materials is defined. Initially, a set of massless tracing points (their coordinates are expressed by the lattice coordinates). These points are labelled so that the material is always on the left side of any two neighboring points. The points at the interface coincide and move in opposite directions. The position of a moving point can be determined by a weighted mesh speed area calculation. The broken line between two neighboring points is the interface.

2. The area under which the interface intersects n sides of a lattice is calculated according to the following three situations:

1) The interface only intersects a side of the lattice once.

In Figure 1, the interface EBCDF between materials (1) and (2) intersects with a side of lattice K once. The area is

calculated by linear interpolation. The intersect E between the interface and the top side of cell K is calculated from the coordinates of two neighboring points on the top edge of cell K. Then, based on the rule that the material is always on the left of the line connecting two neighboring points, we can then determine that the area under which material (1) intersects with the top side of cell K is the convolution of AE. The area under which material (2) intersects with the top side of cell K is the convolution of EF.

ii) The interface intersects the lattice several times.

In Figure 1, the interface of materials (1) and (2) intersects with the right side of lattice K three times. The area of intersection is obtained by adding the area of each intersection and by comparing that area with the entire area of cell K. Specifically, method i) is used along the direction of the tracing points of the interface of material (1) to first calculate the area BA and then the second area CH. Furthermore, CH is added to BA. If BA + CH is less than AH, then the sum remains unchanged. Finally, the area of the third intersection DA is calculated and added to BA and CH. If BA + CH + DH > AH, then AH is subtracted from the sum to obtain BA + DC, which is the area of three intersections between interface (1) and the right side of cell K. The derivation for n intersections can be obtained in analogy.

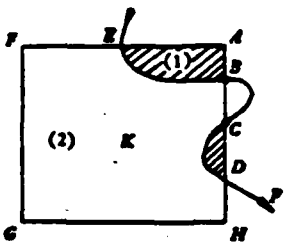

Figure 1

iii) There is no intersection between the interface and n sides of the lattice

In Figure 1, the interface of materials (1) and (2) does not intersect the bottom and left sides of cell K. From the figure we know that the area of intersection between the interface of material (1) and the left and bottom sides of cell K is zero. That of the interface of material (2) is the entire cell. This is achieved by "pre-set" (interface entering cell K) and "re-set" (interface leaving cell K) in the program. Before we describe this method, let us first introduce the four directions connecting the tracing points on the top and right sides of lattice K (See Figure 2).

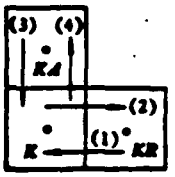

Figure 2

(1) entering cell K, leaving cell KR.

(2) leaving cell K, entering cell KR.

(3) entering cell K, leaving cell KA.

(4) leaving cell K, entering cell KA.

"Pre-set" rules. When the interface of a material intersects with cell K (on the top or right side) n times ($n \geq 1$), if the area of intersection with cell K is less than the total area of the whole cell, other sides of cell K will not be "pre-set". Otherwise, other sides of the cell are pre-set clockwise /132 starting from the intersect until reaching the side of intersection again.

"Re-set" rules. When a material interface intersects n times ($n \geq 1$) with a side of cell K (top or right) and leaves cell K, if the cumulated area of intersection is less than the total area, then other sides of cell K will not be re-set. Otherwise, it will be re-set clockwise from the intersect. The partial area of other side is zero until the interface intersects with the lattice side.

Let us use Figure 1 to explain this situation. If we scan along the direction of tracing points for material (1), when the line connecting two such points for material (1) intersects with the top of cell K once, then the right, bottom and left sides of cell K are pre-set to the total area according to the pre-set rule. When the interface of material (1) intersects with the right side of cell K (at B) and leaves cell K, the left side is re-set to zero area. Because the top side of cell K already intersects with the interface of material (1), therefore, it is not re-set again. When the interface of material (1) intersects with the right side of cell K three times (at points B and C) before entering cell K, because the cumulative area is smaller than the total area to the right of cell K, then the bottom and left sides are "re-set" to the total area. When the interface of material (1) intersects with the right side of cell K three times (at points B, C and D), because the cumulative area is larger than the total area to the right of cell K, then the bottom and left sides are "re-set" to zero. This appears to be correct from Figure 1. Similar "pre-set" and "re-set" rules may be used to determine that the area of intersection between the interface of material (2) and the bottom and left sides of cell K is the total area.

In summary, based on the direction of the tracing points of the "pre-set" and "re-set" rules, we can calculate any partial area of intersection between an interface and a side of the lattice.

§3. Determination of the Problem, Region and Boundary Condition

The LTDL program is capable of calculating mutual interaction among various materials. A material may also include other types of materials (distributed in different regions). The shape of the material may be spherical, hemispherical, cylindrical and conical, as well as their combinations. However, they must be axisymmetric or planar. The boundary conditions include symmetric axis, rigid boundary, transport boundary, free boundary and interfacial boundary. With the exception of transport surface and symmetric axis, other interfaces have massless tracing points.

Let us assume that the area of calculation is the rectangular region ABCD on the (r, Z) surface in a cylindrical coordinate, as shown in Figure 3. Initially, the boundaries of material blocks (1), (2) and (3) are marked by massless points. Thus, the lattice of calculation may be a pure cell of a single material or may contain two or three mixed materials. Initial values of eight mechanical parameters such as u (velocity component in r-direction), v (velocity component in Z-direction), e (specific internal energy), p (density), s_{rr}, s_{ZZ}, s_{rZ} (stress components) and p (pressure) are given as the initial condition. Thus, based on the problem (including the initial condition of the material), shape, boundary condition, equation of state and strength formula, the software can be rationally used to perform the corresponding calculation. In addition to the eight parameters and the dynamic boundary of the material, it is also necessary to provide strength, temperature, positive stress and strain rate.

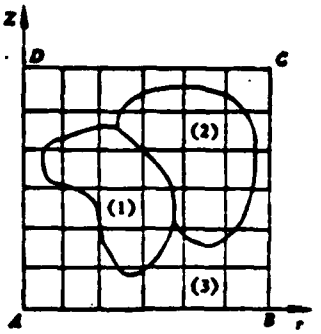

Figure 3

The determination of area of calculation and boundary type can be explained with the following example.

1. Axial Collision of Two Semi-infinite Metallic Bodies

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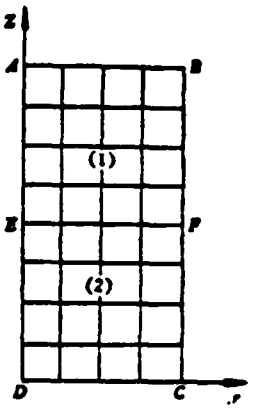

Figure 4

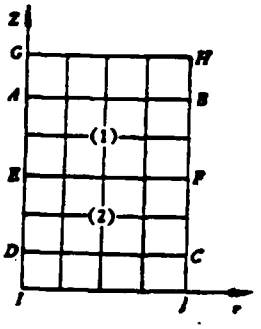

Figure 5

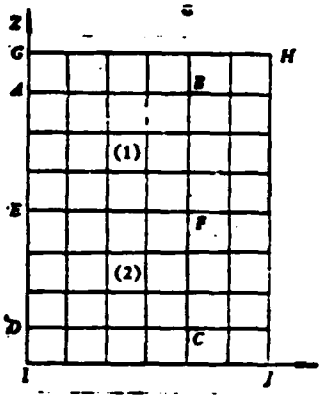

Figure 6

In reality, it is an axial one-dimensional problem and the area of calculation is ABCD (Figure 4). AB, BF, FC and CD are transport boundaries. AED is the axis of symmetry. There is no need for tracing points. EF is the interface between blocks (1) and (2) which requires tracing points.

2. Axial Collision of Two Finite Thickness Infinite Width Materials

This is also a one-dimensional axial problem. The area of calculation is GHJI (Figure 5). AB and CD are free boundaries. EF is an interface. They all need tracing points. BF and FC are transport boundaries and GAEDI is the axis of symmetry.

3. Axial Collision of Two Finite Thickness and Width Materials

The area of calculation of this two-dimensional axisymmetric problem is GHJI (Figure 6). AB, BF, FC and CD are free boundaries. EF is an interface. They should have tracing points. AED is the axis of symmetry.

4. High Speed Collision of Copper Sphere with a Semi-infinite Body (Figure 7)

Because of symmetry, it is only necessary to calculate half of the area (Figure 8). Because the target is a semi-infinite body. Therefore, CD and DB are transport boundaries.AB and AHG are free boundaries. CAGE is the axis of symmetry. The area of calculation is CDFE.

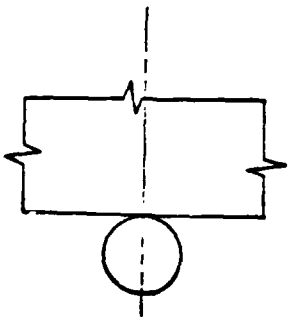

Figure 7

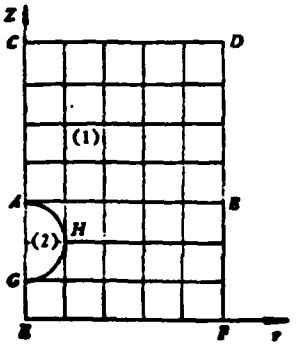

Figure 8

5. Jet Penetrating Steel Target

If the target has a finite thickness, then the back surface of the target CD is a free boundary. CD is a transport boundary if the target is infinitely thick. GB is a free boundary. Let

us assume that the jet is infinitely long, then EH is a transport boundary and GH is a free boundary. AG is an interface and IDAE is the axis of symmetry. When DC and CB are free surfaces, the area of calculation is IJKE. When DC and CB are transport surfaces, the area of calculation is DCFE.

6. Surface Explosion of High Energy Explosive /134

Let us assume that there is a high energy explosive at GFED on the surface of a solid body. ABCEFG is a solid. Outside is the atmosphere. Then, it is necessary to make AB and BC be transport surfaces, CD be a free surface, GFED be an interface and AGDH be the axis of symmetry.

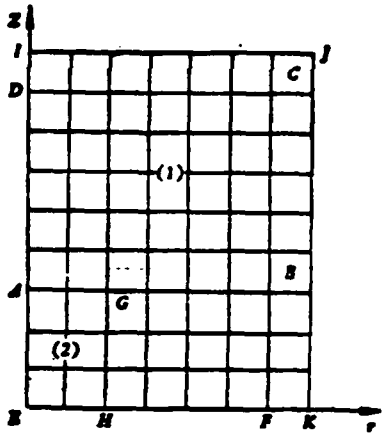

Figure 9

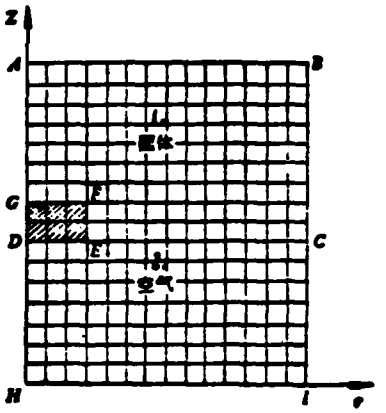

Figure 10

1. solid
2. air

§4. Expansion of Area of Calculation - Techniques for Lattice Reconfiguration

The special feature of a nonstationary motion is that the pattern of motion varies with time. However, due to limited

computer storage space, the number of Euler lattices cannot be too many. After a certain time, the physical picture has filled the entire area of calculation. Then, lattices can be combined by reconfiguration to expand the space of calculation. Lattice combination can be done in one or two directions. For example, the program is calculated to some extent, perturbation may have already affected all the cells. Thus, the original 100 x 50 cells are consolidated into 50 x 25 or 100 x 25 cells. Thus, 3/4 or 1/2 of the storage space can be liberated to extend the area of calculation.

The mechanical parameters, positions of tracing points at the interface, positions of lattice lines and cell sizes must be redetermined after reconfiguration. The calculation can be performed in four steps:

1. Calculate the position of each lattice line, the coordinate of each tracing point and the axial and radial dimensions of each lattice.

2. Calculate mechanical parameters in reconfigured cells. Let us assume that cells L and M are combined into cell K. The principle of recombination is as follows: the mass, axial and radial velocity, and specific internal energy in cell K are calculated from the conservation of mass, momentum and energy in cells L and M. The stress derivation of cell K is calculated by weighted mass average of cells L and M. If the combined cell is a mixed cell, then the mass, velocity and specific internal energy of the cell are obtained by laws of conservation. The density of each material in cell K can be obtained by weighted density mass of the same method in cells L and M.

3. New interface and center tracing points are added to the new lattice in order to calculate the position of the lattice line and the size of the cell. In addition, mechanical parameters in the new cells are defined by those in the boundary cells.

4. Based on the mixed cell pressure iteration principle (see reference [1] for details) and equation of state, the pressure of each cell (pure and mixed) is calculated. Finally, /135 the time interval is recalculated.

In regard to the treatment of a free boundary, the technique is shown in detail in reference [5].

§5. Energy Verification

A stationary problem is often associated with iteration. Therefore, some local error will not affect the entire picture. At best, a few more iterations are needed. However, the problem of nonstationary calculation is different. It is necessary to check for energy conservation at each level (each time interval) for every cell. Otherwise, the result cannot be trusted.

Initially, the total energy of the system ETH is calculated according to the lattice number. The theoretical energy ETH* of the system at the nth level is obtained by adding to or subtracting from ETH with the energy input (work done by the outside) or energy output (work done by the system) across the transport boundary in a time interval Δt. The total energy at the nth level is ESUM. It is required that the relative error should be within the range DMIN, i.e.

$$\left|\frac{ETH^* - ESUM}{ETH^*}\right| < DMIN.$$

This formula must be satisfied to demonstrate that the calculation is correct. Otherwise, it has problems and the calculation is terminated.

If this energy verification is used for each cell, the requirement is even more rigorous.

§6. Examples of Numerical Calculation

1. Jet Penetrating Steel Target Plate

Initial conditions are: target radius 17.44mm, thickness infinite (actual thickness is 18.49mm), $\rho_t^0 = 7.85 g/cm^3$, p = 1atm, e_t^0 0.6369426 x 10^5 ergs/g, u = v = 0. Jet (copper) radius is 1mm. The jet is infinitely long (8mm in calculation). $\rho_j^0 = 8.60 g/cm^3$, p = 1atm, $e_j^0 = 0.5813980 \times 10^5$ ergs/g, u = 0, $v = v_j^0 = 850 m/s$.

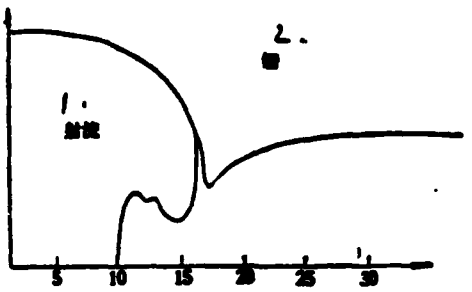

Figure 11. Jet Penetration of Steel Plate Ended at t = 2 s and Stationary Penetration Began

1. jet
2. steel

2. Coppy Ball Colliding with Steel Target at 2km/sec.

Figures 8, 12 and 13 show the external shape at t = 0, 0.12247 and 0.4487 microseconds,

3. Spherical Explosion in Vacuum[6]

Figures 14 and 15 show the external profile at t = 0 and 0.3 μsec, respectively.

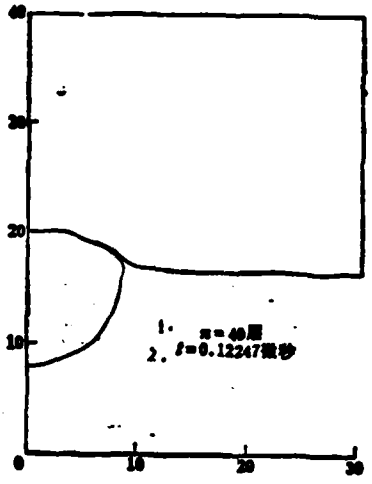

Figure 12
1. n = 40
2. t = 0.12247μsec

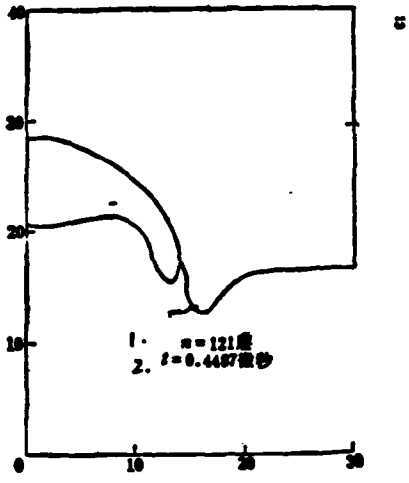

Figure 13
1. n = 121
2. t = 0.4487μsec

Figure 14

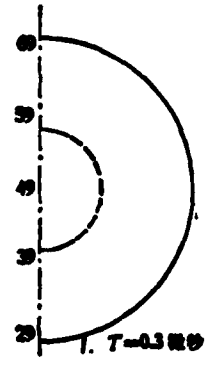

Figure 15
1. T = 0.3μsec

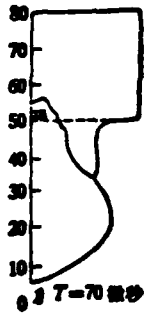

Figure 16
1. T = 70μsec

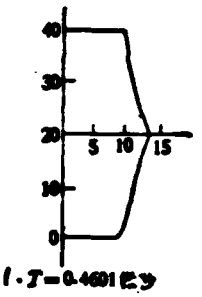

Figure 17
1. T = 0.4601μsec

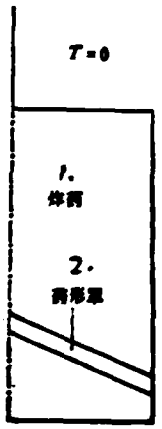

Figure 18
1. explosive
2. charge mask

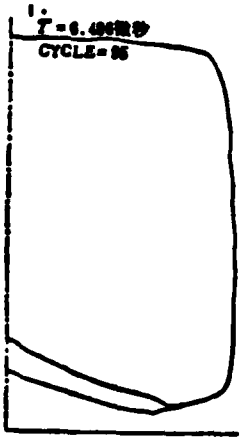

Figure 19. Shapes and Positions of Explosion Product and Charge Mask at t =6.468μsec
1. t = 6.468μsec

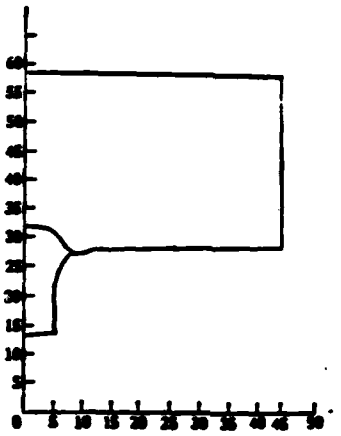

Figure 20. Penetration of Shield in 5μsec

4. Surface Explosion of High Energy Explosive

Figure 10 shows the profile at t = 0. Figure 16 is the pattern at 70μs. The expansion of gas explosive products can be seen in Figure 16.

5. Collision of Two Rods /137

Figures 6 and 17 are the profiles at t = 0 and 0.4601μs, respectively.

6. Calculation of Large Conical Angle Tumbling Projectile [8]

Figures 18 and 19 are the profiles at t = 0 and 6.486μs, respectively.

7. Calculation of Cylindrical Steel Projectile Hitting Steel Target at 900m/s.[7]

Figure 20 is the profile at t = 5μs.

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