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Tracking Sharp Interface of Two Fluids by the CIP (Cubic-Interpolated Propagation) Scheme

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Abstract

A method to treat a sharp discontinuity by the density function is proposed. The surface of the density function is described by one grid throughout the calculation even when the surface is largely distorted. This description is made possible by the CIP method combined with variable transformation. This scheme is applied to the linear wave propagation in one- and two-dimensions. In the nonlinear case, the injection of heavier fluid into lighter fluid his calculated and the winding of mushroom structure is successfully treated by the density function.

Keywords : interface, sharp boundary, numerical method, fluid

I. INTRODUCTION

There have been numerous methods proposed for treating interface between two different materials. These methods are divided into two groups. In one group the interface is described by a surface function[1], while in the other group the interface is defined as surface of a density function[2]. In the former case, a main problem arises from a multi-valued function when the surface is largely distorted or even breaks up. Although this shortcoming does not exist in the latter case, the numerical scheme to describe an evolution of the density function without numerical diffusion is a problem which needs further investigation.

In this paper, we propose a method to treat this density function with high accuracy in multi-dimensions. For this purpose, we use the CIP (Cubic-Interpolated Propagation. In the previous papers, P standed for "Pseudoparticle". Since the word "Pseudoparticle" may lead to misunderstanding of the scheme, we use "Propagation " as P hereafter.) method recently developed by the author[3,4,5,6]. The CIP method can trace a very sharp interface. However, the method is still not sufficient for the problem which we are going to present. The interface must be treated by one grid over the whole calculation. Therefore, we slightly modify the CIP method. By this modification, we have succeeded to trace a sharp interface by one grid throughout the calculation. This method is applied to the injection of fluid into a different fluid.

II. BASIC ALGORITHM

Here we use a density function ϕ to describe the abundance of material A. Therefore, we define

$$\begin{aligned} \phi &= 1 \qquad \text{(Material A)} \\ &= 0 \qquad \text{(No material or different material)} \end{aligned} \tag{1}$$

This density function evolves according to

$$\frac{\partial \phi}{\partial t} + u_i \frac{\partial \phi}{\partial x_i} = 0, \tag{2}$$

where u_i is the fluid velocity component. In the CIP method, this function inside a grid cell is approximated by a cubic polynomial in three spatial directions. Furthermore, the spatial derivatives of Eq.(2)

$$\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial x_j}\right) + u_i \frac{\partial}{\partial x_i}\left(\frac{\partial \phi}{\partial x_j}\right) = -\left(\frac{\partial \phi}{\partial x_i}\right)\left(\frac{\partial u_i}{\partial x_j}\right), \tag{3}$$

are also used to determine the polynomial. Therefore, the dependent variables are ϕ and $\partial \phi / \partial x_j$ and these are determined from Eqs.(2) and (3). Other unknown coefficients to determine the polynomial are found by imposing continuity of the value and the spatial derivatives among neighboring cells. An example of the procedure will be described later on.

Propagation of a linear wave by this method has been described with high accuracy. However, diffusion and undulation at a sharp front is still unavoidable although they are quite small. The previous method to suppress those is successful only in one dimension but is complicated. In the problem of interface tracking, we can use much more effective method to suppress them. We propose here to transform ϕ into F_ϕ which is a function of ϕ only. It is obvious that a new function F_ϕ also obeys the same equation as Eq.(2).

$$\frac{\partial F_\phi}{\partial t} + u_i \frac{\partial F_\phi}{\partial x_i} = 0, \tag{4}$$

Therefore, all the method proposed for ϕ in the CIP method can be used for this F_ϕ and $\partial F_\phi / \partial x_i$. What is the merit of this transformation ? Let us propose a tangent function for F_ϕ as

$$F_\phi = \tan[0.99\pi(\phi - 0.5)], \tag{5}$$

$$\phi = (\arctan F_\phi)/(0.99\pi) + 0.5.$$

The factor 0.99 in this transformation is to avoid the infinite value when $\phi = 0, 1$. If we disregard this 0.99, F_ϕ lies in the range from $-\infty$ to ∞ for $\phi = 0$ to 1. When Eq.(4) is solved for F_ϕ, F_ϕ may be slightly diffusive and may have undulation. In contrast, ϕ is always limited to a range between 0 and 1 because of the characteristics of the tangent function. Furthermore, most of values are concentrated near $\phi = 0$ and 1. Therefore, monotone and sharp discontinuity can be described quite easily. The transformation of this kind is effective only for the case where the value of ϕ is limited to a definite range throughout the calculation. The combination of the CIP with such various transformation can open a variety of application fields.

III. CIP PROCEDURE

Here, we briefly summarize the CIP procedure in two dimensions. Most of equations can be written in a form,

$$\frac{d\vec{f}}{dt} \equiv (\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y})\vec{f} = \vec{g}. \tag{6}$$

For example, $\vec{f} = (\rho, u, v, e)$ and $\vec{g} = (-\rho\nabla \cdot \vec{u}, -\nabla p/\rho, -(p/\rho)\nabla \cdot \vec{u})$ for invicid compressible fluid, where u, v are x, y velocity components, p the static pressure, and e the specific internal energy. The CIP method solves the equation by dividing it into non-advection and advection phases. These are symbolically written as

$$\frac{\partial \vec{f}}{\partial t} = \vec{g}, \quad (\mathrm{non-advection} \quad \mathrm{phase}) \tag{7}$$

$$\frac{d\vec{f}}{dt} = 0, \quad (\mathrm{advection} \quad \mathrm{phase}) \tag{8}$$

In the method described before[3,4,5,6], we have used $\vec{f} = (\rho, u, v, e)$, throughout the calculation. In the present case, however, the density function ϕ can also be a component of $\vec{f}$ because $d\phi/dt = 0$ as given in Eq.(2). In order to include this general case combined with the transformation proposed in section II, we use

$$\frac{d\vec{F}}{dt} = 0, \quad (\mathrm{advection} \quad \mathrm{phase}) \tag{8'}$$

instead of Eq.(8). For example, when $\vec{f} = (\rho, u, v, e, \phi)$, then $\vec{F} = (\rho, u, v, e, \tan\phi)$: only ϕ is transformed, while other quantities remain unchanged.

As another example of this transformation, if the density or energy ratio at a sharp discontinuity is extremely high as in the liquid-vapor interface or at strong shock waves, negative value should appear because even a small error at the large-value side causes a negative value at small-value side. In order to avoid this , we may use $\vec{F} = (\log\rho, u, v, \log e)$. In some cases, however, it is not convenient to transform the quantities in all equations into logarithmic value. For example, for the solution of thermal conduction, Eq.(7) had better be solved implicitly in terms of the temperature ($e = kT/(\gamma - 1)$) instead of $\log T$. Therefore, $\log T$ can not be used in $\partial\vec{f}/\partial t$ of Eq.(7). Therefore, it is recommended to use $\vec{F}$ only in the advection phase. Therefore, we had better use Eqs.(7) and (8') as a whole procedure in any cases.

The CIP method needs equations for spatial derivatives $\partial_x \vec{f}, \partial_y \vec{f}$ of the quantities in the advection phase. In the previous paper[5,6], we have derived the equations for these quantities from the original equation (6) as

$$\frac{d(\partial_x \vec{f})}{dt} = \frac{\partial \vec{g}}{\partial x} - \frac{\partial u}{\partial x}\partial_x \vec{f} - \frac{\partial v}{\partial x}\partial_y \vec{f}, \tag{9}$$

$$\frac{d(\partial_y \vec{f})}{dt} = \frac{\partial \vec{g}}{\partial y} - \frac{\partial u}{\partial y}\partial_x \vec{f} - \frac{\partial v}{\partial y}\partial_y \vec{f}. \tag{10}$$

These equations are divided into two phases as in the case of $\vec{f}$. In the present case, however, we transform the variables $\vec{f}$ into $\vec{F}$ in the advection phase (see Eq.(8')) and therefore we need spatial derivatives of transformed values $\vec{F}$ in the advection phase. In the followings, we shall describe the procedure in detail by including the variable transformation.

(1) non-advection phase

$$\frac{\partial \vec{f}}{\partial t} = \vec{g},$$

$$\frac{\partial(\partial_x \vec{F})}{\partial t} = \frac{\partial}{\partial x}(\frac{\partial \vec{F}}{\partial t})_g, \tag{11}$$

$$\frac{\partial(\partial_y \vec{F})}{\partial t} = \frac{\partial}{\partial y}(\frac{\partial \vec{F}}{\partial t})_g. \tag{12}$$

where the first term $(\partial \vec{F}/\partial t)_g$ symbolically represents the time difference of transformed quantities owing to $\vec{g}$ and will be described explicitly in Eqs.(15) and (16). This term corresponds to $\partial \vec{g}/\partial x$ and $\partial \vec{g}/\partial y$ in Eqs.(9) and (10). In the CIP, since $\vec{g}$ is already calculated as a non-advection part of $\partial \vec{f}/\partial t$ in Eq.(7), we need not calculate $\partial \vec{g}/\partial x, y$ but can use $(\partial/\partial x, y)(\partial \vec{f}/\partial t)$,where $\partial/\partial x, y$ represents $\partial/\partial x$ or $\partial/\partial y$. In the present case, we need increment of $\partial \vec{F}/\partial t$ in non-advection phase owing to $\vec{g}$ and hence we can calculated this contribution as written on the right-hand sides of Eqs.(11) and (12). Here, $\partial_{x,y}\vec{F}$ are the independent variables and therefore $\partial_{x,y}$ will not be put into finite difference form.

(2) advection phase

$$\frac{d\vec{F}}{dt} = 0,$$

$$\frac{d\partial_{x,y}\vec{F}}{dt} = -\frac{\partial u}{\partial x, y}\partial_x \vec{F} - \frac{\partial v}{\partial x, y}\partial_y \vec{F}. \tag{13}$$

This completes the whole procedure. In the previous papers [5,6], we included the righthand side of Eq.(13) into non-advection phase (11) and (12). Strictly speaking, these terms are not the non-advection part but appear from the spatial derivatives of the advection velocities. Therefore, we include them in Eq.(13) in this paper.

The sequence of the CIP method is explicitly written as

1. Obtain the values $\vec{f}$ in non-advection phase.

$$\vec{f}^{*}_{i,j} = \vec{f}^{n}_{i,j} + \vec{g}^{n}_{i,j}\Delta t \tag{14}$$

2. Take $T_F(\vec{f}^*)$ to obtain $\vec{F}^*$, where T_F represents the transformation operator.
3. Solve Eqs.(11) and (12) for gradients $\partial_x \vec{F}^*, \partial_y \vec{F}^*$.

$$\partial_x \vec{F}^{*}_{i,j} = \partial_x \vec{F}^{n}_{i,j} + \frac{\vec{F}^{*}_{i+1,j} - \vec{F}^{*}_{i-1,j} - \vec{F}^{n}_{i+1,j} + \vec{F}^{n}_{i-1,j}}{2\Delta x} \tag{15}$$

$$\partial_y \vec{F}^{*}_{i,j} = \partial_y \vec{F}^{n}_{i,j} + \frac{\vec{F}^{*}_{i,j+1} - \vec{F}^{*}_{i,j-1} - \vec{F}^{n}_{i,j+1} + \vec{F}^{n}_{i,j-1}}{2\Delta y} \tag{16}$$

This procedure is referred to NEWGRD($\vec{F}, \partial_x \vec{F}, \partial_y \vec{F}$).

4. Obtain $\vec{F}^{n+1}$ and their gradients $\partial_x \vec{F}^{n+1}, \partial_y \vec{F}^{n+1}$ by shifting a cubic interpolated profile with velocities u^n, v^n.

$$\begin{aligned}\vec{F}^{n+1}_{i,j} = &[(A1_{i,j}\xi + A2_{i,j}\eta + A3_{i,j})\xi + A4_{i,j}\eta + \partial_x \vec{F}^{*}_{i,j}]\xi \\ &+ [(A5_{i,j}\eta + A6_{i,j}\xi + A7_{i,j})\eta + \partial_y \vec{F}^{*}_{i,j}]\eta + \vec{F}^{*}_{i,j}\end{aligned} \tag{17}$$

$$\begin{aligned}\partial_x \vec{F}^{n+1}_{i,j} = &(3A1_{i,j}\xi + 2A2_{i,j}\eta + 2A3_{i,j})\xi \\ &+ (A4_{i,j} + A6_{i,j}\eta)\eta + \partial_x \vec{F}^{*}_{i,j} \\ &- \partial_x \vec{F}^{*}_{i,j}\frac{(u^{n}_{i+1,j} - u^{n}_{i-1,j})\Delta t}{2\Delta x} \\ &- \partial_y \vec{F}^{*}_{i,j}\frac{(v^{n}_{i+1,j} - v^{n}_{i-1,j})\Delta t}{2\Delta x}\end{aligned} \tag{18}$$

$$\partial_y \vec{F}^{n+1}_{i,j} = (3A5_{i,j}\eta + 2A6_{i,j}\xi + 2A7_{i,j})\eta + (A4_{i,j} + A2_{i,j}\xi)\xi + \partial_y \vec{F}^*_{i,j} - \partial_x \vec{F}^*_{i,j}\frac{(u^n_{i,j+1} - u^n_{i,j-1})\Delta t}{2\Delta y} - \partial_y \vec{F}^*_{i,j}\frac{(v^n_{i,j+1} - v^n_{i,j-1})\Delta t}{2\Delta y} \quad (19)$$

where $\xi = -u^n\Delta t$, $\eta = -v^n\Delta t$ and coefficients $A1 - A7$ are given in Ref.[6]. This procedure is referred to DCIP0$(\vec{F}, \partial_x \vec{F}, \partial_y \vec{F}, u, v)$.

5. Perform inverse transformation to obtain $\vec{f}^{n+1}$ as $\vec{f}^{n+1} = T_F^{-1}(\vec{F}^{n+1})$ for the next nonadvection step.
6. Store $\vec{F}^{n+1}$ and $\partial_{x,y}\vec{F}^{n+1}$ into $\vec{F}^n$ and $\partial_{x,y}\vec{F}^n$ and return to step 1. These $\vec{F}^n$ and $\partial_{x,y}\vec{F}^n$ will be used in Eqs.(15) and (16).

It is interesting to note that we do not need gradients of $\vec{f}$ but those of $\vec{F}$ because dependent variables in advection phase are $\vec{F}$.

IV. LINEAR WAVE PROPAGATION

For the linear wave propagation, only the procedure given by Eqs.(17)-(19) are necessary. As shown in the previous paper [5,6], the CIP0 given here is not a monotone scheme. However, since the error in the CIP0 is quite small with small undulations, most of the problems have been successfully solved with high-accuracy by the CIP0 [5,6].

As was discussed in section II, we had better use some transformation for a special purpose like the density function. In the linear case, this procedure is nothing more than using F_ϕ =tanϕ in Eqs.(17)-(19). This result is inversely transformed into ϕ only when the value of ϕ is necessary. In order to show how it works, we show a result of square wave propagation in Fig.1. In the case of density function, the value of function is always limited to a definite range between 1 and 0, and hence the transformation by Eq.(5) is quite effective.

The CIP is applicable directly to any dimensions without directional splitting as shown in Eqs.(17)-(19)[6]. In Fig.2(b), we show a result of two dimensional rotation of a solid body with the CIP0 method described in the previous paper[6]. The computational condition is the same as that used by Zalesak [7]. In this case, the advection velocity is not constant and hence we need to calculate the time evolution of gradients due to spatial gradients of velocities and this is already included in Eqs.(18) and (19). In the CIP0, the quantity is not transformed and hence $\vec{F}$ in Eqs.(17)-(19) is merely ϕ. Thus the procedure is CALL DCIP0($\phi, \partial_x \phi, \partial_y \phi, u, v$).

Although this result is comparable to and better than other methods[8,9], we can further improve this result by simply using a transformation proposed in Eq.(5) like CALL DCIP0($F_\phi, \partial_x F_\phi$,
$\partial_y F_\phi, u, v$). Figure 2(c) is the result of the present scheme. Surprisingly, the shape of the function is preserved throughout the computation.

V. NONLINEAR EXAMPLE

This method is used for the injection of heavier material into lighter material.The equation used here is the incompressible Navier-Stokes equation.

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i}, \tag{20}$$

where the density is given by $\rho = 1.0 \times \phi + 0.3 \times (1 - \phi)$, and u_i stands for u and v. The density funciton ϕ is described by Eq.(2). In the CIP method, Eq.(20) is split into nonadvection ($\partial u_i/\partial t = -(1/\rho)\partial p/\partial x_i$) and advection ($\partial u_i/\partial t + u_j \partial u_i/\partial x_j = 0$) phases. Although the CIP was first proposed for compressible fluid, it can also be applied to incompressible fluid.

(1) Nonadvection phase

In this phase, only the pressure term is solved with a finite difference method:

$$\frac{u_i^* - u_i^n}{\Delta t} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x_i}. \tag{21}$$

In the above equation, the superscript * means one time step after the nonadvection phase, and these quantities having * will be used in the advection phase. By forcing $\nabla \cdot \vec{u}^* \equiv \partial u_i^* / \partial x_i = 0$, we come to the MAC (Marker and Cell)[10]-like procedure to determine the pressure

$$\frac{\partial}{\partial x_i}\left(\frac{1}{\rho}\frac{\partial p^*}{\partial x_i}\right) = \frac{1}{\Delta t}\frac{\partial u_i^n}{\partial x_i}. \tag{22}$$

After the pressure is obtained from Eq.(22), the velocity is calculated with this pressure in Eq.(21).

(2) Advection phase

After u_i^* is obtained in the non-advection phase, the CIP solver described in the previous section is used as

CALL NEWGRD($u_i, \partial_x u_i, \partial_y u_i$)

CALL DCIP0($u_i, \partial_x u_i, \partial_y u_i, u, v$)

CALL DCIP0($F_\phi, \partial_x F_\phi, \partial_y F_\phi, u, v$)

where F_ϕ is given by Eq.(5). These two phases complete the numerical procedure and are repeated step by step.

This scheme is applied to a problem used previously [11]. Initially two fluids are placed at rest in contact with each other. The density of these fluids is $\rho = 1$ for $0 \leq x \leq 0.3$ and $\rho = 0.3$ for $0.3 < x$. The boundary is free in the x-direction and mirrored in the y-direction. The pressure is uniform and the velocity perturbation of incompressible mode ($\partial u_i / \partial x_i \equiv \partial u / \partial x + \partial v / \partial y = 0$) is imposed around the interface whose amplitude is 0.8×0.72. Figure 3 shows the density contours at $t = 0.2, 0.4$ and 0.6, where the grid size is $\Delta x = \Delta y = 0.01/3 (180 \times 90$ grids). Since the density changes only at the interface, the contour lines concentrate there. Thus, the sharp interface has successfully been treated by one grid throughout the calculation.

The scheme proposed here can also be used for coexisting compressible and incompressible fluids by using CCUP procedure [12].

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FIGURE CAPTIONS

Fig.1 : Propagation of a square wave after 1000 time steps with $u\Delta t/\Delta x = 0.2$.

Fig.2 : Rotation of a solid body. (a) Initial profile, (b) after one rotation with the CIP0, (c) with the present scheme.

Fig.3 : Injection of heavier material into lighter material. Density contours at $t = 0.2, 0.4$ and 0.6.

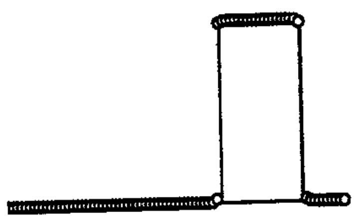

Fig.1

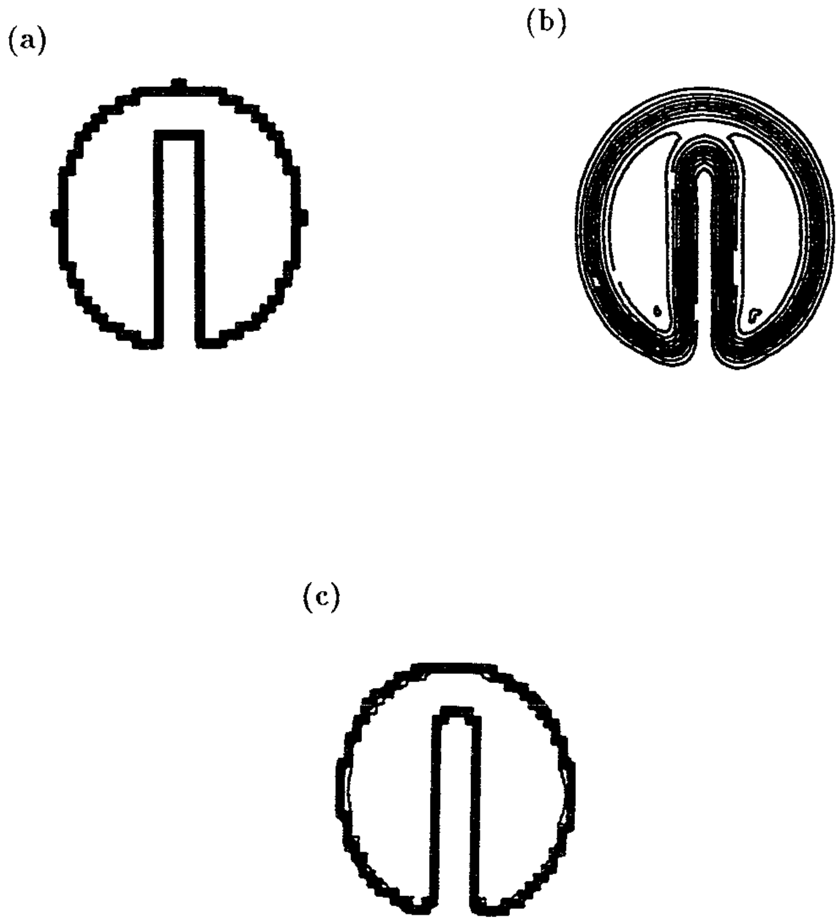

Fig.2

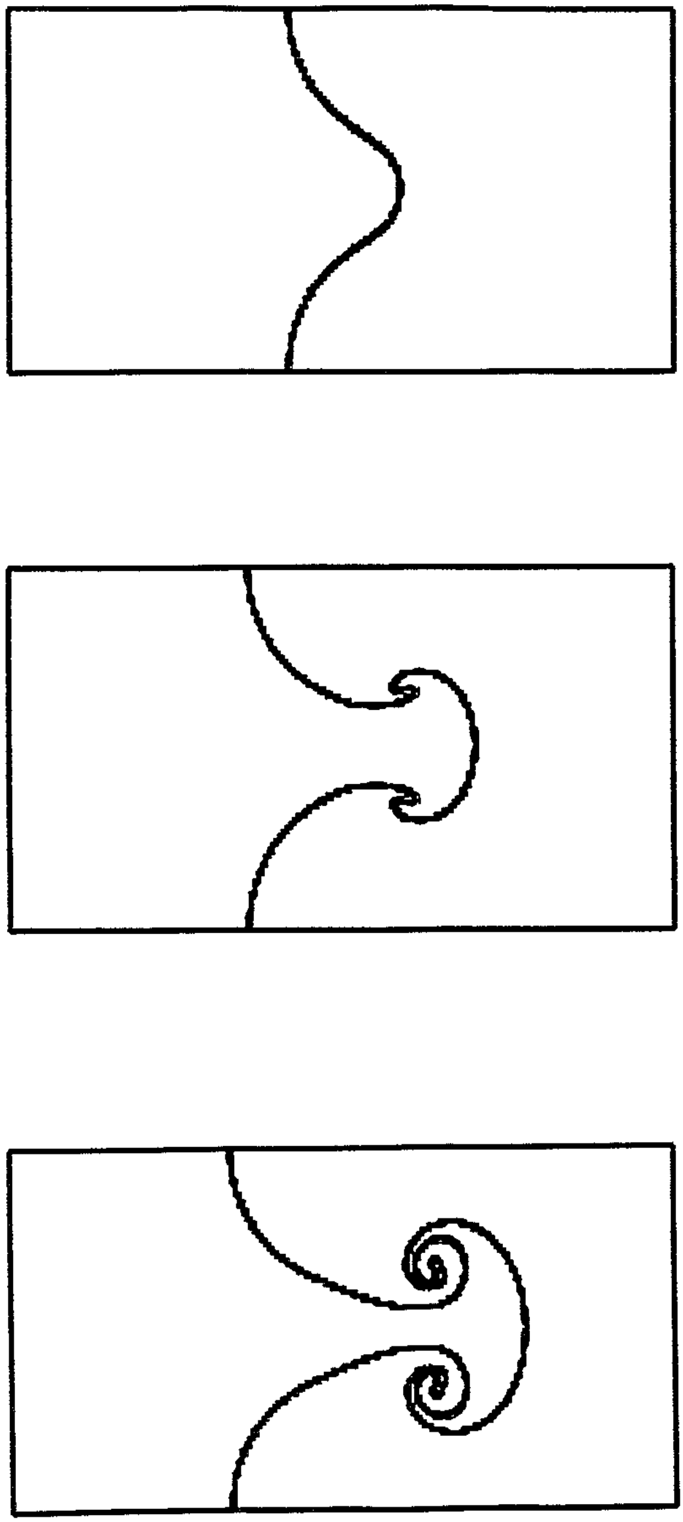

Fig.3

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