Three-Dimensional Simulation of Nonlinear Dynamics of Target Surface at Influence of Intensive Charged Particle Beams

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Abstract – It is suggested and realized a simple method for simulation of nonlinear dynamics of target surface at influence of intensive charged particle beams. There are carried out a computer experiment and comparison of simulation results with experimental and calculated results of other authors. There are investigated mechanisms of a drop formation at influence of target.

1. Introduction

Solid target irradiation by intensive energy streams (they are electron, ion, laser beams) causes acceleration of the treated surface, which ranges from 10^8 to 10^{11} m/s^2 and has impulse behavior. Having such regimes of acceleration, complicated dynamic processes appear on the treated surface such as the formation of gravity waves, Rayleigh surface waves, development of Richtmyer-Meshkov instability [1]. The universal method of problem modeling is direct numerical simulation, which consists in numerical solution of continua mechanics equations. Its main advantage is a possibility to take into account matter compressibility, surface tension, viscosity, arbitrary geometry and boundary conditions. However, these calculations require long super computer work [2–5].

Potential flow of incompressible liquid is often considered to simplify a problem [6]. With this approximation the analytic solution of this problem is possible only for two dimension geometry in case of weak nonlinearly description.

We have developed the numerical method [7, 8] of nonlinear dynamics studying of continuous matters interface with different densities. It is based on the local mapping coordinates method so that Laplace's equation would be the same. This approach lets study interface dynamics without calculating flow in liquid volumes. It makes possible to carry out complete numerical research by means of average capacity computer. Present paper describes this method generalization for three-dimension case, the numerical research results of the treated surface and drop formation, when charged particles beams irradiate one.

2. Model. Computer Experiment. Discussion

In case of incompressible liquid potential flow its interface dynamics is determined by equation set, which consists of Laplace's equations for scalar, φ, and component of vector, $\mathbf{A} = \{\Psi_x, \Psi_y\}$, potentials for fluid volume, Bernoulli's equation and cinematic condition on the boundary between fluids. Three-dimension interface between incompressible liquids with different densities is $Z = Z(x, y, t)$ which is periodic with spacious period L_x along axis x, and L_y along axis y. To simplify we consider function Z has the following symmetry conditions: $Z(x, y, t) = Z(-x, y, t) = Z(x, -y, t) = Z(-x, -y, t)$. Similar to Ref. [7, 8] let us introduce the parametric representation of an interface. Cartesian coordinates of interface points (X, Y, Z) are functions of new variables L, H: $Z = Z(L, H, t); X = X(L, H, t); Y = Y(L, H, t)$. Two planes are passed at the fixed interface point. One of them is parallel to axis x; the other one goes along axis y. The curve length along L-line counted from certain initial value $L_0(H)$ gives value L, while the curve length along H-line determines coordinate H. Periodic function Z in (x, y) is not cycle in (L, H). Therefore to avoid this we use normalized contour lengths: $l = L / L_0(H), h = H / H_0(L)$. Function Z is periodic in variables l, h. Each point has its local basic, so we have $\mathbf{n}$ as normal vector, while

$$\mathbf{e}_L = \{\partial X / \partial l, \partial Y / \partial l, \partial Z / \partial l\},$$
$$\mathbf{e}_H = \{\partial X / \partial h, \partial Y / \partial h, \partial Z / \partial h\}$$

are tangent vectors to L-lines and и H-lines, correspondingly. Normal vector is defined as $\mathbf{n} = [\mathbf{e}_L, \mathbf{e}_H] / B, B = \left|[\mathbf{e}_L, \mathbf{e}_H]\right|$.

To reduce hydrodynamic flow in liquid volume to interface dynamics we carry out transformation of coordinates $(x, y, z) \to (\xi, \varsigma, \eta)$, which converts liquid volumes into half plane in new variables. The additional condition is imposed on coordinate transformation. It is necessary to not change the Laplace's equation form. Then instead of exact coordinate transformation we use local ones to satisfy the mentioned conditions for certain vicinity of the fixed interface point. We have derived the equation-linking scalar and vector potentials by means of coordinate local transformation and analytic solution of Laplace's equation for rectangular area. The closed equation set determining three-dimension interface evolution, is the following:

$$\frac{\partial\varphi(l,h,t)}{\partial t} = \frac{A}{2}v_n^2 + \frac{1}{B^2}\left(1-\frac{A}{2}\right)v_t^2 - AG(l,h,t),$$

$$v_n = (\mathbf{v}\cdot\mathbf{n}) = ([\nabla,\mathbf{A}]\cdot\mathbf{n}) = \frac{1}{B}\left(\frac{\partial\Psi_H}{\partial l} - \frac{\partial\Psi_L}{\partial h}\right),$$

$$\Psi_L = \mathbf{A}\cdot\mathbf{e}_L, \Psi_H = \mathbf{A}\cdot\mathbf{e}_H;$$

$$v_L = (\mathbf{v}\cdot\mathbf{e}_L) = \frac{\partial\varphi}{\partial l},\ v_H = (\mathbf{v}\cdot\mathbf{e}_H) = \frac{\partial\varphi}{\partial h},$$

$$\mathbf{v} = v_n\mathbf{n} + [\mathbf{n},[\mathbf{v},\mathbf{n}]] = \mathbf{v}_n + \mathbf{v}_t =$$

$$= v_n\mathbf{n} + v_L\mathbf{e}_L + v_H\mathbf{e}_H;$$

$$\frac{dX(l,h,t)}{dt} = v_x(l,h,t),\ \frac{dY}{dt} = v_y(l,h,t),$$

$$\frac{dZ(l,t)}{dt} = v_z(l,h,t);$$

$$\Psi_L = -\int_{-1}^{1} dl' \int_{-1}^{1} dh'\varphi(l'.h',t)\frac{\partial g(l-l',B(h-h'))}{\partial h};$$

$$\Psi_H = \Psi_L(\mathbf{e}_H\cdot\mathbf{e}_L) +$$

$$+B\int_{-1}^{1} dl' \int_{-1}^{1} dh'\varphi(l'.h',t)\frac{\partial g(l-l',B(h-h'))}{\partial l};$$

$$g(l-l',h-h') = \sum_{n=0}^{N_0}\sum_{m=0}^{M_0}(1-\delta_{n0}/2)(1-\delta_{m0}/2)\times$$

$$\times\frac{\cos(\pi n(l-l'))\cos(\pi m(h-h'))}{\sqrt{n^2+m^2}}.$$

Here we have the substitution of integration over wave numbers for sum over modes was made; $A = (\rho_+ - \rho_-)/(\rho_+ + \rho_-)$ is Atwood number; ρ_+, ρ_- are fluids densities. Derived system solution was carried out numerically by the method, described in detail in Ref. [7].

The dynamics of three-dimension instability development is given in Fig. 1. The initial perturbation is defined as the production of cosines: $Z = a_0\cos(\pi x)\cos(\pi y)$. At $\tau = 1.2$ the surface Z loses its a single-value that makes impossible plotting three-dimension surfaces by simple graphic editor. Then we show profiles on two planes: $x = 0$ and $x = y$. A drop is formed on the plane $x = 0$ (or $y = 0$), but on the plane $x = y$ a spike does not have a constriction. It is caused by the presence of less movable domain situated in the grid center (x, y). As the initial perturbation is defined as the production of cosines, there is the area for the vicinity of the point (λ/4, λ/4) where $Z \approx 0$.

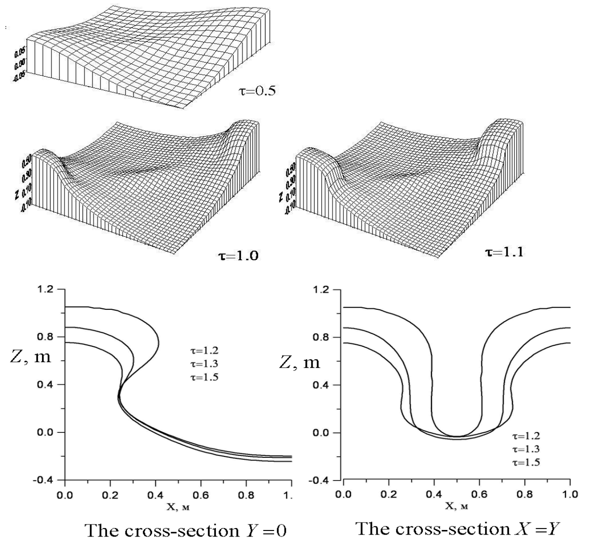

Fig. 1. The dynamics of three-dimensional Richtmyer-Meshkov instability development for a_0 = 0.1 m, λ = 2 m, u = 100 m/s, A = 1

Figure 2 shows the comparison with the results given in Ref. [5]. The calculations have been made before ξ = 1.5 when the computable domain loses its simple connectedness. The results are independent from number of grid points or number of taken modes until ξ = 1.5 as well as ones obtained in case two-dimension instability. On the whole the results are not contradictory and satisfactory fitted at the present theory development stage they. It is worth noting the present computations were carried out on PENTIUM III. It has taken two hours to calculate three-dimension instability with a grid 80×80 in calculating domain and number modes of 8×8.

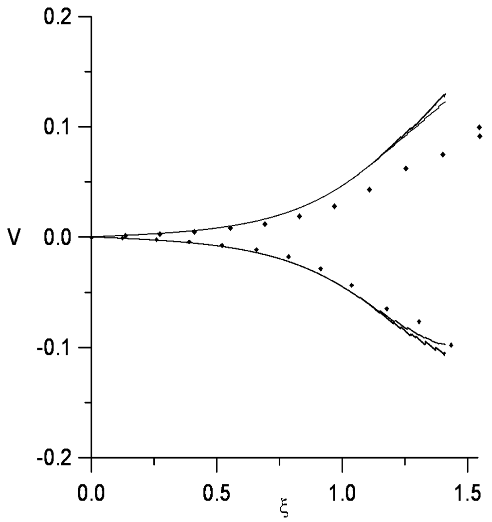

Fig. 2. Dependence of a spike grow rate $v = \sqrt{k(2\pi g)}u$ (positive numbers) and a bubble grow rate (negative numbers) from $\xi = \sqrt{Agk/(4\pi)}t$ for a_0 = 0.1 m, λ = 2 m, g = 200 m/s^2 and A = 0.05. Markers are results of authors of Ref. [5]; lines are our results

We have studied conditions of drop formation and its separation on the treated target surface as a result of interface instability between “plasma–condensed substance” using 2D code [7]. Values on the surface (Atwood number, liquid particle acceleration) were determined by means of code BETAIN1 [9, 10]. The interface fuzziness (density gradient continuity) was taken into account by using an effective Atwood number. The initial perturbation is $Z(x, t = 0) = a_0 \cos(2\pi x/\lambda)$. Irradiating of target by charged particle beams with ranges about microns (ion and low energy electron beams used for technical purposes) the strain of interface is exposed to influence on processes on the free plasma jet surface. There is the highest speed wavelength (λ_0 is the order of some microns). Drop separation is stated to occur when $Z \approx \lambda$. In case of sharp interface (there is density leap) discontinuity amplitude rate is about $\sim\lambda^{-1}$ [1] and so the separation time is about $t_s \sim\lambda^{-2}$. Such estimation is valid for $\lambda > \lambda_0$. Our results show weak dependence t_s on λ at $\lambda < \lambda_0$ and presence of dependence t_s on $a_0 : t_s \sim a_0^{-1}$. According to our calculations drop diameter is $d \sim \lambda/2$. Therefore the most intensive process is drop formation with $d \le \lambda_0/2$. Having initial amplitude large enough $a_0 \approx 0.1–1$ μm formation of such particles may occur during one irradiation impulse.

As our calculations show in case of target irradiation by beams with the range tens microns (light ions with some MeV) drop formation with $d \le \lambda_0/2$ is the most probable. Slow Atwood number approach unit is common feature when target is irradiated by beams with range tens hundreds microns. It is caused by slow massive (“thick”) plasma layer dispersion. As Atwood number is considerably less than unit. It causes flat vortex formation, which afterwards separates from substance volume. At separation time cross drop diameter is $d \sim \lambda$, and so waist constriction is accompanied with merging of neighboring vortexes. Therefore in this case it is better to consider this process as mixing of condensed substance. This question requires further studies and turbulence mixing consideration.

3. Conclusion

Thus we are suggested a simple method of reduction of the three-dimensional hydrodynamic flow in an irradiated target to nonlinear dynamics of its surface. Nonlinear differential equations of the presented model are solved on a personal computer. A computer experiment and comparison of our results with experimental and theoretical results of other authors are carried out. Conditions of a drop formation at influence of target by charged particle beams are investigated in two-dimensional geometry.

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