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COLLISIONS OF LOCALIZED TRAVELING-WAVE CONVECTION CELLS IN BINARY FLUID

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Abstract. We study the collision processes of spatially localized traveling wave(pulses) in convection of binary fluid mixture by an amplitude equation. Qualitative result of pulse collision observed in experiments, the formation of bound states and pulse destruction, is reproduced by this equation. It is shown that even if the pulse collision results in the destruction of one pulse, bound state exists as a solution. We found that an unstable solution is embedded in the collision process, which is a candidate for "scattor", the unstable saddle near which orbits pass through and are sorted out along their unstable manifolds.

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1 Introduction

1.1 Pulse interaction in dissipative systems

Spacially localized moving objects such as pulses and spots are a representative class of dynamic patterns in dissipative systems. The collision processes of such objects include a variety of input-output relations such as annihilation, repulsion, fusion, and even chaotic dynamics. Such phenomena have been observed both experimentally and numerically, for instance, in barchan dunes[13], gas-discharged system[2], CO-oxidization process[34], chemical reactions[6], and reaction-diffusion systems[22, 23, 32].

Although such phenomena are interesting, to our best knowledge, there are no universal viewpoints to understand the collision dynamics (strong interaction between those objects) due to the difficulties such as large deformation and its transient property. Thus most anaysis of pulse-collision dynamics in dissipative systems is case study for each system.

Recently, a new concept was proposed by Nishiura *et.al* [23], which shed a light on this issue. Among complicated and strong interaction processes during pulse collision, unstable solutions embedded in the process is an important key to understand the input-output relations. Such unstable solutions are hidden saddles near which orbits pass through and are sorted out along their unstable manifolds. Typically, they are unstable steady states or unstable time-periodic patterns. They are called "scattor", and the engenfunctions of the linearized operator around scattor, are shown to determine the destination of the pulses in reaction-diffusion systems such as Gray-Scott model and the complex Ginzburg-Landau equation [22, 23, 32].

In this paper, we show by using an amplitude equation that an unstable solution is embedded in the collision process of localized traveling wave in convection of binary fluid mixture. The contents of this paper is as follows. In section 2, we briefly review the convection in binary fluid mixture. Section 3 is devoted to explain the amplitude equation. We show the result of the numerical simulation in section 4.

2 Convection in Binary Fluid Mixture

2.1 Governing equations

One of the most well-known phenomena in nonequilibrium dissipative systems is the convection in a horizontal layer heated from below (*i.e.*, Rayleigh-Benard convection). In this case, the fluid is homogeneous, *e.g.*, water (Fig.1(a)). Here we consider the Rayleigh-Benard convection of binary fluid mixture, which is an example of inhomogeneous fluid. The governing equation of the motion of binary fluid mixture is

$$
\begin{aligned}
(\partial_t + \vec{u}\cdot\nabla)\vec{u} &= -\nabla p + Pr\ Ra\ (T+C)\vec{e}_y + Pr\Delta\vec{u}, && (1)\\
\nabla\cdot\vec{u} &= 0, && (2)\\
(\partial_t + \vec{u}\cdot\nabla)T &= \Delta T, && (3)\\
(\partial_t + \vec{u}\cdot\nabla)C &= \mathcal{L}(\Delta C - \psi\Delta T). && (4)
\end{aligned}
$$

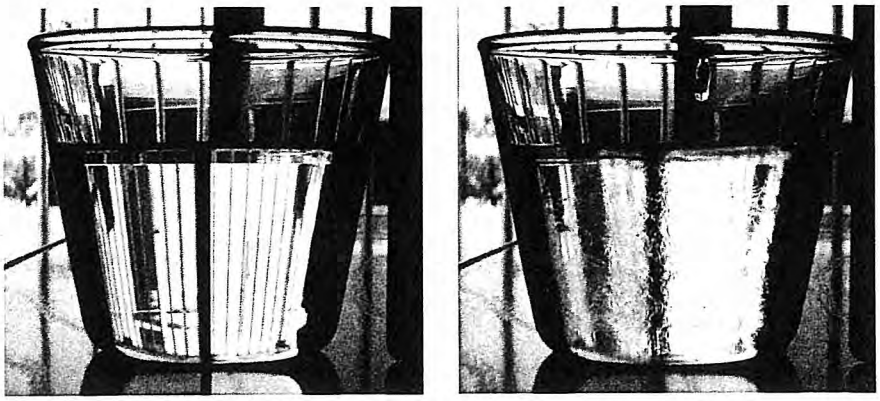

Figure 1: (a) Pure fluid; (b) Binary fluid. Scenery is distorted due to the spatial fluctuation of concentration field of alcohol.

The equations have four variables: $\vec{u}$ is velocity, p is pressure, T is temperature, and C is concentration, and $Pr, Ra, \mathcal{L}$ and ψ are nondimensional parameters.

We can get the equations of ordinary Rayleigh-Benard convection by setting $\psi = 0$ and $\mathcal{L} \to \infty$ (which is equivalent to set $C \equiv 0$), which means that the fluid is homogeneous. Thus, convection in homogeneous fluid is described by two parameters: the Rayleigh number Ra, which is proportional to the temperature difference across the fluid layer, and the Prandtl number Pr, which is the ratio of the momentum dissipation rate to the heat diffusion rate.

If the fluid is a mixture of binary fluid, the index of refraction has inhomogeneity, which makes the scenery through the binary fluid fluctuated (Fig.1(b)). To describe convection in binary fluid mixture, two more parameters are required: the Lewis number $\mathcal{L}$, which is the ratio of the concentration diffusion rate to the heat diffusion rate, and the separation parameter ψ, which is proportional to the concentration flux to an imposed temperature gradient.

When water and alcohol is used to make binary fluid mixture, $\mathcal{L} \ll 1 < Pr$, and $\psi < 0$ [33].

2.2 Onset of convection

A trivial solution of eqs.(1)-(4) is conductive state, which is given by $\vec{u} = 0, T = -y$, and $C = \psi y$ [1]. When negative ψ is assumed, the thermally induced concentration gradients oppose the onset of convection.

The convection is observed if the Rayleigh number Ra surpasses a critical value. For homogeneous fluid, the first flow pattern above the onset of convection is known to be

[1]We assume the top/bottom boundaries are represented by $y = \pm\frac{1}{2}$, and the container has infinite width. Boundary conditions are: $T(x, y = \pm\frac{1}{2}) = \mp\frac{1}{2}$, $\vec{u}(x, y = \pm\frac{1}{2}) = \vec{0}$, and $(\partial_z C - \psi\partial_z T)|_{y=\pm\frac{1}{2}} = 0$.

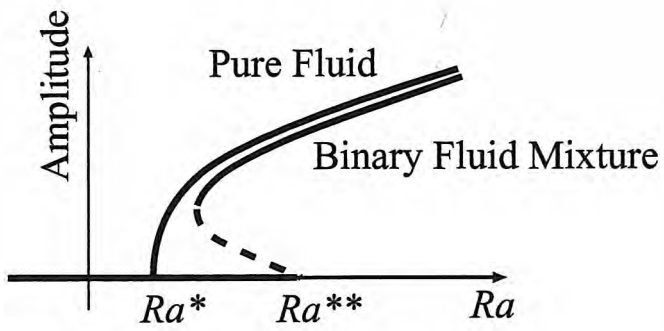

Figure 2: Schematic Picture of the bifurcation diagram in Rayleigh-Benard convection. Supercritical bifurcation causes convective flow for pure fluid, while subcritical bifurcation for binary fluid mixture.

a set of nearly parallel rolls which are stationary in space. In other words, convection is caused by the stationary instability from the conductive state. On the other hand, for binary fluid mixture, the instability of the conductive state leads to a Hopf bifurcation. This transition is described by the parameter ψ, and linear stability analysis reveals that stationary instability is predicted when $\psi > \exists\psi_c = O(\mathcal{L}^2) \simeq 0$ (including pure fluid), and that oscillatory instability (Hopf bifurcation) is predicted when $\psi < \psi_c$[5].

The onset of convection in binary fluid mixture is a subcritical bifurcation, which makes a contrast to supercritical bifurcation in homogeneous fluid (Fig.2).

2.3 Localized convection cells

Convective patterns in binary fluid mixtures can be classified into several types. Near onset, the convection rolls are found to move as the traveling wave train, *i.e.*, spatially periodic traveling wave. It behaves, however, chaotically as Rayleigh number is increased [33]. An interesting fact is the existence of a localized traveling waves (LTW) consisting of localized convection cells. Intuitively, the existence of the localized convection cells may be understood as follows. Because we have a bistable region (conductive state and convective state) by the subcritical bifurcation structure, there may be front solution which connects conductive state to convective state. The velocity of the front depends on the state of both sides, since the convective state has lost right-left symmetry (convection rolls move in one direction). Therefore, a pulse solution consisting of two fronts may move keeping its width. We mention that the breaking of right-left symmetry of convection is a necessary condition for the formation of the pulse. Otherwise, the width of the pulse increases or decreases due to the symmetry.

Niemela *et.al.* measured the localized traveling wave quantitatively, in the size, shape, wave number, frequency and convective heat transport, and show that the properties of LTW are essentially independent of the shape of the containers [21]. It is found numerically that a large scale concentration current loop influences LTW in a way that the group velocity of LTW is smaller [3]. Detailed study of the traveling wave, stationary states [4],

and localized traveling wave was done in ref. [?]. The growth of the convection cells are also studied [7]. The effect of strong Soret coupling is also examined, and LTW is also sustained in this situation [10].

The interactions between two counter propagating LTWs are studied experimentally, and the collision leads to either bound state or a state in which one pulse disappeared depending on the pulse velocity [14, 15, 16, 17]. The effect of phase perturbation to the pulse interaction is also studied [8].

Two-dimensional spatial convection pattern has been studied also. A transition from a curved texture of convection cells to an angular texture is reported [24]. The global dynamics of traveling-wave patterns is studied in different cell geometries [1]. Recently, it is shown exmerimentally that a feedback of spatially varying Ra stabilizes dissipative chaos in binary fluid convection [18, 19]

3 Extended Complex Ginzburg-Landau Equations

We study pulse-collision dynamics by so-called "extended complex Ginzburg-Landau equations(ECGL)", a one-dimensional amplitude equation derived from eqs.(1)-(4) [26]:

$$\partial_t A = d\partial_{xx}A + (a + fC)A + c|A|^2A + p|A|^4A + g|B|^2A, \quad (5)$$

$$\partial_t B = d^*\partial_{xx}B + (a^* + f^*C)B + c^*|B|^2B + p^*|B|^4B + g^*|A|^2B, \quad (6)$$

$$\partial_t C = \delta\partial_{xx}C + \alpha C + h\partial_x(|A|^2 - |B|^2), \quad (7)$$

where $x, t \in R$, $A(x,t), B(x,t) \in C; C(x,t) \in R$, $d, a, f, c, p, g \in C; \delta, \alpha, h \in R$, and * means complex conjugate.

ECGL are derived from the equations of two-dimensional convection in binary fluid mixture by imposing infinite Prandtl number, free-slip-permerable boundary conditions, and small Lewis number. Variable $A(x,t)$ means the amplitude of the right-traveling wave, $B(x,t)$ is the amplitude of the left-traveling wave, and $C(x,t)$ is the amplitude of the concentration field. Parameters d, f, c, p, g and h depend on ψ only. Parameter α depends on $\mathcal{L}$ only, and parameter a depends Ra and $\mathcal{L}$. In this paper, we control Ra by changing a.

This equations have following characteristics. (1) ECGL is invariant under the transform $(A(x,t), B(x,t)) \to (B^*(-x,t), A^*(-x,t))$. (2) interaction terms such as $g|B|^2A$ do not depend on the phase of the counterpart component. In other words, dynamics of A does not depend on the phase of B. This makes the analysis of this problem simpler than the analysis of pulse interaction in complex Ginzburg-Landau system, in which the dynamics of pulse collision depends on the phase difference between pulses[32].

We mention that the same equation is derived to study the sideband instabilities following the onset of traveling interfacial waves in two-layer Couette-Poiseuille flow [25]. Also, a similar but different equation including spatial derivative besides dissipation is also proposed as a simple model of electroconvection in nematic liquid crystals, and a two-dimensional localized wave structures("worm") are reproduced [29]. Theoretical study of instabilities in this equations are done in [31].

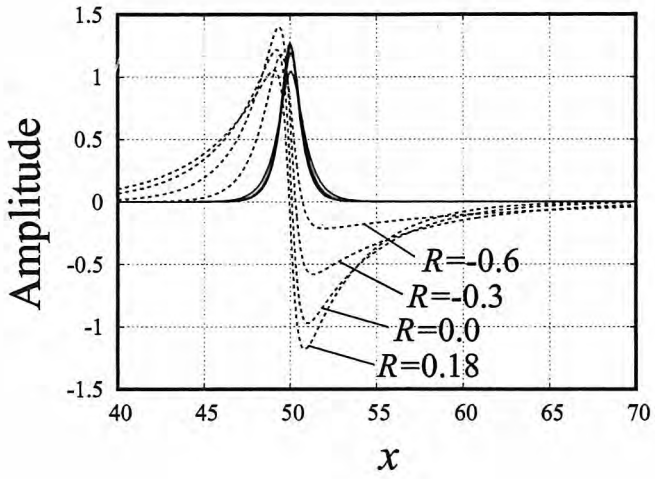

Figure 3: Pulse solutions. Solid line stands for the amplitude of A, and broken line for C.

4 Numerical Approach to Pulse-collision Process and the Role of Unstable Bound State

Eqs.(5)-(7) are integrated by means of a standard Euler scheme with a time step $\Delta t = 0.0001$, computational domain $L = 100$ with periodic boundary condition, and grid spacing $\Delta x = 0.1$. Parameters are taken as follows, $d = 0.15 + 1.0i, f = 0.4, c = 2.4 + 2i, p = -1.65 + 2i, g = -10, \delta = 0.25, \alpha = 0.02, h = 0.5$, where $i = \sqrt{-1}$. Values of parameters are taken from Ref. [28] except $a = (-0.24 + R)$ where R, corresponding to the Rayleigh number, is the only control parameter in this paper.

4.1 Single localized traveling wave

We focus on a class of spacially-localized solution (reffered to as "pulse" hereafter). A pulse consisting of A and C only ($B \equiv 0$) is shown in Fig.3. The amplitude of A is barely influenced by the C field despite its coupling term fCA in eq.(5). Because of the term $\partial_x |A|^2$, the shape of C is asymmetric, while $|A|$ has (almost) symmetric shape[27].

The velocity of pulse can be both positive and negative depending on R as in Fig.4. Since the governing equations do not have (linear) advection term $v\partial_x A$, the propagation of pulse is caused by the coupling with the concentration field C. In Fig.5, typical forward and backward-propagating pulses are shown. We call "forward-propagating" or "backward-propagating" for the propagation direction of a pulse consisting of A and C. For a pulse consisting of B and C, the direction is opposite because of the symmetry of ECGL. The maximum of C of the forward-propagating pulse is smaller than that of the backward-propagating pulse. Linear growth rate in the left half of the backward-propagating pulse is larger than the forward-propagating pulse, which changes the direc-

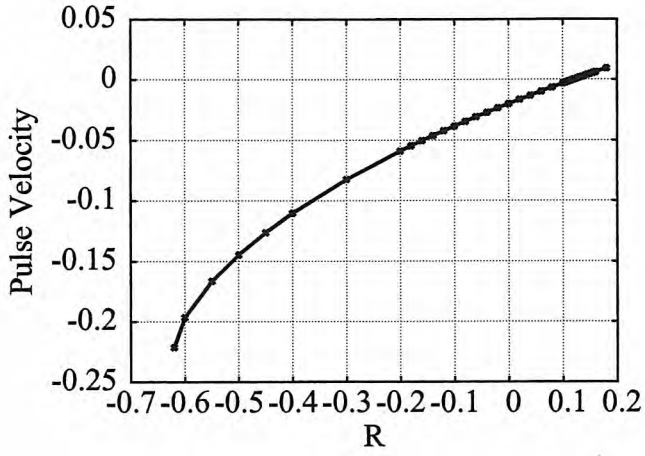

Figure 4: Pulse velocity of a pulse. Pulse solution exists in the region $-0.62 \leq R \leq 0.18$. Depending on R, the velocity can be both positive and negative.

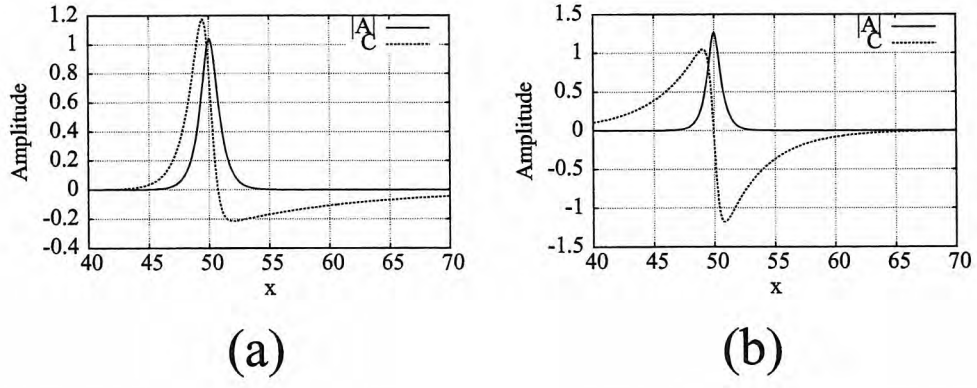

Figure 5: (a) Typical positive-propagating pulse ($R = 0.18$). (b) Typical negative-propagating pulse ($R = -0.6$).

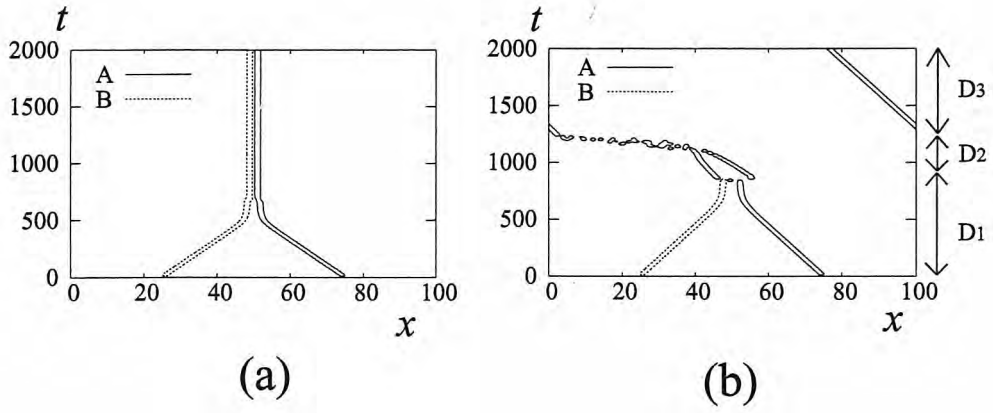

Figure 6: (a) Space-time plot of pulse collision for $R = -0.14$. Contours of $|A|$(solid line) and $|B|$(dotted line) are shown. Asymptotic state is a bound state. (b) Space-time plot of pulse collision for $R = -0.08$. Two pulses come close to each other (D_1). Due to strong interaction, one pulse annihilates. A new order is constructed during the interaction (D_2), but only one pulse survives asymptotically (D_3).

tion of propagation.

The experiments show that the localized convective patterns propagate both forward and backward depending on the Rayleigh number [15], which is qualitatively the same as the result obtained from ECGL. ECGL has been analyzed to study localized traveling-waves for the convection in binary fluid mixture, and the following results are obtained so far: (1)the extremely slow drift velocity, which is observed experimentally, is reproduced [27]. (2)the coexistence of localized waves with different lengths, which was also observed experimentally, is reproduced. (3)As property of ECGL, localized waves can be stable even if all of the coefficient of the equations are real [26]. Ordinary complex Ginzburg-Landau equation does not have this property [30]. The interaction of pulses are studied in terms of the stability of bound pulse [28]. The interaction of fronts is also studied in detail [9]. Therefore, the pulse solution of ECGLE has characteristics similar to the localized convection in binary fluid mixture.

4.2 Pulse collision

In this section, we discuss the detailed process of the pulse collision. We treat the head-on collisions of counter-propagating pulses. The initial condition is made by situating a pulse consisting of A and C and a pulse consisting of B and C with sufficiently large distance (distance $= 50$).

Asymptotic state after pulse collision is either a bound state in which two pulses merge and remains as a motionless bound state or a destruction state in which one or two of the pulses disappear as a result of the strong interaction(see Fig. 5). We characterize the bound state by the distance between two pulses, *i.e.*, the distance of the peak of $|A|$ and

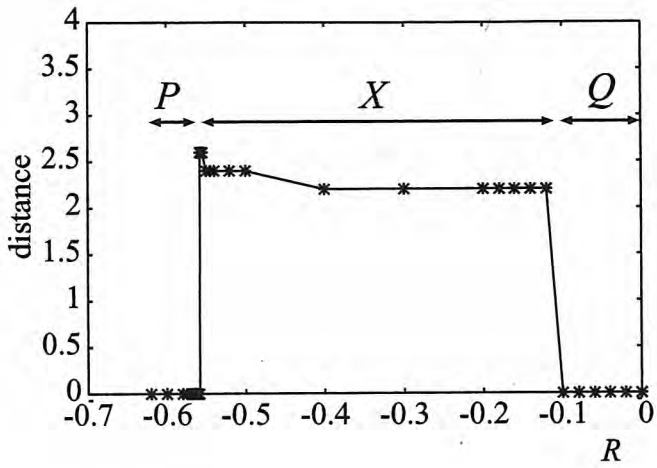

Figure 7: The result of the pulse collision. If bound state is formed as a result of pulse collision (region X), the distance of the bound state is shown. Destruction state is obtained in the region P and Q.

$|B|$.

Fig.7 shows the result of the pulse collision by the asymptotic state. In the region X ($-0.54 \leq R \leq -0.12$), bound state is formed. It should be noted that the bound states are time-periodic solution of ECGL in general, though the amplitudes of A, B are stationary in time. We have two regions representing the destruction state P, Q respectively (the single pulse solution exists for $-0.62 \leq R \leq 0.18$).

4.2.1 Stable bound state in destruction region

In the following anaysis, we focus on the transition between the bound state X and the destrcution state Q.

An intriguing character of this transition is that bound states exist even in the destruction region Q. To show that, we performed a series of simulations by continuation starting at a bound state in X. The result is shown Fig.8, which indicates we have the following bound states in the destrution region Q. When $R \leq -0.14$, we obtain a symmetric bound state in which the peak of one pulse is the same as the other. In the region $-0.12 \leq R \leq -0.10$, we observe an asymmetric bound state, in which the two pulses have different height. The amplitude of these two bound states are stationary in time. On the contrary, when $-0.09 \leq R$, we observe oscillating bound state in which the amplitude of the pulse oscillates in time.

In short, we have bound states even if the destruction of one pulse is observed after the pulse collision, however, two pulses do not fall into such bound states after collision, which needs more detailed analysis.

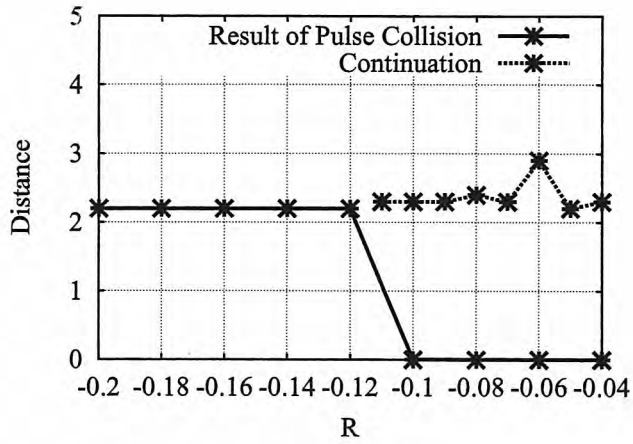

Figure 8: The distance of bound state. Solid line shows the asymptotic state of pulse collision, which is destruction state in the region $-0.1 \leq R \leq -0.04$. Dotted line shows the asymptotic states by continuation starting from the bound state at $R = -0.12$.

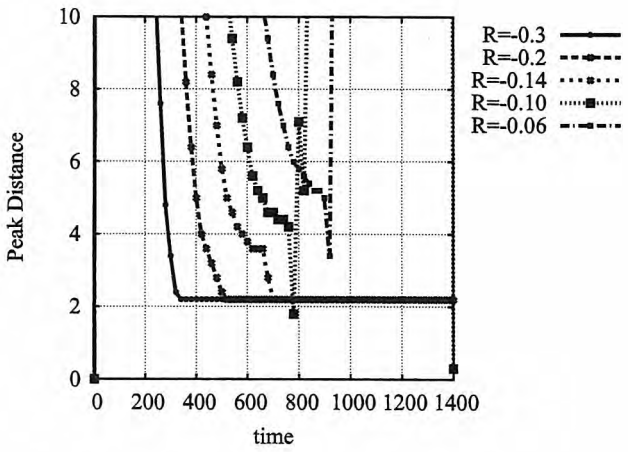

Figure 9: The distance of pulses during the collision process. We can see quasi-steady states for $R = -0.14(600 \leq t \leq 650)$ and for $R = -0.10(t \simeq 750)$.

4.2.2 Pulse-collision dynamics

We study the dynamics of the pulse collision. The distance of counter-propagating pulses is shown as a function of time in Fig.9. A typical peak distance of bound state ($R = -0.14$) is about 2.2. The functions in the destruction range Q look as if it passes through a quasi-stationary state. For $R = -0.10$, the quasi-stationary state is observed when $t \simeq 750$ as a short plateau in which the distance is about 4.2. The similar quasi-stationary state is observed more clearly for $R = -0.14$ by a plateau where the distance is about 3.5 when $600 \leq t \leq 650$.

4.2.3 A role of hidden saddles in the destruction process

To understand the dynamics of the destruction state, the concept 'scattor' developped in [22, 23, 32] may be useful to clarify such a transient process. Scattor is an unstable saddle, which may be a steady state or time-periodic state depending on the system, and control the traffic flow of orbits along its unstable directions. The solution profile deforms into a new state at collision and qualitative change of the output after collison is caused by the orbital switching of unstable directions of the scattor. Therefore it happens frequently near the transition point that the orbit stays near the scattor for certain time and then start to move along one of its unstable manifolds.

In this system, the scattor should be a time-periodic solution, and the system size is much larger than the preceding studies, *i.e.*, number of spatial grid point $N = 1000$ and the ratio of the period of the solution to the time step $m \sim 10000$. This means that we can neither apply computational tools such as *AUTO* into this problem to obtain global bifurcation diagram nor use Newton's method to obtain the scattor. Therefore, we apply another method, delayed feedback control method (DFC), to obtain the unstable time-periodic solution.

4.2.4 Delayed feedback control

Delayed feedback control (DFC) method was originally proposed to stabilize unstable periodic orbit in chaos [20, 11, 12]. Although inclusive understanding has not been done, the condition of stabilization is given for particular case (near period-doubling point) [11, 12].

The procedure of the delayed feedback control method is as follows. Suppose dynamical system in N-dimensional space

$$\dot{X} = F(X) \ \ (X \in R^N) \tag{8}$$

has an unstable periodic orbit (UPO) with period τ; $X_0(t+\tau) = X_0(t)$. Then, $X_0(t)$ can be obtained as a stable periodic solution of the following equation:

$$\dot{X} = F(X) + D, \tag{9}$$

$$D = K(X(t-\tau) - X(t)), \tag{10}$$

where K is a constant.

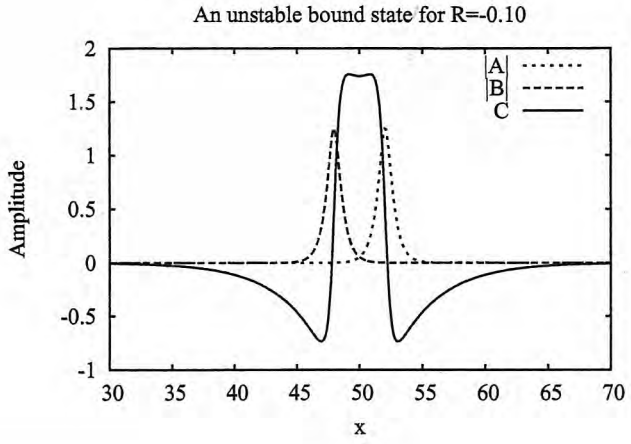

Figure 10: An unstable time-periodic bound solution obtained by the delayed feedback control method.

4.2.5 Unstable bound state

We obtained an unstable bound state when $R = -0.10$ by DFC. The detail procedure is as follows. As an initial condition of eqs. (9) and (10), a snapshot data of pulse-collision process is used. We assumed that the period of the UPO, τ, is close to the period of the input data, and made an interval $[\tau_1, \tau_2]$ such that $\tau \in [\tau_1, \tau_2]$. Then, we performed simulations for several values of τ in $[\tau_1, \tau_2]$, and get the best value so that the amplitude of the control signal, $|D|$, gets minimum. According to the τ, we redefine narrower interval $[\tau_1', \tau_2']$, and continue the above simulations until D is sufficiently small.

In Fig. 10, we show the unstable bound state. It should be noted that the figure only shows amplitudes of A and B only, and both real parts and imaginary parts of them are periodic in time. The period of this unstable bound state is calculated as 1.950475. The peak-distance between the peak of $|A|$ and the peak of $|B|$ is about 4.2, which is different from the distance of the stable bound state discussed in sec. 4.2.1 and Fig.8. Also, the distance is similar to the distance in plateau in Fig. 9. Because the stable bound state can not be reached by the pulse collision, this unstable bound state seems to play a similar role of scattor developped in [22, 23, 32].

5 Summary

In this paper, we studied pulse-collision dynamics in binary fluid mixture by extended Ginzburg-Landau equations(ECGL). Numerical integration shows that ECGL reproduce the qualitatively similar behaviors observed in the experiments: the dependency of the pulse velocity on the Rayleigh number and asymptotic states of the pulse collision such as the formation of bound states and pulse destruction.

We investigated various pulse-collision dynamics numerically. In particular, even in a region where pulse collision results in the destruction of one pulse, bound states are

found as a solution of ECGL. This fact strongly suggests the existence of some mechanism switching the orbit of the pulses before they form a bound state. We obtained an unstable (time-periodic) solution which is related to the characterization of the pulse collision by delayed feedback control method (DFC). We note that DFC has not been applied to study the pulse-collision dynamics.

We have not reached the detailed study of the collision process: much works should be done. To understand the collision process, the concept "scattor" developped in ref.[22, 23, 32] may be useful. The solution profile deforms into a new state at collision and qualitative change of the output after collison is caused by the orbital switching of unstable directions of the scattor. Therefore it happens frequently near the trasition point that the orbit stays near the scattor for certain time and then start to move along one of its unstable manifolds. Now we are doing whether the result of pulse collision can be controlled by a class of engenvectors of the liearized operator of the unstable bound state. We will report the details in the forthcoming paper.

Detailed study of the amplitude equation is an important step for understanding more realistic system described by Navier-Stokes equations. Comparison of the present result with such system is a challenging problem. The key for the analysis is to obtain an appropriate unstable periodic solution embedded in the collision process. DFC may be also applied to this problem, because it only requires the time-series data of the orbit. We believe that our approach is a universal viewpoints for collision dynamics in a wide range of dissipating systems.

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