Observation of a helical-wave resonance in an excitable distributed medium

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The first experimental observation of a resonance of helical waves during periodic modulation of the excitability of an active medium with a frequency close to the natural rotation frequency of the helical waves is reported.

The events which occur in distributed active media have recently attracted much research interest. A distributed active medium consists of self-excited-oscillator elements, flip-flops, or excitable elements which are locally coupled with each other. Energy is supplied continuously to each of the elements, so that dissipative losses are replenished. There are many examples of distributed active media, varying widely in nature.[1,2] In particular, magnetic superconductors carrying a current,[3] nonequilibrium plasmas, and semiconducting media are systems of this sort.[4,5] The most convenient medium for experimental observations is one in which a Belousov-Zhabotinskiĭ chemical reaction occurs.[6]

In an excitable active medium, there is a unique uniform state of rest, which is stable with respect to small perturbations. In addition, solitary self-propagating waves propagate through such a medium without damping, and after their propagation the medium reverts to its original rest state.

Since the states of the medium before and after the passage of a solitary wave are identical, there may be situations in which the wavefront breaks. If we adopt a plane half-wave with a breaking as an initial condition, this broken front will evolve in time and convert into a helical wave if the medium is sufficiently "excitable" (see Ref. 7).

A helical wave is an exceedingly stable formation (its stability results from the conservation of topological charge[8]). In this steady regime, the point of the break revolves in a circle (the boundary of the core of the helical wave) at a constant angular velocity. The revolution frequency and the shape of the front of a helical wave are fundamental characteristics of the given excitable medium. A helical wave may be regarded as one of the basic types of elementary excitation structures in such highly nonlinear media.

The revolution frequncy (and the core radius) of a helical wave are determined uniquely by the characteristics of the active medium—by its effective excitability. With increasing excitability of the medium, the core radius decreases, and the revolution frequency increases. These characteristics were calculated in Refs. 9 and 10 by a kinematic method proposed there.

By varying the parameters of the active medium one can change its excitability. Let us assume that this excitability varies periodically over time in accordance with

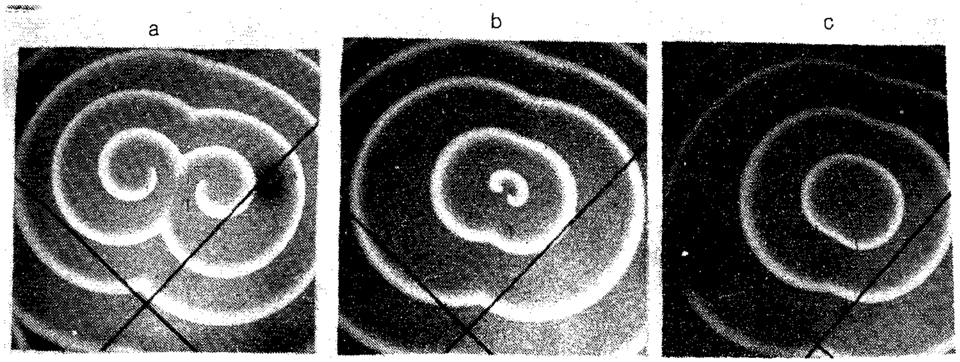

FIG. 1.

$$g = g_0 + g_1 \cos(\omega t + \varphi), \qquad (1)$$

where $g_1 \ll g_0$, and the modulation frequency ω is approximately equal to the natural frequency of the helical wave, ω_0. In this case, as was first shown in Ref. 11, a resonance effect should be observed: When there is a modulation of g, the center of revolution of the helical wave is no longer at rest; it instead begins to move along a circle as time elapses. The radius of this circle, R, increases as ω approaches the natural frequency ω_0, $R \sim 1/|\omega - \omega_0|$, and the velocity of the center is proportional to the modulation amplitude g_1. When the frequencies are precisely equal (i.e., at total resonance, with $\omega = \omega_0$), the center of the helical wave should move at a constant velocity along a straight line. The direction of the displacement of a given helical wave is determined by the initial modulation phase φ and by the wave rotation direction (clockwise or counterclockwise).

As was already mentioned above, one of the most convenient systems for an experimental study of self-propagating-wave structures is an excitable chemical medium consisting of a thin, unmixable layer of a solution in which a Belousov-Zhabotinskiĭ reaction is occurring. This system has the advantages that the self-propagating-wave structures in it are of macroscopic size (on the order of a few millimeters), and the structures evolve fairly slowly (with time scales on the order of a minute). These circumstances substantially simplify the task of detecting self-propagating-wave effects.

For an experimental observation of a resonance, we used a reaction catalyzed by the ruthenium compound $Ru(dipy)_3$. In contrast with the conventional Belousov-Zhabotinskiĭ reaction (in which the catalyst is a ferroin), the reaction with ruthenium is light-sensitive (the conventional Belousov-Zhabotinskiĭ reaction is sensitive only to intense UV radiation): By varying the illuminance one can control the excitability of the medium.[12]

The experiment is carried out in the following way. We pour 4.5 ml of the solution with a modified Belousov-Zhabotinskiĭ reaction onto the bottom of a Petri dish 9 cm in diameter. Using the standard technique,[13] we create a helical wave or a pair of such waves in the medium. After measuring the period of the steady-state rotation of

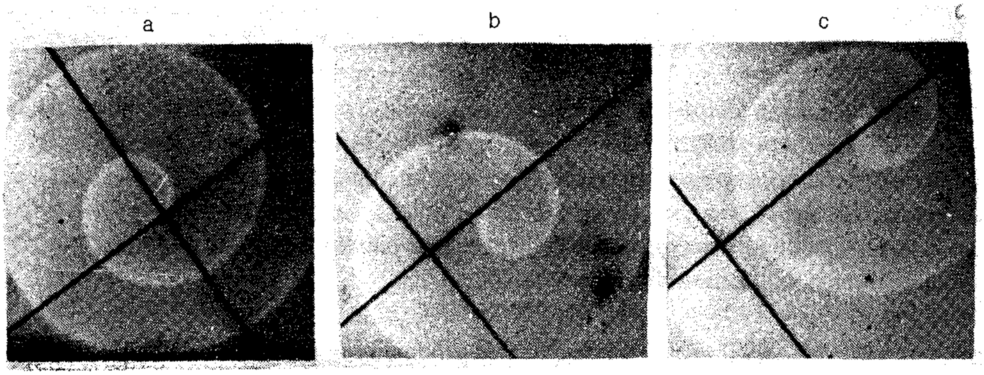

FIG. 2.

the helical wave, we begin to periodically and uniformly illuminate the solution with an intense source (an LÉTI-60M source). The wave pattern is photographed against the background of fixed reference lines at uniform time intervals.

Figure 1 shows successive photographs of a helical wave with a time interval of 10 min under conditions of total resonance (the modulation period is set equal to the natural rotation period of the wave). We see that the center of the rotation is displaced at a constant velocity along one of the reference lines as time elapses; the total displacement is 2 cm.

If there are two helical waves in the medium, rotating in opposite directions, then by choosing the appropriate initial modulation phase we can cause the centers of the two waves to move toward each other and annihilate. This effect can be seen in the series of sequential photographs in Fig. 2.

In the experiments we also observed a displacement of the center of the wave along a circle when the frequencies ω and ω_0 were not exactly equal.

In summary, this experiment completely confirms the theoretical predictions. We wish to stress that this resonance effect is based on some extremely general properties of excitable media and should therefore occur in excitable media of a wide variety of types, including solids. There have been several recent suggestions that self-propagating waves and dissipative structures in distributed active media could be utilized for data processing. The resonance effect is of particular interest in this connection, since it provides a mechanism for effectively controlling self-propagating-wave structures.

[1)] The reaction occurred at $T = 293$ K. The composition of the solution was as follows: 0.28 $NaBrO_3$, 0.42M H_2SO_4, 0.1M $CH_2(COOH)_2$, 0.24M CHBr $(COOH)_2$, and 1.5×10^{-3}M $Ru(dipy)_3$.

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