Experimental study of the interactions of coupled counterpropagating spirals in a viscoelastic Couette–Taylor flow

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ABSTRACT

The addition of small amounts of flexible polymer, with long linear chain, to a newtonian liquid gives to the resulting polymer solution viscoelastic or non-newtonian behaviors. Among the various non-newtonian behaviors observed with polymer solutions, the reduction of the friction drag in turbulent flows is one of the features that had attracted much attention. Although this effect was discovered by Toms in 1949, there is no satisfactory theory available for its explanation. Research on the drag reduction problem requires the joint study of turbulence, which is not fully understood as itself, and viscoelastic flows, for which the lack of universal equations (like the Navier Stokes equations for newtonian flows) is a great flaw. These advocated the need for studies in hydrodynamic model systems like Couette–Taylor, for which various routes to turbulence were characterized for Newtonian flow [1]. Experimental studies of the viscoelastic Couette–Taylor flow reported various results depending of the fluid rheological properties [2]. For Boger fluids, which are very elastic and very viscous fluids, Larson et al. [3] showed that the base circular Couette flow could bifurcate to a nonstationary ”purely elastic” instability mode. Such mode is triggered by elastic effect only and can be observed for vanishing inertia. Inertio-elastic flow regimes result from an interplay between inertia and elastic effects. Of particular interest are flow patterns made of counterpropagating spirals. Such regimes were both observed and predicted for viscoelastic liquids with no or negligible shear-thinning [4,5,6]. With aqueous solutions of polyethylenoxide, we have observed a flow pattern made of strongly coupled counterpropagating spirals [7].

The present study provide further results on the interactions of coupled counterpropagating spirals with the help of complexe demodulation.

The experimental setup consists of a Couette cell with coaxial horizontal cylinders. The inner cylinder is made of black Delrin with a radius $a = 4.46\ cm$. The outer cylinder is made of Plexiglass with a radius $b = 5.05\ cm$. The gap size between the cylinders is $d = b - a = 0.59\ cm$ and has a length $L = 27.5\ cm$. The system radius ratio is thus $a/b = 0.883$ while the aspect ratio is $L/d = 46.6$. The inner cylinder is driven by a DC servomotor while the outer cylinder is kept at rest. Experiments are conducted at room temperature. The polymer solutions were prepared by mixing an initial suspension of polyethyleneoxide (Aldrich, $8 \cdot 10^6\ g/mol$) in 40 ml of isopropyl alcohol with 760 ml of water. The concentration of POE in the resulting solution is 500 weight ppm. The solution is maintained 5 days at rest at $4°$C then approximately 14 h at room temperature. A final homogeneization stage is executed with a magnetic shaker. Viscosity measurements with an AR2000 Rheometer exhibit a shear-thining behaviour. For flow visualization, 2% of Kalliroscope AQ 1000 are added. A linear 1024-pixels CCD camera recorded the reflected light intensity $I(x)$ from a line along the axial direction with 8-bits sampling. Collation of recorded lines at regular intervals (10 Hz) provide spatio-temporal diagrams $I(x,t)$ of flow patterns. We define as Ω_c the critical rotation speed for wich the base flow bifurcates, and $\epsilon = (\Omega - \Omega_c)/\Omega_c$ is the criticality parameter.

We observed a critical instability mode in the form of counterpropagating spirals. The spatio-temporal diagram (Fig. 1) however exhibits a rich dynamics and one may distinguish partialy stationnary waves

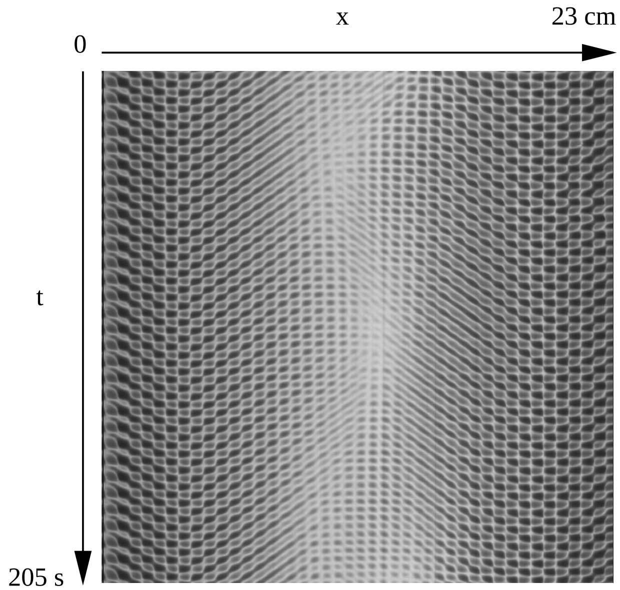

Figure 1: Spatiotemporal diagram of obsberved instability mode, $\epsilon = 0.003$.

patterns. Inspection of the 2D Fourier spectrum $\tilde{I}(q, \omega)$ showed, besides the expected peaks corresponding to the left and right propagating spirals, i.e. at $(-q, \omega)$ and (q, ω), two harmonic modes : one stationary spatial harmonic, $(2q, 0)$, and one time harmonic invariant in space, $(0, 2\omega)$. Thus the signal may be represented as a sum of mode components

$$I(x,t) = Re\left\{ A(x,t)e^{i(qx-\omega t)} + B(x,t)e^{i(qx+\omega t)} + U_\omega(x,t)e^{2i\omega t} + U_q(x,t)e^{2iqx} \right\}.$$

Fourier filtering and complex demodulation (Hilbert transform) allow for the separation of the mode components and the extraction of the amplitudes A, B, U_ω, U_q. Real part for each mode component after Fourier filtering is reported Fig. 2. The associated amplitudes moduli are reported Fig. 3. We see that the right propagating spiral fills largely the right part of the flow system and only a small boundary region of the left part. The opposite is observed for the left propagating spiral. Thus propagating modes cover each other only in two limited region near the boundaries, while a clear partition occured in the middle of the system for propagating modes. Harmonic modes are present in the central part. Slow modulations produce defects and amplitudes holes in the harmonic patterns. From the phase fields (complex amplitude argument) the spatial distribution of frequency is calculated (Fig. 4). It appears that the frequency in the left part and in the right part of the experiment do not match exactly each another. This could lead to the low frequency modulations of the harmonics, as they cross over the left and right part of the flow.

For Newtonian flows, conterpropagating spirals were observed only when both cylinders are counter-rotating [1], and without non-linear coupling effects. With viscoelastic flows, counterpropagating spirals can be observed with only the inner cylinder in rotation, but no strong coupling effects were observed, instead superimposed spirals (interference pattern) were reported. The strong coupling effects in our experiments may be related to the shear-thinning properties of the aqueous POE solutions. Previous experimental studies [4,5] were done with solutions for which shear-thinning was negligble, and numerical work [6] investigated constitutive equations without shear-thinning behavior. Experimental results with shear-thinning liquids could serve as further tests for constitutive equations of viscoelastic liquids such as Giesekus equation [8] and numerical simulations of viscoelastic flows.

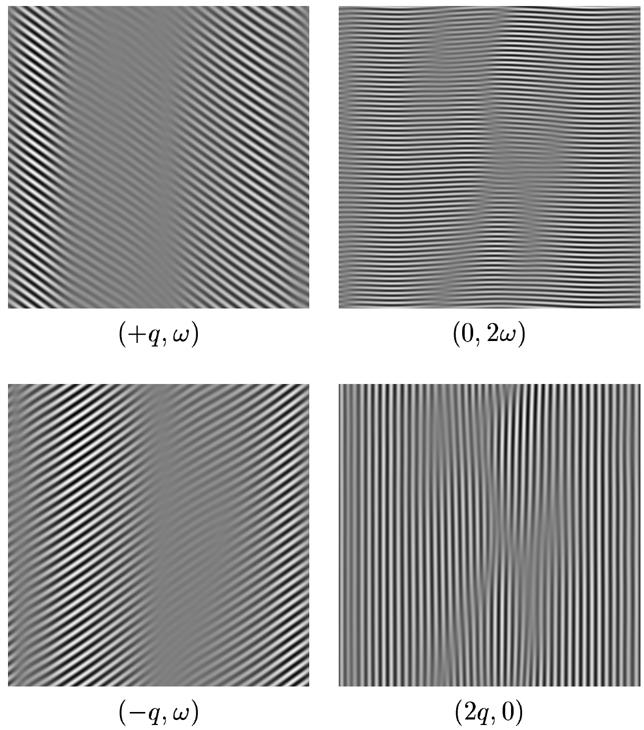

Figure 2: Filtered mode components (real part).

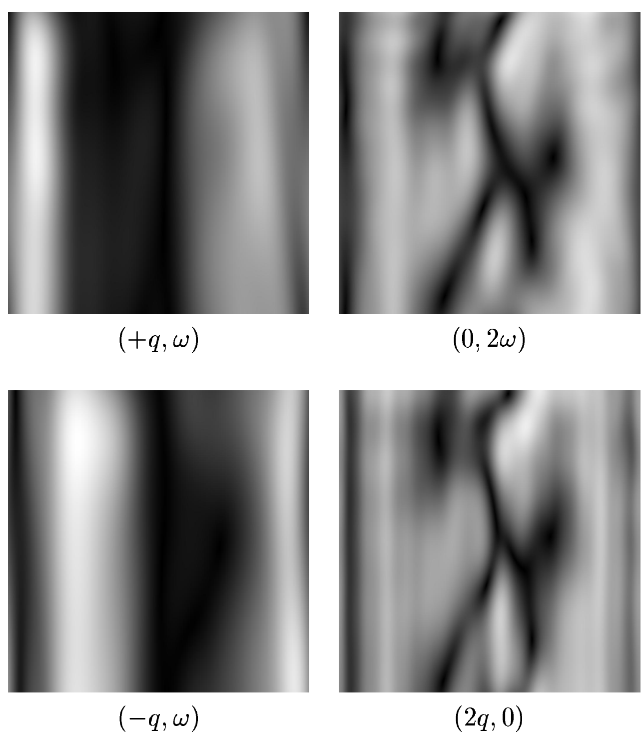

Figure 3: Amplitude of mode components (modulus).

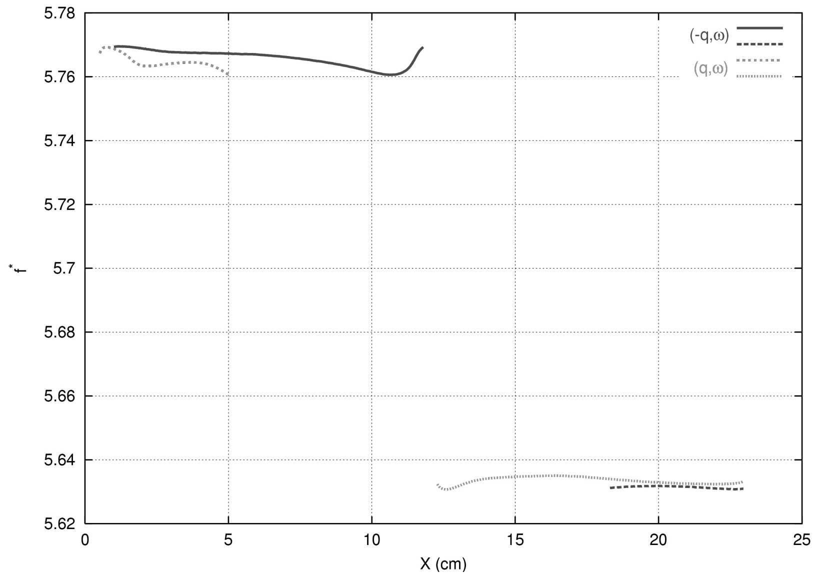

Figure 4: Dimensionless frequency $f^* = \omega d^2/(2\pi \cdot \nu_{water})$ of propagating modes.

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