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Short communication

The negative wake in a second-order fluid

D.D. Joseph *, J. Feng

Department of Aerospace Engineering and Mechanics and the Minnesota Supercomputer Institute,
University of Minnesota, Minneapolis, MN 55455, USA

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Abstract

To investigate the origin of negative wakes in viscoelastic fluids, we used a perturbation method to calculate the flow induced by a solid sphere falling slowly through a viscoelastic fluid in a vertical column of square cross-section. The effects of normal stresses and inertia were determined by solving the perturbation problems numerically using a finite element method. The normal stresses give rise to a negative wake behind the sphere and a reversed flow at the front stagnation point.

Keywords: Finite element method; Negative wakes; Second-order fluid; Viscoelastic fluid

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A negative wake behind a solid object or gas bubble translating through a viscoelastic liquid has been reported by many authors [1–4], but the origin of this unexpected effect is not well understood. Zheng et al. [4] and Bush [5] asserted that negative wakes are caused by the combined effects of elasticity and shear-thinning. In this note, we show that a negative wake arises from normal stresses in slow flow around a sphere at the second order of slowness and, moreover, the same normal stresses also produce an equally unexpected flow away from the front point of stagnation.

Let us consider a solid sphere of radius a falling with velocity U along the centerline of a long cylinder with a square cross-section of side $b = 16a$. Its height $L = 40a$. We look at the sphere at the moment when it is $16a$ from the bottom of the cylinder (Fig. 1). Adopting a coordinate system attached to the sphere, we wish to compute the steady velocity fields around the sphere. We assume that the flow is so slow that the

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* Corresponding author.

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liquid filling the cylinder can be described by the constitutive equation of a second-order fluid:

$$T = -p\boldsymbol{I} + \mu A_1 + \alpha_2 A_2 + \alpha_{11} A_1^2,$$

where A_1 and A_2 are the Rivlin–Ericksen tensors. Introducing dimensionless variables

$$\boldsymbol{u} = \boldsymbol{u}^* U, \qquad \nabla = \nabla^*/a, \qquad A_1 = A_1^* \frac{U}{a}, \qquad A_2 = A_2^* \frac{U^2}{a^2}, \qquad p = p^* \frac{\mu U}{a},$$

we can write the equations of motion as (omitting the asterisk hereafter)

$$\begin{cases} \nabla \cdot \boldsymbol{u} = 0 \\ \nabla p - \nabla^2 \boldsymbol{u} = -R(\boldsymbol{u} \cdot \nabla \boldsymbol{u}) - W\nabla \cdot (A_2 + \epsilon A_1^2), \end{cases} \tag{1}$$

where $R = \rho Ua/\mu$ is the Reynolds number, $W = -\alpha_2 U/\mu a$ is the Weissenberg number and $\epsilon = \alpha_{11}/\alpha_2$. For $R \ll 1$ and $W \ll 1$, the velocity and pressure can be written as

$$\boldsymbol{u} = \boldsymbol{u}_0 + R\boldsymbol{u}_1 + W\boldsymbol{u}_2 + \text{second and higher order terms}$$

$$p = p_0 + Rp_1 + Wp_2 + \text{second and higher order terms.}$$

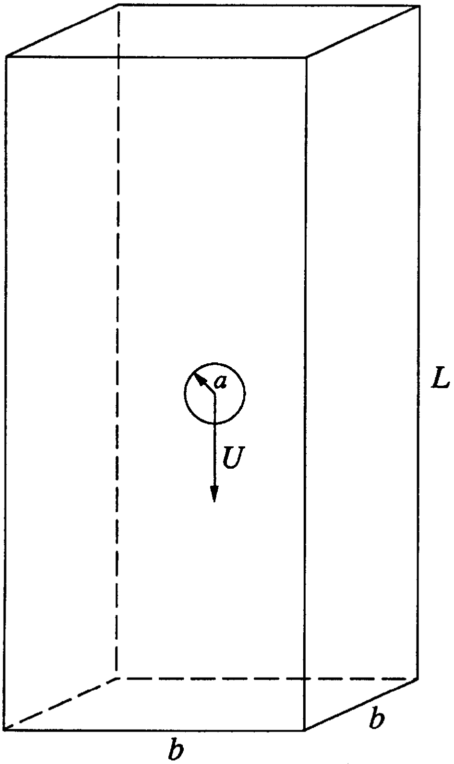

Fig. 1. A sphere of radius a falls slowly in a viscoelastic fluid in a square cylinder. The velocity of the fluid vanishes on the side wall and the top and bottom of the cylinder. In a coordinate system attached to the sphere, the boundaries of the box move up with velocity U.

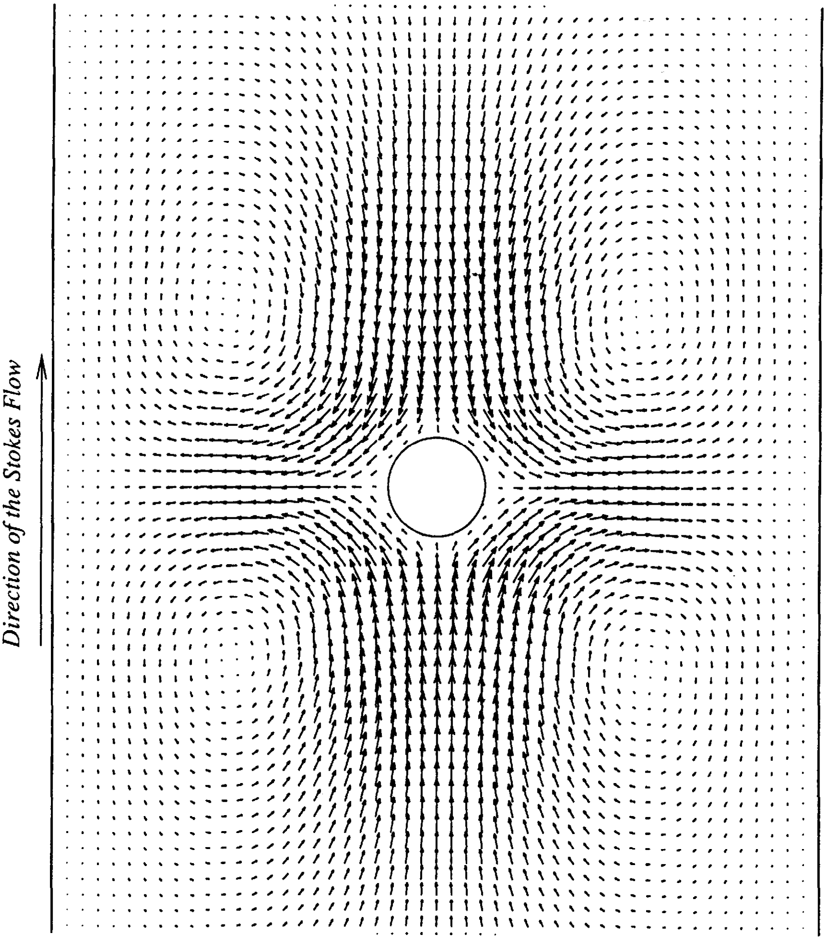

Fig. 2(a).

It is straightforward to substitute the expansions into Eqs. (1) and decompose the original problem into three sub-problems; one is the Stokes flow and the other two are non-homogeneous Stokes problems representing perturbations of inertia and normal stresses. The regular perturbation for inertia is valid because the problem is posed on an effectively bounded domain for which the Oseen expansion is not required (see Feng et al. [6]).

All three problems can be solved numerically using a finite element method with fictitious domains [7]. Undisturbed velocity is imposed on the inlet and the outlet as well as on the four side walls. The velocity fields on the symmetry plane of the flow are shown in Fig. 2 for the two perturbation flows. The perturbation velocity and pressure fields due to inertia and normal stresses are exactly opposite to each other. The longitudinal velocity along the center of the flow is shown in Fig. 3 for the three problems. From Fig. 3c, it is obvious that normal stresses induced a velocity in the wake that points away from the body and a velocity at the front stagnation point that is also away from the body. Inertia gives rise to a velocity that is in the opposite direction but much smaller in magnitude. It is possible to generate a negative wake by superimposing $\boldsymbol{u}_0$, $\boldsymbol{u}_1$ and $\boldsymbol{u}_2$. An example is shown in Fig. 4 which suggests that a reverse flow should also appear at the front stagnation point. It is interesting to plot the velocity field in a frame of reference fixed to the walls (Fig. 5). There is a point of stagnation away from the solid surface, and the negative wake is seen as a pair of reversed eddies behind it. From the simple arguments given above, it is clear that the negative wake results from normal stresses in the liquid, and gives yet another testimony to the ubiquitous antagonism between inertia and normal stresses.

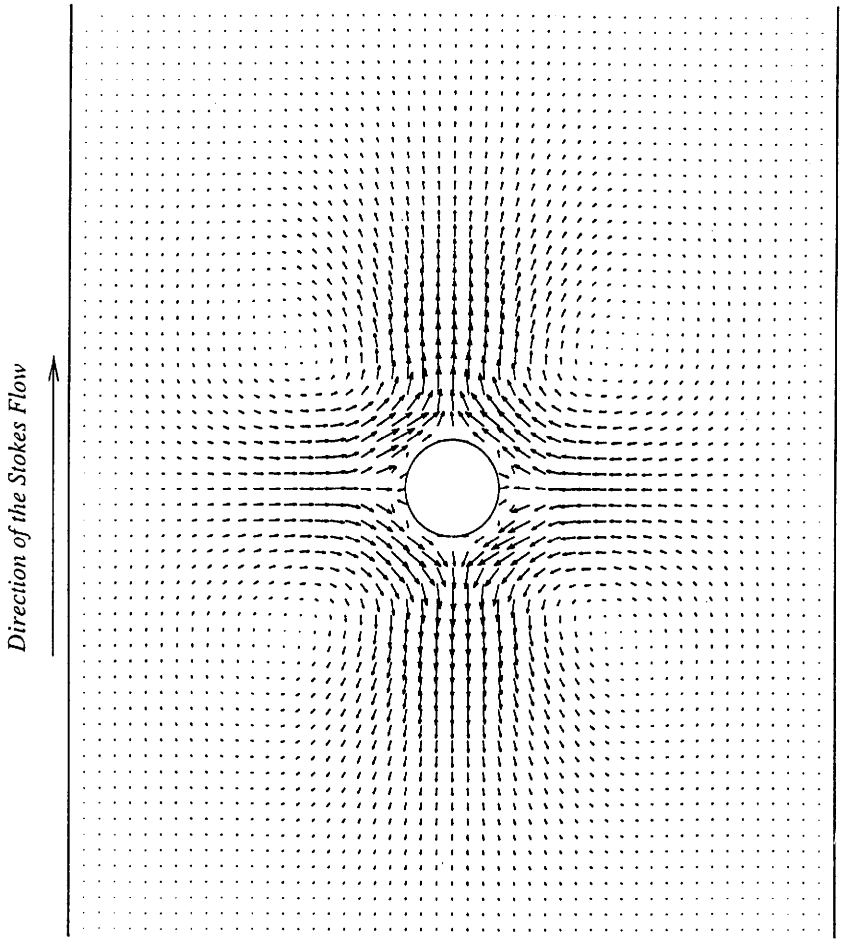

Fig. 2(b).

Fig. 2. (a) Velocity field $\boldsymbol{u}_1$ on the symmetry plane due to the perturbation of inertia. (b) Velocity field $\boldsymbol{u}_2$ on the symmetry plane due to the perturbation of normal stresses. The velocity vector is scaled differently in the two plots and $\boldsymbol{u}_2$ is actually much larger than $\boldsymbol{u}_1$.

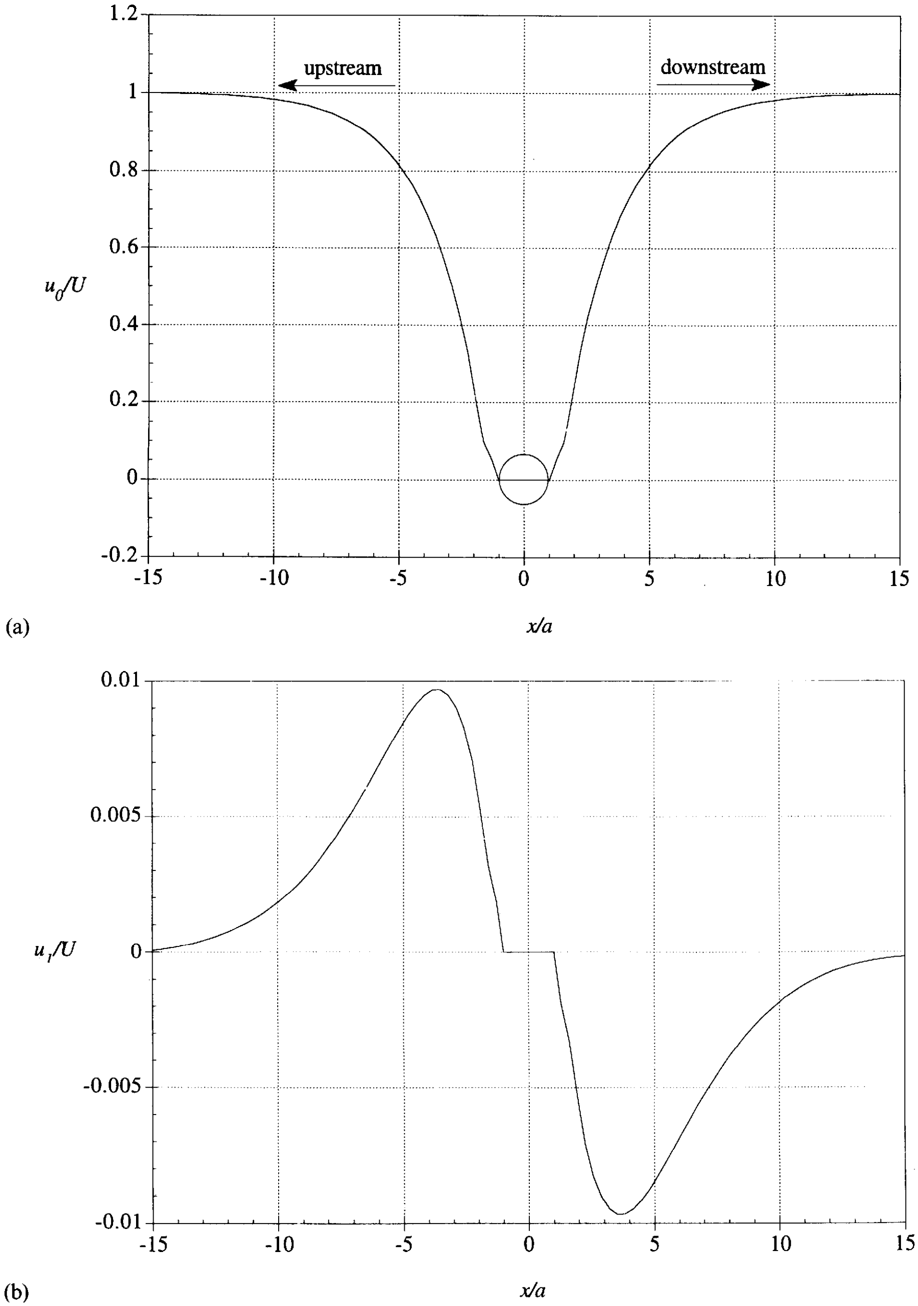

Fig. 3(a–b). (Caption overleaf.)

Sigli and Coutanceau [1] have carried out a perturbation calculation of the motion of a sphere in a spherical enclosure. Their problem is topologically identical to ours; the two solutions are qualitatively the same, giving rise to a negative wake (compare their Fig. 14 with our Fig. 5). This solution is a benchmark for ours.

Leslie [8] and Caswell and Schwarz [9] have computed the slow flow around a sphere in an infinite domain perturbed by weak non-Newtonian stresses and inertia. They found a perturbation flow due to viscoelasticity that is opposite in direction to the one shown in Fig. 2(b). This flow enhances the wake due to inertia and cannot produce a negative wake. It appears that the discrepancy between our results and theirs is caused by the fact that our calculation is done in a box on which the velocity disturbance vanishes. Numerical experiments show that increasing the blockage ratio a/b or the length of the domain L will affect the magnitude of the velocity $\boldsymbol{u}_2$ but will not reverse its direction. It does not appear that the solution in an unbounded domain can be obtained as a limit of solutions in a bounded domain by moving the walls away. This paradox also cannot be resolved by the fact that inertia dominates at infinity, since the leading order viscoelastic perturbation in an unbounded domain depends on the inner solution (i.e., the Stokes flow) only [9]. We do not know how to resolve this paradox.

Obviously, the solutions relevant to experiments are like the one given here in a bounded domain. It is also true that all experimental observations [1–3] of the

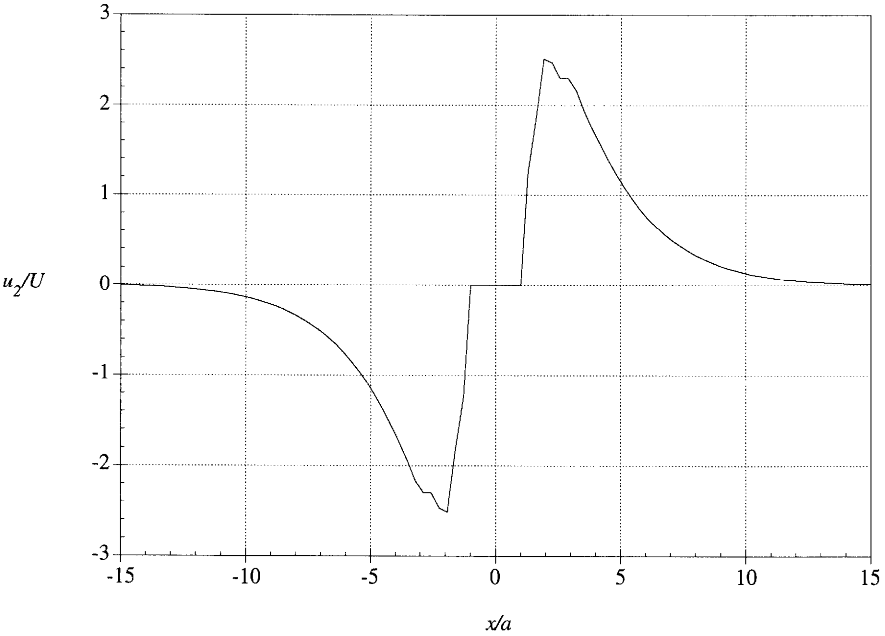

Fig. 3(c).

Fig. 3. Variation of the longitudinal velocity along the centerline of the flow for: (a) the Stokes flow; (b) the perturbation of inertia; (c) the perturbation of normal stresses. The references frame is attached to the sphere and the Stokes flow has a velocity U far from the sphere.

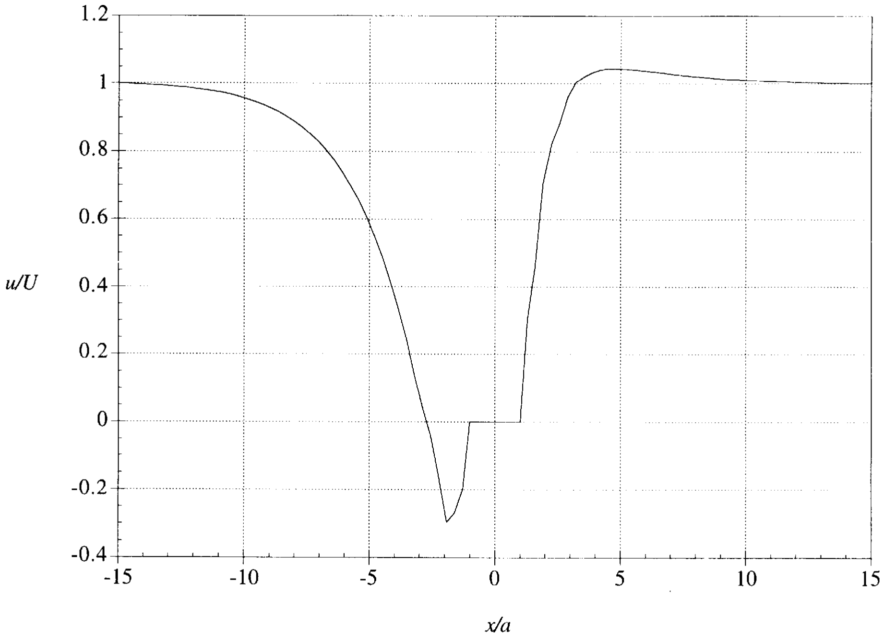

Fig. 4. An example of the negative wake at $R = 0$ and $W = 0.2$. Because of the small magnitude of u_1, R has little effect on the composite velocity profile. Also note the reverse flow in front of the sphere.

negative wake were made at low Reynolds numbers ($R \approx 0.01$), where our perturbation may be valid. Sigli and Coutanceau [1] have noted that the negative wake is suppressed by inertia at larger Reynolds numbers. The characteristic shear-rate in those experiments is very low (on the order of 0.1 s^{-1} in Ref. [1]), and shear-thinning should not be important. In the numerical simulations of Zheng et al. [4], the Reynolds number is possibly too large ($R = 2$). Thus, the negative wake is only discernible in the presence of other factors such as shear-thinning which is known to promote velocity recovery in the wake. The experiment of Bush was at low Reynolds numbers; it is not clear why negative wakes were not observed [5]. Our work here predicts flow away from the front stagnation point whenever the second-order normal stresses are sufficiently large. Such an effect has not yet been reported in experiments.

Acknowledgments

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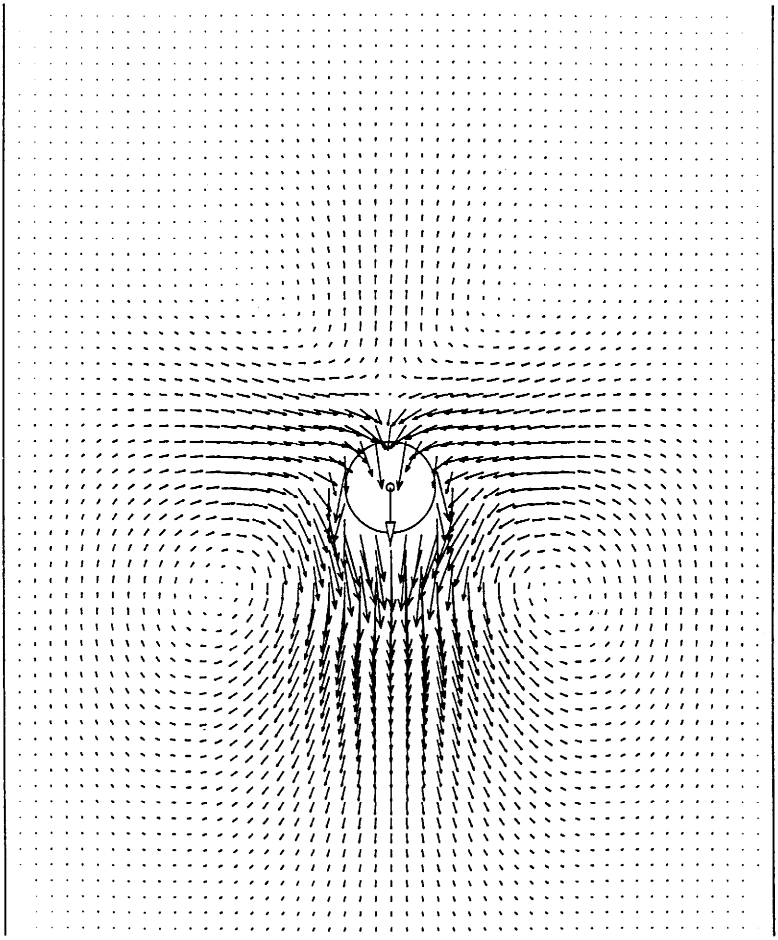

Fig. 5. The negative wake seen in a reference frame fixed to the wall; $R = 0$, $W = 0.2$.

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In transcribing formulae for computation in our paper on negative wakes [1], we inadvertently replaced the velocity gradient $\nabla \boldsymbol{u}$ with its transpose in the expression for the second-order Rivlin–Ericksen tensor A_2. When this mistake is corrected, the secondary motions due to inertia and normal stresses have the same sense, and there is no negative wake. This also explains the discrepancy between our results in Ref. [1] and the analytical results of Leslie [2].

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