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Lionel Fiabane, Marc Gohlke, Olivier Cadot. Contributions à la force des structures cohérentes présentes autour d'un cylindre circulaire. CFM 2011 - 20ème Congrès Français de Mécanique, Aug 2011, Besançon, France. hal-03422611

## HAL Id: hal-03422611 https://hal.science/hal-03422611

Submitted on 9 Nov 2021

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## Contributions à la force des structures cohérentes présentes autour d'un cylindre circulaire

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### Résumé :

Une simulation numérique d'écoulement 2D autour d'un cylindre circulaire est effectuée pour des nombres de Reynolds de 50 à 400. Grâce à la récente formulation de Wu et al. [JFM **576** (2007)], il est possible d'estimer la force à partir d'une intégrale volumique uniquement, dans un petit domaine fluide autour du cylindre n'englobant pas les tourbillons détachés du sillage. Deux structures du domaine fluide sont séparées via le laplacien de vorticité, les couches de vorticité et la zone de recirculation; les contributions de ces structures à la force sont étudiées en fonction du nombre de Reynolds. Cette analyse donne une nouvelle compréhension de l'origine de la force aérodynamique, permettant notamment de séparer des effets de pression.

#### Abstract :

A 2D numerical simulation of the flow around a circular cylinder is investigated during the onset of unsteadiness within the range of Reynolds numbers between 50 and 400. Using the recent formulation of Wu et al. [JFM 576 (2007)], the fluid force is successfully approximated by a volume integral of a force density over a small flow domain surrounding the cylinder that does not contain either the detached vortices in the wake or the vortex formation region. Using the vorticity laplacian, the domain is dynamically divided into two regions : the external flow region containing the two separated vortex layers and the back-flow region between these two vortex layers; the contributions of these coherent structures to the force are quantified and their evolution with the Reynolds number is studied, giving an alternative comprehension of the fluid force origin to that of the classical pressure/viscous formulation.

Mots clefs : force aérodynamique, structures cohérentes, réduction de traînée

### 1 Introduction

The precise origin of the force in the flow (*i.e.* the exact processes or structures in the vicinity of a body that create the force) is a subject of great importance both from a fundamental and practical point of view. Although it is understood and agreed that the whole flow surrounding a body creates the force, the later is generally estimated through a pressure-viscous stress integration over the body surface only :

$$\mathbf{F}(t) = \oint_{\mathcal{B}_{body}} (-p\underline{\mathbf{I}} + \underline{\underline{\tau}}) \cdot \mathbf{n} \, dS, \tag{1}$$

with  $\mathbf{F}(t)$  the instantaneous aerodynamic force vector, p the pressure,  $\underline{\mathbf{I}}$  the identity matrix,  $\underline{\underline{\tau}}$  the viscous stress tensor and  $\mathbf{n}$  the normal vector to the body surface. The projection of equation (1) on the flow direction  $\mathbf{e}_{\mathbf{x}}$  separates the drag into two contributions :

$$D_p = \oint_{\mathcal{B}_{body}} (-p\underline{\mathbf{I}} \cdot \mathbf{n}) \cdot \mathbf{e}_{\mathbf{x}} \, dS, \quad D_f = \oint_{\mathcal{B}_{body}} (\underline{\underline{\tau}} \cdot \mathbf{n}) \cdot \mathbf{e}_{\mathbf{x}} \, dS, \tag{2}$$

with their corresponding force coefficients  $C_{Dp}$  and  $C_{Df}$ .  $D_p$  depends on the pressure and takes into account the form drag and the induced drag. The friction drag  $D_f$  depends on the viscous stress tensor and is known to evolve with the Reynolds number as  $Re^{-1/2}$  [2]. The role of the flow structures surrounding the cylinder could be investigated by studying their fingerprint at the body surface, however the non-locality of the pressure renders this approach difficult. In the case of bluff bodies, it can be shown [13] that the high drag is due to a strong base pressure induced by flow separation and vortex formation. These ingredients cannot be separated using equation (1).

The present study proposes therefore to investigate these origins through a spatial decomposition of the flow made possible by the pioneering work of Wu *et al.* [15] (see also [16]), who introduced an alternative calculation free of pressure. The expression reads in two dimensions :

$$\mathbf{F}(t) = -\mu \int_{\mathcal{F}} \nabla^2 \omega \, \mathbf{x}^{\perp} \, dV + \mu \oint_{\mathcal{B}} \left( \left[ (\mathbf{\hat{n}} \cdot \nabla) \omega \right] \, \mathbf{x}^{\perp} - \omega \, \mathbf{\hat{n}}^{\perp} \right) \, dS, \tag{3}$$

where  $\mu$  is the dynamic viscosity,  $\omega$  the vorticity,  $\mathbf{x} = x\mathbf{e}_{\mathbf{x}} + y\mathbf{e}_{\mathbf{y}}$  the position vector,  $\mathbf{x}^{\perp} = y\mathbf{e}_{\mathbf{x}} - x\mathbf{e}_{\mathbf{y}}$ ,  $\mathcal{F}$  the integration domain (or field),  $\mathcal{B}$  the external boundary of this domain,  $\hat{\mathbf{n}} = \hat{n}_x \mathbf{e}_{\mathbf{x}} + \hat{n}_y \mathbf{e}_{\mathbf{y}}$  the normal vector to this boundary pointing outside the domain and  $\hat{\mathbf{n}}^{\perp} = \hat{n}_y \mathbf{e}_{\mathbf{x}} - \hat{n}_x \mathbf{e}_{\mathbf{y}}$ . In the case of a circular cylinder at large Re = 9500, Wu *et al.* [15] showed that the boundary integral (second term on the right-hand side of equation (3)) decays quickly as the integration domain  $\mathcal{F}$  increases. Hence for a sufficiently large domain, the force can be expressed as a field expression only which allows a decomposition into different areas corresponding to flow structures. This is an advantage compared to other formulations that are also free of pressure but for which the boundary terms cannot be neglected (see for instance [9, 12] and the references therein). Wu *et al.* also showed that the integrand in the field integral is preponderant in the vicinity of the cylinder. This means that the vortices, once shed, do not contribute to the fluid force. In addition to Wu *et al.*'s work, the present paper provides a spatial decomposition of the flow around the cylinder (back-flow region and external flow) and a characterization of their instantaneous contributions to the fluid force.

We choose to investigate equation (3) in the case of the solution of the 2D Navier-Stokes equations for the problem of a circular cylinder (shown in figure 1) in a uniform flow at moderate Reynolds numbers. In order to constitute a database for different Reynolds numbers ranging from 50 to 400 the numerical simulation is performed using a computational code based on a non-dimensional vorticitystreamfunction formulation. This kind of solver has been chosen for the accuracy of both the vorticity and its spatial derivatives which is crucial in the resolution of equation (3). The numerical method is the same as the one used and described in details in [10] except for the use of a physical domain of circular shape in the conformal mapping instead of a NACA shape.

#### 2 Results

#### 2.1 Volume formulation of the fluid force

The mean drag coefficient computed using equation (3) with a circular domain of diameter 5*d* is shown in figure 3(a) (early referral) as a function of *Re*. This mean drag coefficient is taken as a reference and simply referred to as  $C_D$  in the rest of the paper. In this figure we can see a very good agreement with Henderson's fit [7] also based on numerical simulations. We minimize the size of the domain  $\mathcal{F}$ by choosing rectangle domains, bounded vertically in y by  $\pm 0.95d$  (fixed boundaries) and in x by a fixed upstream limit at -0.75d and by a varying boundary downstream at 1*d* to 0.75*d* for *Re* from 50 to 400. Such integration domain  $\mathcal{F}$  is displayed in figure 1(a) at Re = 300. For this Reynolds number the integrals due to the gradient of vorticity (second term on the right-hand side in equation (3)) calculated over each side of the  $\mathcal{F}$  domain are much smaller than the total force, by an order of  $10^{-4}$ . The integrals over the fixed boundaries of the vorticity on the right-hand side in equation (3) are also smaller than the total force by the same order, and there is only one significant remaining term : the integral of the vorticity on the right-hand side in equation (3) calculated over the downstream boundary of the  $\mathcal{F}$  domain. This last integral accounts for less than 1% of the total force and is



FIG. 1 – Instantaneous fields at Re = 300, contributions to the drag force density of the external flow 'E' and the back-flow region 'B' defined in the integration domain  $\mathcal{F}$  of external boundary  $\mathcal{B}$  displayed by the dashed line; (a) Drag force density field  $\mathbf{f}_{\mathbf{V}} \cdot \mathbf{e}_{\mathbf{x}}$  as defined in equation (4); (b) Sign of  $\nabla^2 \omega$  (black : -1, white : +1) with the different areas associated to the external flow 'E' or the back-flow region 'B'; (c) Vorticity field, the continuous line shows the boundaries of the external flow 'E' and the back-flow region 'B'; (d) Drag force density  $\mathbf{f}_{\mathbf{V}} \cdot \mathbf{e}_{\mathbf{x}}$  for the external flow 'E'; (e) Drag force density  $\mathbf{f}_{\mathbf{V}} \cdot \mathbf{e}_{\mathbf{x}}$  for the back-flow region 'B'. The scale in figure (e) is multiplied by a factor 5 compared to that of figure (d).

therefore neglected, which is consistent with [15]. So, the force can thus be estimated instantaneously by the field contribution only (right-hand side in equation (3)):

$$\mathbf{F}(t) \approx \int_{\mathcal{F}} \mathbf{f}_{\mathbf{V}}(\mathbf{x}, t) \, dV = -\mu \int_{\mathcal{F}} \nabla^2 \omega \, \mathbf{x}^{\perp} \, dV. \tag{4}$$

#### 2.2 Flow decomposition

It is worth noting that the domain  $\mathcal{F}$  does not cover either the wake (as mentioned previously and found in [15]) or the vortex formation region. In figure 1(a), we can also see that the drag force density is concentrated in high positive (red) and high negative (blue) areas. From equation (4), these areas are intimately related to the vorticity distribution around the cylinder that is displayed for the same instant in figure 1(c). We can distinguish three different sources of vorticity production on the cylinder. The first two sources are created at the surface by the developments of two boundary layers due to the oncoming flow on the front of the cylinder that then separate from the wall and produce two shear layers of opposite signs. We will refer to these two structures as the *vortex layers*. The third source of vorticity appears at the rear of the cylinder and will be referred to later as the *back-flow region* (in blue in figure 1(c)); this vorticity results from the interaction between the cylinder, the shear layers and the vortex roll-up that occurs downstream.

The aim is now to separate the flow into different parts. We therefore consider the vorticity laplacian  $\nabla^2 \omega$  which appears in equation (4). Areas of different signs of vorticity laplacian are separated in the  $\mathcal{F}$  domain using the sign function (displayed in figure 1 b) and then combined to divide the flow into two parts. The first part constituted by areas denoted with letters 'B' is localized on the back-flow region (see figure 1(c)); the second part associating 'E' areas is called the external flow and encompasses the vortex layers (see figure 1(c)). The two instantaneous regions 'E' and 'B' enclose totally the area of the integration domain  $\mathcal{F}$  where the force density displayed in figure 1(a) is non zero. Figure 1(d)

shows the drag force density field for the external flow only, whereas figure 1(e) shows the drag force density field for the back-flow region only. Next we will analyse the contributions to the total drag coefficient  $C_D$  of the regions 'E' and 'B'.

#### 2.3 Drag and lift contributions

Instantaneous contributions to the fluid force are obtained by integrating the force density over the corresponding regions 'E' or 'B'. They are shown at Re = 300 in figure 2 as a function of dimensionless time. In the case of the drag coefficient (figure 2(a)) it is found that 90% of the total mean drag originates from the vortex layers in region 'E' while almost all the fluctuations are imposed by the back-flow region 'B'. For the lift coefficient (figure 2(b)), we find that both the external flow and the back-flow region contribute similarly. We also observe that the back-flow region lift is phase advanced compared to that of the external flow lift.



FIG. 2 – Instantaneous force as function of non-dimensional time at Re = 300. Plain line is the sum of the contributions, dashed line is the external flow contribution, and dotted line is the back-flow contribution. (a) Drag coefficients. (b) Lift coefficients.



FIG. 3 – (a) Mean drag coefficient of the cylinder estimated from the density force in the reference domain 5*d* ( $\circ$ ), in  $\mathcal{F}$  domain (\*), the dashed line is the fit from [7].  $C_{D_E}$  ( $\triangle$ ) is the external flow contribution.  $C_{D_B}$  ( $\times$ ) is the back-flow region contribution; (b) Drag oscillation amplitudes as function of the Reynolds number for the external flow ( $\triangle$ ), the back-flow region ( $\times$ ) and the total force (\*); (c) Lift oscillation amplitudes (left axis) as function of the Reynolds number for the external flow ( $\triangle$ ), the back-flow region ( $\times$ ) and the total force (\*); (c) Lift oscillation amplitudes (left axis) as function of the Reynolds number for the external flow ( $\triangle$ ), the back-flow region ( $\times$ ) and the total force (\*). ( $\blacklozenge$ ) denotes the phase shift  $\phi$  between the external and the back-flow lift (right axis).

The flow separation into the external flow and the back-flow regions is successfully performed for  $50 \leq Re \leq 400$ . For each Reynolds number, we compute the mean drag coefficients as well as the lift and drag oscillation amplitudes (the mean lift is zero due to the symmetry of the flow around the cylinder). The mean drag coefficients are plotted as a function of the Reynolds number in figure 3(a), with triangles ( $\Delta$ ) for the external flow drag  $C_{D_E}$  and with crosses ( $\times$ ) for the back-flow drag  $C_{D_B}$ . As observed previously, most of the drag is due to the vortex layers in the external flow. At Re = 50 their contribution is almost equal to the total drag  $C_D$ ; then it decreases continuously as the Reynolds number increases. Simultaneously the back-flow drag rises. Figure 3(b) shows that the drag oscillation

amplitudes are only due to the back-flow region in the considered range of Reynolds numbers, while the lift oscillation amplitudes for both the external and the back-flow remain equivalent (figure 3(c)). The phase shift  $\phi$  between the external flow lift and the back-flow lift remains fairly constant ( $\phi \approx \frac{\pi}{4}$ ) for  $Re \geq 100$ .

#### 3 Discussion

We have determined the force contributions of two parts of the flow : the external flow and the backflow region. The force density in the external flow is produced by the vortex layers. The force density in the back-flow region is related to the vorticity created at the rear of the cylinder (figure 1(c)). We discuss now the evolution of these contributions.



FIG. 4 – (a) External flow drag  $C_{D_E}$  and friction drag  $C_{D_f}$  dependence with Re; (b) Back-flow drag  $C_{D_B}$  and form drag  $C_{D_p}$  dependence with (L/d).

The vortex layers contribution is found to evolve as  $C_{D_E} = C_0 + 2.75 Re^{-1/2}$  (figure 4(a)). The vortex layers create locally a friction drag at the surface of the cylinder before the separation. This is consistent with the observed dependence with the Reynolds number [13]. Moreover the external drag  $C_{D_E}$  also contains a large constant contribution which must be ascribed to the separation of the boundary layers from the cylinder. We consider next the back-flow drag  $C_{D_B}$ . It is found to increase with the Reynolds number (figure 3(a)) to reach a contribution of about 20% of the total drag  $C_D$ at Re = 400. This evolution is due to an increase of the force density in the back-flow region that is created by the interactions between the shear layers, the vortex roll-up and the cylinder. This intensification of the vorticity interactions is also accompanied by the increase of the drag fluctuations in the back-flow region (figure 3(b)) that are correlated to the vortex roll-up dynamics : the larger the Reynolds number, the closer to the base of the cylinder the roll-up [8] and the stronger the drag fluctuations. The increase of the fluctuations with the Reynolds number can also be observed in the case of the lift (figure 3(c)) for which the roll-up in the back-flow region drives the whole process [4], as expressed by the phase advance observed between the back-flow lift and the external lift. A way to estimate the distance between the cylinder base and the vortex formation is to compute the recirculation bubble length L [5] (see sketch in figure 4(b)). The relationship between the back-flow drag  $C_{D_B}$ and the reduced recirculation bubble length L/d is found to be almost linear with  $C_{D_B} = 0.11 (L/d)^{-1}$ (figure 4(b)). This means that as the Reynolds number increases, the roll-up occurring closer to the cylinder creates stronger interactions between the rear vorticity and the shear layers, resulting in an increased back-flow drag.

It is interesting to relate the present results to what can be achieved in terms of passive control of bluff body wakes. A splitter plate [1] or a small control cylinder [14] in the wake are known to reduce drag and suppress force fluctuations. The largest drag reduction that can be achieved is about 30% (with no reattachment and when the separation points are not significantly affected). It has been shown [3] that this control technique has the property to push further downstream the vortex roll-up and then to increase the recirculation bubble length. In the light of the present study, these techniques suppress the back-flow region drag  $C_{D_B}$  and its fluctuations as the vortex roll-up is too far away from the body to induce rear vorticity.

We can finally compare our present flow decomposition with the pressure and the viscous stress contributions, namely the form drag  $C_{Dp}$  and the viscous shear drag  $C_{Df}$  (figure 4). Our fit for viscous shear drag in figure 4(a) gives  $C_{Df} = 2.54 Re^{-0.44}$  (similar to that of [7]) which is very close to the dependence in Re that we found for the external flow drag. Hence the vortex layers capture the viscous drag. The fit for pressure drag in figure 4(b) gives  $C_{Dp} = C_0' + 0.12(L/d)^{-1}$ , which is very close to the dependence in L we found for the back-flow drag. We can then write at first approximation  $C_{Dp} \approx C_0 + C_{D_B}$ , where  $C_0$  is the non-viscous contribution in  $C_{D_E}$  (figure 4(a)). The origin of  $C_0$ is not only linked to the pressure evolution in the external flow, but also to that in the back-flow region. We can illustrate this assertion by considering the flow at Re = 50. for which  $C_{D_R}$  is negligible (figure 3 a), meaning that the vorticity activity in the back-flow region is too weak to produce any force density. This can be understood because the vortex roll-up is too far away to induce sufficient vorticity in the back-flow region. On the other hand, the base pressure at Re = 50 is not zero but  $C_{pb} = -0.5$  (in agreement with [7] for instance), meaning that  $C_0$ , associated to the vortex layers only, takes into account pressure effects all around the body. Hence, the technique separates the form drag into two parts, the one due to the separation only and the other due to the vorticity activity inside the back-flow region (*i.e.* vorticity induced by the roll-up process).

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