Shape Deformation and Drag Variation of a Coupled Rigid-flexible System in a Flowing Soap Film

Song Gao (高颂),1,2 Song Pan (潘松),1 Huaicheng Wang (王怀成),1 and Xinliang Tian (田新亮)1,3,∗

1 State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
2 Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208, USA
3 Shanghai Jiao Tong University Yazhou Bay Institute of Deepsea Technology, Sanya 572000, China

(Dated: January 17, 2020)

We experimentally study the flow past a rigid plate with an attached closed filament acting as a deformable afterbody in the soap film. The complex fluid-structure interactions due to its deformable shape and corresponding dynamics are studied. We find the shape of the afterbody is determined by the filament length and flow velocity. A significant drag reduction of up to 9.0% is achieved by adjusting the filament length. We analyze the drag mechanism by characterizing the deformable afterbody shape and wake properties. Our experiment and modeling suggest that such favorable flow control and drag reduction are expected to occur over a specific flow speed regime when the flexible afterbody is suitably added.

Flow past a bluff body is encountered in numerous natural and industrial scenarios, showing rich classifications of wake and fluid dynamics. The shape of the body, serving as the boundary for surrounding flow, dominates the fluid force and wake dynamics. In most circumstances, by simply adjusting the shape of a bluff body, e.g., adding dimples 1 or a splitter plate 2,4, various flow controls including drag reduction, lift enhancement and vibration suppression can be achieved effectively 5. A similar flow control mechanism exists among aquatic animals as well 6. The hydrodynamic performance is enhanced based on their structural and morphological body components, e.g., riblets on shark skin 7 and bumps on whale flippers 8. The bioinspired drag-reducing surfaces/garments have shown efficiency in improving athletes’ performance 9. Though these passive control methods (without sensor and energy input) are efficient, structure or surface modification on the rigid body is requisite. Flying birds tend to show elegant and deft ways to increase speed and reduce energy consumption. Their feathers self-adapt during flight, which is beneficial for aerodynamic performance 10,12. The shape self-adaptation under flow, also referred to as reconfiguration 13,14, to reduce drag occurs universally in the botanic world as plants seek to facilitate their flexibility to bend, fold and twist when subjected to fluid forces, both in water 15 and in air 16,17. As a result of shape reconfiguration, drag scales up more slowly than in the classical rigid body drag~velocity square law 18,20. However, it seems impossible to make the shape or structure of cars or airplanes to compliantly accommodate fluids in the real world, and athletes prefer to wear tight fit garments rather than loose ones. This raises the question of whether adding a suitably flexible coating to a rigid body can import some favorable flow control features and give rise to improved aero/hydrodynamic performance.

In this Letter, we experimentally investigate two-dimensional (2D) flow past a rigid flat plate with an attached flexible afterbody of negligible weight. The compliant feature of the afterbody passively controls the flow over the plate and yields a significant drag reduction, as expected. No additional structure or surface modifications to the rigid body are required and the deformable afterbody can be easily installed/removed and even adjusted in size, making such a flow control method possible and applicable in actual fact.

Experiments.—Soap film, which functions as a 2D flow tunnel, provides convenience for resembling 2D hydrodynamics in several aspects 21-26. The experimental setup has been well introduced 27. In our vertically flowing soap film (soapy water density ρ = 1.065 g/cm3), a rigid rod (length \( L_p = 20 \) mm; diameter 0.45 mm) serves as the flat plate placed normal to the incoming flow, and a closed flexible filament (length embedded in the soap film \( L_d = 20-140 \) mm; diameter 12 \( \mu \)m; bending stiffness \( 3.43 \times 10^{-3} \) g·cm²/s²; linear density \( 1.96 \times 10^{-6} \) g/cm) attached downstream behaves as the deformable afterbody. We use a dimensionless length scale \( \Lambda = L_d/L_p \) to describe the geometry of this rigid-flexible coupled system, where \( \Lambda = 1 \) refers to the situation in which no afterbody is attached. The upper bound of \( \Lambda \) is approximately 7, beyond which a stable and long-lasting flow cannot be achieved. In the parallel test section, a uniform free-stream velocity profile and constant film thickness are approached over 70% of the span about the midline. The tunnel is wide enough (tunnel width, 110 mm) that no obvious blockage is observed. The flow patterns are visualized by an interference technique in which the monochromatic light provided by a low-pressure sodium lamp illuminates the film, and the instantaneous interference patterns caused by the thickness variations can reveal the flow field. The shape of the deformable afterbody is recorded by a camera. The tiny fluid drag acting on the coupled system
FIG. 1. (a) Schematic view of the experiment: test section. The plate and the filament are highlighted in blue and red, respectively. The length of the closed filament is adjustable when the soap film is ongoing. The objects and distances are not to scale. Typical flow features at $U = 1.45$ m/s: (b) plate-like regime, $\Lambda = 1.56$; (c,d) cylinder-like regime, $\Lambda = 2.81$ and $\Lambda = 3.47$; (e) slender shape regime, $\Lambda = 4.25$; (f) rolling vortex regime, $\Lambda = 6.46$ and (g) flapping regime, $\Lambda = 6.95$. The other two cases (h) $\Lambda = 4.26$ at $U_1 = 0.97$ m/s and (i) $\Lambda = 4.30$ at $U_7 = 1.90$ m/s are comparable with (e) to show the influence of the flow velocity $U$ on the afterbody shape and wake pattern.

is obtained by measuring the slight displacement of the supporting cantilever [19]. This method is proven to be both statically and dynamically reliable [28]. During the experiment, $L_D$ can be modified gently and continuously without suspending or even disturbing the flowing film [29]. The layout of the test section is shown in Fig. 1(a). Seven different flow velocities $U$ through the range 0.97–1.90 m/s are tested, and approximately 150 to 200 sets of flow pattern recordings and drag measurements under different $\Lambda$ are conducted per $U$. Each drag data point is time-averaged over 30 seconds. The filament is wetted by the fluid and constrained in the plane of film always, and the deformable afterbody appears to bend only, i.e., its length seldom shows a measurable increase or decrease. The filament is much thicker than the soap film (thickness $f = 1$–3 $\mu$m); thus, no obvious inside-outside fluid exchange is observed either. The Marangoni wave speed [30] is considerably larger than the flow speeds, and thus, no significant effects of compressibility are considered. The kinematic viscosity of flowing soap film is approximately $\nu = 0.07$ cm$^2$/s. Based on the plate length $L_p$, $U$ and $\nu$, the Reynolds number $Re = L_p U/\nu$ is approximately 2700–5500.

Flow pattern.—Some typical flow features at $U = 1.45$ m/s are illustrated in Fig. 1(b-g). As shown in Fig. 1(b), the wake behind a coupled system with $\Lambda = 1.56$ is almost the same as that behind a 2D flat plate (not shown), i.e., the separation points are at the exact edges of the plate, and a ring of counter-rotating recirculating fluid is attached to the rear of the geometry. A very short deformable body occupies only some area of the wake, imposing no obvious influence on the ambient flow. Therefore, the first regime in the stationary state is denoted as ‘plate-like’ (P) regime. As $\Lambda$ increases, fluid plumps up the deformable afterbody at the edges of the plate [Fig. 1(c,d)]. The incoming flow passes along the filament, and separation occurs on the rear part of the deformable afterbody rather than at the plate edges. The significant separation delay along with the flow features observed here resembles the flow past a 2D cylinder [31], indicating the onset of the ‘cylinder-like’ (C) regime. The width of the deformable body in the C regime increases as $\Lambda$ increases until the beginning of the ‘slender shape’ (S) regime [Fig. 1(e)]. In the S regime, the middle section of the afterbody is squeezed by the outside fluid; thus, its shape becomes narrow. The shape of the deformable afterbody observed in the S regime as follows: the longer the filament is, the narrower the profile is presented. In these flow regimes, the afterbody remains nearly stationary and maintains reflectional symmetry about the midline, behaving as a rigid body. However, when $\Lambda$ exceeds a specific value, the deformable afterbody flaps and randomly changes its shape. Beyond the S regime, flow enters the ‘rolling vortex’ regime, where the afterbody shape resembles that in the S regime but the filament traps extremely significant vortex to roll on the sides [Fig. 1(f)]. Finally, when the filament is long enough that it flaps, the last flapping regime is achieved [Fig. 1(g)].

Drag variation.—We further investigate the fluid drag acting on the coupled system to better understand the transitions between different flow regimes [Fig. 2(a)]. The fluid drag is also normalized by the drag of the bare plate ($\Lambda = 1$) to compare the variation at different $U$, respectively [Fig. 2(b)]. Additionally, the drag coefficient $C_D = \text{Drag}/(\rho U^2 L_p f/2)$ is introduced to scale the fluid drag with the flow velocity. It is noted that, $f$ is increased by increasing $U$ in a soap film, following the rule of $f \propto$
After taking this into account, we find all $C_D$ gather together at approximately 2.0-2.1 at $\Lambda = 1$ [Fig. 2(c)], which agrees with the reported results [33, 34]. Our measurement is validated and reliable over the tested speed range, and the bluff body traditional drag $\propto U^2$ law works well for 2D flat plates.

When flow velocity exceeds $U_2 = 1.17$ m/s, the five drag curves show a similar tendency as $\Lambda$ varies, and we find the drag variation is closely related with the transitions between flow patterns reported previously. The normalized drag first decreases from 1, until $\Lambda$ reaches the first threshold at $\Lambda_{c1}$, where the onset of the C regime results in a local minimum drag that yields a significant drag reduction. Then, the drag increases due to the growth of afterbody width in the C regime until the second threshold at $\Lambda_{c2}$. After entering the S regime, the system benefits from its narrow shape and displays the second decrease in total drag. However, when the S regime ends at $\Lambda_{c3}$, the rolling vortex on the sides and the flapping of the deformable afterbody reverses the trend, leading to a general increasing trend of drag. It is hard to explore the drag in these two regimes since the afterbody arbitrarily changes its shape or flaps strongly, making the soap film susceptible to rupture and large measurement fluctuations. The heavier drag burden suffered by the whole system distinguishes these two regimes from previous three regimes, yet the transition between these two regimes is unstable and still not well understood. The reasons that the drag variation is not clear at $U = 0.97$ and 1.17 m/s are that, drag is extremely small at such small $U$ so that the drag variation is even more minuscule; different physics occurs (will be explained in the next section). One should note that, when $U = 1.35, 1.45$ and 1.54 m/s, three curves of normalized drag collapse, and the critical $\Lambda$ values are similar as well ($\Lambda_{c1} \approx 2.3, \Lambda_{c2} \approx 3.3$ and $\Lambda_{c3} \approx 4.2$). Moreover, the most dramatic drag reduction of approximately 9.0% (compared with the bare plate drag) is observed at $\Lambda_{c1}$ in this speed zone. Same physics and significant drag reduction occur in such speed range. Thus this range of velocity is referred to as the ‘favorable drag zone’ (FDZ) in the following parts. Out of the FDZ, flow velocity influences in different ways. First, $U$ leaves further away from this zone, the normalized drag curves deviates more (see black stars at $U_1 = 0.97$ m/s and blue left-pointing triangles at $U_7 = 1.90$ m/s), which means using bare plate drag to normalize drag regardless of the deformable shape of the afterbody has inherent limitations, especially when $U$ is small/large enough to affect its shape in different ways; second, the first threshold $\Lambda_{c1}$ for all $U$ cases show a small discrepancy, but the transition from C to S regime (denoted by $\Lambda_{c2}$) is hysteretic for large $U$ cases, i.e., the C regime lasts significantly longer at higher speeds. This is confirmed by the shape of the deformable afterbody with the same $\Lambda$ at different $U$. The afterbody is easily squeezed at small $U$ such that the section of filament near plate is even embedded in the wake [Fig. 2(b)], while it grows even wider in the spanwise direction at larger $U$ [Fig. 2(i)]. These phenomena suggest that the shape of the deformable afterbody and its suffered drag are closely related, and both of them are affected by the filament length and flow velocity. Therefore, the dependence of afterbody shape on $\Lambda$ and $U$ is investigated. An alternative method to scale the drag considering these parameters is expected.

Shape deformation.—To investigate the shape of the deformable afterbody, we introduce several geometric parameters, including the enclosed area $S_d$, maximum streamwise length (from the plate to the farthest downstream point) $L_{ds}$ and average width $\bar{W} = S_d/L_{ds}$. The shapes of the deformable afterbody at different $\Lambda$
are shown in Fig. 3(a-c). $\overline{W}$ shows the same tendency for all three velocities. As $\Lambda$ increases, $\overline{W}$ first increases, corresponding to the transition from the P to the C regime and the growth of ‘cylinder’. Then, $\overline{W}$ decreases as the flow transits to the S regime. Moreover, a larger velocity gives an overall larger $\overline{W}$ at the same $\Lambda$, which agrees with the phenomena observed in Fig. 1(e,h,i). $L_{ds}$ is found to increase with increasing $\Lambda$ in the same way regardless of $U$ when $\Lambda \leq 2.3$, which can be approximately regarded as $\Lambda_{c1}$ for all $U$. It is reasonable that in the P regime, the filament is short and trapped in the wake, and its shape is not significantly influenced by the flow out of the separated free-shear layer. Beyond $\Lambda_{c1}$, $L_{ds}$ is proportional to $\Lambda$ with a ratio of $c$ and influenced by $U$ such that the smaller $U$ is, the more rapidly $L_{ds}$ tends to grow, albeit only slightly. For $S_d$, all curves collapse when $\Lambda \leq 2.3$ as well, while larger $U$ values result in a faster growth of $S_d$. Given the reverse growth tendency in $L_{ds}$ and $S_d$, the dramatic discrepancy in $\overline{W}$ as a function of $\Lambda$ is expected and showed in Fig. 3(d). All data collapse for $\Lambda \leq 2.3$; otherwise, the deformable afterbody tends to grow much more rapidly in width at larger $U$. Such a difference also becomes more pronounced for large $\Lambda$. $U$ and $\Lambda$ together determine the average width of the deformable afterbody. Since there are no inside-outside fluid interactions and the inside velocity $u$ is at least one magnitude less than that outside, the significant velocity difference causes a fluid pressure difference $0.5\rho (U^2 - u^2) \sim 0.5\rho U^2$ acting on the two sides of the deformable afterbody. On the other hand, the afterbody length $L_{ds} \sim c(\Lambda - \Lambda_{c1})$ determines the real force acting on the sides. Such force reasonably broadens or compresses the afterbody in width. Given any two flow velocities $U_i$ and $U_j$ ($i, j$ are the serial numbers of $U$), the corresponding width difference $\Delta \overline{W}_{i,j} = \overline{W}_i - \overline{W}_j$ beyond $\Lambda_{c1}$ can be written as

$$\Delta \overline{W}_{i,j} \sim 0.5kcρ(U_i^2 - U_j^2)(\Lambda - \Lambda_{c1})$$

where $k$ is a constant fitting parameter with the unit of $\text{m}^2/\text{kg}$ that takes the filament bending stiffness, afterbody mass, etc. into consideration. This form is self-consistent in that for the same $U$, there is no width difference; for $\Lambda = 2.3$, no width difference exists either. If we eliminate the width difference between all the $U_i$ and $U_1$ (black star) by $0.5kcρ(U_i^2 - U_1^2)(\Lambda - \Lambda_{c1})$, all curves remarkably collapse on $\Delta \overline{W}$ [Fig. 3(e)]. This model is capable of explaining the physics underlying the width difference between different $U$. Although the method to fully resolve the afterbody shape and curvature at any given $(\Lambda, U)$ has yet to be determined, it is reasonable that $\overline{W}$ could be represented by a function of $\Lambda$ and $U$. Our model based on the pressure difference is also capable of explaining the phenomena described previously. First, the delayed transition from C to S regime: the larger $U$ is, the smaller the outside pressure is. Thus, the afterbody tends to grow more in width, and the C regime lasts longer. Second, the different physics at $U_1$ and $U_2$: the afterbody shape is easily depressed at small $U$, so that the separation points return to the plate edges [Fig. 1(h)], making the drag increase sharply [Fig. 2(b)]. Since the fluid drag varies in a different way, $U_1$ and $U_2$ are not taken into discussion in the following part.

**Drag scaling based on the afterbody shape.—**Since the afterbody width $\overline{W}$ is also a function of $\Lambda$ and $U$, using
as the characteristic length to normalize the drag gives more physical insights on the drag scaling. As shown in Fig. 4(a), all $C_{D, W}$ show similar trends and approximately coincide in the P, C and S regimes. It is noted that the drag coefficient curves of the cases above the FDZ ($U_6, U_7$, blue left-pointing triangles) get closer to the cases in the FDZ than the previous scaling based on plate length [Fig. 2(b)], suggesting the reconfiguration of the afterbody causes the discrepancy given by the previous scaling without considering the shape deformation. More importantly, similar physics, including shape deformation and drag variation, are reasonably expected to occur at even larger Re regime than the FDZ, though the drag reduction is not that significant. Thus, for similar moving rigid objects in a similar Re regime, with the addition of a suitably flexible coating, such drag reduction will take place as well. One should note that a larger discrepancy is observed even for FDZ cases beyond the S regime ($\Lambda > 4.2$). The possible reason is that the contribution from form drag and skin friction drag to the total drag changes. In the previous study on bluff body flow in the soap film [19], the form drag predominates due to the small upper bound of the estimated skin frictional drag [35, 36]. However, for our coupled system, form drag is no more the exclusively dominating factor, especially in the rolling vortex and flapping regimes (One observation is that $W$ keeps decreasing in these two regimes [Fig. 3(d)] but the whole system suffers a heavier drag burden [Fig. 2(b)]). We introduce the average wake width $\bar{W}_w$ as a quantitative measure of the form drag value [33, 37, 38]. $\bar{W}_w$ is obtained as the average of the wake width from the end of the filament to a length of $L_p$ downstream.

In summary, we investigate the 2D flow past a coupled rigid-flexible system in a flowing soap film, and focus on the shape of the deformable afterbody and the fluid drag acting on the whole system. The flexible afterbody behaves stationarily when its length is short, in contrast to the common sense that flexible loops should flap in flowing fluids [24, 39, 40], but at the same time, its shape reconfigures according to the fluid, which occurs ubiquitously in the biological world. By exploring the underlying physics of this new class of fluid-structure interactions, we expect such shape reconfiguration and flow features to be repeated in a similar and even larger Re regime for bluff bodies. Due to the negligible additional weight and convenient installation/disposal of the flexible afterbody, controlling the flow around a bluff body and reducing its suffered drag in a simple way are possible, which may benefit the performance of athletes, racing cars, diving submarines, etc. and possibly inspire novel designs in many areas.

The authors acknowledge Yufeng Kou and Xia Wu for assisting with the experiment. This work is supported by the Natural Science Foundation of Shanghai (Grant No. 19ZR1426300) and National Natural Science Foundation of China (Grant No. 11632011).

*Corresponding author: tianxinliang@sjtu.edu.cn

[1] P. W. Bearman and J. K. Harvey, AIAA J. 31, 1753 (1993).
[2] A. Roshko, J. Fluid Mech. 10, 345 (1961).
[3] P. W. Bearman, J. Fluid Mech. 21, 241 (1965).
[4] E. A. Anderson and A. A. Szewczyk, Exp. Fluids 23, 161 (1997).
[5] H. Choi, W. P. Jeon, and J. Kim, Annu. Rev. Fluid Mech. 40, 113 (2008).
[6] F. E. Fish and G. V. Lauder, Annu. Rev. Fluid Mech. 38, 193 (2006).
[7] D. W. Bochert and M. Bartenwerfer, J. Fluid Mech. 206, 105 (1989).
[8] E. A. Van Nierop, S. Alben, and M. P. Brenner, Phys. Rev. Lett. 100, 054502 (2008).
The filament is fastened to one end of the plate while passes through the hook on the other end and finally wraps around a roller behind the film. The hooks are tiny and symmetrically made and therefore no obvious impact on the flow is observed. Since fluid forces always stretch the filament, rotating the roller smoothly increases or decreases $L_d$ accordingly. The roller is rotated gently that the bending of cantilever is not influenced. The transverse motion of reflected laser beam is not observed.