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NOTE

On the influence of biomimetic shark skin in dynamic flow separation

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Abstract

The effect of shark skin on the boundary-layer separation process under dynamic conditions (maneuvers) has been studied experimentally. We use a foil covered with biomimetic shark skin to explore how this type of surface impacts boundary-layer dynamics in both steady and accelerating conditions. The effect of denticles is assessed via particle image velocimetry in the wake. It is shown that dynamic conditions and small-scale disturbances can mitigate boundary-layer separation through instantaneous modification of the local pressure-gradient distribution. For instance, the region of favourable pressure gradient can be extended by accelerating the foil. The acceleration results in a thinner separated shear layer on the foil surface when compared to the steady reference case. This remarkable difference indicates that local roughness (introduced through for instance biomimetic shark skin) may trigger an interaction with relatively large-scale structures in the boundary layer for effective boundary-layer control during unsteady propulsion and maneuvering.

1. Introduction

Swimming animals are well-known for their incredible ability to maintain attached flow during rapid maneuvers [1–4]. Intricately microstructured surfaces such as shark skin have evolved over 100s of millions of years to assist in the optimization of propulsion [5]. A shark’s body is covered from head to tail by small tooth-like scales with riblet-like structures known as dermal denticles, and a large body of research has focused on the hydrodynamic properties of shark skin in the context of models traveling at constant (steady) speed and the skin’s influence on drag reduction [6–9]. Many of these papers have elucidated the effects of denticle shape, size, and distribution on drag reduction, by exploring a wide variety of riblet geometries, such as scalloped, sawtooth, and blade designs. It is currently thought that the riblet structure enables streamwise control of vortices in turbulent boundary layers, thus decreasing turbulence fluctuations in the cross-flow direction [9, 10]. While most of these studies are performed with static denticles, the vertical orientation of denticles on some sharks may vary by up to 50°. Recently, such bristling of the denticles has even been shown to delay flow separation as well [11].

The work of Oeffner and Lauder [12] suggests that shark skin can also enhance thrust under dynamic conditions. To test this, they used a flapping mechanical device to control biomimetic, flexible skin foils undergoing dynamic motion. In their study, a strong leading-edge vortex (LEV) was generated and remained attached to the foil surface, resulting in enhanced normal suction at the leading-edge. Wen et al [13] also used flexible foils to study hydrodynamic functions of 3D printed shark skin. They found that the shark-skin foil could alter the vortex core location as well as enhance the strength of the LEV when compared to an equivalent smooth foil. These two studies infer that the process of time-dependent flow separation with shark skin may have an effect on pressure drag, but a detailed investigation has not yet been performed. Limited by spatial resolution, the precise flow modification with denticles was not investigated in these two aforementioned studies.

Body/caudal fin (BCF) undulation is the preferred mode of swimming for the majority of fish species. BCF swimming styles are classified into four modes...
of axial undulatory locomotion (Webb et al [14] and Lindsey [15]), of which the subcarangiform mode is widely distributed among sharks. In this mode, the amplitude of lateral displacement increases over the posterior portion of the body (Gembella et al [16]), creating a favorable pressure gradient in the posterior region [4, 17]. Interestingly, the shape and size of the denticles vary depending on body location, as seen in figure 1. For instance, the denticles are comparatively flat on the nose tip (figure 1(A)) and middle region of pectoral/dorsal fin (figure 1(C)), while the denticles are significantly larger and with more prominent ridges on the lateral posterior portion of the tail (figure 1(E)), corresponding to the point where the body can oscillate with the highest amplitude [3, 18], where flow separation is prone to happen [1, 3]. Therefore, these denticles may serve to expand the favorable pressure gradient region so as to eliminate flow separation and thereby reduce the cost of locomotion during free swimming and/or increase maneuverability during escape and predatory responses.

A first investigation on a developing boundary layer’s dynamic pressure-gradient field was explored by Lighthill [19]. Since then, subsequent studies have focused on boundary vorticity dynamics to establish strategies for the control of flow separation [20–23]. However, the effect of these denticles in a developing boundary layer with local flow separation remains poorly understood, and cannot be treated with quasi-steady assumptions [24–26], as these stationary assumptions do not replicate the real time-dependent flow over a shark’s body where local and periodic acceleration plays an important role.

Thus, the objective of the current study is to understand how shark skin interacts with the local pressure-gradient field under dynamic conditions for effective boundary-layer control. To express this concept, a freely-swimming shark is visualized in figure 2(a) from a top view. Figures 2(b) and (c) illustrate that a small section in the posterior portion of the body can be abstracted as a foil with an apparent local surface curvature. When viewed at a constant angle of attack, this complex, time-dependent motion for a local section of the body can be abstracted most simply as an axially-accelerating foil. Numerous researchers have studied time-varying acceleration of sharks [27–36]. Seamone et al [31] reported that the maximum acceleration of male dogfish sharks ranges from 0 to 1.5 ms$^{-2}$ when they respond to a head-on predator. The acceleration in the current study was set to 0.9 ms$^{-2}$, which falls within the above range. Another way to define the overall dynamic body acceleration is relative to gravitational acceleration (g). The investigation of Gleiss et al [28] found that the acceleration of lemon sharks was 0.072 ± 0.05g for cruise condition and 0.155 ± 0.03g for the initiation of swimming after rest. The acceleration in this study (0.09g) is similar to these above values.
Figure 2. (a) Superimposed body outline showing undulatory (unsteady) locomotion. (b) Sketch identifying a small local section on the shark body with axial acceleration \((a = \frac{dx}{dt})\) in the \(x\) and \(y\) global coordinate system. (c) An accelerating SD7003 airfoil modeling this small local section at a constant angle of attack.

In the first part, theoretical results for the pressure-gradient field around an accelerating smooth foil were derived to provide preliminary insight into the effect of acceleration on the pressure-gradient field. Time-resolved particle image velocimetry (PIV) measurements were then performed both for a smooth foil and a biomimetic shark-skin foil under dynamic conditions to evaluate the effect of skin denticles on the dynamic flow-separation process. In the following, section 2 describes the theoretical dynamic pressure-gradient field around a flat-plate foil based on potential-flow theory, followed by a discussion of the experimental approach in section 3. The time-resolved PIV measurements are presented in section 4. Finally, some concluding remarks for this exploratory study are shared in section 5.

2. Potential flow pressure-gradient field

Potential-flow theory cannot predict flow separation directly. However, flow separation has classically been linked to the presence of adverse pressure gradients [39], and we know that the onset of local separation pressure conforms well with that given by potential theory [40]. As such, we use potential theory to investigate the effect of acceleration on the pressure gradient and then predict its subsequent influence on the flow-separation process [41]. A flat-plate foil as a low-order model was used to simplify this preliminary analysis. We first show the solution for the pressure gradient around the flat-plate foil undergoing constant-speed (steady) motion, and then compare the result with that from a flat-plate foil undergoing acceleration representative of undulation or maneuvering.

The classical approach uses a trigonometric expansion, where the foil leading edge is at \(\theta = 0\) and the trailing edge at \(\theta = \pi\), as shown in figure 3. The Kutta condition needs to be satisfied to obtain the following unique solution:

\[
\gamma(\theta) = 2U_\infty \left[ A_0 \frac{1 + \cos \theta}{\sin \theta} + \sum_{n=1}^{\infty} A_n \sin(n\theta) \right],
\]

where \(U_\infty\) is the translational velocity of the flat-plate foil and \(\theta\) is the azimuthal position from the leading edge for the transformation \([37, 38]\). For a flat-plate foil, the circulation coefficients become \(A_0 = \alpha\), \(A_n = 0\), and equation (1) can be reduced to:

\[
\gamma(\theta) = 2U_\infty \alpha \frac{1 + \cos \theta}{\sin \theta}.
\]

2.1. Steady analysis

The tangential velocity on the suction side of a flat-plate foil is given by:

\[
u = U_\infty + \frac{1}{2} \gamma.
\]

From the classical solution, the above equation can then be written as follows:

\[
u = U_\infty + U_\infty \alpha \frac{1 + \cos \theta}{\sin \theta},
\]

where \(\alpha\) is the geometric angle of attack.

The relationship between pressure gradient and tangential velocity can be established via the steady Euler equation:

\[-\frac{1}{\rho} \frac{\partial p}{\partial s} = \frac{\partial u}{\partial s},\]

which yields as follows:

\[-\frac{1}{\rho} \frac{\partial p}{\partial s} = \left( U_\infty + U_\infty \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \times U_\infty \alpha \left( -\frac{1}{R} \right) \frac{1 + \cos \theta}{\sin^2 \theta},
\]

where \(s\) is shown in figure 3(b) and \(\rho\) is the density of the fluid. Using the following definitions, \(s^* = s/\tilde{s}\) and \(p^* = p/\tilde{p}\), where \(*\) represents respective
non-dimensional quantities and ∼ refers to characteristic values (3 = R), the above equation becomes:

\[- \frac{1}{\rho R} \frac{\partial \tilde{p}}{\partial s^*} = - \frac{U_\infty^2}{R} \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \times \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

and yields the following expression:

\[ \frac{\tilde{p}}{\rho U_\infty^2} \frac{\partial \tilde{p}^s}{\partial s^*} = \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

For mathematical convenience, we can let \( \tilde{p} / \rho U_\infty^2 = 1 \), and it follows that \( \tilde{p} = \rho U_\infty^2 \). Finally, the pressure gradient can be written as

\[ \left( \frac{\partial \tilde{p}}{\partial s} \right)^* = \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

where \( (\partial \tilde{p}/\partial s)^* \) represents the pressure-gradient field on the suction side of this flat plate in non-dimensional form.

The pressure gradient from equation (9) is plotted against the azimuthal position in figure 4, showing that the whole upper surface is subjected to an adverse pressure gradient such that \( (\partial \tilde{p}/\partial s)^* > 0 \).

2.2. Dynamic analysis

For an accelerating flat-plate foil, a similar analysis can be performed by using the unsteady Euler equation:

\[ - \frac{1}{\rho} \frac{\partial \tilde{p}}{\partial s^*} = - \frac{U_\infty^2}{R} \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \times \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

For a flat-plate foil undergoing acceleration, the translational velocity is a function of time:

\[ U_a = U_1 + at \]

where \( U_1 \) is the speed when the foil starts to accelerate and \( t \) is the instantaneous time during acceleration. The velocity on the suction side of a flat-plate foil is expressed by:

\[ u = (U_1 + at) + (U_1 + at) \alpha \frac{1 + \cos \theta}{\sin \theta} \]

yielding the following expression if the velocity is substituted into the unsteady Euler equation

\[ - \frac{1}{\rho} \frac{\partial \tilde{p}}{\partial s^*} = a \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

As in the steady case, we use the following definitions: \( s^* = s/R, \tilde{p}^* = \tilde{p}/\tilde{p}, \) and \( t^* = t/t \). Here, \( t \) is defined as the characteristic time, \( t = U_\infty/a \). As above, setting \( \tilde{p} = \rho U_\infty^2 \), we obtain:

\[ - \frac{\partial \tilde{p}^s}{\partial s^*} = \left[ - \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \left( U_1 + at \right)^2 \frac{aR}{U_\infty^2} \right] \times \left( 1 + \alpha \frac{1 + \cos \theta}{\sin \theta} \right) \]

To exclude the impact of a variable Reynolds number during acceleration, we only study the pressure gradient at the same instantaneously translational velocity for both the constant-speed (steady) case and acceleration cases:

\[ U_\infty = U_a = U_1 + at \]

We substitute equation (15) into equation (14) and denote the acceleration modulus by non-dimensional parameter \( a^* = aR/U_\infty^2 \). The dynamic pressure gradients may be written as:

\[ \left( \frac{\partial \tilde{p}}{\partial s^*} \right)^* = \left[ \frac{1}{\sin \theta} \frac{1 + \cos \theta}{\sin \theta} \right] - a^* \]

Note that as \( a^* = 0 \), equation (16) in turn reduces to equation (9).

The pressure gradient from equation (16) is plotted in figure 4, which illustrates that the region of adverse pressure gradient can be reduced by increasing acceleration. Note the acceleration intervals in figure 4 are integer multiples of the experimental modulus (\( a^*_0 = 0.4 \)). When \( a^* = 0 \), which resembles the steady condition, the value of \( (\partial \tilde{p}/\partial s)^* \) becomes...
positive throughout. The suction side of the flat-plate foil is naturally subjected to an adverse pressure gradient. However, even for a relatively low acceleration, the reduction in pressure gradient is noticeable when compared with the steady case. For $a^* = a^*_e$, the favourable pressure gradient appears in the posterior portion of the flat-plate foil ($\theta > \pi/2$). As the acceleration modulus increases to $a^* = 4a^*_e$, the region of favourable pressure gradient occupies most of the flat-plate foil surface. Equation (16) illustrates that the region of the adverse pressure gradient can theoretically be eliminated for an infinite acceleration.

3. Experimental methods

3.1. Experimental model
To validate the effects of biomimetic shark skin on dynamic separation, we performed accelerating experiments to model unsteady propulsion and/or maneuvers. The skin was fabricated by casting silicone rubber onto a 3D-printed mold, which itself was reconstructed from 3D scanning electron microscopy (3D-SEM) of shark denticles, as described previously [42]. This technology can measure structures at micrometer scale on dentine surfaces [13, 43]. The skin sample was taken from the posterior-dorsal region of a spiny dogfish (Squalus suckleyi), a region which can bend in high curvature and in which the denticles have prominent ridges, as shown in figure 1(E). As described above, this local region of curvature is modeled using a smooth SD7003 foil. The biomimetic shark skin was then adhered onto this smooth foil surface, as shown in figure 5.

3.2. Particle image velocimetry measurements (PIV)
All experiments were performed in a 15 m long towing-tank facility with a cross section of 1 m by 1 m. The two-dimensional profile model was towed through the tank via a vertical streamlined sting. Time-resolved PIV was used to measure the velocity field on the suction side and in the wake. The schematic of the towing tank along with the mounting configuration is depicted in figure 6. The flow field was imaged using a Photron SA-Z high-speed camera operating at 1500 Hz with a resolution of 1024 x 1024 pixels. A 40 mJ-per-pulse high-speed laser (Photonics DM40-527) was used to create a vertical sheet 1.5 mm in thickness. The PIV measurements were repeated for 15 trials in each case, and the data sets were then phase-averaged. At smaller angles of attack, such as $0^\circ$ to $4^\circ$, the separated shear layer on the SD7003 foil suction side was extremely thin and relatively stable when the adverse pressure gradient was modest. Conversely, the foil was close to stall at $11^\circ$ [44]. As such, the present measurements were performed at a constant geometric angle of attack of $8^\circ$, at which point the foil surface exhibited a significant curvature at the separation region, which can be used to abstract the local pressure gradient of a static or undulating shark body [45]. The model was tested for two different conditions: constant (steady) speed and acceleration. Both motions were normalized by $x^* = x/c$, where $x$ is the physical distance traveled and $c = 0.2$ m is the chord of the model. Figure 6(c) presents these two motions through normalized velocity plotted against dimensionless distance. Freely-swimming spiny dogfishes displayed relatively low absolute speeds compared with bony fishes [25], at average Reynolds numbers between 90,000 and 127,000 [12]. For the constant (steady) speed test, the model started from rest to a steady towing velocity ($U_\infty$) as shown in figure 6(c), corresponding to $Re = 90,000$ based on the chord. The accelerating motion involved a similar process to a steady towing velocity ($U_1$), followed by a constant acceleration to a second steady velocity ($U_2$), corresponding to $Re = 120,000$. This motion represents unsteady propulsion or a rapid maneuver of a spiny
Figure 5. Schematic of the biomimetic shark-skin-covered foil. Colored skin denticles are used to identify the orientation on the suction side (blue) and the pressure side (red) of the foil, respectively.

Figure 6. (a) Schematic of the optical towing tank. (b) Schematic of the experimental set-up for PIV measurements. (c) Normalized velocity plotted against dimensionless distance \((x^* = x/c)\) for steady motion (red curve) and dynamic motion (blue curve). \(U_\infty = 0.45 \text{ m s}^{-1}\) represents the towing velocity during steady motion. The model was accelerated from \(U_1 = 0.3 \text{ m s}^{-1}\) to \(U_2 = 0.6 \text{ m s}^{-1}\) for the dynamic motion. For all experimental cases, the geometric angle of attack was held constant at 8°.

dogfish, and is shown by the blue curve, which has an intersection point with the red curve at \(Re = 90\,000\).

4. Results and discussion

4.1. Normalized streamwise velocity contours

In order to better understand the contributions of both acceleration and shark skin to boundary-layer separation, we now analyze the mean velocity fields on the suction side of the model and in the near wake. To visualize the boundary-layer behavior under various conditions, contours of the phase-averaged streamwise velocity for the smooth surface and the denticle surface are presented in figure 7. Figures 7(a) and (c) show steady cases at \(Re = 90\,000\), while figures 7(b) and (d) present dynamic cases with the same acceleration modulus \((a^* = aR/U_\infty^2 = 0.4, R = c/2)\). The acceleration selected in the study \((a = 0.9 \text{ ms}^{-2})\) was representative of shark swimming in the wild [27–36]. Importantly, velocity contours for the dynamic cases (figures 7(b) and (d)) are also provided only at an instantaneous value of \(U_a\) \((Re = 90\,000)\) to compare all cases at the same effective Reynolds number.
Figure 7. Contours of phase-averaged streamwise velocity distribution on the suction side of the model and in the near wake. (a) and (b) show the velocity distribution on the smooth surface. (c) and (d) represent the velocity distribution on the denticle surface. Steady cases ((a) and (c)) are at $Re = 90,000$, while dynamic cases ((b) and (d)) with the same acceleration are also at an instantaneous $Re = 90,000$. A thinner separated shear layer in the dynamic case is observed when compared to the steady reference case. The origin of the coordinate system is relocated to the trailing-edge of the foil and the axes are reversed relative to figure 6. Gray color indicates the regions of the flow fields in the shadow of the foil. The location of the dashed line was used to depict the velocity profile in the near-wake region (see figure 8).

The effect of the acceleration on the boundary-layer behavior can be observed by comparing figures 7(a) and (b). For an inclined foil under steady conditions, previous studies have shown that a steep adverse pressure gradient appears near the leading edge and decreases gradually toward the trailing edge [46–48]. This trend of the pressure distribution is also predicted by equation (16) in this study. Owing to the presence of an adverse pressure gradient, a relatively thick separated shear layer is apparent in figure 7(a). However, for an inclined foil during acceleration, equation (9) suggests that the adverse pressure gradient near the trailing edge can be easily switched to a favourable pressure gradient. Harun et al [49] compared the large-scale structures in turbulent boundary layers under favourable and adverse pressure gradients. They reported an increase in the number and strength of large-scale structures in the outer region when the boundary layer is subjected to an adverse pressure gradient. Similarly, the favourable pressure gradient caused by the acceleration in this study leads to a thinner separated shear layer on the suction side and a relatively narrow wake region, as seen in figure 7(b).

A considerable influence of the surface condition (biomimetic shark skin) on boundary-layer behavior are found in figures 7(c) and (d). Compared to the smooth surface under steady conditions (figure 7(a)), the separated shear layer is substantially thicker for the denticle surface shown in figure 7(c). Note that present turbulent boundary layers in these two cases (figures 7(a) and (c)) are subjected to the same level of adverse pressure gradient. This larger separated shear layer is explained as a result of the separation occurring earlier when the rough elements (denticles) are present in a fully-turbulent boundary layer [50–52]. In contrast, a substantial decrease in the size of the separated shear layer and wake region was captured in the dynamic case, as observed in figure 7(d). For this case, the boundary-layer behavior is attributed to the combined effects of acceleration and denticles roughness. As discussed above, the primary consequence of the acceleration is the extension of the favourable pressure gradient region, which will result in a thinner, separated shear layer on the surface. Harun et al [49] pointed out that the basic character of the large-scale fluid motions will remain essentially unchanged on a smooth wall when the pressure gradient increases from favourable to adverse. In particular, the geometry of large-scale structures remains universal in their study. However, compared to the small effect of acceleration on a smooth surface, the significant effect on accelerating shark skin (figure 7(d)) indicates that an interaction between the suppressed shear layer and denticles may have occurred in the local favourable pressure gradient flow. As a result, we can infer that it is possible to change the boundary-layer character to further mitigate flow separation. Indeed, for a
Figure 8. Mean velocity profiles in the near-wake region (see dashed line in figure 7) for the smooth surface and the denticle surface under steady ($\alpha^* = 0$) and dynamic ($\alpha^* = \alpha_t^*$) conditions, respectively. The coordinate system is consistent with that in figure 7.

2D rough surface, Talapatra [53] has confirmed that pyramidal elements can create U-shaped structures in the turbulent boundary layer.

4.2. Mean velocity profiles in near-wake region
Further analysis of the PIV data reveals significant differences in the wake properties between the various test cases. Figure 8 shows the four velocity profiles in the near-wake region (downstream location $(x' - x^*)/c = 0.005$ in figure 7). As has already been noted in section 2, the acceleration of the foil has a significant impact on the pressure gradient. As shown recently by Kitsios et al [54], the static pressure gradient plays an important role in the static separation process. For acceleration, the dynamic reduction in the instantaneous pressure gradient is expected to have considerable effect. Furthermore, the surface roughness can also modify boundary-layer dynamics close to the foil surface [55].

Figure 8 also presents the impact of the denticle surface on the momentum deficit. What stands out here is the greater variance between static and accelerating cases. In contrast to the smooth surface, the denticle surface induces a wider wake and smaller velocity gradient close to the airfoil. Another interesting observation is the combined effects of the dynamic pressure gradient and the denticle surface. The momentum deficit near the trailing-edge $(y/c = 0)$ for the accelerating denticle surface is lowest among all four cases. One possible implication is that the considerable reduction of the momentum deficit near the trailing-edge may result in a global decrease in skin friction drag.

4.3. Discussion
As a first proof-of-concept investigation of boundary-layer behavior on accelerating shark skin, this study opens up the path forward toward assessing the role of denticle roughness in dynamic swimming of sharks. Although a series of preliminary results has been presented, this work is meant to generate many more new questions than it necessarily first answers. What is the three-dimensional flow topology near the denticle surface during acceleration? To what extent does the denticle surface affect thrust performance and maneuverability under dynamic conditions? How does the denticle surface influence the dynamic boundary-layer separation process in severe stall conditions (at high incidence angles)? More research on this topic needs to be undertaken before a definitive association between dynamic boundary-layer behavior and denticle surface is more clearly understood. Many studies so far have revealed a correlation between foraging behavior and swimming strategies [31, 34, 36, 56, 57], which suggests there is good reason to continue this line of research. The acceleration of the shark’s body has a significant impact on the effectiveness of suction feeding. The study of Higham et al [56] suggests that species that generate higher magnitudes of acceleration will commonly exhibit significantly greater strike accuracy. Thus, it is conceivable that the denticle surface during acceleration (unsteady propulsion and maneuvering) benefits feeding performance. Although this study was not able to provide definite answers to these questions, it represents one of the first attempts to explore the impact of the denticle surface on such dynamic motions.
5. Conclusions

In this study, we investigated the impact of acceleration and denticle roughness on boundary-layer separation. A bio-inspired shark skin, inspired by samples from a spiny dogfish, was tested on an accelerating foil in a towing-tank facility. First, we used potential theory to assess the influence of acceleration on the instantaneous pressure gradient on an idealized flat-plate foil. As the acceleration increased, the transition from an adverse pressure gradient to the favourable pressure gradient was observed. These findings established the physical basis for the pressure-acceleration relationship and its influence on boundary-layer dynamics during acceleration.

Subsequently, time-resolved PIV measurements were collected on accelerating foils with and without the bio-inspired shark skin. These results show how acceleration does in fact alter the boundary-layer separation process and the foil wake. For an accelerating smooth foil, a thinner separated shear layer and a narrower wake were observed compared to the steady reference case. For the accelerating shark skin, a substantial decrease in the size of the shear layer and remarkable differences in the near-wake velocity distribution were observed due to the combination of acceleration and the presence of the synthetic shark skin.

As a first proof-of-concept investigation of boundary-layer separation behavior on accelerating shark skin, this study opens up the path toward assessing the impact of shark skin on dynamic motions such as undulatory swimming and maneuvering. Further experimental investigations are needed (and planned) in order to study the three-dimensional flow topology near the denticle surface as well as in the wake.

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