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Current state and future trends in boundary layer control on lifting surfaces

Jelena Svorcan[1], **Jonathan M. Wang**[2] **and Kevin Patrick Griffin**[2]

Abstract
Successful flow control may bring numerous benefits, such as flow stabilization, flow reattachment, separation delay, drag reduction, lift increase, aerodynamic performance improvement, energy efficiency increase, shock delay or weakening, noise reduction, etc. For these purposes, many different flow control devices, which can be classified as passive, semi-active and active, have been designed and tested. This review paper aims to highlight the most promising and commonly employed boundary layer control methods as well as outline their potential in specific applications in aerospace and energy engineering. Referenced studies, performed on various geometries (flat plates, channels, airfoils, wings, blades, cylinders), are primarily numerical or experimental. Although enhanced aerodynamic performance is achieved in many cases, further research is required to draw general conclusions. This paper aims to demonstrate that, in the future, we may expect further developments of flow control actuators, as well as their increased application.

Keywords
Flow control, boundary layer, aerodynamic performance, energy efficiency, separation, transition

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Background and introduction

Although the title of the paper refers to the current state and future trends in flow control, for a clearer perspective of this interesting and actively flourishing topic, it is helpful to remind ourselves how it all began and what the initial ideas were and to introduce some basic terms.

Various flow machines (such as wings, rotor blades, compressors, turbines, pumps, etc.) of different shapes and sizes, present in almost every industrial and engineering sector, are commonly used for energy conversion through generation of forces and moments (in aeronautics referred to as lift, thrust, drag, and torque). They are usually equipped with lifting that is, streamlined surfaces whose cross-sections are airfoils (complex curves with curvature and thickness that can vary greatly depending on the application). They operate in a wide range of conditions, spanning from small to extremely high Reynolds (Re) and Mach (M) numbers and reliable estimation of their performance has been the topic of numerous analytical, numerical, and experimental studies. Their efficiency is also greatly reduced by viscosity (an important fluid property) that leads to the formation of boundary layers thereby increasing drag. At the leading edge of an airfoil, the boundary layer is laminar and attached but further downstream, it can transition to turbulence or even separate.

[1]Faculty of Mechanical Engineering, Department of Aerospace Engineering, University of Belgrade, Belgrade, Serbia
[2]Stanford University, Center for Turbulence Research, Stanford, CA, USA

Corresponding author:
Jelena Svorcan, Faculty of Mechanical Engineering, Department of Aerospace Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia.
Email: jsvorcan@mas.bg.ac.rs

However, it took centuries to recognize and quantify the significance of viscosity in real applications.

Ever since Prandtl revolutionized fluid mechanics by introducing the concept of boundary layer (a marvelous narrative is provided by Anderson[1]), more than 100 years ago, it has been extensively studied, for its great significance and applicability, and myriads of investigations have sought to mitigate the negative consequences of its instability, transition and separation that generally imply losses in energy and efficiency, that is, poorer performance. Prandtl proposed the wonderfully simple idea to separate the control volume/inspected zone of interest into two distinctive zones: (1) the outer region (where viscosity effects can be neglected) and (2) the boundary layer (BL), a thin zone adjacent to the walls where viscosity plays an important role. Even though viscosity is generally very small for most real fluids, its influence on flow behavior and overall performance is exceedingly important. Viscosity affects friction and therefore drag (as well as other aerodynamic characteristics such as maximal lift), flow transition and separation (that in turn compromises the pressure distribution), momentum and heat transfer in the wall vicinity, noise, etc. It is therefore not surprising BLs have been widely investigated and that numerous exquisite books and papers have been written on the topic, including their characterization and computation,[2–4] transition,[5] and ultimately separation.[6–8]

Typically, as the angle-of-attack increases, lift increases until the onset of flow separation, at which point it sharply decreases. In addition, flow separation is usually something to be avoided since it is chaotic, uncontrollable, and accompanied by a drastic increase in drag and noise, and general losses of energy and efficiency. Two necessary conditions for flow separation are adverse pressure gradient (usually happening along the second half of the airfoil suction side where flow area expands) and viscosity (present in all real fluids). A natural conclusion then comes to mind that if we manage to avoid one of these two necessary requirements, it is possible to avoid flow separation.[6] That is also why the idea of boundary layer control (BLC) is so alluring and has been around for quite some time. The oldest and primary method for BLC is to design the geometry to maximize favorable values of pressure gradient, reduce drag, delay transition to turbulence, avoid shock wave formation along the airfoil suction side, etc. depending on design priorities. However, the problem with this simplest and most natural means is that it is adequate for a single operating point and can be highly sensitive to external disturbances. That is why more robust methods of BLC are typically preferred. The second approach for BLC is to diminish, that is, alleviate the effects of viscosity either by moving the walls (such as with rotating cylinders) or by completely removing/sucking out the boundary layer (where viscosity effects are important). The third approach is to enhance mixing of flow streaks. This can be accomplished by carefully designed or modified (with additives) surface and/or positioned geometric shapes/devices. Mixing can also be enhanced by energizing the BL with additional sources of mass, momentum and/or energy. Many different approaches have been tried with respect to the type of flow (laminar or turbulent, sub- or supersonic, single- or multiphase) and its application. Again, exhaustive historic literature can be found on the subject of BLC, in the form of books and review papers,[9–11] and here, just a small, representative sample is mentioned.

This paper is intended for both researchers and engineers. Achieving optimal performance of flow machines remains a challenge for a number of reasons: (1) whereas actual experiments are costly and timely, numerical models are not always closed, (2) flow behavior cannot easily be scaled up or down (i.e. what is applicable on small geometries or speeds, doesn't always befit the larger ones, and vice versa), (3) flow processes and aerodynamic loads can change rapidly and in ways that are difficult to predict. Therefore, understanding how flow control devices operate and choosing the most appropriate (robust, rapid-response) type is extremely important, primarily in terms of aerodynamic efficiency but also structural analysis and control algorithms. The objectives of this review are twofold:

- to articulate a comprehensive and critical recapitulation of both existing and innovative flow control devices, and
- to provide a set of guidelines to facilitate the design of more efficient lifting surfaces for researchers and engineers and make a good starting point for the preparation of future numerical and experimental studies.

This has been done in the following manner. In the next chapter, useful and interesting review papers on the topic are mentioned. Then, different flow control devices are categorized, briefly described, compared, and their most basic applications as well as advantages and disadvantages are mentioned. In the end, the paper also discusses some possible future applications and directions of further development.

Summary of most representative review papers on BLC

BLC usually implies: decreasing the BL thickness (that is defined as the distance from the wall needed to recuperate 99% of freestream velocity) since it increases as fluid flows along the object's surface, reducing friction drag, delaying or inducing laminar-turbulent transition (dependent on critical Re, freestream characteristics, surface quality, etc.), suppressing or provoking turbulence as well as preventing or at least postponing or prompting boundary layer separation (a very interesting and important flow phenomenon studied by Chang[6]). If flow adjacent to walls can be manipulated, it is possible to achieve various benefits – most common are: improvement in lift and drag reduction, performance and efficiency improvement, heat transfer enhancement (both cooling and heating), flow stabilization, noise reduction (particularly when controlling/affecting the wake), etc. The reader may observe that it is sometimes extremely useful to induce turbulent boundary layers (as they are less susceptible to separation) or flow separation (particularly in super- or hypersonic flows) since losses might be decreased.

From the above, it is obvious that the topic of flow (boundary layer) control is extremely broad and that many research studies have already dwelled on these topics. As a result, there is also a number of high-quality review papers available that summarize certain aspects of this diverse subject matter. In this section, some of them are mentioned. The choice of referenced literature is undoubtedly biased and can be further expanded. However, the authors chose some of the most useful, interesting, applicable, and representative papers and organized them chronologically (rather than by topic).

A very clear and comprehensive overview of BLC development and trends till the end of the 20th century, with possible applications to different types of flow as well as reactive (closed-loop) control aspects, is provided by Gad-el-Hak.[12] Though more than two decades have passed, the main approaches to flow control remain the same, and this paper persists as a good starting read. On the other hand, in his review paper, Modi[13] covers the topic of BLC by a particular method – moving surfaces (achieved by rotating cylinders located on the leading or trailing edge or at the suction side of the airfoil). The obtained results were very promising and show this method can significantly delay separation of the boundary layer and reduce the pressure drag. Although reported maximal lift values were astonishing (close to 4.8), this technique's applicability in real operation is still questionable. Another example of a thorough review on passive flow control by vortex generators (static devices located within boundary layer thickness) is prepared by Lin.[14] It is proven these instruments can effectively postpone separation and suppress noise if properly designed. Today, vortex generators of various shapes and arrangement are extensively used on large-scale wind turbine blades as well as engine inlets, wing-fuselage intersections and aft parts of fuselage. Kim[15] reviews numerical studies on applications of linear optimal control theory to boundary layer control (i.e. coupling of fluid mechanics, control theory and state-of-the-art sensor/actuator technologies) conducted at University of California, Los Angeles. Control input was in the form of steady blowing and suction, and significant reduction in wall shear is reported. Chernyshev et al.[16] prepared a review of activities in laminar flow control performed at the Central Aerohydrodynamic Institute named after Prof. N.E. Zhukovsky (TsAGI). This thorough summary, covering both numerical and experimental studies, describes laminar flow control methods such as special geometric shaping, suction, surface cooling, local heating of the airfoil leading edge, and receptivity control, that is, active surfaces equipped with microelectromechanical systems (MEMS), electrohydrodynamic methods (electric discharges), etc. On the other hand, a coherent discussion of actuator types, characteristics, specifications, selection and design in aeronautical applications is made by Cattafesta III and Sheplak.[17] The aims of their paper are to provide key advantages and disadvantages of most common actuator types as well as to facilitate the choice of the most appropriate fluidic, moving object/surface, or plasma actuators. Kornilov[18] reviews the possibilities of aerodynamic drag reduction, particularly viscous drag, for simple model configurations (flat plate) by micro-blowing through permeable surfaces. It is reported that both experimental and numerical studies confirm that the skin friction coefficient can be reduced by more than 50%. However, this is accompanied by thickening of the boundary layer and increased pressure drag, and successful application to curved surfaces remains to be shown. Another example of practical applications is provided by Tiainen et al.,[19] where the focus is on both active and passive BLC in centrifugal compressors at low-Reynolds-numbers. Possible benefits for unmanned air vehicles (UAVs) and small turbomachines include reducing drag, increasing blade loading, or reducing tip leakage. Although various approaches are considered, it is not possible to provide a definitive answer on what an optimal control method would be. Amitay and Gildersleeve[20] review different methods of controlling laminar BLs. They considered both active (synthetic jets, dynamic pins) and passive (static pins/vortex generators) devices individually as well as a combination, thus generating a hybrid actuator that has potential to be a more efficient controller than the baseline devices for certain flow fields. In their review, Zhang et al.[21] focused their attention on active wall drag reduction. They summarized previous works on actively disturbing the turbulent boundary layer in order to reduce the skin-friction drag of vehicles by one of the following: wall motion, wall deformation, wall micro oscillation, or effects of volume force. Their work serves as a starting point for the research of active BLC. Likewise, Kumar et al.[22] examine state-of-the-art BLC methods, which are mainly based on contemporary advances in material science. In this paper, somewhat unconventional boundary layer control techniques which can help in drag reduction such as polymer additives (similar to slime covering fish scales), super hydrophobic surfaces (containing small micro groves/roughness), flexible skin, air-bubble drag reduction, etc. are reviewed. A review of (both numerical and experimental) works on passive BLC by wavy surface is given by Zverkov and Kryukov.[23] The authors demonstrate "that the use of a wavy surface of wings or blades of flying vehicles can improve their aerodynamic characteristics." Clear recommendations for defining the parameters of the wavy surface are also provided. An extensive review on the possibilities of skin friction reduction in turbulent BLs primarily by active control methods such as wall oscillations, rotating disks or plasma actuators (but also some passive methods) that accelerate the near-wall fluid in the transverse direction is provided by Ricco et al.[24] The authors claim that, by inducing a varying crossflow component, relative drag-reduction approaching 50% can be achieved. Lastly, Greenblatt and Williams[25] assembled an extremely useful summary on flow control techniques applied to some popular UAVs of various sizes, spanning from nano- to large-scale. Air vehicle size, and consequentially its energy availability, primarily dictate which approach to employ. Small vehicles are usually equipped by deforming/flapping wings and plasma actuators, which also serve to generate propulsive force, while fluidic systems continue to dominate on larger UAVs. For more information on a particular theme, the reader is strongly advised to have a more detailed look at these reviews.

Although the list of review papers ends here, as previously mentioned, it is by no means a complete account of available literature on the topic of BLC. It merely serves to stimulate the reader's curiosity and to demonstrate the broadness of the research field as well as its incompleteness. Although BLC has been investigated for decades, there are still numerous open questions and substantial work to be done, as each flow is specific and requires a customized design approach. There isn't a unique methodology to be employed that will certainly lead to positive results. Rather, each control technique, no matter how beneficial, comes at a cost (increased mass, energy input, drag, etc.) and is closely connected to the current technological development. Therefore, the authors' intention here is not only to add supplementary material to previously covered topics but also to focus on the most influential flow control applications (particularly their pros and cons) in aerospace and energy engineering. Due to the perennial relevance of this research area to industrial applications, particularly to meet the increasingly demanding emissions and performance standards, new views and works appear all the time, and it is necessary to mention them in one place once in a while and compare their applicability and effectiveness. Finally, one cannot think of advanced practices in aerospace and energy engineering (as the name of this Special Collection suggests) without looking back at BL control and examining its current trends. Secondly, this review paper aims to provide insight into the future tendencies and possible advances in boundary layer control. It is already apparent that future actions will be based on developments in the fields of artificial intelligence combined with reduced-order modeling, materials and morphing structures, nano/micro devices – MEMS, automation – active flow control, but also advanced turbulence modeling – direct numerical simulation (DNS), large-eddy simulation (LES) and state-of-the-art experimental techniques since all flow control concepts require exhaustive validation and verification. It would have been impossible to adequately describe and model these fascinating flow phenomena had it not been for the close connection between (complex) theory and experiments.[2] Many relations used to close numerical models are obtained empirically through extensive measurements. That is why both numerical and experimental studies are equally important and mentioned in this review.

Before delving into the peculiarities of different BLC approaches, one last statement should be given. Thermal boundary layers, where temperature and velocity fields are affected, are equally important and interesting. However, they were not inspected here in detail, as their main application is for heating/cooling, and are only mentioned in relation to supersonic and hypersonic flows where heating of the surface is significant.

The paper is organized in the following manner. Classification and main characteristics of different BLC methods are given in the next section. Methodologies employed for their inspection are covered in section 4, together with the indication of future trends. In the last section, select conclusions are summarized.

Classification and description of flow control methods

Although flow control methods can be categorized according to various criteria[12] that cannot always be easily differentiated, it is most usual to classify them according to their operation mode, effects on fluid flow, and required input. Here, the designation similar to the one proposed by Chernyshev et al.[16] is followed. As indicated in Chernyshev et al.,[16] boundary layer control techniques can generally be divided into three categories: passive, semi-active, and active. Generally, passive techniques are applied to the surface once, where they remain and act constantly on the flow field. They do not require additional sources/sinks (except regular maintenance). On the other hand, semi-active methods require additional sources/sinks (of mass, momentum, or energy), can be turned on and off, but act steadily on the flow field while active. Flow control devices belonging to these two categories aim to stabilize the flow inside the boundary layer, usually by appropriate geometric modeling (e.g. by ensuring favorable values of streamwise pressure gradient, surface modifications, enhanced mixing, etc.) or by constant action on the fluid flow. They are generally simpler and less expensive to realize but do not offer fine controllability. Again, the main difference between them is that passive devices aren't controlled (their action on the fluid flow is continuous), while semi-active methods can be turned on or switched off during operation/flight. On the contrary, active methods are always "dynamic." They act on particular unstable disturbances inside the boundary layer with the aim of suppressing them. Their operation is transient, they act locally and usually require additional sources of mass, momentum, energy. As can be concluded from the existing research and white papers, all three approaches are widely investigated and employed since it still cannot be said which methods are the most efficient and sufficiently robust for practical applications.[16] Furthermore, often there is overlap between the effects of physically different devices as well as many examples of coupled application (a combination of both passive and active devices). In the remainder of this section, basic descriptions and examples of various flow control devices are given.

Passive flow control

Without going into details on designing optimal streamlined shapes that ensure favorable pressure gradient distributions that produce prolonged zones of laminar flow (since that is a separate, immense topic), the passive approaches discussed here include surface modifications and additional small geometric devices located along the exterior (skin) that serve to prevent or delay flow separation by inducing flow reattachment (in the case of laminar flow) or by accelerating the transition to turbulence. This can be achieved by affecting surface roughness (by applying coatings, corrugations, riblets, dimples, bumps, porous patches, etc.), by vortex generators, or by modifying leading or trailing edges. Unlike semi-passive or active flow control techniques, passive flow control requires no external addition of mass or energy. Passive devices mainly impact the flow through the generation of small vortices that enhance the mixing of the slower streaks near the wall with the faster streaks further away. Thus, either flow reattachment or laminar-to-turbulent transition (implying a BL that is more resistant to separation) can be induced.

Surface modification. Here, very diverse surface modifications are grouped together for their relatively similar effects on fluid flow – generation of vortices and spanwise mixing that may postpone flow separation. However, their nature and geometric properties (scales and shapes) may be quite different. Roughness denotes "the smallest" and arbitrary surface irregularities, whereas coatings may be equally small but "designed" and more regular in shape. Riblets follow a pattern (similar to shark skin or bird feathers) and stretch along patches of a surface. Dimples are dents/imprints that may be arranged in arrays (the most basic example is a golf ball), while bumps "stick out" of the surface.

Flows (usually turbulent) over rough walls have always been an interesting topic since they are so often found in real life (surface roughness of every machine inevitably exists and may evolve with operation). Many studies have been performed, including the experimental work reported in Jiménez,[26] and the conclusions are reconfirmed again and again, that tiny irregularities/obstacles greatly affect boundary layer flow. However, these effects do not always have to be negative. A study on loaded turbomachinery by Bons[27] draws some interesting conclusions. In low-Re flows, roughness can eliminate laminar separation bubbles (LSBs) appearing on the blades, whereas at high-Re it can promote flow separation. Roughness can also augment convective heat transfer (that is desirable in cooling channels, but undesirable along blade surfaces). Ultimately, its effects are significant and should be carefully examined in order to use it advantageously. In Oliveira et al.,[28] a hybrid flow control technique, involving both a rough cylinder and a moving wall, is numerically investigated. The authors report that it appears to be possible to affect the aerodynamic performance of the cylinder as well as the shedding vortices by this coupled action.

Moving on from random roughness, we proceed to discuss tiny obstacles. Bocanegra Evans et al.[29] numerically and experimentally investigated the ability of an engineered coating to manipulate the large-scale recirculation region in a separated flow. The coating, composed of uniformly distributed cylindrical pillars with diverging tips (Figure 1(a)), successfully reduces the size of the separation bubble and shifts it downstream. The authors accentuate the main benefits of this technique – easy fabrication and installation as well as operability under both dry and wet conditions.

Tiny obstacles can be made larger resulting in wavy, undulating surfaces. A numerical boundary layer analysis is performed over a heated horizontal wavy surface,[30] where it was concluded that surface geometry (undulations) plays a vital role in controlling heat transfer rate. Similarly, in Raayai-Ardakani and McKinley,[31] the effects of periodic sinusoidal riblet surfaces aligned in the flow direction (also known as a "wrinkled" texture) on the evolution of a laminar

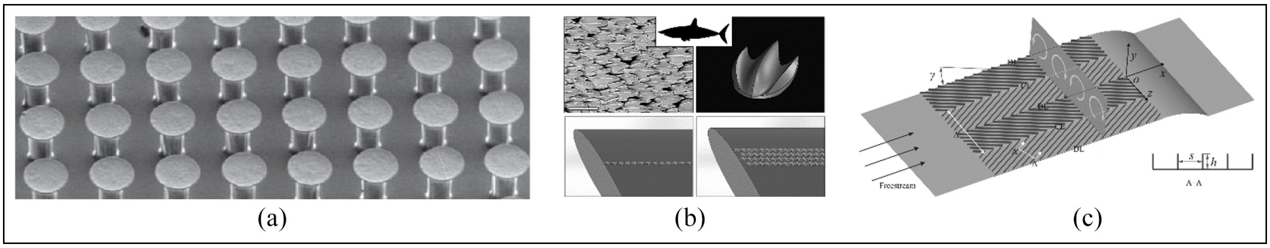

Figure 1. Illustrations of: (a) applied coating,[29] (b) bio-inspired riblets,[34] and (c) regularly-shaped riblets.[39]

boundary layer flow are explored. It is shown that in the laminar boundary layer regime, sinusoidal undulations are able to retard the viscous flow inside the grooves creating a cushion of stagnant fluid that the high-speed fluid above can partially slide over, thus reducing the shear stress inside the grooves and the total integrated viscous drag force on the plate. Another interesting example are bio-inspired corrugated airfoils (derived from dragonfly wings), studied in,[32] that generally show favorable aerodynamic characteristics such as high lift coefficient and delayed stall at low-Re and can be applied for micro UAVs. In Sooraj et al.,[32] two-dimensional (2D) DNS together with experimental particle image velocimetry (PIV) measurements have been performed, and results match.

Many studies report drag reductions on the order of 10% by riblets in comparison to smooth flat surfaces.[33] However, since great varieties in geometries exist (often inspired by animal skin, but also of regular shape), a multitude of studies has been performed. In Martin and Bhushan,[33] to optimize riblet pattern for low drag, three different geometries were modeled, and their drag properties and vortex structures were compared. In Domel et al.,[34] experimental and simulation-based investigations into the aerodynamic effects of novel denticle-inspired designs (Figure 1(b)) placed along the suction side of an airfoil are performed. The authors claim that particular denticles can achieve simultaneous drag reduction and lift generation. At low angles-of-attack (AoAs), efficiency improvements amount to 323%. As previously mentioned, riblet shape can also be more regular. The development of a laminar boundary layer over a rectangular convergent-divergent riblet section with a finite streamwise length is studied experimentally using dye visualization and PIV in a water flume.[35,36] It is observed that riblets create secondary (spanwise) flow that depends on rib geometry. In Okabayashi et al.,[37] drag-reducing performance of a zigzag riblet is investigated. The authors propose an analogy between the drag reduction mechanisms of spatially periodic forcing and the zigzag riblet because both methods induce similar sinusoidal velocity profiles can be assumed. Furthermore, micro-scale riblets are shown to systematically modify viscous skin friction in laminar flows at high-Re. Raayai-Ardakani and McKinley[38] numerically investigated how geometrical parameters of denticles as well as Re affect drag reduction. Guo et al.[39,40] describe systematic computations undertaken to examine the effects of riblet geometry (height, wavelength, and yaw angle illustrated in Figure 1(c)) on the strength of the generated secondary flow as well as the extent of the flow separation zone. The authors report the suppression of the LSB, but not the net reduction in the total pressure losses, although they point out that further research is possible. An example of a riblet application to a lifting surface can be found in Zhang et al.[41] This paper studies the riblet drag reduction effect for an infinite swept wing (where riblets are applied along the second half of the suction side) with low-Re using LES. The results show that the drag reduction ratio is not linear under different sweep angles. The maximum reported drag reduction ratio is 9.5% for a wing with a 45° sweep angle. Another current (and complex) topic, which has possible applications to small devices (labs-on-a-chip) that include two-phase flows, is covered in Ren et al.,[42] where flow and heat transfer between two walls with eccentric transverse microgrooves were numerically studied to investigate their effects on overall drag reduction and heat transfer enhancement. And although heat transfer is not the main topic of the present work, one more paper that considers surface micro turbulator as a potential cooling technique is mentioned.[43] In that study, numerical simulations, by the Reynolds-Averaged Navier-Stokes (RANS) approach and LES, as well as experimental research were undertaken to evaluate the turbulent flow heat transfer and pressure loss in channel with a typical 2D micro rib on one wall with different rib heights. The results show that the pressure loss and heat transfer show different trends with the rib height, which is mainly due to the enhancement of near-wall turbulence caused by the small rib height and the form drag caused by the large rib height. And here we accentuate an important conclusion – riblets must be carefully designed in accordance with the intended application and desired performance.

The dimples on golf balls are a well-known and well-proven mechanism to accelerate transition to turbulence. An experimental study described by Choi et al.[44] provides a good clarification of this flow phenomenon. Dimples cause local flow separation and trigger the shear layer instability along the separating shear layer, resulting in the generation of large turbulence intensity. With this increased turbulence, the flow reattaches to the sphere surface with high momentum near the wall and overcomes a strong adverse pressure gradient formed in the aft side of the sphere. As a result, dimples delay the main separation and reduce drag significantly. Of course, dimples are not applied only to spheres. In Tay et al.,[45] arrays of shallow dimples with depth to diameter ratios of 1.5% and 5% are experimentally studied in a turbulent channel flow (the Re spans from 5000 to 35,000). Pressure measurements show that drag reduction of up to 3% is possible. The mechanism of skin friction drag reduction with dimples is the same as that observed for flat surfaces using active methods such as spanwise wall motions or transverse wall jets since dimples introduce spanwise flow components. Shallow dimples reduce skin friction, but when too deep, they can increase pressure/form drag (similarly to the previously mentioned riblets). It was concluded that, by customizing dimple shapes, further benefits can be achieved. However, further knowledge of flow physics is necessary. Lastly, D'Alessandro et al.[46] applied dimples to blades in order to increase wind turbine performance. Reported numerical (obtained by LES) and experimental results are in good agreement. Here, it seems dimples can reduce pressure drag but at increased viscous drag. Overall, it may be concluded that the usage of dimples may be critical, and is highly dependent on the baseline geometry, operating conditions, and location (for, at, or aft of the LSB).

A device that is the inverse of a dimple is a bump. Again, it might come individually or arranged in arrays. Either way, bumps have been widely employed. In Song et al.,[47] the negative effects of backflow vortices in a centrifugal pump are decreased by specially designed orifice plates (that actually act like bumps on the flow field). Both computational and experimental studies were performed. In Chae et al.,[48] a new adaptive-passive control device is introduced to optimally reduce the drag on a sphere over a wide range of Re. It is a variable height ring that acts like a circumferential bump. At the optimal setting, drag decreases monotonically by up to 74% compared to that of a smooth sphere due to either energizing the flow at low-Re (which leads to flow reattachment) or by transition to turbulence at higher Re. A particularly interesting application of bumps is in transonic flow (applicable to airliners), to decrease the negative effects of shock wave/boundary layer interaction.[49–52] Generally, a bump alters the wave structure and reduces wave drag by improving the boundary layer velocity profile downstream of the shock wave. The geometry of such bumps is usually smooth, comprising two sine functions. In Nejati and Mazaheri,[49] in order to reduce shock wave/boundary layer interaction, three methods (bump, suction, blowing − both individually and together) are numerically investigated (by 2D RANS), and their parameters are optimized. Achieved increases in aerodynamic efficiency range from 4% to 22%. In Nejati and Mazaheri,[50] clean and bumped airfoils and wings are investigated. Two more complex bump geometries, linear and periodic (in the span-wise direction), are considered. The authors conclude that both options seem effective, but the periodic one appears slightly better. One more paper by the same group of authors[51] provides recommendations on optimal positioning of these coupled control devices. In Zhou et al.,[52] a coupled passive shock wave/boundary layer control for drag reduction by a porous strip and a bump was investigated numerically and experimentally at transonic flow ($M = 0.8$). Geometric parameters of control devices were optimized with the ultimate goal of drag reduction. Experiments confirmed slight drag reduction and lift-to-drag ratio increase.

Vortex generators. In most cases, vortex generators (VGs) are geometrically simple. Shaped like rectangular, triangular, or trapezoidal plates arranged in pairs (and arrays), they serve to generate vortices, as the name suggests. The idea is not new and has been employed not only on aircraft wings, fuselage, and rotor blades, but also on other transport vehicles.[53–64] There are even patented solutions.[59] It is interesting that vortex generators are utilized in both sub- and supersonic flows. Some examples (very few in comparison to the existing literature) are listed below.

Shan et al.[53] performed a numerical investigation of subsonic flow separation over a symmetric airfoil at $AoA = 6°$ as well as simulating flow separation control with vortex generators (Figure 2(a)). The passive vortex generators were able to partially eliminate the separation by considerably reattaching the separated shear layer to the surface. The size of the averaged separation zone has been reduced by more than 80%. However, the authors insist that the flow control with active vortex generators is more effective and that the separation zone is not even visible in the time-averaged results. In Zhen et al.,[54] both experimental and numerical works are carried out with an array of VGs attached on the wing of a UAV. The parametric study showed that higher maximum lift coefficient is achieved when the VGs are placed nearer to the separation point. In addition to this, shorter spanwise distance between the VGs also increases the maximum lift coefficient. In the end, the authors conclude that rectangular and curved-edge VGs perform better than triangular VGs.

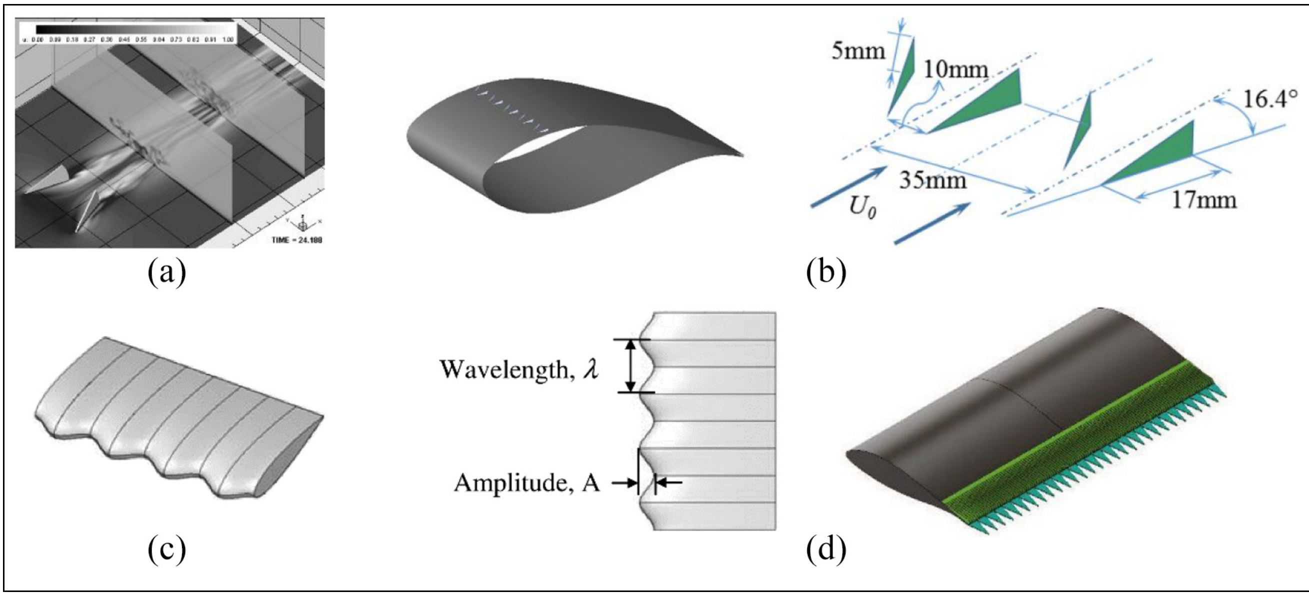

Figure 2. Illustrations of: (a) vortex generators on airfoils,[53] (b) vortex generators on blades,[64] (c) wavy leading edge,[77] and (d) sawtooth trailing edge.[80]

Micro VGs are considered today as attractive passive flow control devices in supersonic flows. A potential application of micro VGs to shock wave/boundary layer interaction control at M = 3 is both experimentally and computationally investigated in Lee et al.[55] LES predictions suggest that there is a strong interaction between the shock wave, turbulent eddies and primary vortices generated by the micro-ramp. It is indicated that significant reduction of boundary layer thickness as well as improved downstream boundary layer structure can be achieved. Similar results (that velocity profile in the boundary layer can be ameliorated) are outlined in Zhang et al.[56] where the effect the dissymmetric micro-ramp was numerically studied at M = 2.5 via RANS simulations. Lee and Loth[57] proposed and numerically investigated (by LES) a novel vortex generator design positioned upstream of a normal shock followed by a subsequent diffuser. The authors emphasize that theirs is one of the first studies that investigates the size effect of the ramped-vane for flow control device in terms of shape factor, flow separation, and flow unsteadiness. They conclude that the largest ramped-vane produced the largest benefits. Finally, when heat transfer is of interest (as it often is in supersonic flows), the experimental results in Khoshvaght-Aliabadi et al.[58] reveal that the use of the VG inserts inside a tube yields higher heat transfer coefficient and pressure drop than a baseline tube, and that these benefits augment with increasing the number of delta winglets.

As previously mentioned, V-shaped VGs installed on a surface, affect the boundary layer, generate a pair of counterrotating vortices, and are even patented by Wheeler.[59] This form (although any other shape and arrangement is also possible) is most often employed on the root sections of large-scale wind turbine blades to mitigate the effects of flow separation. Given the importance of the topic, a truly great number of both experimental[60–63] and numerical[64–71] research studies is available. Different VGs are experimentally explored by Zhang et al.[60] The results show that the maximum lift coefficient increases with VGs installed toward the leading edge of airfoils. However, at small AoAs, the lift decreases when the chordwise position of VGs is smaller than 20% chord. The authors also indicate that it is possible to employ a second, additional row of VGs. Another experimental study is described in Baldacchino et al.[61] where it is demonstrated that the chordwise positioning, array configuration, and vane height are of prime importance. Experimental study in Skrzypiński et al.[62] emphasizes that, although VGs can increase annual energy production, blade surface roughness and wind turbine characteristics should also be considered, and all three influential factors should be adequately matched. The possibility of suppressing dynamic stall on wind turbine blades is experimentally investigated by De Tavernier et al.[63] On the other hand, the effects of VGs on blade aerodynamic performance are computationally studied (by RANS) by Zhao et al.[64] (Figure 2(b)). Numerical investigation of VGs by scale-resolving methods performed by Mereu et al.[65] The authors conclude that scale-resolving approach provides better results than RANS modeling and that it is possible to capture the stalling angle with higher accuracy. Numerical simulation, performed using very-large-eddy/lattice-Boltzmann method,[66] focuses on the effect of vortex generators on the aerodynamic performance and far-field noise. Interestingly, it is concluded that similar noise levels are obtained for both configurations (with and without VGs). The importance of examining the effects of VGs on a rotational blade (not just stationary airfoils and blade segments) is accentuated through a numerical study by Zhu et al.[67] An interesting approach that implies a simplified (or parameterized) representation of VGs is numerically explored in.[68–70] There, the geometry of VGs isn't actually modeled, but only its effects on the flow field (generated circulation and trailing vortex). Thus, computational complexity is significantly reduced since it is not necessary to create refined meshes around the VGs. The authors highlight their approach can considerably accelerate the research efficiency of VG arrangement on wind-turbine blades. Also, possibilities of applying VGs to vertical-axis wind-turbine (VAWT) blades are explored in Jeong and Ha.[72] As can be observed, the material on VGs applied to blades is truly abundant. Today, we can even find clear recommendations on the shape and location of "optimal" VGs, though this of course, directly depends on the baseline geometry, surface quality, and operating conditions. Again, we come to the same conclusion that the geometry of passive flow control devices must be carefully designed with a concrete nominal operating condition in mind. It should also be stated that there are still many problems to be resolved, including accurate detection of possible extra power production (that may be as low as 1%–5%) as well as conducting a controlled experiment (due to the large size of wind turbines). These issues are tackled in the paper by Hwangbo et al.[73] that presents an academia-industry joint study concerning effective methods to estimate and quantify the effect of VG installation on wind power production.

Lastly, we conclude this section with an application of VGs to road vehicles where base drag is a significant contributor to the overall drag (and consequently fuel consumption). In Tian et al.,[74] a numerical study is conducted on different types of flaps (differing in size and built-in angle) added to an Ahmed body with the aim of reducing drag (and ultimately, necessary fuel). The geometry of applied devices differs from the previously described, but their effects on the flow are similar – generating vortices that enhance the mixing of slower and faster fluid streaks.

Ramps and leading/trailing edge modifications. In comparison to the previous two subcategories where modifications, that is, flow control devices are barely visible by naked eye, and should stay within the boundary layer, inclusions of ramps and alterations of leading/trailing edges are larger and more obvious. For that reason, they introduce larger disturbances to the flow (e.g. vortices, instabilities). Ramps (or fences) are vertical plates positioned at a certain spanwise location, usually in the vicinity of the wing tip. They are supposed to separate the flow into two streams (negating the effects of tip vortices on the inner part of the wing) as well as enhance turbulent mixing. On the other hand, leading/trailing edge modifications literally mean altering the straight edge into a different form, usually periodic (sinusoidal or sawtooth) that again induces vortex generation and interaction.

Walker[75] experimentally evaluated the effects of both passive fences and active boundary layer control by blowing on a laminar swept wing. It is observed that passive ramp, located at 70% half-span, can increase maximal lift by approximately 15% and postpone critical AoA by 10°. On the other hand, active BLC, on the same position, increases maximal lift by 13% (which is slightly lower), but increases critical AoA by 18° (which can be considered significant). Similarly, in Hussain and Bons,[76] passive (fence) and active (normal air jet) flow control were investigated on a laminar wing model. It is found that the fence located closer to mid-wing increases lift (up-to 20%), whereas the one located near tip delayed the onset of unstable pitching moment. The jet located at the same spanwise locations increased maximal lift by 10%–23%, and delayed stall. Flow visualization via fluorescent tufts revealed the presence of the fence and tip vortices responsible for the performance benefits.

An experimental investigation of a sinusoidal leading-edge (illustrated in Figure 2(c)) is presented by Hansen et al.[77] It is concluded that its impact depends on the baseline airfoil geometry, and that reducing the tubercle amplitude leads to a higher maximum lift coefficient and a larger stall angle, while larger-amplitude tubercles are more favorable in the post-stall regime. It appears tubercles act in a manner similar to conventional VGs and act favorably at high AoA. A numerical investigation (by LES) of a wing with different wavy leading edges in heaving motion is described in Degregori and Kim.[78] Performance improvement at low and moderate AoAs is detected due to the drag reduction in the leading-edge region and downstream of the laminar-turbulent transition point. This approach can also be used to control the sonic characteristics of the wing. The potential application of leading edge modifications to small-scale wind turbines is covered in Zhao et al.[72] and Zadorozhna et al.,[79] The conclusion of Zadorozhna et al.[79] is that small tubercles outperform the larger ones. A very detailed study on trailing-edge noise that also examines different ways to mitigate it (by sawtooth, sketched in Figure 2(d), and sinusoidal trailing edge serrations) is given by Lee et al.[80] The modifications (serrations) applied to wind turbine blades, rotorcrafts, fans serve to scatter the pressure field fluctuations. Porous coating can also be used for the same purpose.

Semi-active flow control

The first thing that comes to mind when we think of semi-active boundary layer control, usually in the form of stationary (tangential) suction or blowing, is the mechanization of an aircraft wing – slots and flaps, that are active during take-off and landing flight phases. These conventional and well-proven techniques undoubtedly affect the aircraft aerodynamic performance in a favorable manner, by increasing maximal lift coefficient (as well as drag coefficient) and enhancing stall characteristics.

Suction generally serves to remove the decelerating boundary layer, while blowing jets change the velocity profile adjacent to the wall and energize the boundary layer. Since they decrease or increase the mass flow, momentum, and energy of the boundary layer, they are sometimes referred to as active. However, since their action is continuous, here they are named semi-active. They can also be designed in such a way as not to require additional mass flow sources.

Suction. Suction has been tried on various geometries including channels, airfoils, cylinders, spheres, etc. with more or less success. In the following discussion, some recent examples are mentioned.

A study on the effects of flow suction on the laminar boundary layer separation behind a two-dimensional step is described by Dovgal and Sorokin.[81] Experimental measurements by hot-wire probes are performed in a subsonic wind-tunnel. Suction slots are located within the recirculating region. It is demonstrated that this method of flow control allows suppressing the formation of large-scale vortices determined by global stability properties of the separation region while no particular effect to small-scale high-frequency vortices is observed.

An experimental and theoretical study of applying passive and active flow control techniques to a small vertical-axis wind turbine is performed and presented by Morgulis and Seifert.[82] Several flow control approaches: passive – passive porosity and surface roughness – useful only at low-Re, and active – suction and pulsed suction – were tested in an attempt to improve airfoil lift and drag characteristics. With active methods, at Re below 100,000, maximum lift coefficient was increased by 15%–20%, and drag was reduced by at least 50% at most incidence angles. It is also pointed out that pulsed (active) suction slightly outperforms steady suction at lower pulse frequencies. Sun and Huang[83] present a numerical study (by 2D RANS) of flow control by suction on VAWT airfoils in order to increase the wind turbine efficiency. Suction slots come in pairs, located on both pressure and suction sides of the airfoil, and their several chordwise positions (10%, 30%, 50%, and 70%) are inspected. Obtained results indicate that positive suction effects depend on its position, which is related to both the separation point location as well as airfoil shape (thickness/curvature). Apparently, a higher turbine power coefficient can be achieved (though this is hard to quantify since many different turbulence models were employed).

Yang et al.[84] provide an experimental study (by PIV) on a circular cylinder with steady suction in the boundary layer. Again, suction slots are symmetrically positioned on two sides, lower and upper, in the vicinity of the separation point. Different suction flow rates are considered in order to reduce the wake (and accompanying losses). As can be expected, it is observed that shedding is weakened with increased suction rates. In addition, quite vivid vortex evolution is documented.

A final example investigates a coupled control method based on both wall cooling and suction, as demonstrated in Wang et al.[85] Numerical research (by LES) is performed to investigate these influences on the transition process as well as fully developed turbulence of a supersonic flow over a flat plate. Different wall temperatures and suction intensities are considered. It is found that the wall cooling and suction are both capable of changing the mean velocity profile within the boundary layer and improving the stability of the flow field, thus delaying the onset of the spatial transition process. The transition control becomes more effective as the wall temperature decreases, whereas there is an optimal wall suction intensity for the given operating conditions. Moreover, the development of large-scale coherent structures can be effectively suppressed via wall cooling, while wall suction has no particular influence. That is why a small note is made here. Cooling/heating certain wall patches is also an efficient method of flow control, especially in high-speed flows.

Injection. Like suction, fluid injection has often been employed and investigated. It generally adds mass, momentum, and energy to the main flow, but depending on the desired effect – attaching the flow to the wall or enhancing mixing, it may be introduced in tangential or normal directions, respectively.

A numerical study (by RANS) of nearly tangential blowing over wind turbine blade in order to alleviate the effects of flow separation is presented by Mohammadi and Maghrebi[86] (Figure 3(a)). The authors report that, at the best conditions, the resulting torque (and therefore generated power) increases about two times with respect to the baseline blade. As

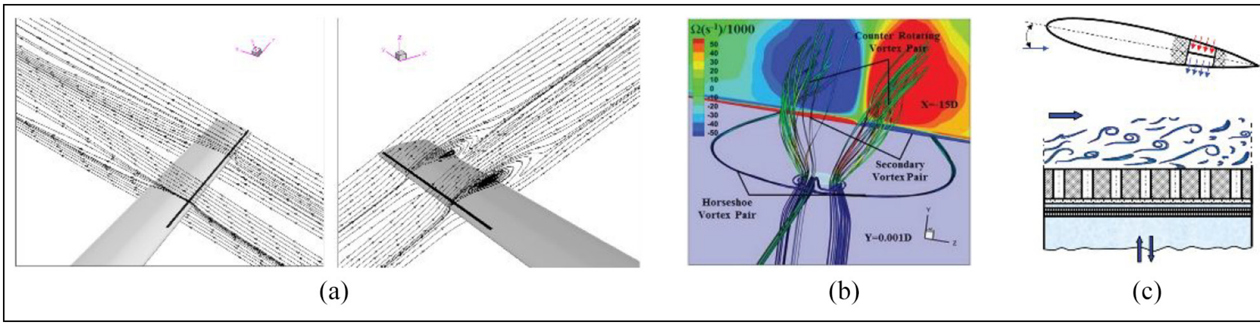

Figure 3. Illustrations of: (a) tangential blowing over wind turbine blade,[86] (b) normal blowing,[92] and (c) micro-blowing applied on airfoils.[97]

expected, the jets are most effective if they are located toward the blade tip (since this part of the blade aerodynamically contributes the most).

The benefits of injection flow control applied to turbomachinery are examined by Hu et al.[87,88] In Hu et al.,[87] the focus is on a high-load cascade equipped with a mixed passive-active flow control devices, namely VG and a slot (through which flow is injected onto the suction side). Both numerical and experimental results proved the performance gains. As the authors state, there are two main benefits of this coupled approach: the slot produces high-speed jets to re-energize the suction side separated flows and reattach them to the suction surface whereas the vortex generator creates a counter-rotating vortex in the cascade passage to further reduce the end-wall cross flows. This work is then continued onto actual compressors[88] where the proposed flow control method is implemented in a single-stage transonic compressor (a part-span slot into the rotor and a full-span slot and a VG into the stator). Results show great improvements of performance and stability of the compressor.

An interesting review of jet flow control techniques which have been used or are worth being used in VAWTs, including the blowing, synthetic and plasma jet actuators, is provided by Zhu et al.[89] Although initial numerical results indicate that VAWT performance can be dramatically increased by jet actuators, it should be noted that optimal jet flow control strategies are yet to be developed.

The dynamics and control (by coupled blowing/suction) of a vortex pair in ground effect are investigated in a planar, incompressible, and laminar setting by Wakim et al.[90] Although it is just a conceptual approach to deal with large-scale vortices shed from airplanes in the vicinity of runways, the proposed methodology can also be applied to the control of coherent structures in wall bounded turbulence.

On the other hand, the experimental study by Walker et al.[91] investigates the possibilities of semi-active flow control on swept wings via discrete jets that steadily eject fluid normal to the suction surface. It appears there are benefits, but further research is necessary. Likewise, in Liu et al.,[92] the effects of nozzles blowing air normal to the oncoming flow are considered (Figure 3(b)). Detailed numerical investigations (by RANS) of the supersonic flow field at different injection pressure ratios, various actuation positions, and different nozzle types are conducted. It is concluded that subsequent shocks can be weakened, and losses diminished. Finally, there are attempts to use the mentioned flow control mechanisms not just as auxiliary, but as main control devices. The possibility of using micro-vortex generator jets to improve the flight stability by regulating the vortex distribution along the surface is studied numerically by detached eddy simulation (DES) by Ma et al.[93] The effects of jets are similar to passive VGs which generate strong vortex pairs attached to the surface.

Permeable/porous surfaces with micro-blowing. In this section, micro/weak flows through permeable surfaces are mentioned. These, relatively novel techniques could probably be also considered passive, since permeable patches, incorporated into the walls, are typically activated in a continuous mode of operation rather than in dynamic response to the instantaneous flow. However, since there is blowing through them and into the main flow, they are classified as semi-active. They primarily affect the main flow by adding a normal component to the velocity, thus changing its gradient, and ultimately skin friction.

An interesting experimental study of a kind of a multi-phase micro-blowing is presented by Sanders et al.[94] where the premise is that the turbulent boundary layer skin friction in liquid flows may be reduced when air bubbles are injected near the surface on which the boundary layer forms. It is demonstrated that, at the lowest test speed and highest air injection rate, buoyancy pushes the air bubbles to the plate surface where they coalesce to form a nearly continuous gas film that

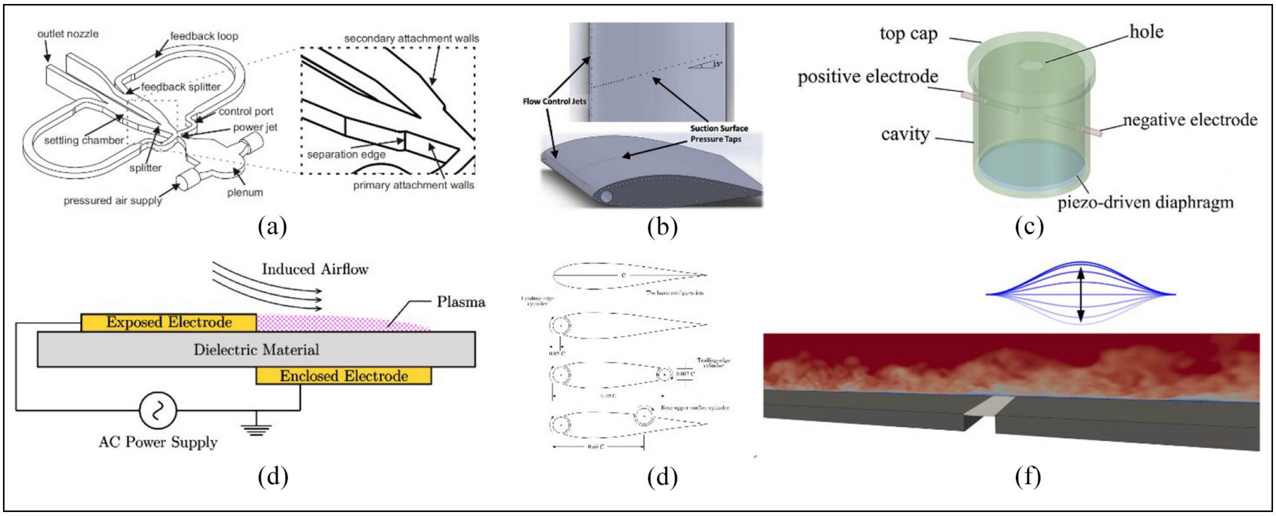

Figure 4. Schematics of: (a) fluidic oscillators,[102] (b) wall-normal pulsed jets,[108] (c) hybrid SJA,[119] (d) DBD actuators,[129] (e) moving walls,[13] and (f) deforming wall patch.[155]

persists to the end of the plate, which nearly eliminates the skin friction drag. At higher speeds, the bubbles remain distinct. However, if they remain near the wall, skin friction reduction may be observed. When bubbles migrate from the surface, these benefits are lost.

The possibilities of turbulent flow control over a wing by micro-blowing are investigated in detail in Refs.,[95–98] both experimentally and computationally. The aim is to achieve improved aerodynamic performance, namely increased lift, reduced drag, and improved lift-to-drag ratio. In order to achieve the desired enhancements, micro-blowing devices (sketched in Figure 3(c)) should be carefully designed (since they may induce an increase in pressure drag) or even combined with suction on the opposite side to increase the lift force. In the end, the authors report that the lift of the wing can be increased by at least 10%.[98]

Recently, porous materials are also being employed in aerodynamics for supersonic flow control.[99–101] By blowing through, heating or cooling the porous insert material it is possible to "virtually" change the body shape and influence its wave drag. The problem of cooling a supersonic aircraft by "weak" blowing through porous surface is numerically addressed by Garaev and Mukhametzyanov.[99] Results of experimental and numerical investigations of supersonic flows around cylinders with porous frontal inserts are reported by Mironov et al.[100] Possibilities of drag control are studied for both external and internal heating. Roy et al.[101] have carried out a computational study (by RANS) to assess the effectiveness of a porous medium as a control device suitable for reducing the drag caused by a shock wave/boundary layer interaction at transonic speeds. The authors point out that the reduction in overall drag is achieved via recirculation inside the porous medium, which primarily weakens the shock structure and hence reduces the wave drag. In future, this method could be applied to aircraft wings.

Active flow control

Apart from requiring additional energy/power to operate, the main characteristic of active flow control devices is their transient (usually oscillatory) operation. This can be achieved through pulsed and synthetic jets, plasma actuators, moving/oscillating walls, morphing surfaces, etc.

Pulsed jets. While pulsed jet actuators (PJA) somewhat resemble injection since they introduce mass and momentum into the BL, due to their transient operation (that implies periods of action followed by inaction forming a duty cycle), their overall effects on fluid flow can be quite different. Their oscillatory operation is usually achieved mechanically, or, in recent years, by fluidic oscillators (actuators constituted of a flow vane with no moving parts, using steady suction and oscillatory blowing, have been thoroughly investigated in previous years). More analytical and explanatory material on fluidic oscillators is available in Löffler et al.[102] (Figure 4(a)). Various types of PJAs are mentioned here, and their applications are truly extensive. While the actual realization of pulsed jets is not important in numerical studies (where only their effects are simulated), it is extremely important in experimental investigations. For that reason, substantial parts of papers based on experimental measurements are devoted to the description of employed types of pulsed jets. There are also papers that focus solely on the construction and operation of PJAs.

Aul'chenko et al.[103] injected periodic pulses of energy into the supersonic region of a transonic airfoil. They found that a significant reduction in wave drag can be achieved.

In a DNS study by Chung and Talha[104] the effects of amplitude and phase of wall blowing and suction control input were investigated. The conclusions are as follows: the amplitude plays an important role in the skin friction drag reduction, drag reduction is proportional to the wall blowing/suction strength, and it is strongly correlated to the fluctuations of the normal components of velocity and vorticity.

A useful experimental work on fluidic oscillators embedded in an airfoil intended for the operating part of wind turbine blades is provided by Cerretelli et al.[105] The authors report that the effects of the unsteady actuation on the lift and drag strongly depend on the Reynolds number, the level of actuation, and the state of the airfoil surface. However, strong improvements have been obtained throughout the whole testing envelope, with relative lift increase spanning from 10% to 60% and substantial stall margin extension. In addition, employing fluidic oscillators strongly reduces the suction surface boundary layer thickness and the unsteadiness of the mean flow velocity.

Unsteady turbulent flows inside fluidic oscillators (suction and oscillatory blowing actuators) are simulated (by LES) and characterized to provide better physical understanding of the complex actuator flows and their operation by Kim et al.[106] The authors declare that good agreement between numerical and the corresponding experimental results is achieved.

The paper by Dolgopyat and Seifert[107] experimentally examines somewhat unconventional methods of manipulating pressures, forces, and moments acting on an airfoil without movable control surfaces. Again, this is an example of how flow control devices can be employed for flight stability. By the generation of unsteady vortices emanating from suction and oscillatory blowing actuators, attached or incipiently separated flows are forced to separate or become more attached. In the future, the proposed methods can be used for increasing lift or drag, instead of relying on flaps and spoilers.

The performance of active flow control on a laminar airfoil at a post-stall AoA is evaluated experimentally using discrete, wall-normal pulsed jets (Figure 4(b)) by Hipp et al.[108] It is observed that, for a given blowing ratio, as the duty cycle is reduced, the lift coefficient increases. On the other hand, at extended jet-off times, a complete separation may reoccur.

An application of active flow control to the delay of dynamic stall appearing on a pitching airfoil is addressed by Visbal and Benton[109] by high-fidelity wall-resolved LES and stability analysis. In the uncontrolled case, flow separation is governed by the LSB. By matching very high-frequency actuation with the LSB instabilities it is possible to achieve effective control.

The possibilities of reducing drag of a spatially developing supersonic turbulent boundary layer by pulsed wall blowing are numerically investigated (by DNS) by Liu et al.[110] Different blowing slot spacings and widths are considered, as well as blowing amplitudes. The authors report that drag reduction spanning 7%–15% was achieved.

Work presented in Raibaudo and Kerhervé[111] focuses on different robust control strategies suitable for controlling a 2D turbulent boundary layer with substantial separation. In this experimental study, an array of fluidic jets located upstream of the separation location is used as actuation to reattach the flow.

Lastly, pulsed injection is not only used for flow control, but also in aeroengines (to increase the combustion efficiency by improved mixing or for thrust vectoring). The transverse injection of a pulsed jet into a supersonic flow for thrust vectoring in solid rocket motors is investigated numerically.[112]

Synthetic jets. Synthetic jet actuators (SJA), also called zero-mass (or zero-net mass flux) jets, incorporate a vibrating surface that produces the effects of interchangeable suction and blowing into the main flow. Their operation is also oscillatory, but their duty cycle comprises two opposite phases: inflow and outflow, which differentiates them from PJAs. Another characteristic distinction of SJAs is that they do not require additional mass sources, since they ingest small portions of fluid from the main flow, that are then accelerated and thrown back out. The duty cycle of SJAs is usually described by velocity ratio (the ratio of peak exit jet velocity to the freestream velocity) and actuation waveform (shape). SJAs have also been widely investigated, and even some different designs have been proposed.

A new, improved design derived from a synthetic jet is described by McCormick.[113] It has an acoustically excited neck like traditional synthetic jets, but the neck is curved in the downstream tangential direction instead of remaining in the wall-normal direction. That way, the boundary layer flowing over the neck or slot is energized via suction removal of the approaching low momentum fluid on the in-stroke and tangential blowing of high momentum on the out-stroke, thereby making it in the time average more resistant to separation. The author claims that the proposed method leads to the complete suppression of BL separation.

For the traditional SJA design, numerical study of synthetic jets applied to a fixed or free (allowed to oscillate in the cross-flow direction) cylinder are described by Wang et al.[114] Simulation results indicate that the

Kármán vortex street formed behind the cylinder can be effectively suppressed when the SJ pair operates with sufficiently high momentum coefficient.

Various measures of aerodynamic performance of airfoils and wings equipped with SJAs are estimated computationally by wall-modeled (WM) LES by Lehmkuhl et al.[115] Numerical predictions indicate that, at high AoAs, the active control successfully eliminates the laminar and turbulent recirculation zones located downstream of the actuator. This change leads to aerodynamic performance improvements.

Ja'fari et al.[116] investigate the effectiveness of a spanwise array of SJAs for the control of boundary layer separation over a circular "hump" model. The impacts of geometrical and operational parameters (actuator position, velocity ratio, and actuation waveform) on the flow separation control are investigated experimentally. The results show that the best performance of the SJA array from the viewpoint of separation control occurs at the velocity ratio of 1.85 with a reduction of the length of recirculation region of around 42%–44% by using sine- and square-wave excitation.

An interesting new derivative of the SJA is the plasma synthetic jet actuator (PSJA) also named sparkjet actuator (that can also be classified under the category of plasma actuators described in the next section). This special type of zero-net mass flux actuators is driven thermodynamically by pulsed arc/spark discharge. A very thorough and clear review on PSJAs is made by Zong et al.[117] Their capabilities to produce high-velocity jets (faster than 300 m/s) at high frequencies (greater than 5 kHz) make them exceptionally suitable for aerospace engineering applications involving high speeds (and high Re) such as flow separation control in airfoils and ramps, jet noise control, shock wave/boundary layer interaction control, etc. This work is very contemporary and on-going. Zhang et al.[118] experimentally investigated the interaction between a ramp-induced shock wave and a PSJA array. The obtained results showed that the jets can penetrate into the supersonic flow field with a considerable depth (approximately 1 cm). Both the shocks and the controlling gas bulbs generated by PSJA arrays can affect the separating shock wave.

Another new design, illustrated in Figure 4(c), of a millimeter-scale hybrid SJA (of increased power and external gas volume) is proposed by Li and Zhang.[119]

Finally, like PJAs, SJAs can also be used for controlling the complete aircraft and not just local flow zones. The article by Wang et al.[120] shows a series of studies that involved manipulating a vehicle without moving control surfaces.

Plasma actuators. Plasma actuators have multiple advantages for flow control: absence of moving parts, rapid response time, low mass, small size, easy installation (they do not greatly disturb the surface quality). Among the most popular are dielectric barrier discharge (DBD) actuators, which incorporate a pair of electrodes separated by a dielectric material. When an oscillatory voltage difference is created between the electrodes, the resulting electric field locally ionizes the air, and a layer of cold plasma forms along the surface. The ions are accelerated by the electric field and can transfer momentum to the neutral species in the flow, thus energizing the BL.[17] Despite many advantages, DBD actuators still seem far from practical applications, due to their low efficiency for high freestream velocities and significant electrical power that often exceeds the savings in mechanical power. However, they represent a promising research field, as detailed below.

An experimental study into the induced airflow around a plasma actuator (designed for BLC) that might lead to future skin-friction drag reduction is presented by Jukes et al.[121] Both velocity and temperature distributions around the electrode in initially static air are considered. Observed velocities seem sufficient for flow control at low speeds, while temperature rise seems insufficient to incur buoyancy effects. Similarly, details of the flow field induced by a plasma actuator in quiescent air are addressed by Yang et al.[122] using both Schlieren visualization technique and PIV measurement. Since the pressure wave and generated vortices are observed, the study provides enhanced insight into the operation of plasma actuators.

The paper by Cho and Shyy[123] focuses on feedback flow control investigations, particularly in unsteady, low-Re flows. One of the examples of effective BLC is by a DBD actuator used to stabilize the lift at high AoAs under fluctuating freestream velocities, representing outer disturbances such as atmospheric turbulence, gusts, etc. System nonlinearities and control challenges are also discussed. Another study of possible flow separation and its suppression by DBD actuators in uncertain operating conditions is given.[124] The authors report that the mitigation of fluctuating forces is achieved by modifying the wall pressure near the actuator as well as by promoting vortex evolution. Finally, the same pair of authors also studied means to control both dynamic stall and the evolution of separation bubbles in a disturbed.[125]

An interesting approach is proposed by Greenblatt et al.,[126] in which DBD actuators are used to produce periodic loads and induce vibrations of a one-degree-of-freedom pivoted cylindrical body that is mounted vertically within a blow-down wind tunnel. Large amplitude oscillations are achieved by alternating dynamic separation and attachment of the boundary layer. This concept is intended for energy generation. For now, energy generation is low, but the idea seems very promising.

Application of DBD actuators to suppressing BL instabilities on a flat plate at various freestream velocities is covered by Simon et al.[127] The focus of the paper is on adequate control algorithms.

A computational study, by DNS, of a controlled turbulent channel flow by two plasma actuators (located on both upper and lower wall) is presented by Li et al.[128] Two changes in the behavior of skin-friction coefficient are observed. Over the forcing region, there is a large increase in the skin-friction coefficient due to the change in the velocity gradient. On the other hand, the skin-friction coefficient rapidly decreases when moving away from the actuators. Overall, the authors report mean skin-friction drag reduction of approximately 13%.

Numerical studies using LES[129,130] investigate flow separation control over an airfoil by two DBD actuators located near the leading and trailing edges (Figure 4(d)). According to the results, actuation manipulates the shear-layer instabilities and modify the wake patterns remarkably. Although the front DBD actuator contributes more to the increases in lift and lift-to-drag ratio, the proposed dual excitation seems most promising for full-stall control in a wide range of excitation frequencies, as reported by Ebrahimi et al.[130]

Zhang et al.[131] study flow control on a circular cylinder by two symmetric DBD actuators located at the top and bottom surface. Each actuator induces a pair of counter-rotating vortices traveling upstream and downstream. The ones traveling upstream and interacting with the oncoming flow bring in momentum from the freestream to the BL, thus energizing it and suppressing its separation. On the other hand, the downstream traveling vortices act as wall jets. Apparently, the rotating vortical structures around the circular cylinder created by the plasma actuators lead to a reduction in the drag coefficient of up to 25%, providing an effect similar to that observed in moving-surface BLC.

Plasma actuators have also been exercised in supersonic boundary layers. In contrast to some techniques reviewed here, plasma actuators can produce rapid changes in temperature, which lead to thermal expansions and changes in flow structures. A nanosecond-pulsed plasma actuator was used to mediate the interaction between a shock and Mach 2.8 boundary layer,[132] and it was shown that the effect on separation depends on the electrode geometry. In one configuration, the heated gas generated by the actuator enlarges the separation bubble and intensifies backflow, while in another configuration the enhanced momentum transfer due to vorticity generation suppressed separation.

The effects of flow control by plasma actuation on a compressor airfoil are numerically studied by LES.[133] By generating density and pressure disturbances, plasma actuators induce small vortical structures that travel along the airfoil and act as jets. In laminar BLs, they suppress mixing and reduce the total pressure loss. In turbulent BLs, larger vortical structures are created that can also restrain turbulent flow mixing.

An additional application of active flow control for flame stabilization is explored by Chen and Liao[134] where an experimental investigation of flow interactions downstream of a bluff body equipped with an annular plasma actuator is presented.

Additional research[135–137] includes somewhat unconventional examples of plasma actuator applications, in which plasma is induced by different methods than previously covered. Possibilities of controlling the subsonic vortex flow appearing around a cone at non-zero AoA is experimentally explored.[135] It is demonstrated that asymmetric flow can be transformed to symmetric, and vice versa, which enables the control of the side force. The effects of laser-induced plasma on the low-speed separating boundary layer over a laminar airfoil have also been investigated experimentally.[136] In this application, the laser discharge is focused just upstream of the leading edge of the airfoil which creates a high-temperature, low-density bubble that expands and creates a shock wave and a coherent zone of heated and highly turbulent air. As the authors report, the hot, low-density fluid induced significant exchange of momentum between the freestream and the incipient separation zone, leading to the reattachment of the flow for a period lasting seven orders of magnitude longer than the plasma lifetime. The described technique shows promise for future flow control. Finally, some fundamental questions on the physics of thermal perturbations initiated by pulsed plasmas and lasers are raised by Little.[137] These devices have demonstrated possibilities of application in BLC of high-speed turbulent shear flows and are reviewed and assessed in the paper.

Moving and oscillating walls. As mentioned in the beginning of the paper, the idea of moving walls in the streamwise direction is quite appealing since fluid particles in the wall vicinity are not retarded. Hence, there is neither significant velocity gradient nor the resulting skin friction. Work on this topic was performed continuously throughout last two decades of the 20th century.[13,138–143] It was mostly based on experimental research but also included numerical studies. The surface movement was achieved by rotating cylinders (Figure 4(e)) that were applied to airfoils, wings, bluff bodies, diffusers, etc. Overall, improvement of aerodynamic characteristics was confirmed,[138] although the method was seldom deployed in practice, probably due to the complexity and weight of the moving mechanism. On airfoils, rotating cylinders were located at the leading and trailing edges. It was observed that the leading-edge rotating cylinder extends the lift curve without substantially affecting its slope, thus effectively increasing the maximum lift and delaying stall (which quite resembles the effect of slats). On the other hand, the action of the rotating trailing-edge cylinder resembles a flap. The authors reported the maximal lift coefficient of approximately 2.5.[139,140] In subsequent studies,[141,143] even greater values of maximum lift coefficient were realized (around 2.7) accompanied by the delay in stall of nearly 50°. The authors experimented on different cylinder configurations (changing their number, position, and rotation rate). Bluff bodies were also considered and drag reduction was confirmed.[142] All things considered, moving surfaces still present an attractive flow control technique and examples of newer studies also exist.[144,145] Experimental results of the flow around a circular cylinder with moving surface BLC are presented by Korkischko and Meneghini.[144] Two small rotating cylinders strategically located inject momentum in the BL of the cylinder, delaying its separation, narrowing the wake, and reducing the fluctuating transverse velocity, resulting in a recirculation-free region that prevents the vortex formation. The authors report that the use of this flow-control method results in a mean-drag reduction of almost 60% while the wake is highly organized and visibly narrower. Numerical investigation, by RANS, of flow control with moving surface over an airfoil is conducted by Li.[145] Again, two rotating cylinders added to the airfoil greatly delayed flow separation and lead to an improvement of various measures of aerodynamic performance. An experimental study of a flat plate with wall movement in the streamwise direction documented that the velocity profiles near the wall were altered.[146] The authors demonstrated that velocity profile further away from the wall matches the one corresponding to a turbulent BL on a stationary wall and that wall movement leads to reduced shear.

One unconventional moving wall should also be mentioned.[147] In this experimental investigation, the moving wall is designed as a rotating disk which is embedded into the surface of a flat plate with its principal axis aligned with the wall normal. One half of the disk is covered, whereas the other part is exposed to the flow. The authors report that the interaction between the rotating disk and the flow can lead to the drag reduction of nearly 17%. We come upon an interesting conclusion here, that spanwise movement may also be beneficial and lead to improved mixing as well as reduced drag. That is why a significant number of studies also investigates the effects of oscillating walls in both the span- and streamwise directions.

Another experimental study[148] indicates that turbulence intensities are reduced by the spanwise-wall oscillation. The authors report that, in optimal configurations, skin-friction reductions of as much as 45% are observed within five boundary-layer thicknesses downstream of the start of the wall oscillation. Drag reduction seems to be connected to the generated spanwise vorticity (and reduced streamwise vorticity), which reduces the mean velocity gradient. A turbulent boundary layer modified by spanwise wall oscillations is experimentally studied in a water channel.[149] The mean streamwise friction at the wall and all the most relevant turbulence statistics are attenuated by the oscillation, thus confirming that an oscillating wall is an effective means of reducing drag. A comprehensive review on the topic of oscillating walls is provided by Quadrio.[150] There, different drag-reduction techniques capable of reducing the level of turbulent friction through wall-parallel movement of the wall are described, whereas special emphasis is placed on spanwise movement. DNS of fully developed turbulent channel flow with the aim of establishing the effectiveness of spanwise wall oscillation in compressible flows is performed by Yao and Hussain.[151] Furthermore, the dependence of drag reduction on Mach number is inspected. While the transonic case resembles the incompressible one, at supersonic conditions, different trends in drag reduction are observed as well as a surprising relaminarization of the flow. LES of the flow over an airfoil equipped with spanwise oscillating walls is performed[152] where nearly 65% of both the upper and lower sides of the airfoil are fully actuated. The authors confirmed drag (and wall shear) reduction as well as lift increase.

Morphing surfaces. Localized wall motions (deformations) may also be used for BLC since they introduce perturbations to the BL, and consequently delay its separation and reduce drag. This is usually realized by incorporating MEMSs or piezoelectric devices (that deform when voltage is applied) into the surface. Again, various studies have been performed.

Surface-mounted piezoelectric actuators are used to excite the turbulent boundary layer upstream of the separation point, where the actuators interact directly with the boundary layer.[153] The authors demonstrate that these actuators are both effective in flow control as well as energy efficient. In effect, they resemble oscillating walls.

Possibilities of reducing skin friction coefficient in a turbulent channel flow by active wall motions are considered.[154] Results show that overall 13%–17% drag reductions are obtained, and that turbulence intensities and near-wall streamwise vortices are significantly weakened. In shape, wall motions resemble riblets, but not in effect.

For a turbulent BL, the effects of a wall patch deforming in spanwise direction are studied computationally, by DNS.[155] Different actuator lengths, as well as actuation amplitudes and frequencies were considered (Figure 4(f)). The authors conclude that this localized actuation affects not only the flow in the immediate vicinity, but also at a significant distance downstream.

Numerous wall-resolved LESs are performed to study the impact of spanwise traveling transversal surface waves in zero-pressure gradient turbulent boundary layer flow.[156] The proposed technique somewhat resembles oscillating walls. In the optimal setting (defined by the amplitude and frequency of the sinusoidal wall motion) a significant decrease of friction drag of up to 26% is achieved. Furthermore, a substantial attenuation of the near-wall turbulence intensity and especially a weakening of the near-wall velocity streaks are observed.

Moving thin films. In this, very novel flow control method a very thin film of ferrofluid is kept strongly attached to the surface by a magnetic field from below while it is being pumped and pushed tangentially along the wall. Possible application of ferrofluid moving thin films in flow control is discussed.[157] By utilizing a simplified physical model in combination with available experimental data, the expected lift increase is assessed. Although the technique shows promise, further research is required.

Methodology

As can be deduced from the referenced literature, research of flow control is usually performed by numerical or experimental means. Therefore, this section serves to summarize the employed methodologies but also to provide some recommendations for particular applications as well as to indicate some accomplishments that may be expected in the future.

Numerical modeling

Numerical modeling implies solving the equations that govern the fluid flow. While we somehow struggle with laminar flows, transitional and turbulent ones are still a challenge that may be approached in several ways. However, in modeling flow control, we come across additional complexities – unsteadiness (since generated vortices are transient) and the small scales of flow control devices and of physical structures in the flow. Therefore, if we wish to accurately resolve such flows, we need extremely fine spatial and temporal discretizations and high-performance computing platforms. Primarily due to the limitations in available computational resources, solving RANS equations on both 2D and 3D geometries is still the most employed approach, particularly in industrial applications. When transitional flows are considered, RANS equations are usually closed by multi-equation turbulence models that in some way consider transition. However, these approaches imply significant amount of modeling, particularly in the wall vicinity, which has led to a number of studies based on both wall-modeled and wall-resolved LES and DNS. Future trends will certainly move toward these more complex flow simulations (particularly when active flow control methods are in question), but that will also require additional knowledge of flow physics and improved insight into the accompanying flow phenomena. It may be observed that it is not always necessary to model the actual flow control device (especially when it is thin or embedded into the wall), but only to incorporate its effects (e.g. added mass, momentum, energy, generated vorticity, pressure, or temperature change, etc.) into the flow simulation. While this approach simplifies the computation, it requires understanding of the device's characteristics that is not always available for new or insufficiently experimentally tested actuators.

Overall, the main challenges of reduced-order numerical studies of flow control are the following: accurate modeling of the small-scales in near-wall turbulence and how they interact with various flow control methods. Though it is not probable that numerical modeling will be the sole method used in the design of BLC devices in the near future numerical simulations are extremely useful, as they provide abundant data that enable both quantitative and qualitative analyses. It just means they should be constantly improved and validated for each of the many types of flow control methods.

Experimental testing

Although it is very hard to come close to the wall without disturbing the flow, in the experimental investigations of flow control listed above, diverse techniques for measuring the flow have been employed. If global aerodynamic characteristics are of interest (e.g. drag reduction or lift increase are the main goals, without going into the small-scale flow features) force measurements are performed. On the other hand, measured pressure coefficient distributions can provide insight into certain recirculating zones appearing along the surface, while skin-friction coefficient values may point to the separated regions. In plasma induced actuation or high-speed flows involving shocks, the temperature field is also determined. For measuring speed at a particular point, usually hot-wire probes or laser Doppler anemometry (LDA) is used, while PIV is employed for simultaneous velocity measurement over a fluid region. To obtain qualitative insight into high-speed flows around bodies, the Schlieren visualization technique is used. Pressure sensitive paint (oil film interferometry) or fluorescent tufts are employed to visualize the occurrences along the walls/surfaces. If noise is of primary interest, microphones may be used.

The main challenges here are performing accurate flow measurements and disturbing the flow as little as possible.

Some recommendations

Although each case has unique challenges, certain recommendations can be made. Some of them are not new and have been formulated in Gad-el-Hak.[12] In laminar flows, suction/injection as well as heating/cooling of wall inserts (in high-speed flows) proved effective. Negative effects of shock wave/boundary layer interaction can be mitigated by porous patches, bumps, suction/blowing. As laminar-to-turbulent transition is highly dependent on surface quality, slight surface modifications and coatings may prove useful to relaminarize the flow. Otherwise, riblets and vortex generators can accelerate the transition to turbulence (and a sturdier BL). Likewise, riblets, vortex generators, injection/suction may be used in turbulent flows to energize the BL and postpone flow separation. Active flow control methods such as pulsed jets, synthetic jets, plasma actuators, oscillating walls should be employed to act on particular disturbance/instability of the BL. For that, they require adequately defined duty cycles and control strategies as well as reliable sensors. On the other hand, active BLC devices often reduce the drag penalties that are (inevitably) present in passive BLC devices.

When choosing an appropriate BLC device, several factors play an important role: system cost and complexity, added weight, increased drag, energy input, and reliability and applicability to a range of operating conditions. There is also another important thing to consider. These devices act on the flow; they enforce certain changes of the flow field variables but that usually comes at a cost. By trying to improve one aspect, often, another may be compromised. In the end, as previously mentioned, all three mentioned categories of flow control devices have their advantages and disadvantages and can be applied for specific purposes with more or less success.

Synthesis and future perspectives

Although much work has already been performed on flow control, undoubtedly, this will also continue in the future. Existing actuators will be improved/tailored to specific geometries and operating conditions. With the advent of widely available high-performance computing and complex flow modeling as well as additive manufacturing, it will not be necessary to shape passive devices as regular bodies. Rather, much more design freedom will be available. New techniques, involving for example, new materials, highly controlled and refined wall movements (morphing walls) or most recent microelectromechanical devices, will certainly be used in practical applications. Improved control strategies and faster analyses of flow fields (drowning in big data) will be developed with the use of artificial intelligence (AI). Also, AI will be combined with reduced-order modeling more and more, thus significantly accelerating the computation of flow control cases, as we develop data-informed reduced-order models. At the same time, advanced turbulence modeling and resolution will be increasingly employed, even in industrial applications. Experimental techniques will also continue to advance, particularly the optical (and other non-invasive) ones, thus providing abundant quantities of data that may be used to verify both the performance of flow control devices as well as the numerical models used for their computation. Furthermore, the range of possible usages of developed methods will certainly expand (e.g. to complete flight control or energy harvesting). Overall, we may expect an increased application of flow control devices in almost every area of energy and aerospace engineering.

In particular, due to its lower cost, passive actuators will increasingly be used in everyday engineering (including bioengineering) subsonic applications. Surface modifications (including coatings, riblets, etc.) as well as vortex generators will be used more and more on rotating machinery as well as to enhance mixing and heat transfer. We may also expect an escalation of applying semi-active flow control devices on novel aircraft, including unmanned and urban air-vehicles, in order to achieve maximized efficiency in all operating regimes, including takeoff, hovering, parcel deployment, and landing, as well as noise reduction. Active flow control, as the most complex and expensive among the flow control approaches, will be regularly employed in cases where careful, localized and rapid response is of extreme importance. This is expected to be the case in higher speed flows, where a pulsed source can greatly affect the flow and change it in a beneficial manner, for example to delay transition or boundary-layer/shock interactions, or to rapidly stabilize the flow and control aerodynamic loads.

Conclusions

It is always difficult to conclude a review paper. However, an attempt to summarize the fundamental findings, and reiterate core principles regarding the design, operation, and efficacy of flow control devices is made here. This narrative provides brief descriptions of key methods that are employed in boundary layer control. While techniques are nominally separated into three categories – passive, semi-active, and active –

comparison of their physical mechanisms and respective advantages makes various similarities apparent. Not all existing flow control devices are fully covered, especially as the imperative for energy efficiency drives continual growth in this research area and further development of novel and coupled methodologies.

Adequate flow control may yield many benefits, such as flow stabilization, flow reattachment, separation delay, drag reduction, lift increase, aerodynamic performance improvement, energy efficiency increase, shock delay or weakening, and noise reduction. This has led to the design and testing of a wide variety of devices, each suitable for a specific application. Apart from being economical, passive methods are particularly effective in low-speed (laminar or transitional) flows. They may also be used to alter the shock structure in transonic flows (and beyond), but usually in combination with active methods. Semi-active and active devices typically afford greater control authority and act in a more directed way on particular flow structures. They may be efficiently used in a greater number of operating regimes, but require additional sources, parts, expenses as well as control strategies. From the list of referenced research studies, it is obvious that each case is specific (e.g. a flat plate differs from a cylinder or an airfoil, and subsonic and supersonic behaviors differ, etc.) and requires a customized approach.

One thing can be stated with certainty. In order to design and apply the most suitable BLC device, a thorough knowledge of flow physics is required, which can only be acquired through in-depth and strong interconnection of numerical and experimental studies. To progress from an inspiring idea of how to modify the flow field to a practical and cost-effective application, it is necessary to perform a multitude of research studies that cover every aspect of the design and operation of a BLC device. There are numerous examples of flow control methods that have been investigated for decades but have not yet been deployed in real applications due to their insufficient performance or high cost. The exciting and diverse research area of flow control offers significant promise yet many challenges for the future.

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ORCID iDs

Jelena Svorcan https://orcid.org/0000-0002-6722-2711
Kevin Patrick Griffin https://orcid.org/0000-0002-0866-6224

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