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A Comprehensive Study of Modern Flow Control Methods and Their Applications

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Abstract

Flow control is a rapidly developing technological area which is relevant to several engineering sectors with goals such as the reduction of drag and the reduction in flow-induced vibrations. It involves aero-acoustics, fluid instabilities and closed-loop control of unstable fluid systems. Development of control strategies involves simulation followed by laboratory testing of control models. To design a fluid flow system, a thorough understanding of the available flow control technologies is crucial. In this paper we will go through the developments in the flow control technology over last few decades and then study some modern techniques which will give us a whole new viewpoint on the science of flow control.

1. Introduction

Flow Control techniques have been used for many years to control the fluid flow, and some employ diverse concepts to serve this purpose in past decades. Flow control comprises of passive or active devices to effect a beneficial change in wall-bounded or free-shear flows. Whether the task is to delay or advance transition, to suppress or enhance turbulence or to prevent/provoke separation, useful end results include drag reduction, lift enhancement, mixing augmentation and flow-induced noise suppression. This area of Fluid Mechanics has always interested the researchers because of its wide range of potential benefits for the military as well as civilian sectors. Prompted by the fresh advances in chaos control, micro fabrication and neural networks, reactive control of turbulent flows is now in the realm of the possibility for future practical devices.

The objective of flow control problems may at times be interconnected, leading to potential conflicts as the attainment of one particular goal may undesirably affect another goal. For example, consider an aircraft wing for which the performance is measured by the improvement in lift-to-drag ratio. Promoting transition will lead to a turbulent boundary layer that is more resistant to separation and increased liftcan be obtained at higher angle of incidence. The viscous or skin-friction drag for a laminar boundary layer can be an order of magnitude smaller than for a turbulent boundary layer. However, a laminar boundary layer is more prone to separation resulting in a loss in lift and an increase in form drag. The design trade-offs of a particular method of control must carefully be evaluated and compromises are often necessary to reach a particular design goal.

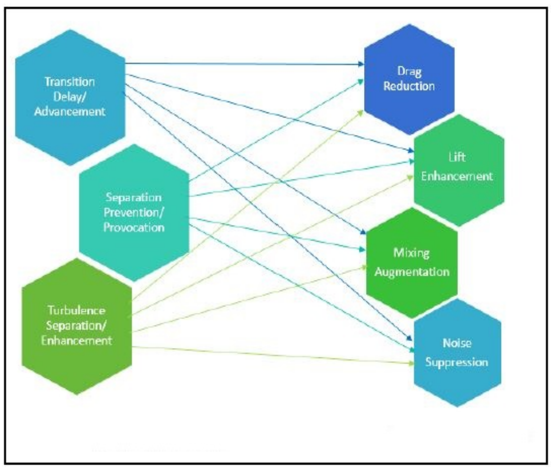

Fig: 1. Engineering Objectives and Corresponding Flow Changes

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Flow control is rapidly developing as a key technological area relevant to several engineering sectors with goals such as the reduction of drag and the reduction in flow-induced vibrations. It involves aero-acoustics, fluid instabilities and closed-loop control of unstable fluid systems. Development of control strategies involves simulation followed by laboratory testing of control models.

2. Historical Developments in Flow Control Technology

Flow control methods are being used since very early times. The development of this technology to what it is today spans over five major eras. The empirical era (prior to 1900); the scientific era (1900-1940); the World War II era (1940-1970); the energy crisis era (1970-1990) and the 1990s and beyond. The art of flow control probably has its roots in prehistoric times when streamlined spears, sickle-shaped boomerangs, and fin-stabilized arrows evolved empirically by archaic Homo sapiens. Relatively soon after the dawn of civilization and the establishment of an agriculture way of life 8,000 years ago, complex systems of irrigation were built along inhabited river valleys to control the water flow, thus freeing man from the vagaries of the weather. For centuries, farmers knew the value of windbreaks to keep top soil in place and to protect fragile crops.

The science of flow control originated with Prandtl (1904), who, in a mere 8-page manuscript, introduced the boundary layer theory, explained the physics of the separation phenomena and described several experiments in which a boundary layer was controlled. Thus, the birth of the scientific method to control a flow field. Slowly but surely, the choice of flow control devices is no longer a trial and error feat, but physical reasoning and even first principles are more often than not used for rational design of such artefacts.

Stimulated by the Second World War and the subsequent cold war, that trend accelerated significantly during the third era (1940-1970). Military needs of the superpowers dictated the development of fast, highly maneuverable, efficient aircraft, missiles, ships, submarines and torpedoes, and flow control played a major role in achieving these goals. Natural laminar flow, laminar flow control and polymer drag-reduction are notable achievements during this era. Partial summaries of flow control research during this period are contained within the books edited by Lachmann (1961) and Wells (1969).

The energy crises exemplified by the 1973 Arab oil embargo brought about a noticeable shift of interest from the military sector to the civilian one. During the period 1970-1990, government agencies and private corporations around the world but particularly in the industrialized countries invested valuable resources searching for methods to conserve energy, and hence drag reduction for civilian air, sea and land vehicles, for pipelines and for other industrial devices was emphasized. The availability of fast, inexpensive computers made it possible to simulate numerically complex flow situations that have not been approachable analytically. Some control strategies, for example transition-delaying compliant coatings (Gad-el-Hak, 1996), were rationally optimized using computational fluid dynamics. Large-eddy breakup devices (LEBUs) and rib lets are examples of control methods developed during this period to reduce skin-friction drag in turbulent boundary layers. Good sources of information on these and other devices introduced during the fourth era are the books edited by Hough (1980), Bushnell and Hefner (1990), and Barnwell and Hussaini (1992). Numerous meetings devoted to flow control, particularly drag reduction, were held during this period. Plentiful fuel supplies during the 1990s and the typical short memory of the long gas lines during 1973 have, unfortunately, somewhat dulled the urgency and enthusiasm for energy conservation research as well as practice. For the 1990s and beyond, more complex reactive control devices, geared specifically towards manipulating the omnipresent coherent structures in transitional and turbulent shear flows (Cantwell, 1981; Robinson, 1991), are pursued by several researchers. Theoretical advances in chaos control and developments of micro electro mechanical systems (MEMS) and neural networks should help such efforts. Papers specifically addressing reactive control strategies include those by Wilkinson (1990), Moin and Bewley (1994), and Gad-el-Hak (1994).

3. Active Flow Control

Active flow-control (AFC) is a fast growing multi-disciplinary science and technology aimed at altering a natural flow state or development path into a more desired state (or path).

Active control schemes can be divided into predetermined or interactive methods. A predetermined method of control involves the introduction of steady or unsteady energy inputs without consideration for the state of the flow field. E.g. jet vectoring using piezoelectric actuators (Smithand Glezer, 1997).In interactive methods of flow control, the power input to the actuator (controller) is continuously adjusted based on some form of measurement element (sensor). The control loop for interactive control can be either a feed forward (open) or feedback (closed) loop.

Active flow control has received increasing attention in the last decade, where n knowledge from fluid mechanics is combined with control theory to affect the properties of flow systems. A common goal is to stabilize a flow subject to linear instability, like for instances the Tollmien-Schlichting waves on an aeroplane wing (see e.g. Hogberg & Henningson (2002), or force the flow back to a laminar regime, like for instance in a turbulent channel flow (see e.g. Hogberg et al. (2003); Kim (2003)).

3.1 Contribution of Reynold's & Navier-stokes to A.F.C. & Rise of "Closure Problem"

Reynolds (1883) discovered the phenomenon of transition in pipe flows. He differentiated between quiescent (laminar) flow and sinuous (turbulent) flow separating the instantaneous velocity vector into steady and random components. Turbulence due to its non-deterministic nature was described in statistical terms that decomposed the velocity and the pressure into mean and fluctuating components. This decomposition created a new set of equations unsolvable by Reynolds Time averaging equations (Reynolds, 1894), this problem also being referred as closure problem. Currently Reynolds averaged Navier-Stokes (RANS) methods are practically used in industrial applications since they are capable of postdicting the type of flows about which there is a substantial amount of information, rather than predicting the behavior of an entirely novel flow.

3.2 Prandtl's Contribution to A.F.C. & The Separation Concept

The most important advance leading to the AFC concept was Prandtl's boundary-layer theory which separated the flow field into a thin layer of rotational fluid adjacent to a solid surface, surrounded by a large body of irrotational flow that can be considered to be in viscid explaining the flow around streamlined bodies and also the frictional losses and the convective heat transfer occurring between the surface and the adjacent fluid.

3.3 The concept of a "Super Layer"

The use of Reynolds-averaged equations was practically limited to homogeneous and isotropic only. Corrsin and Kistler (1955) recognized this shortcoming and introduced the concept of a "super layer", which represents a thin, highly contorted boundary separating the turbulent from the irrotational zones. Vorticity is imparted to their rotational fluid along this boundary through the action of viscosity. By assuming that the super layer is continuous without islands of turbulent fluid being present in the irrotational zone, Corrsin and Kistler were able to measure the duration T of the large eddies at the outer edge of the boundary layer, determining that TU8 /d ˜ 2.5. This was probably the first measurement delineating the average size of a large eddy propagating at the outer edge of the boundary layer and indicating that turbulence is not as random as it was previously believed to be.

3.4 Coherent structures in Turbulence

Large coherent structures in turbulent shear flows were discovered. And the most important discovery in this was made by Brown and Roshko (1971, 1974) in a two-dimensional mixing layer. Their Schlieren photograph showed that the turbulent mixing layer is dominated by large-scale eddies, which transport within them much smaller and approximately homogeneous turbulent eddies. The mixing-layer spreading rate could clearly be related to the growth of the large eddies, which engulf irrotational fluid from the surrounding streams.

3.5 The concept of "Triple Decomposition"

The triple decomposition (Reynolds and Hussain, 1972) recognizes that the unsteady motion may be decomposed into large, coherent, deterministic structures that are predictable and smaller ones that presently cannot be predicted and are described by statistical methods and therefore presumed to be random.

3.6 Interrelation of Flow control Goals

One important issue is interrelation of flow control goals, showed by (Gad-el-Hak, 1998). Let us consider an external wall bounded flow, such as that developing on the exterior surface of an aircraft or a submarine. This kind of flow can be manipulated to achieve transition delay, separation postponement; lift increase, skin friction and pressure drag reduction, turbulence augmentation, heat transfer enhancement, or noise suppression. These objectives are not necessarily mutually exclusive.

To focus the discussion further, think of the flow developing on a lifting surface such as an aircraft wing. If the boundary layer becomes turbulent, its resistance to separation is enhanced and more lift could be obtained at increased incidence. On the other hand, the skin-friction drags for a laminar boundary layer can be as much as an order of magnitude less than that for a turbulent one. If transition is delayed &

so on. The ultimate goal of all this is to improve the airfoil's performance by increasing the lift-to-drag ratio.

All of the above points to potential conflicts as one try to achieve a particular control goal only to adversely affect another goal. A skilled engineer has to make continuous compromises to achieve a particular design goal.

4. Recent Innovations in Actuator Technology

One of the greatest challenges in making active flow control technology practical is the development of robust actuators. Desired characteristics of actuators include low power consumption, fast response, reliability, and low cost. Three different actuator concepts are highlighted below to give a brief overview of the variety of actuators that can be used in flow control

4.1 Synthetic jet Actuator

A recent breakthrough in actuator concepts is the synthetic jet actuator developed at Georgia Institute of Technology. This class of actuators uses an oscillatory surface within a cavity to generate a jet from the flow that is being controlled without the need for mass injection (Smith and Glezer, 1998). Flow enters and exits the cavity through an orifice. On the intake stroke, fluid is drawn into the cavity from the area surrounding the orifice. As this fluid is driven out of the cavity, a shear layer is formed between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form a vortex ring. By the time the diaphragm begins to move away from the orifice to pull fluid back into the cavity, the vortex ring has moved far enough away that it is virtually unaffected. Thus a train of vortex rings is created by the actuator. These are compact and requiring no flow plumbing. A variety of flow control results have been achieved using the synthetic jet actuator including thrust-vectoring, mixing enhancement, separation control and virtual surface shaping.

4.2 The second-generation Cavity Noise Suppression Actuator

A promising actuator concept was developed by Cattafestaet al. (1999) for cavity noise suppression. This actuator was an improved design over the first generation piezoelectric flaps developed by Cattafesta et al. (1997). The first generation piezo flap sex hibited a tendency to fail mechanically before reaching their respective electrical limitations. The second-generation actuator is used to construct an active, segmented flap at the upstream separation edge of the cavity and is called a monolithic, piezoelectric flap actuator. The separation edge is an appropriate choice for active control devices because it is the location of maximum receptivity

4.3 Lorentz Force Actuator

The third actuator concept highlighted here is a Lorentz-force actuator. Experiments performed by Nosenchuck and Brown (1992), Nosenchuck et al. (1995), and Nosenchuck (1996)using a specific electromagnetic forcing have indicated that viscous drag can be reduced by as much as 90%. Flush-mounted Lorentz force actuators are used to induce a current-density field ,j, and a magnetic field, B, in the vicinity of the wall to provide a three-dimensional body force L=j x B. The actuator is comprised of a pair of subsurface permanent magnets and two surface-mounted. The arrangement creates a three dimensional Lorentz force above the actuator. The curl of the Lorentz force represents a source of Vorticity.

5. Turbulence Control

The flow in which the various quantities of flow show a random variation with space and time coordinates is called turbulent flow. Due to loss of mechanical energy (as a result of eddying motions) a lot of heat is dissipated. The effects of turbulence is predicted by turbulence modeling. The aim of turbulence control is to identify turbulence cycles and improving the turbulent models.

Turbulence in its own way is necessary in some areas as well as poses a threat of energy losses. While in the case of aircrafts and ships, it has adverse effects on their progression as it generates friction drag due to air or water and increasing fluid noise, it is advantageous and necessary as it accelerates mixing, combustion and heat transfer.

The turbulence control methods are necessary for research purposes as it has the potential of reducing drag during water transportation, pipeline oil and air transportation.

Turbulence can be controlled both by active and passive methods. Turbulence can be reduced by Feed forward (Reactive) as well as Predetermined methods. Feedback control has a great advantage that it can control the flow at each time. Turbulent drag can also be reduced by using in-plane wall motion.

As far as the present scenario is concerned, research in the field of turbulence control is being extensively carried out due to the development of hardware for control, CFD and modern control theory.

6. Flow Separation Control

Flow separation occurs when the boundary layer travels far enough against an opposing pressure gradient that the speed of the boundary layer relative to the object falls almost to zero. The fluid flow becomes detached from the surface of the object, and instead takes the forms of eddies and vortices, leading to Flow Separation. To improve the performance of natural or man-made flow systems, it may be beneficial to delay or advance this detachment process. In aerodynamics, flow separation can often result in increased drag, particularly pressure drag which is caused by the pressure differential between the front and rear surfaces of the object as it travels through the fluid. And therefore, Separation delay is one of the key aspects of flow control. Much effort and research has gone into the design of aerodynamic and hydrodynamic surfaces which defer flow separation and keep the local flow attached for as long as possible. Examples of this include the fur on a tennis ball, dimples on a golf ball, turbulatorson a glider, which induce an early transition to turbulent flow regime; vortex generators on light aircraft, for controlling the separation pattern.

6.1 Phenomenon of Flow Separation

Fluid particles in a boundary layer are slowed down by wall friction. If the flow is sufficiently retarded, for example, owing to the presence of an adverse pressure gradient, the momentum of those particles will be reduced by both the wall shear and the pressure gradient. In terms of energy principles, the kinetic energy gained at the expense of potential gradient in the favourable-pressure-gradient region is depleted by viscous effects within the boundary layer. In the adverse-pressure-gradient region, the remaining kinetic energy is converted to potential energy but is too small to surmount the pressure hill, and the motion of near-wall fluid particles is eventually arrested. At some point, the viscous layer breaks away from the bounding surface. The surface streamline nearest to the wall leaves the body at this point, and the boundary layer is said to separate (Maskell, 1955).

Usually Flow Separation implies a loss of lift, an increase of drag, diminished pressure recovery etc. Therefore, a considerable amount of research has been devoted to the control of flow separation and many

possibilities to achieve separation control have been investigated. Among the most popular are shaping as a passive means and suction, blowing and wall movement as active control methods. While passive means naturally do not produce any running costs, achievable improvements are modest and performance under off-design conditions is mostly poor. Active control methods may be adjusted to actual operating conditions, but require additional power, i.e. running costs.

The performance and stability of an airplane is often degraded by flow separation. In recent years, control devices involving zero-net-mass-flux oscillatory jets or synthetic jets have shown good feasibility for industrial applications and effectiveness in controlling flow separation (Glezer & Amitay 2002; Rumsey et al. 2004; Wygnanski2004). The application of synthetic jets to flow separation control is based on their ability to stabilize the boundary layer by adding/removing momentum to/from the boundary layer with the formation of vortical structures. The verticalstructures in turn promote boundary layer mixing and hence momentum exchange between the outer and inner parts of the boundary layer.

6.2 Inspiration from Nature

Inspired from the natural properties of birds' feathers, i.e. porosity, anisotropy and compliance, an original model for a hairy layer was proposed and tested by Julien Favier et al. (J. Fluid Mech. (2009) A model of hairy medium was developed using a homogenized approach, and the fluid flow around a circular cylinder partially coated with hair was analysed by means of numerical simulations. It was found numerically that such a coating was capable of increasing global aerodynamics performances of an immersed body, by adapting to the separated flow.

The effects of the control were found to be of order one, and appear on the mean pressure and velocity fields. The topology of the flow was changed in the vicinity of the wall but also further downstream, thus modifying the vortex shedding process, and positively affecting the pressure distribution, to reduce lift fluctuations and drag.

The flow dynamics is dominated by the shear layer instability, and the pressure is found to play a coupling role between separation and re-attachment, potentially leading to global instability. The large dimensionality of the discretized flow system is a challenge for control design.

6.3 Introduction of Vortices

In the technical report by Ola Logdberg in 2008, turbulent boundary layer separation control by means of longitudinal vortices was studied. In an experiment stream wise vortices were introduced in turbulent boundary layers to transport higher momentum fluid towards the wall. This enabled the boundary layer to stay attached at larger pressure gradients.

6.4 Change in Synthetic Jet Design

The performance and stability of an airplane is often degraded by flow separation. In recent years, control devices involving zero-net-mass-flux oscillatory jets or synthetic jets have shown good feasibility for industrial applications and effectiveness in controlling flow separation (Glezer&Amitay 2002; Rumsey et al. 2004; Wygnanski2004). The application of synthetic jets to flow separation control is based on their ability to stabilize the boundary layer by adding/removing momentum to/from the boundary layer with the formation of vortical structures. The verticalstructures in turn promote boundary layer mixing and hence momentum exchange between the outer and inner parts of the boundary layer. The control performance of the synthetic jets greatly relies on parameters such as the amplitude, frequency, and location of the actuation, and numerical simulations are especially suitable for an extensive parametric study to optimize the control parameters.

In 2007, the experimental founding that the synthetic jets which are produced through a slot across the entire span on suction surface at 12% chord location, effectively delays the onset of flow separation and causes a significant increase in the lift coefficient[1] [2], was confirmed[4] using Large Eddy Simulation Techniques. It was found that in the case of 20. angle of attack where flow separates near the leading edge, LES provides comparable results to experimental data when grid resolution is sufficient to predict the separated shear layer. The synthetic-jet actuation at 12% chord location is found marginally effective in controlling leading edge separation.

6.5 Local Surface Modulation

It has been shown in the literature[21] that blowing or suction over the air foil surface is an economical process to prevent flow separation by energizing the boundary layer (in the case of blowing) or pulling the separated flow towards the airfoil due to pressure differential (in the case of suction). Furthermore, it has been shown that a process of periodic blowing is even more efficient than steady blowing. Therefore, if both the blowing and suction process are repeated alternatively and periodically, the process is expected to be even more efficient. This can be achieved by a periodic modulation of the local airfoil surface, which helps in re-attaching the flow.

7. Drag Reduction

Drag is a force which acts on a solid object in the direction of the relative fluid flow velocity, it depends on velocity. Drag forces always decrease fluid velocity relative to the solid object in the fluid’s path. Drag can be reduced by drag reducing agents, micro bubble, surfactant solutions, electromagnetic flow, and feedback control.

Drag reducing agents are polymers used as additives in pipelines to reduce turbulence in a pipe. In petroleum pipelines, they increase the pipeline capacity by reducing turbulence and therefore allowing the oil to flow more efficiently. They are used in very small amount in the pipelines. In pipelines oil pushes up against the inside wall of the pipe, the pipe pushes the oil back down causing a swirling of turbulence to occur, then the polymer is added, it interacts with the oil and the wall to help reduce the contact of the oil with the wall. Temperature, diameter of pipe, roughness inside the pipe effect the working of reducing agent. At higher temperature, the drag reducing agent is easier to degrade. At a low temperature the drag reducing agent will tend to cluster together. This problem can be solved by adding another chemical, such as aluminium to help lower the drag reducing agent's attraction to one another. With decrease in pipe diameter, the drag reduction is increased. The rougher the inside, the higher the percent drag reduction occurring.

Microbubbles are used for reducing the skin friction when small gas bubbles are injected into he flow from an upstream position. Gas is injected into liquid turbulent boundary layer to form bubbles which reduces skin friction drag locally by as much as 80 %. The bubble sizes in a micro bubble cloud are subject to any of three competing mechanisms: the initial formation at the wall; bubble splitting by turbulence action and bubble coalescence upon collision. The most significant characteristic of the bubble sizes (500 – 1200 µm) is their diameter in comparison to the boundary layer scales.

7.1 Anionic Surfactants

Anionic surfactants reduce drag in the aqueous solution. Alkali metal and ammonium soaps are used to reduce drag upto 30 % for 0.2% sodium oleatesolutions. Addition use of an electrolyte (eg.KCl) increases the drag reduction as KCl helps in the enhancement of the association of the soap molecules and that the soap micelles, which were initially spherical in the aqueous solution, were rearranged under the influence of the electrolyte into cylindrical shapes, which forms a network of interlaced rod-like elements. The concentration of soap is 0.1 %, which is considerably higher than the polymer concentration.

7.2 Cationic Surfactants

Cetryltrimethyl ammonium bromide (CTAB) is the cationic surfactant which also reduces drag. CTAB naphthol mixture is used to reduce turbulent friction, because the mixture shows shear-thinning characteristics. Similar to anionic surfactant solutions, the drag reducing ability of the CTAB-naphthol solution terminated at some upper Reynolds number corresponding a critical shear stress where there was a scission of the micelles. One marked advantage of cationic surfactants over the anionic ones is that these complex soaps do not precipitate in the presence of calcium ion.

Drag reduction in turbulent pipe flow with feedback control is applied partially to the wall. In this the control input is applied only partially over a limited length in the stream wise direction, but not on the entire wall surface. The upstream control effect remains over a distance of about 11–14 times the pipe radius downstream of the point where the control is terminated. Active feedback control system generally consists of three functional hardware components, i.e., sensors, controllers and actuators, and an additional software component, i.e., a control algorithm which determines the action of actuators depending upon the sensor output. In parallel with intensive R&D studies of hardware components, the control algorithm has been develop and assessed by using direct numerical simulation of controlled turbulent flow field. Following results were obtained by simulation with the control on partial surface.

1. Average drag reduction is proportional to the area of control.
2. The local skin friction coefficient exhibits a complex stream wise variation despite the simple relation for the average drag reduction rate.
3. The flow recovers to the uncontrolled state about 11R–14R downstream of the controlled region.
4. The rapid recovery of the skin friction is observed right downstream of the controlled region.

7.3 Electro-Magneto-Hydro-Dynamic

(EMHD) Flow Control is used for reducing the intensity of the turbulence fluctuations which reduce frictional drag and heat transfer of turbulent boundary layer. In this the electromagnetically generated force field, or Lorentz field is generated by arrays of magnets and electrodes, called actuators, placed justbeneath or on a wall. Traditionally two types of actuator design have been used. One type generates a Lorentz field which is mostly parallel to the wall in the stream wise direction and the other generates a Lorentz field which is mostly normal to the wall. Although actuators which generate forces normal to the wall show promise of successfully controlling turbulent fluctuations.

8. Modern Methods of Flow Control

The manipulation in path of flow of the fluid for reduction in drag, increase in lift, increment in heat transfer can be done by techniques and methods that fall under the field of flow control. A few of the latest flow control technologies are discussed below.

8.1 A magneto rheological fluid (MR fluid) is a smart fluid. It is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid. Magneto Rheological Fluids (MRFs), i.e. suspensions of ferri- or ferromagnetic particles in a water or an oil-based carrier fluid, stabilized by a surfactant or polymer, are deemed suitable for fluid flow control in oil and gas recovery operations. Porsche has introduced magneto rheological engine mounts in the 2010 Porsche GT3 and GT2.

8.2 In High Altitude Long Endurance (HALE) Aircrafts there is a necessity of high fuel storage. But due to vortex shredding, the wings of theaircraft cannot be made thick enough for carrying the extra load. So for this purpose, vortex entrapping is done to avoid vortex shredding and hence preventing reduction in lift. One way of doing this is to design a cavity on the surface of the airfoil around the point of separation which prevents the flow speed in the region around the mouth of the cavity to not drop to zero.

8.3 Plasma Actuators fall under the category of active flow control and is a type of actuator. These are used for flow control techniques due to their properties like induced body force by strong electric field. These can behave as vortex generators by inducing a local flow perturbation. Plasma actuators can be used for flight control by mounting actuators on the air foil to control the flight altitude and flight trajectory.

8.4 MEMS (Micro Electro MechanicalSystems)are one of the major advances in flow control is the emergence of Micro Electro Mechanical Systems (MEMS) technology, which employs the methods developed for the fabrication of silicon chips to construct very small-scale mechanical devices. The significance of micro machine technology is that it makes it possible to provide mechanical parts of micron size, batch fabricated in large quantities, and integrateablewith electronics. Miniaturized actuators also simplify the integration of the control system with the overall structure or subsystem.

MEMS fabrication processes provide not only miniaturization, but also modular integration of sensors, actuators, and electronics and the affordability enabled by batch processing. However, micro devices for active flow control do not obviate the role of meso devices in flow control technologies.

9. Conclusion

In this paper we looked upon the developments in the Flow control technology in an organized and concise fashion. We studied about its historical advancement over five eras and its modern application in Turbulence Control, Separation Control and Drag Reduction. In the end we saw some examples of modern technologies like MR Fluid and MEMS which gave us a whole new outlook on how the science of flow control has changed over time.

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