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The History and Current State of the Art in Flow Control

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Abstract: *Flow control refers to the idea of analyzing and modifying the behavior of fluid flows in order to achieve a desired outcome. In this paper we review the history and current state of the art in flow control. Various past and present techniques are categorized and discussed.*

1. Introduction

Flow control is one of the most dynamic aspects of fluid mechanics. Conceptually, Yousefi and Saleh (2015) defined fluid flow control as any minute change in configuration that serves an engineering benefit that is ideally huge. Examples of such engineering benefit include: lift increase, drag reduction, noise reduction and mixing enhancement. Such changes are typically achieved with the help of active and passive devices. According to Yousefi and Saleh (2015), whereas active devices operate in time-dependent manner, passive devices are basically stable. Unlike passive devices, the active devices require energy (Bushnell and Hef, 1990; Gad-el Hak, 2000). Examples of passive devices include turbulators, riblets, vortex generators and steady suction; while valves and plasma actuators are good examples of active devices.

Viscosity is one of the most important physio-chemical features of every fluid. Base on this feature, two major classes are obtainable. These are: Newtonian fluid and non-Newtonian fluid. Newtonian fluids include any fluid, whose strain rate is linearly proportional to the stress located at specific individual point. Examples of such fluid include; air, water and majority of gases. On the other hand, Non-Newtonian fluid refers to fluid that doesn't possess the characteristic features of Newtonian fluids. They include; sludges, blood, emulsion, suspension, gels and pastes.

2. Current state of the art in Fluid Flow

Fluid flow control is obviously one of the most keenly studied aspects of fluid mechanics. Basically, the process is broadly categorized by control loop system and energy expenditure. This process is illustrated by Gad-el Hak (2000) in Figure 1.

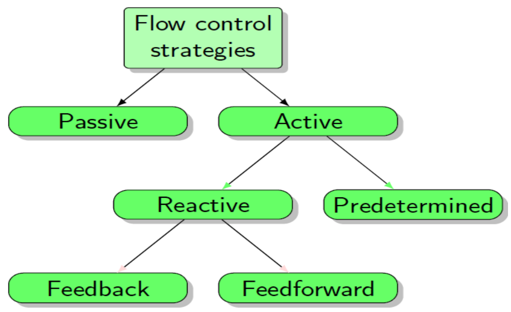

Figure 1. Categorization of Flow Control Strategies. (Gad-el Hak, 2000)

As already indicated, passive control requires neither control loop nor expenditure of energy for its operation (Bushnell and Hef, 1990; Gad-el Hak, 2000; Yousefi and Saleh 2015). Normally, passive techniques involve the use of geometric shaping in the manipulation of pressure gradient; reduction of drag by placing riblets on a surface and achieving separation control with the help of fixed mechanical vortex generators (Chatto, 2006; Garcia-Mayoral and Jimenez, 2011). A practical example can be seen in an aircraft's wings that are specifically designed to minimize the drag and improve lift. A study conducted by Bewley, 2001; Collis et al., 2004 and Gad-el Hak, 2000 indicated that passive control majorly has practical application in shape optimization.

Conversely, active control requires energy. Studies have indicated that, reactive and predetermined controls collectively made up the active flow control (Bewley, 2001, Collis et al., 2004 and Gad-el Hak, 2000).The authors speculated that expenditure of energy may possibly be as a result of the actuator's power, which is known for providing the force that act on the flow. Passive flow control has the advantage of being less complex, more affordable to design and produce and less difficult to maintain. Thus, passive flow can be employed in real-world scenario, especially in the aviation sector. Unfortunately, this form of flow strategy is too simple for most complex engineering flow applications. Specific examples of such complex flow include any flow that has high incidence of turbulence and instabilities. Consequently, researchers have focused more attention on active flow control. In reality, current state of the art in fluid flow control focus mainly on active flow control.

3. Active flow control

According to Kral (2000), active flow control consists of three major components namely: sensors, actuators and method of flow control.

Sensors: These are devices used in providing feedback information that are highly essential in the quest to control the flow. According to Monsma et al. (1995), velocity and pressure are variables usually measured in fluid flow. The sensors responsible for measuring these variables are of two types namely; optical sensor and Micro-Electro-Mechanical-System (MEMS) sensor.

Actuators: These are devices used for controlling the flow (Cattafesta and Sheplak, 2011). Contemporarily, there are various types of actuators. Examples include; synthetic jets, piezoelectric, MEMS and electromagnetic actuators. Figure 2 shows a diagrammatical representation of a synthetic jet actuator and its generated flow patterns.

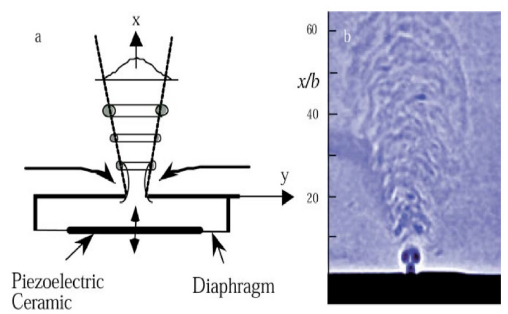

Figure 2. Synthetic jet actuator and flow patterns: (a) schematic and (b) schlieren flow visualization. (Smith and Glezer, 1998)

The use of actuator to control flow is typically accomplished through a wide variety of processes like; virtual surface shaping, thrust-vectoring, separation control and mixing enhancement (Amitay et al., 2001).

Methods of reactive flow control: Moin and Bewley (1994) identified four major types of reactive feedback control strategies as: adaptive, physical model-based, dynamical systems-based and optimal control strategies. The adaptive control strategy focus mainly on controllers and models In other words, the details of flow mechanism are not usually regarded in this method of reactive control. Specifically, schemes used in adaptive control system are mainly products of feedback control theories (nonlinear and linear control theories) and neural network control (Kasnakoglu and Efe, 2008; Kasnakoglu, 2010).

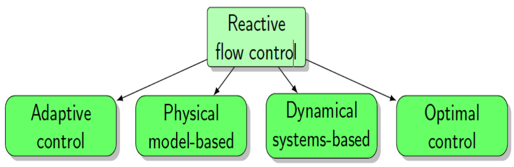

Figure 3. Methods of Reactive Flow Control

Experimental studies have indicated that the successful usage of nonlinear adaptive control technique, in controlling transition process under turbulent boundary layers (Rowley, 2005). Turbulence control aimed at reduction of drag has also been achieved with the help of the neural network technique (Rowley, 2005).

The physical model-based is majorly suitable for situation, in which the flow mechanics are well comprehended (Choi et al., 1994). The reduction of drag through mitigation of effects near vortices' wall is a very good practical example of physical model-base control strategies. However, the applications of this method of reactive flow control are restricted simple flows only. The third method of reactive flow control known as dynamical systems-based control involves the control of flow on basis of a reduced model. Basically, it is possible to decompose turbulence to a reduced model, in which control theory is highly applicable. This process is made possible by the nonlinear dynamical system theory. A practical example can be seen in the case of Proper Orthogonal Decomposition (POD), where a model reduction is derived from analytical results of turbulent flows (Willcox and Peraire, 2002).

Lastly, the optimal control strategy is based on Navier-Stokes equations. Actually, the cost function is curtailed by direct application of the Navier-Stokes equations. Consequently, the controllers used in this method of reactive flow control are based on the Navier-Stokes equations. Joshi et al. (1999) listed some of the acceptable Navier-Stokes equations as; linear feedback control (sub-optimal control), LQR control and PID control.

4. Types of flow

Fluid flow control involves the study of various types of flow. Examples of such flow include: plane channel flow, cavity flow and flow exiting around a cylinder (Rowley and Williams, 2006; Kasnakoglu et al. 2009; Paksoy et al.). Figure 4 is a diagrammatic illustration of cavity flow. The acoustic waves generated by the process are clearly visible in the diagram. Cattafesta et al. (2003) noted that such wave actually possess lots of problematic sources for a typical aircraft. This is probably the main motivation behind increased interest in the study and consequent development of active closed loop control.

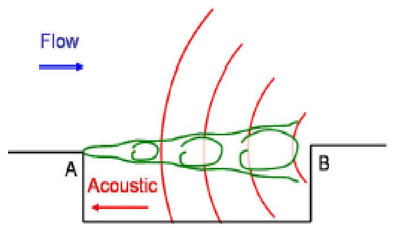

Figure 4. Cavity flow in an acoustic source. (Cattafesta et al., 2003)

An illustration of typical shallow cavity flow at low Mach, as depicted by Samimy et al. (2007), Kasnakoglu and Serrani (2007) is shown in figure 5. This study as well as similar studies conducted earlier by (Yuan et al., 2005) and (Yan et al., 2006) lead to obtainment of control flow and model reduction. Control flow was specifically achieved with the help of synthetic jet actuators, while Proper Orthogonal Decomposition technique is used to achieve a model reduction and control the flow.

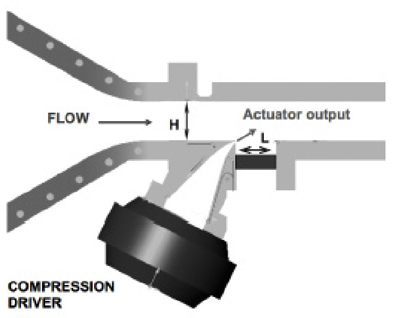

Figure 5. Shallow cavity (Samimy et al., 2007)

In literature, one of the most crucial examples of classical active flow is that which occurs around a cylinder. Figure 6 illustrates a typical configuration flow around a cylinder. Both turbulent and laminar flows are clearly demonstrated in the figure. According to Choi et al., (2008), the suction or blowing serves as the control signal in this case, while the reduced cost functions form the basis for the development of feedback control. The main objective of minimizing cost function is to cut down vortex shedding and drag.

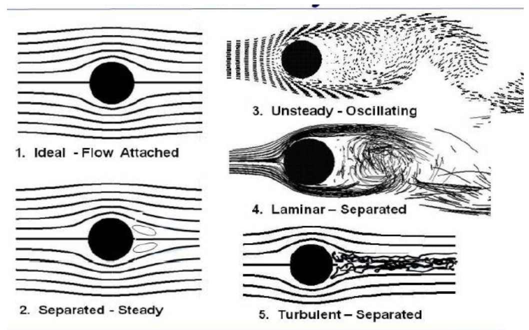

Figure 6. Flow around a cylinder and the phenomenas. (Choi et al., 2008)

The type of flow that can easily be evaluated in context of classical theory is the plane Poiseuille flow. Diagrammatic representation of this unique type of flow is shown in Figure 7.

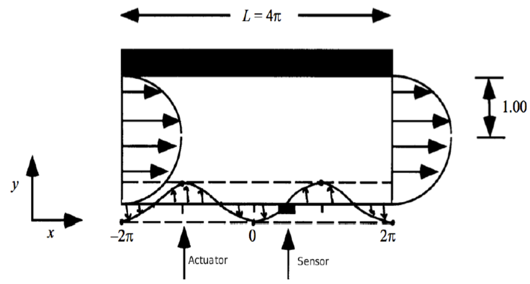

Figure 6. Plane Poiseuille Flow (Joshi et al., 1997).

Actually, the use of linear model from full nonlinear process to develop a linear feedback was first achieved by Joshi et al, (1997). Joshi's success prompted intense research on Poiseuille flow. This led to the development of a Linear Quadratic Gaussian control for the 2D plane Poiseuille flow. The Linear Quadratic Gaussian comprises of Linear Quadratic Estimator and Linear Quadratic Regulator. Cortelezzi and Speyer (1998) discovered that the controller's order can be minimized by applying Linear Quadratic Regulator to the reduced model. Additionally, it was also discovered that the plane Poiseuille flow can be stabilize with the help of a simple Proportional Integral Derivative control. Kang et al. (1999) and Bewley and Liu (1998) carried out extensive studies on how to control 3D plane Poiseuille flow. The transient energy growth is the main focus whenever plane Poiseuille flow is considered. Consequently, Bewley and Liu (1998) obtained a stable 3D plane Poiseuille flow by using H2=H1. Through this way, the two researchers were able to reduce the kinetic energy density. Studies conducted by Aamo et al., (2003) and Balogh et al. (2001) indicated that, 2D plane Poiseuillel flow can also be stabilized by using a feedback control. The feedback controls used in those two cases are based on the analysis of Lyapunov function.

5. Issues in Computational Fluid Dynamics (CFD)

Over the years, fluid flow control has increasingly being recognized as an important aspect of computational fluid dynamics. Basically, computational fluid dynamics focus mainly on numerical concepts that are involved in active flow-control and no-control configurations. Examples of such numerical issues include; boundary conditions, discretization and modeling (Erbil and Kasnakoglu, 2009). The ability of CFD to progress with time was first revealed by Chapman (1976). The possibility of using time-dependent CFD, viscous time-averaged and computer-speed forecast is predicted during the latter parts of 1970s and middle of 1980s. Twenty-five years later, vicious calculations that are dependent on time are calculated accurately, but only on simplified configurations and low Reynolds numbers (Joslin, 1997, 2001). Researchers at this stage indicated that, vicious calculations at high Reynolds numbers require turbulence models. This case doubts on the accuracy and interpretation of such results, especially in regards to time-dependent flows as it pertains to intrinsic assumptions stated in various turbulence models. The immediate implication was difficulties in the obtainment and consequent interpretation of the CFD solutions.

Contemporarily, the difficulties encountered in course of CFD are further compounded by the emergence of active control technologies, especially in cases where control involves the use of local actuation that has large amplitude. However, current practical results indicated the feasibility of using timed dependent actuation to improve the system's overall performance. This timed dependent actuation, which is often periodic, has the potential of boosting current tools' ability to predict the performance benefits of active flow-control in the near term. At the end, the functionalities of time-dependent optimization can be integrated into design tools to enhance active flow control in highly complex engineering applications. Currently, such design approaches, which are hugely responsible for the operation of many applications, have actually been included in many design tools and CFD analysis with considerable success. Examples of such applications are very obvious in aeronautic engineering. Even though the empirical designs are very costly, the innate inadequacies of contemporary computational tools make them a necessity. Active flow control techniques can only be acceptable in engineering applications, if the analytical tools and design are robust, reliable and perfectly covers the mechanism of the actuator-induced flow phenomena.

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