Chapter 1
Introduction and Literature Survey

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1.1 Introduction

Nowadays, the expectations for more efficient military and civil rotorcraft which will be faster, easier to control and invisible are very high. To achieve these goals, emphasis has been placed on control of the flow around the rotor for aerodynamic enhancement, vibration decrease and noise elimination. Modern flow control has a great influence on every major area of aeronautic engineering such as external aerodynamic enhancement, internal flows through propulsion engines, aero-acoustics and control of turbulence. The ability to change the flow behaviour to a great extent, while a small amount of energy is required, consists the gain of flow control techniques. Thus, the understanding of the stability characteristics of the flow is necessary to control it.

Referring to Hak (2001), to choose a specific type of flow control, the presence or lack of wall, the Reynolds number, the Mach number and the flow instabilities should be taken into consideration. The interrelation between different control goals shows that engineers have to make compromises to achieve at least some of the goals. The first way to classify a flow control method is by indicating whether the control is applied at the wall or away from it. Parameters such as wall surface, temperature, mass transfer, suction or injection, different additives and control devices are some examples which can influence the flow. A second classification has to do with the energy expenditure and the control loop involved. There is passive control which needs no power and no control loop and active control

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which requires energy expenditure. As far as the active control goes, it is further divided into predetermined and reactive. The predetermined control is not affected by the particular state of flow and requires no sensors, while in reactive control the input is always adjusted based on some measurements. Reactive control can be either feedforward or feedback. Reactive feedback is classified into four categories: adaptive, physical model based, dynamical systems based and optimal control.

From this survey it is pointed out that the variety of flow control devices can be classified into two categories. The first contains fluidic mechanisms that try to change the flow behaviour by adding or removing momentum where is needed. Surface blowing circulation control, surface suction devices, jets vortex generators (VGs), synthetic jets and plasma technology are such devices. On the other hand, there are devices which do not affect directly the flow characteristics, but they contribute to the control of the flow by altering the shape of the body. Leading edge slats, drooped leading edge, trailing edge flaps and Gurney flaps are common mechanisms of this second category. However, the way these devices are used and their effectiveness on flow control are strongly related with the specific target of the control. That may be the delay of flow separation caused by dynamic stall or blade vortex interaction (BVI) or even the blade vibration decrease and noise diminution. Another significant factor which is considered when choosing the appropriate device is the type of control, as classified above (Hak 2001), the energy that will be consumed and the load penalty. These characteristics make flow control a demanding and challenging process which, however, has the potential to improve aerodynamic performance and extend the capabilities of current rotor systems. Figure 1.1 presents the interrelation between flow control objectives to give an idea of how strongly they are connected.

Considering the performance of a helicopter, the weight-speed envelope faces limitations due to the advancing blade restricting speed and due to the retreating blade stall restricting weight. In order to minimise these limitations, drag should be decreased and pitching moment should be controlled at the advancing side, while maximum lift without stall should be achieved at the retreating side. As a result, flow control devices must affect these requirements in order to be suitable for rotor application. According to Bousman's dynamic stall function (Joo et al. 2005) presented in Fig. 1.2 at the end of this survey, the flow control mechanisms will be classified in terms of increase of lift coefficient and decrease of moment coefficient.

1.2 Vortex Generators

Vortex generators were first introduced by Taylor (1947), and their principle of operation relies on the increased mixing between the external stream and the boundary layer due to longitudinal vortices produced by the VGs. Fluid particles with high momentum in the streamwise direction mix with the low-momentum viscous flow inside the boundary layer; therefore, the mean streamwise momentum of the fluid particles in the boundary layer is increased. The process provides a continuous source of momentum to counter the natural boundary layer momentum decrease and the growth of its thickness caused by viscous friction and adverse pressure gradients. Vortex generators can reduce or eliminate flow separation in

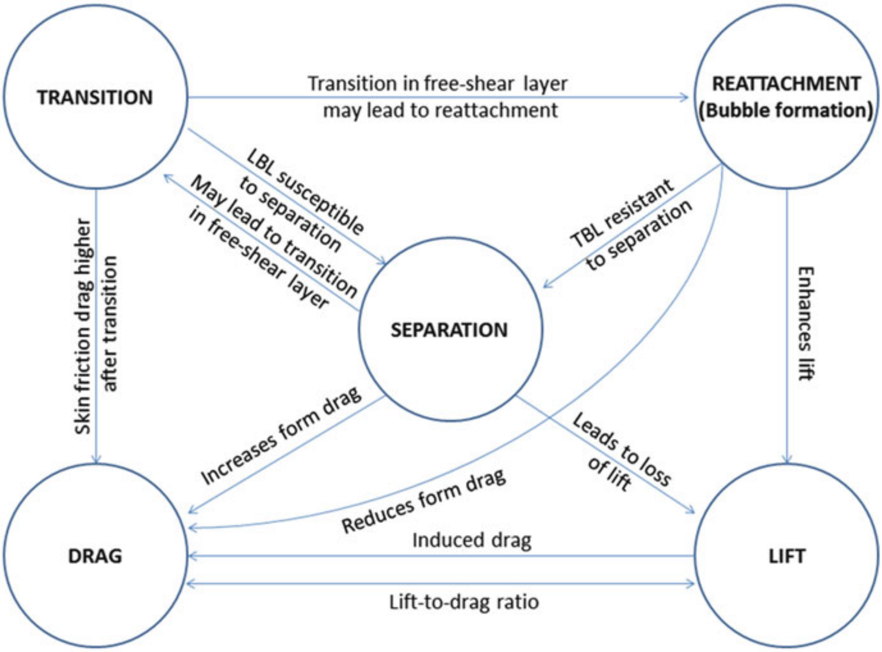
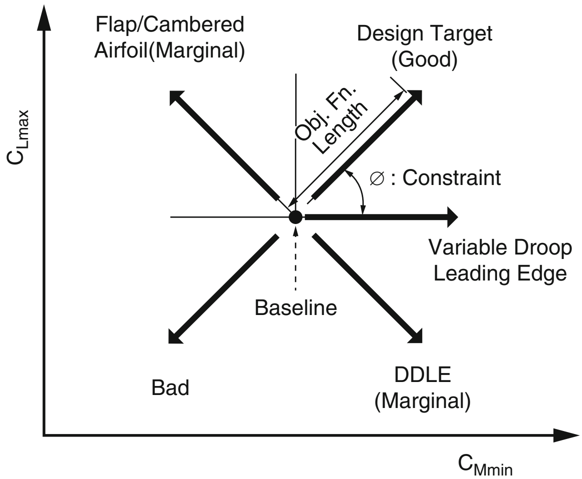


Fig. 1.1 Interrelation between flow control objectives

Fig. 1.2 Optimising for stall control—Bousman's dynamic stall function (Joo et al. 2005)



moderate adverse pressure gradient environments. Even when separation does occur for cases of large adverse pressure gradient, the mixing action of trailing vortices will restrict the reversed flow region in the shear layer and help maintain some pressure recovery along the separated flow. Thus the effects of separation may be localised or minimised (Fig. 1.3).

Fig. 1.3 Different types of vortex generators. From left to right: delta wing, rectangular wing, delta winglets and rectangular winglets (Chu et al. 2009)

The concept of micro vortex generators was most probably first introduced by Keuthe (1972). In his work, wave-type micro VG with height of 27 and 42 % of the boundary layer thickness were installed in an aerofoil to reduce trailing edge noise by suppressing the formation of a Karman vortex street and by reducing the velocity deficit in the aerofoil wake. Since the late 1980s, these devices appeared in the literature under different names such as sub-boundary layer vortex generator (Holmes et al. 1987) (SBVG), submerged vortex generator (Rao and Kariya 1988), low-profile vortex generator (McCormic 1993) and micro vortex generator (Lin et al. 1994).

The main difference between the SBVG and the VG is in terms of the device height. In general, the velocity deficit within a turbulent boundary layer is dominant near the wall within the inner 20 % of the boundary layer thickness. In that region, an adverse external pressure gradient tends to lower the velocity and thus promotes flow separation. Although both devices operate based on a similar mechanism (generation of streamwise vortex), there are some major differences. For example, the SBVG produces a larger velocity gradient close to the wall and has a stronger- and lower-deficit region in the profile. A vortex generator achieves boundary layer control only at the penalty of possible considerable drag. A sub-boundary vortex generator produces vortices that travel downstream along the surface, causing flow mixing between the inner layers of the boundary layer. Although these SBVGs will produce extra drag as compared with a clean surface, their drag penalty is less than with VGs.

The wide range of conditions where the rotor is operating at makes the parasitic drag a particular limitation, which consists the main drawback of VGs. The only way to avoid this problem is the use of sub-boundary layer VGs as they remain within the low energy flow in the boundary layer and consequently they have low drag. On the other hand, Lin et al. (1994) and Lin (2002) used SBVGs on a multi-element aerofoil in a landing configuration and showed that VGs as small as 0.18 % of reference wing chord can effectively reduce boundary layer separation on the flap which will lead to the reduction of drag and increase of lift for a given angle of attack. In fact during his experimental study trapezoidal vanes were placed on the 25 % of the chord of the flap of a wing at flow conditions $M = 0.2$ and $\mathrm{Re} = 5 \times 10^6$ creating counter-rotating vortices, and they achieved a 10 % lift increase, 50 % drag decrease and 100 % increase of L/D ratio.

As stated in Kenning's review (Kenning et al. 2005), the potential applications of VGs and SBVGs include control of leading edge separation, shock-induced separation and smooth surface separation. SBVGs have less parasitic drag, but in case of shock-induced separation, they must be located closer to the separation line which may be a major limitation in the unsteady application of the rotorcraft. Sub-boundary vortex generators have also been studied at ONERA by Meunier and Brunet (2008) as part of AEROMEMS Project in order to control separation on a variable sweep wing. The results of this study show that the efficiency of SBVGs is linked with local boundary thickness which dependents on Reynolds number and angle of incidence. Ashill et al. (2001) also performed a separation control experiment where separation was introduced by placing a bump in the test section. The turbulent boundary layer tunnel was used with a free-stream velocity of 40 m/s and a boundary layer thickness of 40 mm over the bump. Three types of SBVGs including the micro ramp, micro vane and split micro vane (with a gap $g = 1$ h) were tested. All the devices had the same height of $h = 10$ mm, resulting in a height ratio of $h/\delta = 0.25$. Laser Doppler anemometry (LDA) was used to perform velocity measurement in streamwise and lateral planes. The velocity fields revealed a significant reduction of the separation region at the rear of the bump for all three devices; furthermore it was found that the split micro vane yielded the best results.

1.3 Air-Jet Vortex Generators

Flow separation is a complex phenomenon influenced by a combination of factors, of which adverse pressure gradients play a significant role. Adverse pressure gradients may reduce the relative motion between the various fluid particles within the boundary layer. If this relative motion is reduced to a sufficient level, the boundary layer can separate from the surface. Furnishing the boundary layer with additional momentum may allow greater penetration against adverse pressure gradients with a reduction in the magnitude of flow separation. Generating a series of longitudinal vortices over the surface of an aerofoil is one technique for achieving this aim. Transferring high-momentum free-stream fluid to the near wall region provides the boundary layer with additional momentum. The presence of a series of vortices again promotes such behaviour. An alternative to vane vortex generators is an active fluid jet vortex generator. Fluid injection via inclined and skewed wall-bounded jets act to induce longitudinal vortices for flow control, instead of solid vane vortex generators. Air-jet vortex generators (AJVGs) usually consist of an array of small orifices embedded in a surface and supplied by a pressurised air source, wherein longitudinal vortices are induced by the interaction between the jets issuing from each orifice and a free-stream fluid flow. The orifices are pitched at angle φ with respect to the surface tangent and skewed at angle ψ with respect to free-stream flow. Prior studies have highlighted the advantages of carefully selecting parameters such as the pitch and skew of the jet axis, as well as the orientation and the preference of certain orifice shapes. Prince and Khodagolian (1996) and Prince et al. (2009) compared the effectiveness of passive and active blowing over a NACA 23012 and a NACA 63_2–217 and showed that by comparing the ratio $C_L/(C_D + C_M)$, it is obvious that active AJVGs are more effective than passive ones only at highest angles of attack. Moreover, a very important factor for the passive system is the pressure difference between the air-jet intake and exit which drives the flow through the duct. For that reason Krzysiak proposed to use the aerofoil overpressure regions as a source of the air for the AJVGs. These self-supplying air-jet vortex generators are characterised by the fact that they remain inactive at low angles of attack and only become active at higher angles of attack, close to critical values, as a result of the greater pressure difference between the upper and the lower aerofoil surfaces. However, although this type of AJVG is technically significantly simpler than the conventional one, it works well and delays separation only for Mach number up to 0.4, but for higher speeds, its influence deteriorates. Shun and Ahmed (2011) studied experimentally the exponential injection scheme over a NACA 63–421 aerofoil. The exponential jet appears to be a promising device for separation control as the velocity profile varies in space, but not time. Its main features are an injection width that increases by a given factor of *e* (2.71828) and a fluid injection velocity profile that also increases by the same given factor. The experiment showed that the exponential jet produces worthwhile performance gains and an increase in energy efficiency. In many cases it was found that the conventional vortex generators could be successfully replaced by the air-jet vortex generators for boundary layer control because of the ease of control accompanied by a minimal drag penalty (Prince and Khodagolian 1996). However, the complexity of the installation of AJVGs in comparison with the simplicity of the vane vortex generators has limited their practical usage. The identification of the optimum air-jet configuration is not simple and needs careful study, because the effectiveness of AJVGs depends on a number of parameters such as the pitch and skew angles, the jet mass flow rate, the ratio of the boundary layer thickness to the jet diameter, the jet Reynolds number and the ratio of mean jet velocity to mean free-stream velocity. In addition, using active or passive blowing depends on the energy required and its source such as the engine of the helicopter from where intake air can be bled away to feed the jets. In this case, the system will result in a small loss in engine efficiency, equivalent to an increase in parasitic drag which must be taken into consideration when calculating the overall efficiency of AJVGs. A research that could lead to useful conclusions concerning the application of AJVGs in helicopter rotors is conducted by Singh et al. (2006). In that study two arrays of AJVGs were located at $x/c = 0.12$ and $x/c = 0.62$ on an oscillating RAE 9645 aerofoil. The effect of operating only one or both of the arrays, as well as the influence of blowing rate, was investigated, and the results showed that blowing from the front array at $C\mu = 0.01$ is more effective than blowing either from the rear array or from both arrays simultaneously. However this work is restricted to low-speed dynamic stall. For most helicopters the retreating blade operates at Mach number of about 0.4, which means that the blowing requirements may increase under these conditions and the optimum location of the arrays may also change. Furthermore, the sensitivity of AJVG at real rotor effects such as flow skew angle, radial flow and time-varying Mach number may also be an issue. Finally, if the AJVG is used around the azimuth, then its influence on the advancing side has to be investigated.

1.4 Synthetic Jets

Synthetic jets consist of a vibrating diaphragm at the base of a small cavity just under the aerofoil surface. The diaphragm is activated electrostatically or through the use of a piezoelectric material with frequencies that span 1–14 kHz. A small hole through the surface allows the production of a stream of ring vortices travelling out from the surface as shown in the schematic (Fig. 1.4).

Hassan and Janakiram (1998) and Hassan (2001) showed by numerical study that zero-net-mass jets can, with careful selection of their peak amplitude and oscillation frequency, enhance the lift characteristics of aerofoils. Indeed, a NACA0012 was used at a free-stream Mach number of 0.6 and Reynolds number $Re = 3 \cdot 10^6$ and for jet velocities 0.05, 0.1 and 0.2. It is shown that as the jet velocity is increased, the lift is increased while the moment and drag are decreased. As far as rotor blades are concerned, two arrays of synthetic jets can be used to change the local pressure distribution near the leading edge resulting in lower temporal pressure gradients and lower blade vortex interaction noise levels. The effectiveness of these devices for lift enhancement increases with the increase of free-stream Mach number and the

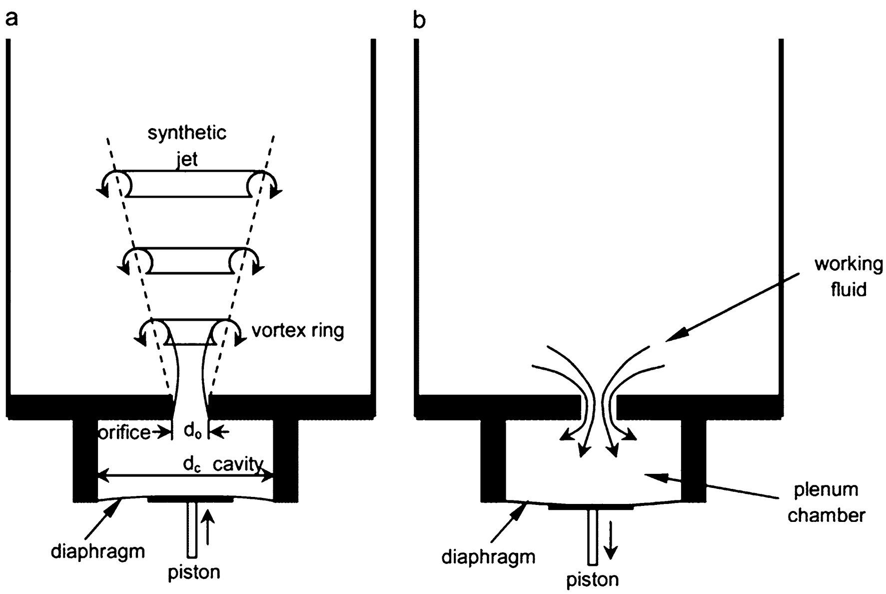


Fig. 1.4 Synthetic jet (Mushtak 2011). (**a**) Compression stroke. (**b**) Expansion stroke

decrease of the ratio between the jet Mach number and free-stream Mach number. When comparing synthetic jets with AJVGs, the advantage is that it is easier to provide power rather than air. On the other hand, researchers must always keep in mind that the implementation of any device will be pointless if the power needed exceeds the power gained by controlling the flow.

1.5 Surface Blowing Circulation

Blowing air tangentially to the aerofoil surface has been employed both at leading and trailing edges of the wings. Park and Choi (1999) showed that in the case of uniform blowing from a slot, the skin friction on the slot rapidly increased. The near wall streamwise vortices were lifted up by blowing, and as a result, the interaction of the vortices with the wall became weaker. Moreover, the lifted vortices became stronger in the downstream due to less viscous diffusion above the slot and more tilting and stretching downstream of the slot, resulting in the increase of the turbulence intensities as well as the skin friction downstream of the slot. Yu et al. (1995) investigated numerically the concept of upper-surface blowing over a NACA 0012 which has been tested in the Army's water tunnel at NASA Ames Research Centre in the early 1980s. The aerofoil was oscillating with a pitching motion of $\alpha = 10° + 10° \times \sin(2\pi\ ft)$, a reduced frequency k of 0.49 and a Reynolds number of 30,000. The tangential blowing slot was located at the quarter chord on the upper surface of the aerofoil. Three blowing rates were tested. Without blowing ($C\mu = 0.0$) the aerofoil stalls at 13°. For the case of injection at twice the free-stream velocity, the blowing delays the stall until about 25° and shows a moderate amount of increase in lift. For the third case where the injection was four times the free-stream velocity, there is no sign of stall even at 30°, while the lift is higher compared to the second case. Again the power losses related to a blowing system are difficult to estimate without undertaking a full rotorcraft design study. The experimental results show that the upper-surface blowing concept delays the dynamic stall phenomenon by trapping the stall vortex. Further study with the computational method indicates that a stall vortex does not form on the airfoil when there is upper-surface blowing at the quarter chord. Although the concept seems to have some effectiveness in delaying dynamic stall, the application of these concepts to rotorcraft requires further tests on the effects of high Mach numbers and high Reynolds numbers (Fig. 1.5).

Mitchell et al. (1996) of ONERA also used blowing circulation as a method to control the vortex breakdown location. In general the vortex breakdown phenomenon can be characterised by a rapid deceleration of both the axial and swirl components of the mean velocity and, at the same time, a dramatic expansion of the vortex core. The no-blowing configuration $C_1 = 0$ of the delta wing was examined for $U = 15$, 24 and 40 m/s at a = 20, 27, 30 and 40°. The Reynolds numbers associated with each U are, respectively, $Re_c = 9.75 \times 10^5$, 1.56×10^6 and 2.6×10^6.

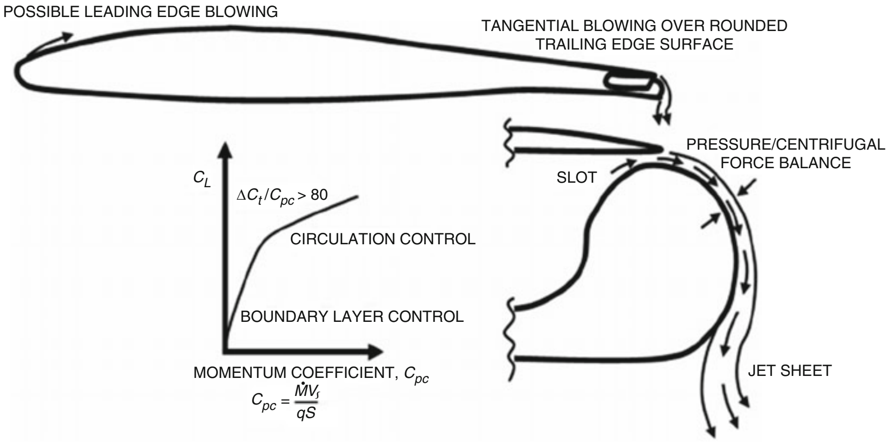


Fig. 1.5 Illustration of surface blowing circulation (Djojodihardjo et al. 2011)

Open-loop, asymmetric, blowing along the core of the portside leading edge vortex on the leeward surface of the delta wing was shown to be effective for controlling the vortex breakdown location over the delta wing.

1.6 Surface Suction

In the case of highly manoeuvrable aircraft like helicopters, suction technique can be applied to delay stall by delaying the detachment of stall vortex and taking advantage of the increased dynamic lift. The objective of Karim's experimental study (Karim and Acharya 1994) was to reduce the dynamic stall vortex (DSV) formed on a NACA0012 by removing the reverse-flowing fluid at the same rate as it arrives in the leading edge region. It is shown that the pitch rate of the aerofoil is the main factor that influences the suction requirements, and when this rate is low, the Reynolds number becomes significant as the transition of turbulence in the shear layer makes the flow more complex. The location of the slot used for the suction is less important, as long as it is the area where the reverse-flowing fluid can be removed, and when the suction is applied in a uniform way, it requires less velocity and therefore energy rather than when it is applied in a concentrated way. As far as the suction activation goes, this should happen before the angle at which the shear layer lift-up takes place and the control should be continued as long as it is desired as if its termination before the right time will lead to an immediate formation of the dynamic stall vortex. Badran et al. (1998) and Lorber et al. (2000) investigated the effect of suction on the wing surface on vortex breakdown with leading edge suction and surface suction.

In first the case suction was found to be more effective in delaying vortex breakdown for suction slits closer to the leading edge. On the other side, the exact mechanism of how the surface suction affects the vortex breakdown was not clear. Surface suction is also being studied as a means to reduce viscous drag by delaying laminar to turbulent boundary layer transition, but as a conclusion surface suction is less effective than leading edge suction.

1.7 Plasma Technology

The last few years, researchers Kato and Breitsamter (2015), Dadfar et al. (2014) and Moralev et al. (2014) have focused on plasma technology for enhancing the flow around aerofoils and wings. Caruana (2010) describes the plasma technology and its applications on aerodynamic control for civil aircraft as part of PLASMAERO project. The technology of plasma can be classified into the family of the active means of control. The advantages of using plasma are located at the fact that their use can be of a big simplicity, their high frequency of functioning will allow a real-time control, their consumption of electric energy is reduced and no pneumatic circuit is useful. According to Post and Corke (2006), the main advantages of plasma are:

1. They are fully electronic with no mechanical parts and, therefore, are able to withstand high force loading.
2. They can be laminated onto wing surfaces and, therefore, they do not require slots or cavities.
3. They have a broad frequency response bandwidth so that they can have fast response for feedback control (Fig. 1.6).

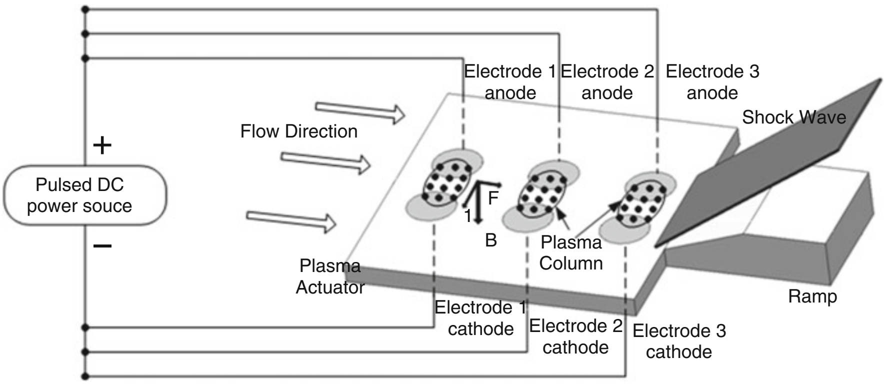


Fig. 1.6 Plasma flow control (Li et al. 2011)

The plasma actuator consists of two copper electrodes separated by a dielectric insulator. The electrodes are supplied with a high-order AC voltage. When the voltage is sufficiently high, the surrounding air ionises and plasma forms in the regions of high electrical field potential. These regions are generally located at the edges of the electrode(s) exposed to the air. The ionised air, in the presence of an electric field gradient, results in a body force on the flow. The body force is a vector that can be tailored for a given application through the orientation and design of the electrode geometry. One of the applications of plasma studied in ONERA was the separation reattachment using dielectric-barrier discharge (DBD) for the generation of plasma. For that method a nonthermal plasma is generated by the application of a high-voltage discharge between two electrodes (5–50 kV) which create an ionisation field, which generates regions where the density of one species, positive or negative ions, is dominant, and amongst the outcomes, a corresponding ionic wind due to the movement of ions at the surface of the aerofoil very close to the wall. This adds flow momentum to the main flow that can influence or modify the aerodynamic parameters like boundary layer velocities.

1.8 Nonfluidic Devices

1.8.1 Leading Edge Geometries

Putting a slot in an aerofoil to permit airflow from the lower surface to the upper surface has the potential to increase maximum lift coefficients. The maximum lift coefficient of the slotted aerofoils is significantly increased compared to that of the baseline aerofoil. However, a large drag penalty is observed for the slotted aerofoils, especially at low angles of attack (Fig. 1.7).

Apart from leading edge slats, variable droop leading edge (VDLE) has been tested in many cases both experimentally and numerically. In both (Chandrasekhara et al. 1998, 2001) studies delay of dynamic stall is observed by the use of VDLE. Dynamically drooped leading edge nose has been shown to significantly reduce or eliminate the massive flow separation and the dynamic stall vortex for a given angle of attack condition. Another case of leading edge modification is that of Huang and Mao (2002), where the performance of a wing model subjected to the influence of a leading edge control rod was tested. In fact the separation resistance of the boundary layer on a vibrating rod controlled wing is remarkable larger than the natural. More detailed results show that stall angle is delayed by around 80 %, the maximum lift coefficient is increased by 20 % and the lift to drag ratio can be increased by 50 % at large angles of attack.

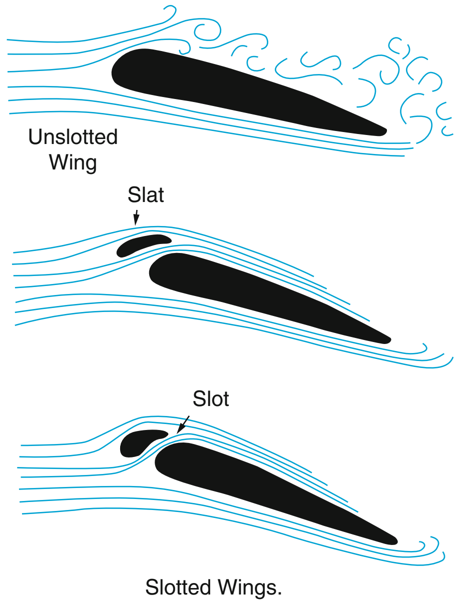


Fig. 1.7 Leading edge geometries

1.8.2 Trailing Edge Flaps: Gurney Flaps

The use of Gurney flaps for lift enhancement is well established in the aerospace community, and several research works (e.g. Wang et al. 2008) document the advantages and disadvantages of these devices. The Gurney flap was introduced by Dan Gurney, and its aerodynamics was first studied by Liebeck (1978). This has been followed by numerous experimental studies (Jeffrey and Zghang 2000; Troolin et al. 2006; Lee and Su 2011). Tang and Dowell (2007) compared the loading of a NACA0012 wing section with both static and oscillating trailing edge Gurney flaps using an incompressible Navier-Stokes code against experiments conducted in a wind tunnel by them. Due to the scarcity of experimental data with dynamically deployed Gurney flaps, this set of data has been used in several computational studies (Chow and van Dam 2006; Baker et al. 2007; Kinzel et al. 2010).

The Gurney flap is a short flat plate placed at the trailing edge, perpendicular to the chord line on the pressure side of the aerofoil, and works by providing a stagnation area near the trailing edge resulting in an increase of lift. It increases the zero lift angles and keeps the lift slope constant, so there is a decrease in the stall angle. The pitching moment coefficient is also increased (i.e. more nose down) as presented in Gai and Palfrey (2003), and unless the Gurney is sized carefully, substantial drag penalties may also occur. Based on the review of flow control mechanisms (Yeo 2008), Gurney flaps are generally less than 3 % of the wing chord. Previous studies (Jeffrey et al. 2008; Maughmer and Bramesfeld 2008) have concluded that the optimal height for a Gurney flap should be close to the

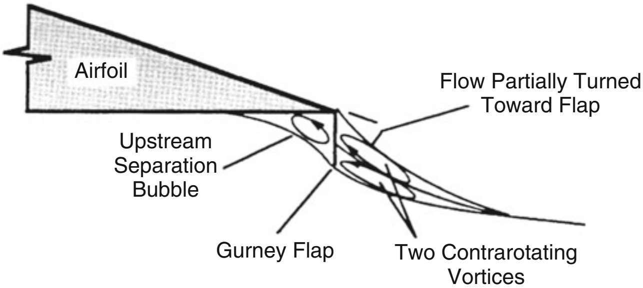


Fig. 1.8 Gurney flap

boundary layer thickness on the pressure side of the aerofoil. If the Gurney flap height is smaller than the boundary layer thickness, then its influence is significantly decreased, while increasing the size of the flap leads to a drag penalty (Fig. 1.8).

Most of the studies found in the literature are dealing with commonly used aerofoils in rotorcraft applications and try to derive conclusions concerning the potential effect of the Gurney flap on rotor blades according to two-dimensional calculations. Several researchers (Yee et al. 2007; Liu et al. 2011; Min et al. 2009) studied the effects of Gurney flaps on the blade root loads and hub vibratory loads. In their study, a Gurney flap was deployed over the entire span of the BO-105 rotor in forward flight with three different deployment schedules. A carefully chosen azimuthal deployment schedule of the Gurney flap was found to reduce the peak-to-peak variations in hub loads. The 4-per-revolution normal force at the hub was compared with the loads for a higher harmonic controlled rotor and the baseline rotor. The simulations showed that the Gurney flap deployment reduced by 80 % the 4-per-revolution normal force vibration. For the same rotor in descending flight, a Gurney set at 30° angle relative to the mean chord resulted in a 40 % decrease of the vertical descend rate. However, the Gurney flap resulted in local nose down pitching moment, which indicates that additional fluid structure coupling analysis for aeroelastic deformation is required.

Active Gurney flaps were also studied by Liu et al. (2011) to determine their effectiveness in reducing noise and vibration in rotorcraft, as well as improving rotor performance. Active control studies employing microflaps were conducted on a hingeless rotor configuration resembling the MBB BO-105, and various spanwise configurations of the flaps, including a single, a dual and a segmented five-flap configuration, were evaluated. Results indicate that the Gurney flap is capable of substantial reductions in blade vortex interaction (BVI) noise ranging from 3 to 6 dB. Vibration reduction ranging from 70 to 90 % was also demonstrated. Vibration and noise reduction was also examined at the same time and was found that reduction in one was linked to an increase on the other. Finally, the Gurney flap appeared to be more effective in reducing the BVI noise at both advancing and retreating sides, while the plain flap was more effective in reducing the vibrations.

The effectiveness of a single active Gurney flap in reducing vibration of a UH-60A Blackhawk helicopter in high-speed flight ($\mu = 0.35$) was studied by Bae and Gandhi (2012). An elastic blade was considered, and the Gurney flap was extending from 70%R to 80%R and was deployed to amplitude of 0.5 % of the chord. The Gurney flap actuation was most influential in reducing the vertical vibratory hub force. The most effective actuation input was 4/rev, and it led to 80 % reduction.

Comparing the above studies (Min et al. 2009; Liu et al. 2011; Bae and Gandhi 2012), to the ones conducted by Milgram et al. (1998) and Viswamurthy and Ganguli (2004), it seems that a Gurney flap can have a similar effect on the vibratory loads of the rotor hub like a conventional trailing edge flap. Such a flap is used in Viswamurthy and Ganguli (2004) on a soft hingeless rotor leading to a 72% reduction of the vibratory loads. However, the advantage of using a Gurney flap compared to a trailing edge flap is on the amount of energy required for the actuation and the ease of the implementation of the Gurney flap.

A further computational study (Yeo 2008) tried to assess active control mechanisms for rotor performance enhancement. A four-bladed rotor was considered at medium (80 kt) and high (150 kt) speed forward flight cases, and the Gurney flap was assumed to be either completely deployed or retracted. A significant increase in thrust for a given power was found when the Gurney was extended from 60%R up to 100%R and activated at the retreating side, which agrees with the outcome of the study by Cheng and Celi (2005) who defined the optimum 2-per-revolution inputs in order to improve the rotor performance by either increasing the thrust of the rotor or decreasing the torque requirement. However, the positive effect of the Gurney was observed at medium speed flight while at high speed the performance improvement diminished.

Gagliardi and Barakos (2009) studied a low twist hovering rotor and the effects of trailing edge flaps on its performance. A flap located inboard resulted in hover performance similar to a blade of 6° more twist. At the same time, a reduction of the trim angles was observed. A flap located outboard did not improve the performance of the rotor although by carefully optimising its configuration similar trim benefits as for the inboard flap were achieved. The majority of the previous studies are computational, and there is a need for experimental investigations of Gurney flaps on rotors.

1.8.2.1 Actuation Mechanism

The small size of the Gurney makes it promising for high-bandwidth active control with low actuation power requirements and minimal impact to the blade structure when compared to conventional control surfaces. Piezoelectric materials could be used for the actuation mechanism of the Gurney. The existence of piezoelectric materials has been known for many years, and they have been widely researched with numerous applications such as sonar, filters, microphones and mechanical actuators. The ceramic material, for example, lead zirconate titanate (PZT), generates an electrical charge in response to a mechanical stress and also the converse; the application of an electric field results in a mechanical strain of the ceramic material. The application of this effect can be used to apply loads to structures to achieve a desirable deformation.

1.9 Conclusions

Significant efforts have been made to delay or alleviate the retreating blade stall and improve the aerodynamic performance of rotorcraft. Passive and active control devices have been tested both experimentally and numerically mainly in aerofoils and to a lower extent in helicopters main rotors, either scaled or full models. As part of the Innovative Methods of Separated Flow Control project (IMESCON), the following study will focus on the use of active Gurney flaps as a means of controlling the retreating blade stall.

So far, Gurney flaps were used as passive control devices on race cars and recently as active control devices on rotorcraft for aerodynamic enhancement and alleviation of vibration. The control of blade stall can be addressed with a 1/rev actuation of the flap which may alter the handling qualities and the trimming of a helicopter. Thus, the main target of the current investigation is to prove that a Gurney flap can be fully deployed during hover to increase the thrusting capability of the main rotor, while in forward flight will be actuated on demand to delay or alleviate stall on the retreating side without changing the manoeuvrability of the helicopter.

References

Ashill PR, Fulker JL, Hackett KC (2001) Research at DERA on sub boundary layer vortex generators (SBVGs). In: 39th Aerospace Sciences Meeting and Exhibit

Badran B, McCormick S, Gursul I (1998) Control of leading-edge vortices with suction. J Aircr 35(1):163–165

Bae ES, Gandhi F (2012) Upstream active gurney flap for rotorcraft vibration reduction. In: Annual Forum Proceedings—AHS International, pp 1354–1362

Baker JP, Standish KJ, van Dam CP (2007) Two-dimensional wind tunnel and computational investigation of a microtab modified airfoil. J Aircr 44(2):563–572

Caruana D (2010) Plasmas for aerodynamic control. Plasma Phys Control Fusion, 52(12)

Chandrasekhara MS, Wilder MC, Carr LW (1998) Unsteady stall control using dynamically deforming airfoils. AIAA J 36(10):1792–1800

Chandrasekhara MS, Wilder MC, Carr LW (2001) Compressible dynamic stall control: comparison of two approaches. J Aircr 38(3):448–453

Cheng RP, Celi R (2005) Optimum two-per-revolution inputs for improved rotor performance. J Aircr 42:1409–1417

Chow R, van Dam CP (2006) Unsteady computational investigations of deploying load control microtabs. J Aircr 43(5):1458–1469

Chu P, He L, Tao WQ (2009) Three dimensional numerical study of flow and heat transfer enhancement using vortex generators in fin-and-tube heat exchangers. J Heat Transfer, 131(9):1–9

Dadfar R, Hanifi A, Henningson DS (2015) Feedback control for laminarization of flow over wings. Flow Turbul Combust, 94(1):43–62
Djojodihardjo H, Abdulhamid MF, Basri S, Abdul Majid D (2011) Numerical simulation and analysis of Coanda effect circulation control for wind-turbine application considerations. IIUM Eng J, Journal Spacial Issue, Mechanical Engineering
Gagliardi A, Barakos GN (2009) Analysis and design of a flap-equipped low-twist rotor for hover. J Aircr 46(1):74–84
Gai SL, Palfrey R (2003) Influence of trailing-edge flow control on airfoil performance. J Aircr 40(2):332–337
Hak MG (2001) Flow control: the future. J Aircr 38(3):402–418
Hassan AA (2001) Applications of zero-net-mass jets for enhanced rotorcraft aerodynamic performance. J Aircr 38(3):478–485
Hassan AA, Janakiram RD (1998) Effects of zero-mass “synthetic” jets on the aerodynamics of the NACA-0012 airfoil. J Am Helicopter Soc 43:303–311
Holmes A, Hickey P, Murphy W, Hilton D (1987) The application of sub-boundary layer vortex generators to reduce canopy “Mach rumble” interior noise on the Gulfstream III. 25th AIAA Aerospace Sciences Meeting, Aerospace Sciences Meetings. http://dx.doi.org/10.2514/6.1987-84
Huang RF, Mao SW (2002) Separation control on a cantilever wing with a self-excited vibrating rod. J Aircr 39(4):609–615
Jeffrey D, Zghang X (2000) Aerodynamics of gurney flaps on a single-element high-lift wing. J Aircr 37(2):295–301
Jeffrey D, Zhang X, Hurst DW (2008) Aerodynamics of gurney flaps on a single-element high lift wing. J Aircr 45(6):2062–2067
Joo W, Lee BS, Yee K, Lee DH (2005) Optimization of passive control devices for dynamic stall control. 43rd AIAA Aerospace Sciences Meeting and Exhibit - Meeting Papers, pp 5351
Karim MA, Acharya M (1994) Suppression of dynamic-stall vortices over pitching airfoils by leading-edge suction. AIAA J 32(8):1647–1655
Kato K, Breitsamter C (2015) Flow control on go 387 airfoil by using nanosecond pulse plasma actuator. Fluid Mech Appl
Kenning OC, Kaynes IW, Miller JV (2005) The potential application of flow control to helicopter rotor blades. 30th European Rotorcraft Forum, p 129
Keuthe AM (1972) Effect of streamwise vortices on wake properties associated with sound generation. J Aircr 9(10):715–719
Kinzel MP, Maughmer MD, Duque EN (2010) Numerical investigation on the aerodynamics of oscillating airfoils with deployable gurney flaps. AIAA J 48(7):1457–1469
Lee T, Su Y (2011) Lift enhancement and flow structure of airfoil with joint trailing-edge flap and gurney flap. Exp Fluids 50(6):1671–1684
Li Y-H, Wu Y, Song H-M, Liang H, Jia M (2011) Plasma flow control. Aeronautics and Astronautics book
Liebeck RH (1978) Design of subsonic airfoils for high lift. J Aircr 15(9):547–561
Lin JC (2002) Review of research on low-profile vortex generators to control boundary-layer separation. Prog Aerosp Sci 38:389–420
Lin JC, Robinson SK, McGhee RJ, Valarezo WO (1994) Separation control on high lift airfoils via micro-vortex generators. J Aircr 31(6):1317–1323
Liu L, Padthe AK, Friedmann PP (2011) Computational study of microflaps with application to vibration reduction in helicopter rotors. AIAA J 49(7):1450–1465
Lorber P, McCormick D, Anderson T, Wake B, MacMartin D (2000) Rotorcraft retreating blade stall control. Fluids Conf Exhibit
Maughmer MD, Bramesfeld G (2008) Experimental investigation of gurney flaps. J Aircr 45(6):2062–2067
McCormic DC (1993) Shock/boundary-layer interaction control with vortex generators and passive cavity. AIAA Paper 31(1):91–96

Meunier M, Brunet V (2008) High lift devices performance enhancement using mechanical and air-jet vortex generators. J Aircr 45(6):2049–2061
Milgram J, Chopra I, Straub F (1998) Rotors with trailing edge flaps: analysis and comparison with experimental data. J Am Helicopter Soc 43(4):319–332
Min B, Sankar LN, Rajmohan N, Prasad J (2009) Computational investigation of gurney flap effect on rotors in forward flight. J Aircr 46(6):1957–1964
Mitchell AM, Barberis D, Molton P, Dalery J (1996) Oscillation of vortex breakdown location and blowing control of time-averaged location. AIAA J 38(5):793–803
Moralev I, Klimov A, Bityurin V, Kazansky P (2014). Lift and drag control of NACA 23012 airfoil model by surface HF plasma actuator. In: 52nd AIAA Aerospace Sciences Meeting, SciTech
Mushtak A-A (2011) Experimental investigation of the use of synthetic jets for mixing in vessels. J Fluids Eng Trans ASME 133(9)
Padthe AK, Liu L, Friedmann PP (2011) Numerical evaluation of microflaps for on blade control of noise and vibration. Collection of Technical Papers—AIAA/ASME/AHS/ASC Structures
Park J, Choi H (1999) Effects of uniform blowing or suction from a spanwise slot on a turbulent boundary layer flow. Phys Fluids 11(10):3090–3105
Post ML, Corke TC (2006) Separation control using plasma actuators: dynamic stall vortex control on oscillating airfoil. AIAA J 44(12):3125–3135
Prince SA, Khodagolian V (1996) Low-speed static stall suppression using steady and pulsed air-jet vortex generators. AIAA J 49(3):642–654
Prince SA, Khodagolian V, Singh C, Kokkalis T (2009) Aerodynamic stall suppression on airfoil using passive air-jet vortex generators. AIAA J 47(9):2232–2242
Rao JR, Kariya TT (1988) Boundary layer submerged vortex generators for separation control—an explanatory study. 1st National Fluid Dynamics Conference
Shun S, Ahmed NA (2011) Airfoil separation control using multiple-orifice air-jet vortex generators. J Aircr 48(6):2164–2169
Singh C, Peake DJ, Kokkalis A, Khodagolian V, Coton FN, Galbraith RA (2006) Control of rotorcraft retreating blade stall using air-jet vortex generators. J Aircr 43(4):1169–1176
Tang D, Dowell E (2007) Aerodynamic loading for an airfoil with oscillating gurney flap. J Aircr 44(4):1245–1257
Taylor HD (1947) The elimination of diffuser separation by vortex generators. Rep. R-4012-3, United Aircraft Corporation Research Department
Troolin D, Longmire E, Lai W (2006) Time resolved PIV analysis of flow over a NACA 0015 airfoil with gurney flap. Exp Fluids 41(2):241–254
Viswamurthy SR, Ganguli R (2004) An optimization approach to vibration reduction in helicopter rotors with multiple trailing edge flaps. Aerosp Sci Technol 8(3):185–194
Wang JJ, Li YC, Choi KS (2008) Gurney flap—lift enhancement, mechanisms and applications. Prog Aerosp Sci 44(1):22–47
Yee K, Joo W, Lee DH (2007) Aerodynamic performance analysis of a gurney flap for rotorcraft applications. J Aircr 44(3):1003–1014
Yeo H (2008) Assessment of active controls for rotor performance enhancement. J Am Helicopter Soc 53(2):152–163
Yu YH, Lee S, McAlister KW, Tung C, Wang CM (1995) Dynamic stall control for advanced rotorcraft application. AIAA J 33(2):289–295