Heavy Class Helicopter Fuselage Model Drag Reduction by Active Flow Control Systems

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Abstract. A comprehensive experimental investigation of helicopter blunt fuselage drag reduction using active flow control is being carried out within the European Clean Sky program. The objective is to demonstrate the capability of several active flow technologies to decrease fuselage drag by alleviating the flow separation occurring in the rear area of some helicopters. The work is performed on a simplified blunt fuselage at model-scale. Two different flow control actuators are considered for evaluation: steady blowing, unsteady blowing (or pulsed jets). Laboratory tests of each individual actuator are first performed to assess their performance and properties. The fuselage model is then equipped with these actuators distributed in 3 slots located on the ramp bottom edge. This paper addresses the promising results obtained during the wind-tunnel campaign, since significant drag reductions are achieved for a wide range of fuselage angles of attack and yaw angles without detriment of the other aerodynamic characteristics.

1. Introduction
The performance of heavy transport helicopters, having a large, and almost flat, loading ramp suffer from poor aerodynamics of the aft body.

In cruise flight condition, the component of the rotor power due to counter balance the helicopters parasite force is of the order of 45% to 55% of the total requirements depending by the helicopter class, as observed in 1975 by Stroub and Rabbit [1] and later by Gatard et al in 1997 [2]. More recent fuselage and rotor head drag breakdown studies [3], [4], indicate that about 69% of the total parasite drag can be ascribe to the fuselage and the remaining 31% is due to the rotor head for heavy class helicopters. Further detailed drag breakdown (Figure 1) indicates that the basic fuselage contributes with about 19%, engine cowls by 11%, sponson about 5%, empennage with 7%, tail rotor head, cooling system and Aerials respectively for about 5%, 6% and 16%.

Consequently, fuselage drag reduction is one of the main objectives in order to improve helicopter performance, to reduce fuel consumption and environmental impact. Heavy helicopter fuselages are often characterized by a rear loading ramp that significantly affects the aerodynamic performance. The transport helicopter fuselage can be assimilated to a blunt body and the aft region is typically characterized by flow detachment at the lower corner, generating a separation bubble and a system of streamwise vortices at the sides. These vortical structures present some similarity to those separated from hatch-back cars [5]. The flow separation and the longitudinal vortex always cohabit on the aft region, when the flow separation is predominant the flow is named “eddy flow” otherwise it is called “vortex flow.” The fuselage drag magnitude is strictly influenced by the hatch flow topology, being related with the fuselage incidence angle (α) and with the loading door upsweep angle (ϕ) as widely
discussed by Seddon in 1990 [6]. Furthermore, a point not to be neglected is that the flow separation interacting with the fuselage tail induces strong vibration and submits the airframe to fatigue cycles.

Fuselage drag reduction can be obtained by means of an optimization of the aerodynamic design [7] - [8] and by improving the streamlined geometry [9](for example fishtailed geometry characterized by small upsweep angles $\phi=15^\circ$ instead of blunt body fuselage with large upsweep angles ranging between $30^\circ$ to $35^\circ$). In alternative, fuselage drag reduction can be pursued by using flow control systems [9], when the operative requirements prevent substantial modifications of the fuselage geometry or the retrofit of existing rotorcraft is required.

During the last years several research teams investigated the possibility to reduce helicopter fuselage parasite drag by means of active flow control (AFC) systems. Large interest was driven by synthetic jets (SJ) actuators. In 2005 Martin et al [11] investigated numerically and experimentally the influence of 12 SJ actuators on a helicopter fuselage obtaining drag reduction in the range between 6 and 10% and estimating the possibility to reduce by almost 40% the lift download. Analogous results were obtained by Ben-Hamau et al in 2007 obtaining drag reductions in the range between 3 to 11% for different attitudes and yaw angles [12] using blowing coefficient values ranging between $C_\mu$: 0.025 to 0.05. In 2010 a NASA and ONERA collaboration [13] investigated numerically and experimentally the behavior of different AFC systems (steady blowing and SJ), obtaining remarkable results in drag reduction, with the steady blowing system able to reduce up to 35% the fuselage drag at a $C_\mu$ of 0.06 and the synthetic jets inducing a decrement up to 26% operated at a $C_\mu$ of 0.038. A contribution to understanding the ACF influence on the helicopter fuselage has been provided by Le Pape et al in 2013 [15] with their comprehensive work investigating its effect on fuselage drag and lift download. A further promising control system is the COMPACT (Combustion Powered actuation) [16], a novel technology which exploits the chemical energy of gaseous fuel/oxidizer mixture to create a high pressure burst and subsequent high momentum jet of exhaust products. In 2011 the chemical powered actuators were investigated by George et al [17] and by Woo et al [18] on the ROBIN fuselage model obtaining a drag reduction of the order of 12 to 17 % but also a significant increment of the lift download. The authors claimed that the COMPACT actuator is the possible solution to overcome the shortage of momentum of the SJ based on piezoelectric membranes. Another interesting actuator is the fluid oscillators investigated by Martin et al [19] on the ROBIN fuselage equipped of powered rotor. The results indicated, in some cases, a reduction of the total drag of the order of the 20% with respect to the baseline configuration.

Although many efforts have been made in the past, there is still a large interest and different flow control systems are being investigated in order to increase the fuselage performance. Additional efforts are necessary in order to understand the interaction between the flow topologies and the selected actuators. Previous experiments duly investigated the fuselage behavior for different attitude angles but many presented some shortcomings regarding the influence of the yaw angle on the effectiveness of the flow actuators and few discussed the effect on the lift download and on the pitching moment.
This research was driven by the interest to understand the flow topology of a heavy transport helicopter fuselage and in what manner it could be possible to obtain a drag reduction by using steady and unsteady blowing (or pulsed jet) actuators without penalizing the other aerodynamic characteristics. As initial activities, a comprehensive experimental and CFD investigation was conducted at laboratory level on a small simplified fuselage model equipped by steady blowing and pulsed jets at a Reynolds number based on the fuselage length of about 1 million [20]. The investigation provided a clear picture of the flow characteristics in the region of the loading ramp for different values of the incidence angle. The Wind Tunnel Test (WTT) delivered a better understanding of the effect of the steady and pulsed jets in alleviating the pressure drag inducing flow reattachment and deflecting the longitudinal vortex path. Furthermore, fundamental indications regarding the position and the direction of the jet slot were gathered.

This research foresees the experimental assessment of the flow control systems on a heavy class helicopter fuselage model at larger Reynolds number (Re: 8.2*10^6). The paper first describes the simplified helicopter model and the wind-tunnel test set-up. A second part is dedicated to the presentation of the different actuators and their property and performance evaluation during specific laboratory tests. Wind-tunnel tests measurements that include aerodynamic loads acting on the fuselage, static pressure taps and PIV measurements are presented and discussed. An overall analysis of the results including actuators comparison with respect to achieved drag reduction is then presented.

2. Experimental Set up
An overview of the investigated test article, wind tunnel, experimental set up, model measurement instrumentation, flow control system and flow velocity measurement system is provided in this section.

2.1. Wind tunnel description
The test campaign was conducted at the RUAG LWTE wind tunnel, an atmospheric closed loop wind tunnel with closed test section.

Test section main sizes are: height of 5 m, width of 7 m and length equal to 11 m. The test section sizes assure negligible wall interferences on the load measurements (Figure 6). The ratio between model cross section and the tunnel test section is 0.45%, much smaller than the value of 5% where the wall interference becomes significant and wall corrections are necessary [21].

Maximum achievable flow speed is 70 m/s with a turbulence level of 0.3% on longitudinal velocity and 0.15% on the lateral velocity at 65 m/s. The full test campaign was carried out at constant speed of \( V_U = 50 \text{ m/s} \) and Reynolds number, based on the fuselage length, of 8.2*10^6. The fuselage was investigated varying the incidence angle in sweep mode between -12° to +16° at fixed yaw angle of \( \beta = 0° \) and \( \beta = 5° \), and sweeping the yaw angle \( \beta \) between -15° to +15° at incidence angle of \( \alpha = 0 \) and at cruise flight incidence angle of \( \alpha = -3° \). The model was mounted in the up-right position and supported by a dorsal strut in order to minimize disturbances in the regions of interest.

2.2. Simplified fuselage Model
The investigation was carried out on the basic fuselage model representing the main characteristics of a well-known heavy class helicopter. The term “basic fuselage” indicates that sponsons, cowls, empennage, landing gears, rotor head and aerial excrescences have been removed. The tested model was geometrically scaled 1 to 7 with respect to the full scale vehicle and it is characterised by a rear loading ramp having an up-sweep angle of \( \phi = 32° \). The model is composed of an internal structure on which are mounted the external fuselage surfaces and the measurement instrumentations.

The model is equipped by 135 pressure taps (Figure 2). The pressure taps are located on the model nose, on the plane of symmetry, on several waterlines (\( y/H = 0, 0.26 \) and 0.54 where \( H \) is the fuselage height) and on the aft region at different stations (\( x/L = 0.64, 0.68, 0.72 \) and 0.75 where \( L \) is the fuselage length) along the loading ramp and the tail boom. A single transition strip was placed on the nose cone to facilitate the laminar to turbulent transition on the fuselage.
2.3. Model Instrumentation
The aerodynamic loads were measured by an internal six components balance, whose main characteristics in terms of full scale and accuracy are summarised in Table 1. The balance was installed in the model central part on a steel plate as close as possible to the mass centre.

| Table 1: Balance type 192 RUAG main characteristics |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | $F_x$ [N]        | $F_y$ [N]        | $F_z$ [N]        | $M_x$ [Nm]       | $M_y$ [Nm]       | $M_z$ [Nm]       |
| Design loads   | 350             | 250             | 1200            | 100             | 120             | 130             |
| Accuracy       | 0.4             | 0.7             | 0.9             | 0.02            | 0.02            | 0.06            |

Two inclinometers with accuracy of 0.03° degree were installed to measure the pitch and roll attitude of the wind tunnel model. The yaw angle position was provided by the rotating model support. In addition, an electrolevel was used to reliably and quickly set the model to the zero reference pitch attitude and a further MEMS inclinometer was placed as backup. All these instrumentations were mounted on the aluminum plate available on the front of the fuselage (Figure 3).

A total of three pressure transducers modules with 64 ports each (with full scale of 1 psi and accuracy of 0.03 % FS) were used for measuring the 135 pressure ports. One pressure transducer module was mounted on the front part of the model to cover the nose pressure taps while the remaining two were mounted in proximity of the model aft where the PTS are concentrated.

2.4. Flow control system description
The simplified fuselage model foresees three actuator slots, crosswise directed and located on the bottom of the ramp. Each blowing slot is characterised by length and width respectively of $L_j=105$ mm and $W_j=1.8$ mm and directed with respect to the ramp surface of a jet angle of $\alpha_j=-37^\circ$. Each slot was connected to a dedicated pneumatic circuit feed by pressurized air. Up-stream of each slot a resonant cavity is present in order to level the flow coming out from the slots. Particular care in designing the pneumatic circuit was given in order to minimize the pressure losses.
Figure 4: AFC operating scheme

Two different AFC systems were considered: steady blowing and pulsed jet operating from the rear bottom slots. The steady blowing jet was obtained feeding the cavity by external air supply through the model allowing several flow rates and blowing velocities to be tested. The pulsed jet was achieved modulating the supplied mass flow by means of a rotating valve. The valve consists of two concentric cylinders. The inner cylinder (or rotor) rotates around its axis of revolution driven by an electrical stepper motor. The Outer cylinder (or stator) is fixed. The inner cylinder contained 7 apertures with diamond shape and equally angular spaced on the same circumference. The outer cylinder contains 3 circular apertures along the circumference and in correspondence of the rotor apertures. The air transfer is obtained when the rotor apertures align with the stator apertures. The pulse frequency $f_j$ is calculated multiplying the rotating speed by the number of rotor apertures $f_j = \omega \times N_s$. Varying the rotating speed and the flow rate was possible to change the jet frequency and the blowing speed. Figure 3 shows the rotating valve, inlet and outlet, tube routing and the plenum chambers mounted inside the model. The rotating valve supply the pressurised air to the three slots at the same time. A strong Coanda effect induces the jet flow attachment to the rear ramp (Figure 4).

2.5. Flow Measurements

The flow field characteristics downstream of the fuselage aft region were investigated by two PIV measurement systems: a standard two components PIV (2C-PIV) system and a stereo PIV (S-PIV) system. The stereo measurements were carried out at three different vertical cross planes at different distances from the model nose ($x/L=0.75$, 0.81, and 0.86) and respectively named PIV1, PIV2, PIV3. The two components measurements were performed on the symmetry plane ($y/W=0$) downstream the loading ramp and indicated as PIV4 (Figure 5).

Figure 5: PIV recording region

The S-PIV system was composed of two Nd-Yag resonator heads providing a laser beam of about 320 mJ each at 532 nm and by two double frame CCD cameras (2048x2048 pixels) whereas the 2C-PIV system was composed of two Nd-Yag resonator heads ($E=200$ mJ at 532 nm) and by a single PIV sCMOS sensor camera (2560x2160 pixels). Particles of about 1 \(\mu\)m of diameter, composed of DEHS oil, were used as seeding. The seeding was injected downstream of the test section in order to obtain uniform seeding concentration of the full circuit. The lasers were located under the test section. The
laser light sheet was projected upward into the test section trough an acrylic window installed in the test section floor. The light sheet optics were mounted on a linear traversing system remotely controlled in order to translate the light sheet along the wind tunnel longitudinal axis. Each recording camera belonging to the S-PIV was mounted on a 2D linear traversing system and located outside of the test section, inside the door frames of the side wall rear doors, downstream of the model. The traversing systems allowed to rigidly translate the cameras and light sheet plane without the need for additional calibrations of the stereo set up. Each camera was equipped with a motorised Scheimpflug support, 200 mm Canon EOS lens and lens remote control. The viewing angle between the stereo cameras was about 82°, close to the optimum values of 90°. The 2C-PIV camera equipped with an 80mm Canon lens which was mounted in a fixed position outside the left lateral wall behind a windows (Figure 6). The camera was directed towards the model loading ramp region.

Figure 6: Recording lay-out in WT test section.

3. Active Flow Control laboratory characterization.
Before the wind tunnel test campaign, particular care was taken for characterising the steady blowing and pulsed jet pneumatic system. A dedicated laboratory test campaign was carried out in order to obtain the transfer function relating the flow volume rate to the mean and maximum jet velocity for each single slot.

Figure 7: Steady and Pulsed Jet velocity vs the flow rate. Steady jet velocity are indicated by a triangle symbol, the pulsed jet maximum, mean and minimum speed are indicated respectively by circle, square and diamond symbols. The jet frequency is indicated next to the symbol.
The flow rate was measured by a flowmeter model SD8000 with measuring range between 0.25 to 225 m$^3$/h and accuracy equal to the 3% of the FS. The flow velocity at the different slot exit was measured by means of an IFA300 constant temperature anemometer system using single and double wire sensors.

The steady blowing jet speed was measured varying the volume flow rate. Analogously the velocity time history was measured varying the jet frequency and the volume flow rate for the pulsed jet actuators. The results indicate an almost linear behaviour of the mean jet speed varying the flow rate for the case of the steady blowing actuators (Figure 7). The pulsed jet characterization presents similar behaviour for the mean velocity while an influence of the jet frequency is evident on the maximum and minimum values. The results (Figure 7) present a reduction of the velocity amplitude increasing the jet frequency. The pulsed jet induces an increment of the maximum speed of about the 30-35% with respect to the steady jet for the same flow rate.

Once that the steady and pulsed jet were characterized in terms of mean and peak velocity in the full achievable frequency range it was possible to calculate the characteristic non dimensional quantities defined for evaluating the flow control systems [9]. In particular the jet frequency normalised as:

$$F^+ = f_j \cdot \frac{W}{V_\infty}$$

where $f_j$ is the pulse jet frequency, $W$ the fuselage width and $V_\infty$ the free stream velocity and the blowing coefficient $c_{\mu}$, defined as the sum of the contribution of each blowing jet:

$$c_{\mu} = \sum_j \frac{\rho_j A_j V_j^2}{A_{CS} 0.5 \rho_\infty V_\infty^2}$$

where $A_j$, $\rho_j$ and $V_j$ are respectively the actuator slot surface, flow density and maximum speed and $A_{CS}$, $\rho_\infty$ and $V_\infty$ are the fuselage cross section, free stream density and velocity. The AFC laboratory characterization provided the achievable non dimensional parameters reported in Table 2.

| Parameters                  | range      |
|-----------------------------|------------|
| Reduced Frequency $< F^+ >$ | 0.15 – 1.4 |
| Blowing momentum coefficient $< c_{\mu} >$ | 0.02 – 0.1 |
| Number of slots             | 5          |

4. Test Matrix

The test matrix foresaw first the investigation of the aerodynamic behaviour of the baseline model without AFC system varying the angle of attack at fixed yaw angle and for prefixed values of the angle of attack varying the yaw angle. The model incidence angle was varied in the range between -12° to +16° in sweep mode with an angle resolution of 0.1° at $\beta=0$ and $\beta=-5°$. Similarly the fuselage behaviour was investigated varying the yaw angle in sweep mode from $\beta=-15°$ to $\beta=15°$ at fixed attitude: null angle of attack ($\alpha=0°$) and cruise condition ($\alpha=3°$).

Once that the baseline behaviour was assessed, the influence of the steady and pulsed jet was investigated varying the flow control parameters for all the selected incidence angles in the operating range reported in Table 3.

| Actuators     | Flow Volume [m$^3$/h] | Blowing coefficient $c_{\mu}$ | Frequency [Hz] | $F^+$ [-] |
|---------------|-----------------------|------------------------------|----------------|---------|
| Steady Blowing| 50-60-80              | 0.005-0.007-0.012            | -              | -       |
| Pulsed Jet    | 50-60                 | 0.008-0.012                  | 140            | 1.14    |
5. Results
The wind tunnel flow quality and experimental set up provided very high quality measurements, and an excellent test repeatability. The comparison between the aerodynamic forces and moments coefficient show a fairly good agreement. For example the drag coefficient discrepancy was much smaller of the CD accuracy ±0.4·10⁻⁵.

5.1. Baseline
The basic fuselage model was considered as baseline configuration and compared with the different flow control systems. The alpha sweep polar were carefully investigated (Figure 8). For confidentiality reason the discussion of the results is carried out normalizing the aerodynamic coefficient with respect to their values at null incidence angle (CD₀, CL₀ and CMY₀). The normalized drag coefficient indicates a reduction varying the model incidence from α=−12° to about α=−5°. Here the curve slope decreases in concomitance with the occurrence of the flow separation on the loading ramp for reaching a minimum value at about α=+3°. Further increasing the angle of attack, the drag shows a continuous increment up to α=+11.4° where an abrupt reduction is present with a minimum at about α=12.10°. At this point, the flow is fully attached. Increasing the angle of attack the drag coefficient presents a positive slope with a marked CD growth. The normalized lift coefficient shows a constant positive slope along the full sweep range, characterized by a slope reduction in the region affected by the flow separation. Similarly the flow separation region is visible also in the pitching moment behavior, where the curve slope increases in the range between α=−5° to α=12°.

![Figure 8: Baseline aerodynamic characterization: normalised drag, lift and pitching moment coefficient with respect to the corresponding values at α=0° varying the incidence angle at β=0°.](image)

The surface pressure distribution measurements provide valuable information of the flow behavior. The longitudinal pressure distribution indicates the values of the incidence angle where the eddy flow condition occurs (left diagrams in Figure 9). For the cases of α≤−5° and α≥ 12°, the pressure coefficient presents a marked expansion in concomitance of the sweep angle followed by a pressure recovery along the length of the model, indicating a fully attached flow.

For the fuselage attitude interval between −5°<α<12°, immediately downstream the rear sweep angle, the pressure coefficient shows a constant value confined between x/L=0.63 to x/L=0.68 indicating separated flow on the ramp. Furthermore, the pressure data indicates that increasing the incidence angle the separated region presents an increment (right diagram in Figure 9).
Figure 9: Baseline longitudinal pressure distribution at different angle of attach and $\beta=0^\circ$. The boundaries of the loading ramp are indicated by the vertical red lines.

This result is confirmed by the flow velocity measurement on the rear ramp symmetry plane. At $\alpha=-3^\circ$, the ensemble average velocity field colour map shows a recirculating region extending from the bottom edge of the fuselage to about the 70% of the loading ramp. As the angle of attack is increased, the flow separation presents a growth up to reach at $\alpha=+7.3^\circ$ the tail boom (Figure 11).

The spanwise pressure distribution (Figure 10), together with the cross flow measurement (Figure 12), provides a clear indications about the flow topology. At $\alpha=-8^\circ$, the spanwise pressure distribution at different stations ($x/L=0.64, 0.68, 0.72, 0.75$ and $0.86$) shows a pressure recovery moving along the $x$ direction, indicating an attached flow. Analysing the spanwise direction, an expansion toward the fuselage edge is encountered suggesting the presence of two longitudinal counter rotating vortices. At $\alpha=0^\circ$, the pressure distribution shows at the first two stations straight constant values representative of the presence of flow separation. Moving downstream the ramp, the pressure coefficient indicates a flow reattachment and the presence of longitudinal vortices. At $\alpha=12^\circ$ straight spanwise distributions indicate the absence of vortex flow and the pressure recovery suggest a fully attached flow.

Figure 10: Baseline crosswise pressure distribution at different incidence angles. Left diagram $\alpha=-8^\circ$, central diagram $\alpha=0^\circ$ and right diagram $\alpha=12^\circ$.

Also in this case the pressure indications are confirmed by the PIV results (Figure 12). For angle of attack of $\alpha=-3^\circ$, the cross flow velocity map indicates the presence of separated flow and two counter rotating vortices. Similar behavior is encountered at $\alpha=0^\circ$ but in this case the vorticity colour maps suggests that weaker vortices are present. Flow velocity results at $\alpha=+4.5^\circ$ and $+7.3^\circ$ indicate the presence of eddy flow and the absence of vortex flow.
Figure 11: Baseline flow velocity contour map at different incidence angles. Longitudinal plane PIV4

Figure 12: Baseline flow velocity field contour map at different incidence angles. Crosswise plane

Helicopters are often operated in side flow conditions. For this reason the fuselage behaviour was investigated sweeping the yaw angle between $-15^\circ < \beta < +15^\circ$ at constant values of the incidence angle ($\alpha=-3^\circ$ and $\alpha=0^\circ$). The drag coefficient presents a symmetric behaviour whereas the lift and pitching moments presents an hysteresis contribution (Figure 13). The side flow induces an increment of the fuselage drag as an increment of lift download.

Figure 13: Baseline aerodynamic characterization: normalised drag, lift and pitching moment coefficients versus beta sweep angle at $\alpha=0^\circ$.

5.2. Steady Blowing Actuator Results

The experimental assessment of the AFC systems in terms of drag reduction was the main scope of the project. At the same time, it was of great importance to verify that the benefits obtained by the drag alleviation were without detriments to the other quantities in particular lift and pitching moment coefficients.

Three different values of the blowing flow rates were investigated corresponding respectively to $c_p=0.005$, 0.007 and 0.012. In the full incidence angle range, the diagram of the drag coefficient presents a clear benefit in terms of drag reduction varying from a minimum of 5% to a maximum of 22% with respect to the baseline configuration (left diagram in Figure 14). The case characterised by a flow rate
of $Q_1=50 \text{ m}^3/\text{h}$ corresponding to $c_{\mu}=0.005$, shows a drag alleviation although the data still indicate that flow separation occurs in the range between $\alpha=-2^\circ$ to $\alpha=+11^\circ$. The drag reduction is further enounced for $Q_2=60 \text{ m}^3/\text{h}$ ($c_{\mu}=0.007$), but still limited flow separation occurs in the range between $\alpha=0^\circ$ to $\alpha=+10^\circ$. The larger flow rate value ($Q_3=80 \text{ m}^3/\text{h}$ corresponding to $c_{\mu}=0.012$) provides the best behaviour inducing a full flow reattachment on the fuselage.

The steady blowing system presents a positive effect on the lift coefficient as well. The steady blowing results indicate a benefit in terms of lift download reduction up to 70% for almost all the attitude angles except in the range between $\alpha=-5^\circ$ to $\alpha=+1^\circ$ where a maximum price of about 22% is paid in terms of download increment (central diagram in Figure 14).

Some consideration can also be made regarding the effect of the steady jet on the pitching moment behaviour. The steady blowing actuator generates a benefit increasing the aerodynamic stability of the fuselage. Mostly the pitching moment coefficient decreases with respect to the baseline and it presents an advantage in terms of longitudinal stability.

![Figure 14: Steady blowing actuator contribution on the normalised aerodynamic coefficients](image)

In detail the effect of the steady blowing actuators is described by the longitudinal and spanwise pressure distribution (Figure 15). The longitudinal pressure distribution shows a pressure recovery with respect to the baseline behaviour as the blowing coefficient increases. The lower value of the blowing coefficient is not sufficient to induce the flow reattachment partially obtained with $c_{\mu}=0.007$ and fully reached using $c_{\mu}=0.012$. The flow velocity map on the fuselage symmetry plane at $\alpha=-3^\circ$ confirms this behaviour. The baseline presents a noticeable flow separation on the loading ramp, that almost disappears activating the steady blowing actuators at $c_{\mu}=0.007$ (Figure 20). Just a limited circulation bubble is located on the conjunction between the ramp and the tail boom.

![Figure 15: Steady blowing contribution to pressure distribution. Longitudinal (left diagram) and spanwise (centre and right diagrams) behaviour for different blowing coefficient.](image)

The spanwise distribution at $x/L=0.72$ and 0.75 confirms the pressure recovery and the presence of two longitudinal vortices, characterised by two expansion peaks. The spanwise pressure distribution
indicates a reduction of the expansion peaks due to the steady blowing actuators justifying the reduction of the fuselage pressure drag. The crosswise PIV plane at x/L=0.81 shows a fully attached flow and the presence of the two counter rotating vortices shedding by the fuselage. The results indicates an increment of the intensity of the vortices due to the steady blowing actuator and a displacement of the centre of the vortices moving apart by the symmetry plane (Figure 21).

The actuator effectiveness is demonstrated also on the sweep beta polar carried out at α=0°. The drag coefficient presents a reduction ranging between 6% to 16% with respect to the baseline configuration. The lift download is characterised by an increment up to a maximum value of 50% in the incidence range between α=-4° to α=+5° and a marked reduction up to 70% on the rest of the angle range. The pitching moment coefficient presents for the complete range of the yaw angle a reduction (Figure 16).

5.3. Pulsed Jet Actuator Results

The main characteristic of the unsteady blowing with respect with the steady blowing actuator is to provide larger momentum and blowing coefficient for equal flow rate used. In the following the discussion is centred on the pulsed jet assessment at flow rate of Q=60m³/h and characterised by a total blowing coefficient of cμ=0.012 versus the steady jet operated at flow rate of Q=80m³/h and similar blowing coefficient.

The drag coefficient indicates a reduction with respect to the baseline ranging between 4% to 24% along the full incidence sweep. The pulsed jet, although fed by a flow rate quantity smaller by 25%, has almost the same behaviour if not slightly better with respect to the steady blowing system (Figure 17). Analogously to the steady blowing behaviour the lift coefficient presents improvements with respect to the baseline up to 100% for α<-7 and α>+6 and a loss in terms of download increment up to a maximum of 50%. The pitching moment coefficient shows a reduction of the diagram slopes indicating an increment of the longitudinal stability.

Figure 17: Pulsed jet and steady blowing contribution on the normalised aerodynamic coefficients.

The longitudinal and spanwise pressure distributions show a flow reattachment induced by the activated pulsed jets (Figure 18). The pressure track of the steady and pulsed jet are almost equivalent.
up to $x/L=0.72$. Downward the additional flow rate quantity of the steady blowing actuators further forces the pressure recovery. The wake investigation downstream the rear part of the fuselage provides similar results. The flow separation is reduced and almost removed by the pulsed jets except on the edge between the ramp and the tail boom (Figure 20). The longitudinal vortex flow detected on the crossplane at $x/L=0.81$ presents a behaviour similar to that one induced by the steady blowing. Larger vorticity intensity and core displacement moving apart from the symmetry plane (Figure 21).

Figure 18: Pulsed Jet and Steady Blowing contribution to pressure distribution. Longitudinal (left diagram) and spanwise ($x/L=0.72$ on centre and $x/L=0.75$ on the right) behaviour at $c_{\mu}=0.012$.

The pulsed jet effectiveness is demonstrated also on the sweep of the beta polar carried out at $\alpha=0^\circ$. The drag coefficient presents a reduction ranging between 8% to 20% with respect to the baseline configuration and a better behaviour regarding the steady blowing. The lift download is characterised by an increment up to a maximum value of 70% in the incidence range between $\alpha=-5^\circ$ to $\alpha=+5.5^\circ$ and a marked reduction up to 80% on the rest of the angle range. The pitching moment coefficient presents a reduction for the complete range of the yaw angle (Figure 19).

Figure 19: Pulsed Jet effect on the sweep yaw angle polar.

Figure 20: Flow axial velocity contour map comparison: Baseline, steady blowing and pulsed jet.
6. Conclusions
A comprehensive test campaign was successfully performed at the RUAG LWTE wind tunnel aimed to investigate the possibility to reduce the helicopter fuselage passive drag by means of different flow control systems. Two types of AFC systems were designed, manufactured and tested: steady blowing and pulsed jets operating from the bottom of the rear fuselage hatch.

The comprehensive test campaign has foreseen the following activities:

- Aerodynamic model force and moments measurements;
- Model surface pressure characterization;
- Wake flow field measurements by 2C and 3C PIV measurements.

Both flow control systems provided remarkable results in terms of drag reductions without almost any detriments of the other aerodynamic quantities. The flow control systems were effective for all the investigated incidence and yaw angles.

The flow control systems were successful for values of the blowing coefficient smaller respect the values reported in the literature [13] and [15] and with respect to the values measured during the previous laboratory test [20].

The following main results are reported:

1. The steady blowing actuators, operated from the ramp bottom at different values of the blowing coefficient, induce a model drag reduction with respect to the baseline configuration from a minimum of 5% to a maximum of 23% for the complete incidence model range.
2. The steady blowing actuator generates a benefit in terms of lift download reduction up to a maximum of 100% for the total angle of attack range except between -5° < α < +2° where the lift down can increases up to a maximum of 50%.
3. Some consideration may be made regarding the effect of the steady blowing on the pitching moment behaviour. The slope of the pitching moment diagram decreases with respect to the baseline and it presents an advantage in term of longitudinal stability.
4. The steady blowing system presents benefits in terms of aerodynamic coefficients also for the complete sweep of the beta polar. In particular the results show a drag reduction with respect to the baseline configuration between 6 to 16%, benefits and some drawback are encountered for the lift coefficients and reduction of the pitching moment diagram slopes increasing the longitudinal stability.
5. The pulsed jet actuator operated at different values of the blowing coefficient and jet frequency of fj=140 Hz, induces a model drag reduction with respect to the baseline configuration between 4 to 24% for the model incidence range of -12° < α < 12°. For values of α > 12° a small increment of about 1% is present.
6. The Pulsed Jet actuator induces a remarkable benefit in terms of lift download reduction up to 100% for the total angle of attack range except between -7° < α < +6° where the lift download can
increases up to a maximum of 70%. With respect to the steady blowing the lift detriment is increased.
7. Analogously, the pulsed jets induce a model drag reduction with respect to the baseline configuration between 8 to 20% also for the complete sweep of the beta polar.
8. The longitudinal pressure measurements clearly indicate a flow separation reduction and an increment of the pressure recovery on the loading ramp due to the flow control systems. The spanwise pressure distribution indicates the flow topology occurring on the loading ramp, whether eddy or vortex flow and the effect induced by the AFC systems.
9. The flow field measurements indicate clear wake alleviation in terms of size and momentum loss due to the flow control systems and confirms the indication provided by the pressure measurements regarding the flow separation and topology.
10. The vortices development for the different model attitudes has been measured and vortex growth and the dissipation phenomena can be investigated.
11. A comprehensive experimental data base has been generated for future comparison with the CFD simulations.

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