HANDLING QUALITIES ASSESSMENT OF THE EFFECTS OF TAILBOOM STRAKES ON THE BELL 412 HELICOPTER

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Abstract

Flight tests were recently conducted at the National Research Council of Canada Flight Research Laboratory on the Bell 412 helicopter to evaluate the effects of the Boundary Layer Research tailboom strakes on aircraft handling qualities and control margins. Handling qualities were assessed using a selection of the standard hover/low speed manoeuvres from ADS-33, while control margins were examined by collecting trim position data at various low airspeeds and relative wind azimuths. The results indicated that the strakes offer a 0.5 to 1.0 Cooper-Harper handling qualities rating improvement for most manoeuvres, particularly with the stability augmentation system turned off. The strakes also improved the pedal margins resulting in the pilot using less left pedal when flying at low speed and reduced pedal activity at the critical relative wind azimuth.

Nomenclature

ASRA	Advanced Systems Research Aircraft
BLR	Boundary Layer Research
FRL	Flight Research Laboratory
GVE	Good Visual Environment
HQR	Handling Qualities Rating
kt(s)	knot(s)
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
NRC	National Research Council
OFE	Operational Flight Envelope
SAS	Stability Augmentation System
shp	Shaft Horsepower
UCE	Useable Cue Environment
Φ	Airflow angle around tail boom

Introduction

Tail boom strakes have been proposed to enhance the performance and handling characteristics of a helicopter, particularly in the low speed/hover flight regime. Indeed, a single tail boom strake was installed on Sea King helicopters in the early 1980's that provided significant improvement to low speed yaw control (ref. 1). As well, NASA conducted wind tunnel testing in this same time period to determine the aerodynamic characteristics of various helicopter tail boom cross sections (AH-64, UH-60 and UH-1H (ref. 2) and OH-58A and OH-58D (ref. 3)). The UH-1H tail boom is nearly identical to the civilian Bell 205, Bell 212 and Bell 412 aircraft. Using the NASA wind tunnel results as a basis, Boundary Layer Research developed a certified strake installation for the Bell 412 aircraft. The BLR tail boom strakes consist of a series of angled aluminium sheet metal sections attached to the upper and lower left side of the tail boom. The strakes protrude approximately 2.5 inches (for the upper strake, 1.5 inches for the lower strake) out at a right angle to the side of the tail boom at the root, and taper down in proportion to the boom size towards the rear of the tail boom. The strake installation on the NRC Bell 412 ASRA is shown in Figure 1.

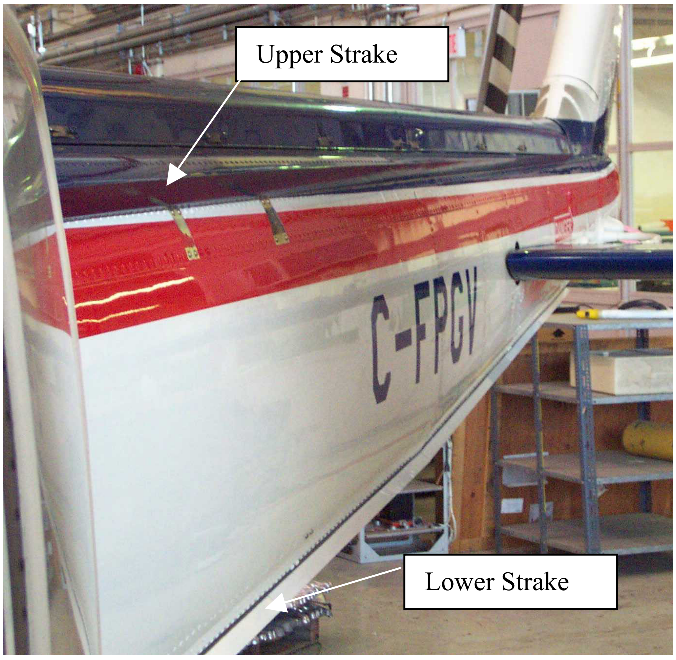

Figure 1: Bell 412 Tail boom with Strakes Installed

The BLR strakes function by physically determining the attachment and separation points of the airflow over the boom, thereby creating consistent and favourable aerodynamic behaviour. The aerodynamic mechanism by which the strakes operate is described in Figure 2. The upper strake separates the airflow on the left side of the tail boom (as viewed from the rear of the aircraft), leading to a pressure rise. On the right side, a beneficial decrease in pressure results. The lower strake becomes more effective as the airflow angle Φ becomes larger. This pressure field around the boom results in a favourable aerodynamic force to the right that decreases the left pedal input required to counter the torque of the main rotor. The size of this beneficial force varies with changes in Φ and the dynamic pressure of the flow over the boom. However, the design has one small drawback. The strakes also cause a region of reduced pressure below the tail boom, creating a small force downwards that must be counter-acted by the main helicopter rotor. Further details on the aerodynamics of the strakes installed on this tail boom shape are available in ref. 2.

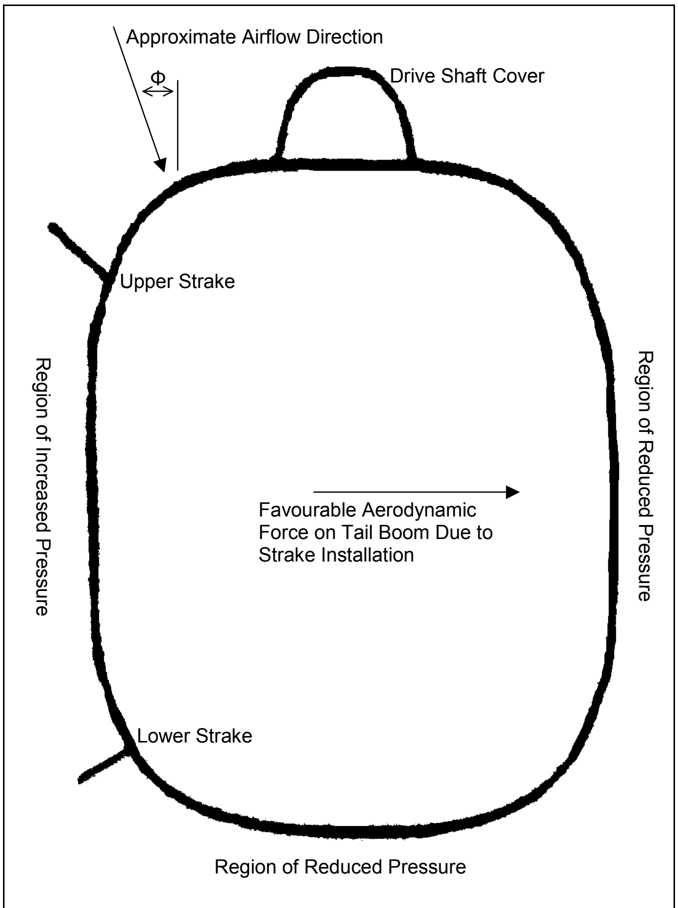

Figure 2: Tail Boom Cross-Section with Strakes

NASA performed flight evaluations in 1986 to test a single strake on the tail boom of a UH-60 helicopter (ref. 4). The results were inconclusive as the strake provided very little change in the control margins in the helicopter, and the pilot detected no significant difference in flying qualities. However, this testing was limited in scope and no formal handling qualities evaluation manoeuvres were flown. The study did recommend that the UH-1H helicopter be considered a candidate for a strake evaluation due to known problems with tail rotor control margins during hover and sideward flight.

A 1993 follow-up study (ref. 5) investigated the effects of two different strake configurations on the direction control of a Bell 204B. Although a smaller aircraft than the UH-1H, the tail boom shape and rotor configuration (two bladed teetering) were similar. This study was more comprehensive than the UH-60 study, and included cross-wind tail rotor power and control position data for increments of airspeed from 0 to 35 kts at various relative wind azimuths. Qualitative results were also gathered in forward flight, including climbs and descents, turns, and autorotation. The study concluded that the strakes improved pedal margins by 7% at the critical azimuth and airspeed, and reduced the tail rotor horsepower required by 17%. Pilot comments indicated that yaw rate transients, normally experienced in sideward flight making heading control difficult, were greatly reduced with the strakes installed on the test aircraft. The report's authors postulated that the airflow separation remained at a fixed location on the boom due to the strakes and that random separation and reattachment of the airflow did not occur. The study further concluded that the strakes did not affect the flying qualities of the aircraft in forward flight at airspeeds between 35 and 100 kts.

Recently, NRC acquired a set of BLR tail boom strakes for installation on the Bell 412. Although the 412 tail boom size and shape are very similar to that of the Bell 204B, the Bell 412 main rotor system is significantly different. Thus, it was desirable to determine whether the results of the study detailed in ref. 5 were applicable to this aircraft. Flight testing was conducted at NRC's Flight Research Laboratory to evaluate the effects of the BLR tail boom strakes on aircraft handling qualities, control margins and performance. The effects on handling qualities were evaluated using a selection of the Aeronautical Design Standards (ADS 33-E-PRF, ref. 6) hover mission task elements. The effects on control margins were evaluated by measuring trim pedal positions during low speed flight at varying headings with respect to the wind. The tests were repeated at equivalent referred weights (weight corrected for air density and rotor rpm) prior to and after the installation of the tail boom strakes. Approximately 50 hours of flight test data were gathered to document the effects of the tail boom strakes. This paper describes the results of the low speed handling qualities and control margin testing, including Cooper-Harper handling qualities ratings for the ADS-33 manoeuvres, and control margin data for various cross-wind conditions up to 35 knots.

Test Equipment

The National Research Council operates a highly instrumented Bell 412 HP Advanced System Research Aircraft (ASRA) serial number 36034, which was used for the evaluation of the effects of the tail boom strakes on aircraft handling qualities (Figure 3). The Bell 412 HP is a medium, twin engine helicopter with a gross take-off weight of 11,900 lbs. It is powered by two PT6T-3BE turboshaft engines, rated at 1800 shp (total) and has a 4-bladed soft-in-plane rotor system. BLR has received a Supplemental Type Certificate for the installation of tail boom strakes on the Bell 412 aircraft.

Figure 3: Bell 412 Advanced Systems Research Aircraft

Instrumentation

The data acquisition system installed in ASRA records a large selection of parameters at 128 Hz.

Control Positions. All of the aircraft control positions are measured using potentiometers and recorded via the data acquisition system. The recorded parameters include: the lateral and longitudinal cyclic, pedal, collective and throttle positions, as well as the swash plate position and tail rotor actuator position.

Air Data Measurement. A nose boom is attached to the aircraft to enable accurate measurements of angle of attack and sideslip, using vanes; and static and total pressure, using a directional probe. Both the vanes and the directional probe are positioned well ahead of the aircraft and out of the rotor downwash while in forward flight. The boom protrudes from the fuselage by approximately 7.5 ft, and is made of a carbon fibre composite for high stiffness. Pressure transducers, installed in the forward avionics bay, acquire the pressure data.

GPS. A NovAtel GPS receiver is installed in the Bell 412 ASRA to provide a high degree of position and velocity accuracy. The unit can operate in differential mode using a real time link to a differential GPS ground station, to achieve a sub-meter level accuracy. The GPS receiver antenna is located above the cabin to limit line of sight obstructions between the aircraft and the satellites during manoeuvring.

Inertial Data. The Litton 92 Inertial Reference System is a high precision sensor installed in the ASRA to provide aircraft accelerations, rates and attitudes. The unit also provides ground speed and position information.

Engine/Main Rotor Data. Engine parameters, including fuel flow, torque, temperature, compressor discharge pressure, governor lever position, compressor and power turbine speed, as well as mast torque, are acquired through a combination of sensors.

Radar Altimeter. A commercially available aircraft radar altimeter is installed in the helicopter to provide an accurate measure of height above ground.

Weight & Balance

The aircraft's weight and centre of gravity were carefully controlled during the strakes flight test using lead weights placed in a ballast box in the main cabin and in the baggage compartment. The take off centre of gravity was maintained at approximately 139 inches while the weight was held within +/- 200 lbs of 10300 lbs for the control margin testing. For the handling qualities tests, the weight was controlled by beginning the manoeuvres at a weight of 9900 lbs, and flying all manoeuvres for the strakes on and off cases in the same order. This method controlled the weight to within +/- 200 lbs for each manoeuvre.

Table 1: ADS 33-E-PRF Manoeuvre Description

Manoeuvre	Performance Standard	Deviation from ADS 33	Description of manoeuvre
Hover	Cargo/Utility GVE	Nil	Check ability to transition from translating flight to a stabilized hover with precision and a reasonable amount of aggressiveness.
Hovering turn	Scout GVE	Heading tolerance of 5° was used instead of 3°.	Check for undesirable handling qualities in a moderately aggressive hovering turn.
Pirouette	GVE	Nil	Check ability to accomplish precision control of the rotorcraft simultaneously in the pitch, roll, yaw and heave axes.
Vertical manoeuvre	Cargo/Utility GVE	Nil	To assess the heave axis controllability with precision station keeping.
Sidestep	GVE	Target sideward airspeed of 25 kts (OFE-10kts) was used instead of 30 kts.	Check lateral-directional handling qualities for aggressive manoeuvring near the rotorcraft limits of performance.
Acceleration and deceleration	GVE	A power limit of 90% power within 1.5 sec was used instead of 95%.	Check pitch axis and heave axis handling qualities for highly aggressive manoeuvring.

Test Procedures

Weather Conditions. The low speed control margin and handling quality test points were flown in less then 5 kts of steady wind. Handling quality test points were flown in UCE 1, as defined by ADS 33 (ref. 6).

Handling Qualities. Six ADS 33-E-PRF hover mission task elements were evaluated with the helicopter stability augmentation system on and off, for both the strakes on and off test configurations. A brief description of each manoeuvre, along with the performance standards and any deviation from the ADS 33 requirements, are depicted in Table 1. Each pilot conducted two or three training manoeuvres followed by one rating manoeuvre. The Flight Test Engineer recorded pilot comments and Cooper-Harper handling quality ratings (ref. 7) following the rating manoeuvre.

Control Margins. Out of ground effect critical azimuth performance was assessed by conducting the following manoeuvre: the pilot stabilized the aircraft on the runway heading at a height of 75 ft above ground and then accelerated down the runway to attain and hold a fixed ground speed of 5 knots for at least 20 seconds. The pilot then accelerated in 5 knots increments until 35 knots was attained. At the end of the run, the aircraft was repositioned, the target heading was increased by 30° with respect to the runway, and the process was repeated. In this manner, the entire low speed cross wind envelope of the aircraft was documented. The pilot attempted to maintain the target ground speed within ± 1 kt, height within ± 10 ft and heading within ± 5° with as few control inputs as possible. The wind speed was recorded from an anemometer located on the roof of a nearby hangar. Ground speed was determined by the LTN-92 ring laser gyro based inertial navigation system, with differential GPS data as a backup. The measured variable of interest was the pedal position. All control margin tests were flown with the aircraft SAS on. This provided a more stable aircraft making it easier for the pilots to achieve the above performance standards.

Results and Discussion

The results of the flight testing indicated that the BLR strakes improved handling qualities during ADS-33 manoeuvres and reduced the left pedal requirement during low speed flight at certain wind azimuths. These results are detailed below.

Handling Qualities

Two Qualified Test Pilots performed the hover flight ADS 33-E-PRF mission task elements over 10 flights. During the strakes off tests, the ground was partially snow covered, however the lighting conditions still provided good cueing (UCE-1). For the strakes on tests, Pilot A conducted the manoeuvres over a snow covered field with some points occurring in light re-circulating snow, while Pilot B conducted the manoeuvres over a grass covered field. The wind was light at less then 5 kts for all MTEs conducted.

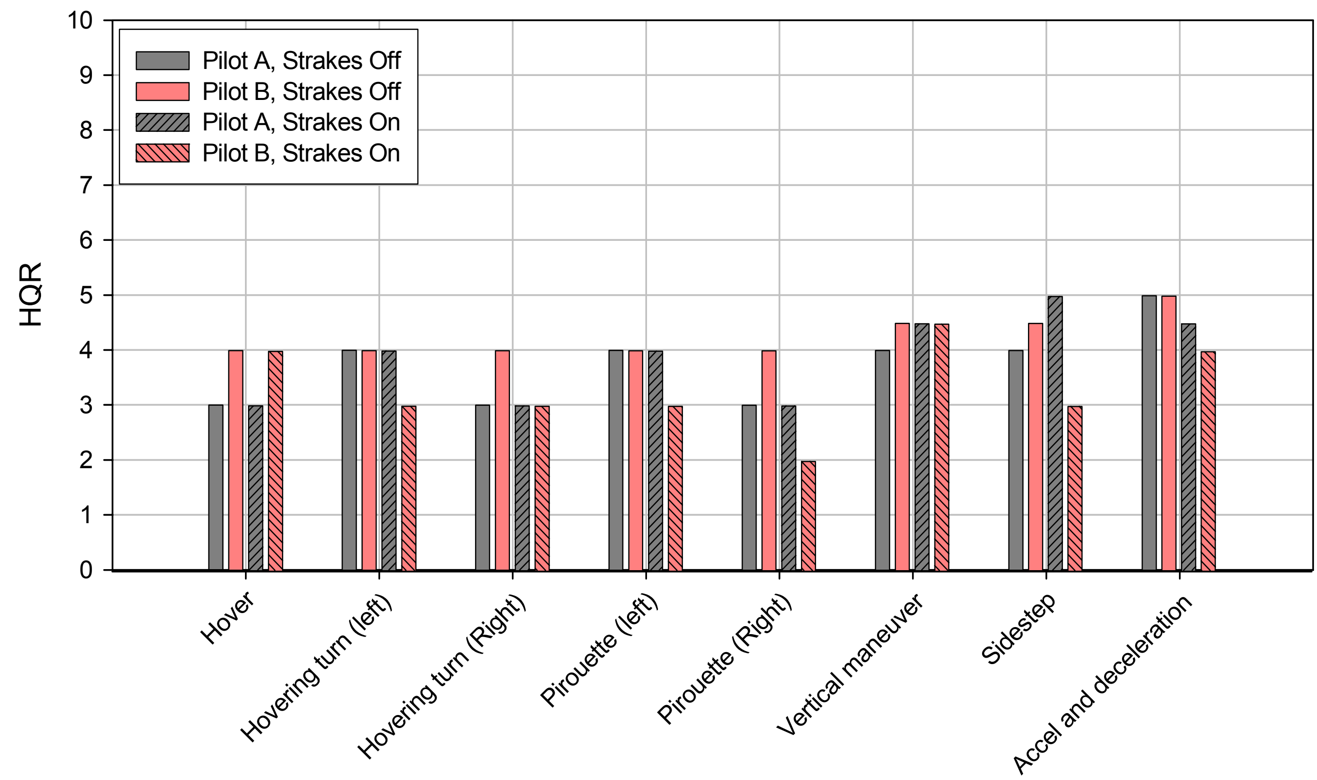

Figure 4: Handling Quality Ratings (SAS On)

General Comments. The majority of the pilot comments referred to the compensation required to mitigate the effects of the engine governor. The character of the engine governor has been well documented in previous research (ref. 8 & 9), which has established that the damping ratio is in the order of 0.35. These under-damped torque dynamics were excited during manoeuvres requiring tight position tolerances (Hover and Hovering Turn), but were most prevalent following the return to the hover after an aggressive manoeuvre (Vertical Manoeuvre, Acceleration and Deceleration and Sidestep) and were manifested as a coupling between the collective, yaw and roll axes. This coupling resulted in a constant, elevated level of pilot workload to stabilize the attitude of the aircraft during the hover portions of a manoeuvre. It also required the pilot to be very careful of large, rapid applications of power during the more aggressive manoeuvres, requiring the pilot to be "eyes inside" the cockpit a large portion of the time to prevent an over-torque of the aircraft. This subsequently resulted in poorer task performance and higher task workload than would have been the case with a more benign engine governor.

The Effect of SAS. The Bell 412 SAS provides rate damping in pitch, roll and yaw, which makes the aircraft more stable and easier to fly. Although the system has approximately 10% control authority, the pilots did not note any SAS actuator saturation, even during the aggressive manoeuvres. However, even with the SAS on, the characteristics of the engine governor did interfere with the pilot's ability to perform tasks. During tasks requiring tight position tolerances, such as the hover and hovering turn, the pilot had to make continuous small lateral cyclic, collective and yaw adjustments (0.5 inches at 1 Hz) to compensate for the engine governor dynamics. During tasks requiring rapid power applications, such as the Vertical Manoeuvre, Acceleration and Deceleration, and Sidestep, the pilot had to regulate collective application and pay particular attention to the torque gauge to avoid a mast over-torque. The pilot workload momentarily increased following the rapid collective and pedal inputs that were used to return the aircraft to the hover after aggressive manoeuvres. Large collective to yaw, and to a lesser extent pedal to roll, coupling were very evident.

With the SAS off, the characteristics exhibited by the aircraft described above were amplified. The aircraft was notably more sluggish in the roll and yaw axes. This, combined with the engine governor dynamics, tended to increase the pilot compensation required during all the tasks. Furthermore, the pilots noted an evident coupling between the yaw and roll axes, that

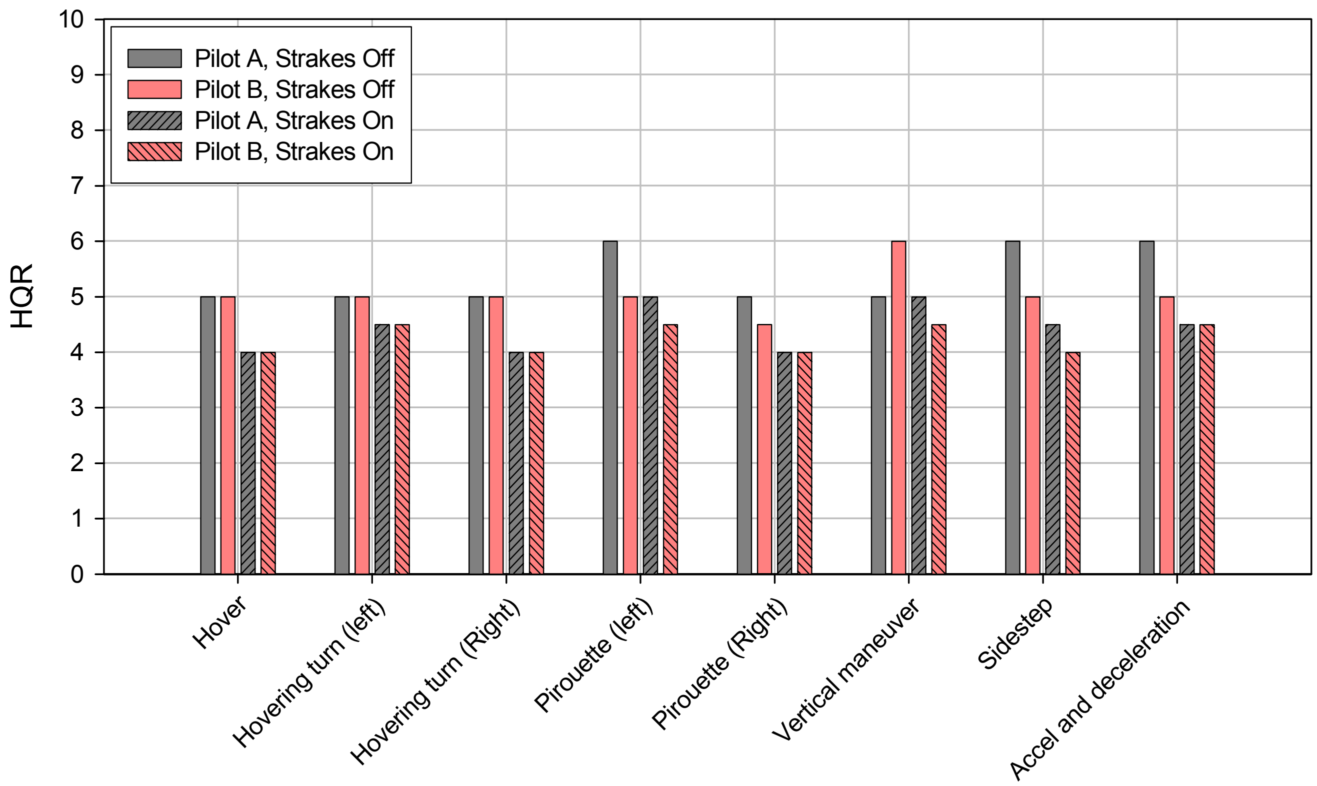

Figure 5: Handling Quality Ratings (SAS Off)

was far more pronounced SAS off (the SAS suppressed this behaviour).

The Effect of Strakes. The handling quality ratings comparing the strakes off and on test configurations for the SAS on test condition are detailed in Figure 4. For the strakes off cases, the precision tasks were rated as having borderline level 1 handling qualities based on the Cooper-Harper scale, with slightly worse ratings noted for the aggressive manoeuvres. The results show a slight improvement in the ratings once the strakes are installed. The improvement is more noticeable where the effects of the governor are least present, namely during the hover turn and the pirouette MTEs. The precision hover MTE requires tight vertical positioning which tends to excite the governor. The acceleration deceleration, vertical manoeuvre and side step all require large collective inputs, which once again excites the governor dynamics. When the governor dynamics are present, they mask any handling qualities improvements that may be present due to the strakes.

For the SAS off case the handling qualities results are detailed in Figure 5 and show a noticeable improvement across all manoeuvres. As one might expect, with SAS off the aircraft gust rejection is reduced thus requiring an increased level of control activity when the pilot is striving to maintain a precise aircraft state. Furthermore, cross coupling between the yaw and roll axis and between the collective and the yaw axis are more pronounced with SAS off. In the strakes on test configuration, the pedals were less active and the yaw response was more predictable. This led to a respective reduction in lateral cyclic and collective activity over the strakes off test configuration. The improvement in handling qualities ratings for the SAS off case is particularly significant. The ratings move from being predominantly 5 or 6, for the strakes off case, to predominantly 4 or 4.5, for the strakes on cases. This implies that with the strakes off, desired performance was not achieved. However, with the strakes on, the pilots were able to achieve desired manoeuvre performance, albeit using moderate to considerable compensation.

Basis of Improvement. The major difference between the strakes on and off test configurations was that the aircraft response was more predictable and pedal activity was slightly reduced when strakes were installed on the aircraft. This was most noticeable while conducting precision type manoeuvres but was also evident during the aggressive manoeuvres. Although not used as a handling qualities task, the pilots commented that precision landings to a raised pad were conducted more easily and quickly with the strakes installed. The yaw rate that developed after a pedal application was also cited to be more predictable during hover turns and pirouettes. Figure 6 shows a typical comparison between strakes on and off cases for a hovering turn MTE. Without the strakes present, the yaw rate that developed was oscillatory in nature, giving the aircraft a 'jerky' feeling during the turn. With the strakes on, the pilot was able to be significantly more aggressive, and the aircraft developed a smoother yaw rate. With the strakes present, the manoeuvre was completed in less time and the pedal inputs were less tentative with a crisper capture of the desired final heading.

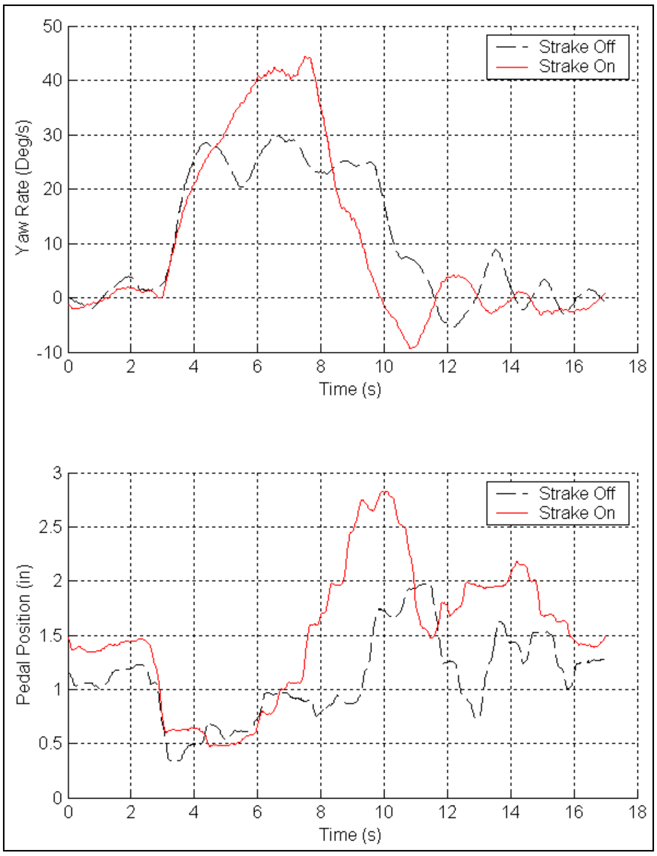

Figure 6: Hovering Turn MTE

While conducting the side step and acceleration/ deceleration MTEs, pedal reversals were used to counter lateral velocity or collective applications. With the strakes on the pedal reversals were less frequent and more predictable, an indication that the coupling effects were reduced. The pedal displacement required during the lateral displacement and return to the hover for typical Side Step MTEs (strakes on and off cases) are compared in Figure 7. During manoeuvres conducted with similar levels of aggressiveness for both strakes on and off cases, the strakes on condition exhibits fewer control reversals and a less tentative control strategy. The reduction in pedal activity typically led to a corresponding reduction in lateral control input and the magnitude of the torque oscillations. This behaviour is also demonstrated during a typical acceleration/deceleration manoeuvre, as shown in Figure 8. The frequency content of the pedal inputs is reduced, particularly in the 10-15 second range on the plot. The reduction in yaw axis control activity resulted in improved HQRs for this manoeuvre.

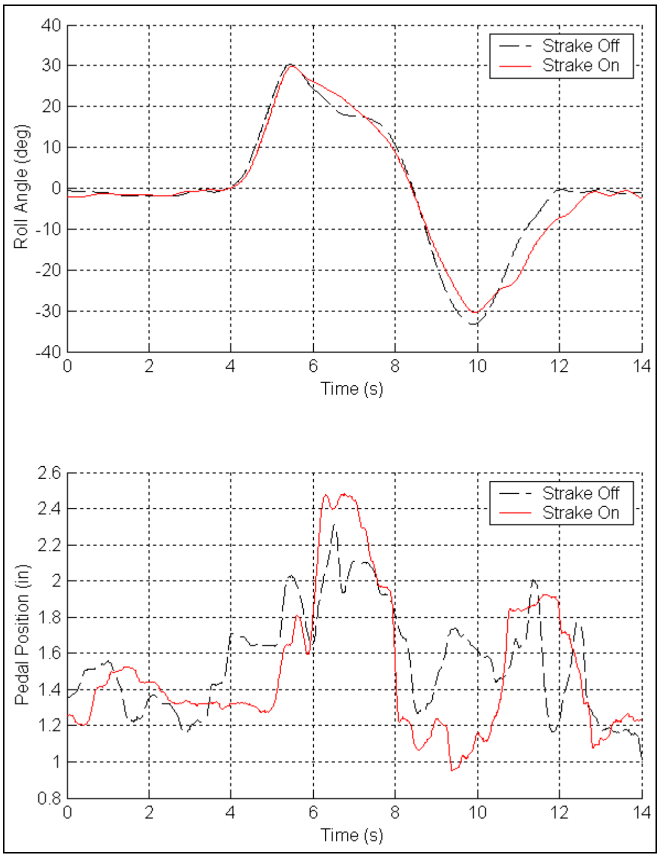

Figure 7: Side Step MTE

Further reductions in yaw axis control activity were also apparent during the control margin testing. During left sideward flight, for counter clockwise turning main rotor blades (North American direction), most rotorcraft equipped with tail rotors exhibit increased pedal activity within a small azimuth band between 10 and 25 kts. For the Bell 412 with strakes off, this effect was most notable at an azimuth of 264 degrees. The pilot comments for this azimuth indicated a large increase in pedal workload with larger heading deviations than for all other azimuths (including rearward flight). The strakes on control azimuth test points did not reveal any particular azimuth where pedal activity increased significantly. The standard deviation of pedal displacement was taken for the stabilized conditions during the control margin testing. Figures 9 and 10 show the results for strakes off and on respectively. Although the average pedal displacement standard deviation is not reduced for most azimuths, the critical azimuth, with respect to pedal control activity, shows a significant reduction from values as high as 0.43 (strakes off) to 0.27 (strakes on).

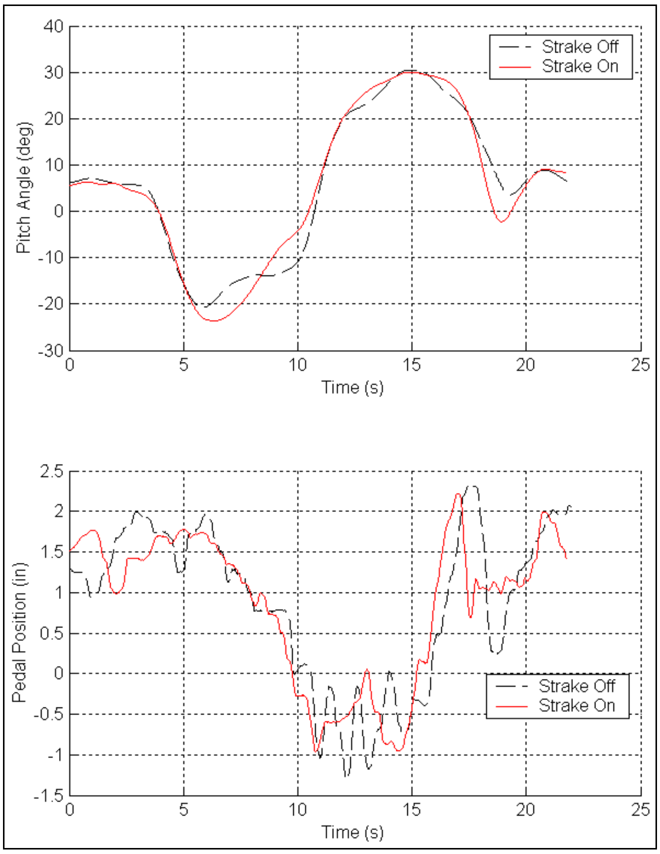

Figure 8: Acceleration/Deceleration MTE

Control Margins

Out of ground effect critical azimuth performance was assessed by examining the pedal position data for both the strakes on and off cases. The ground speed data was first corrected for the measured wind conditions that resulted in aircraft wind speed and azimuth relative to the helicopter. As well, the measured pedal position was corrected for referred aircraft weight (corrected for density altitude) by correlating referred weight to pedal position for equivalent conditions. These values were then plotted with airspeed so pedal position at a specific airspeed could be determined for comparison purposes. This analysis was finalized in a series of polar plots showing pedal position at various azimuths for each airspeed condition.

The results for each airspeed exhibited similar trends, therefore only the 25 knot case is shown in Figure 11, positive pedal position is left pedal forward. Thus, for North American rotor rotation direction, a smaller value along this axis represents less power required from the engines to drive the tail rotor. It can be seen in Figure 9 that pedal position reductions of 0.5 to 1.0 inches (7% to 15%) are realized due to the strakes, at certain azimuths. This reduction is most prominent at relative wind azimuths between 30 and 90 degrees, where pedal requirements are normally critical and 210 to 270 degrees where increased pedal control activity is normally present.

Conclusions

The NRC conducted approximately 50 hours of flight testing to evaluate the effects of the BLR tail boom strakes on the performance and handling qualities of a Bell 412 helicopter. The following conclusions can be drawn from this work:

- The presence of the BLR tail boom strakes reduces pilot workload during ADS-33 manoeuvres as evidenced by improvements in handling qualities ratings, particularly with the aircraft SAS off.
- The BLR tail boom strakes significantly reduce the pedal activity in left sideward flight at the critical azimuth commonly associated with pedal reversals due to tail rotor airflow issues.
- The BLR tail boom strakes increase pedal margins by up to 15% at the critical wind azimuths between 30 and 90 degree during low speed flight at 25 knots. These results are similar to those documented in ref. 5.

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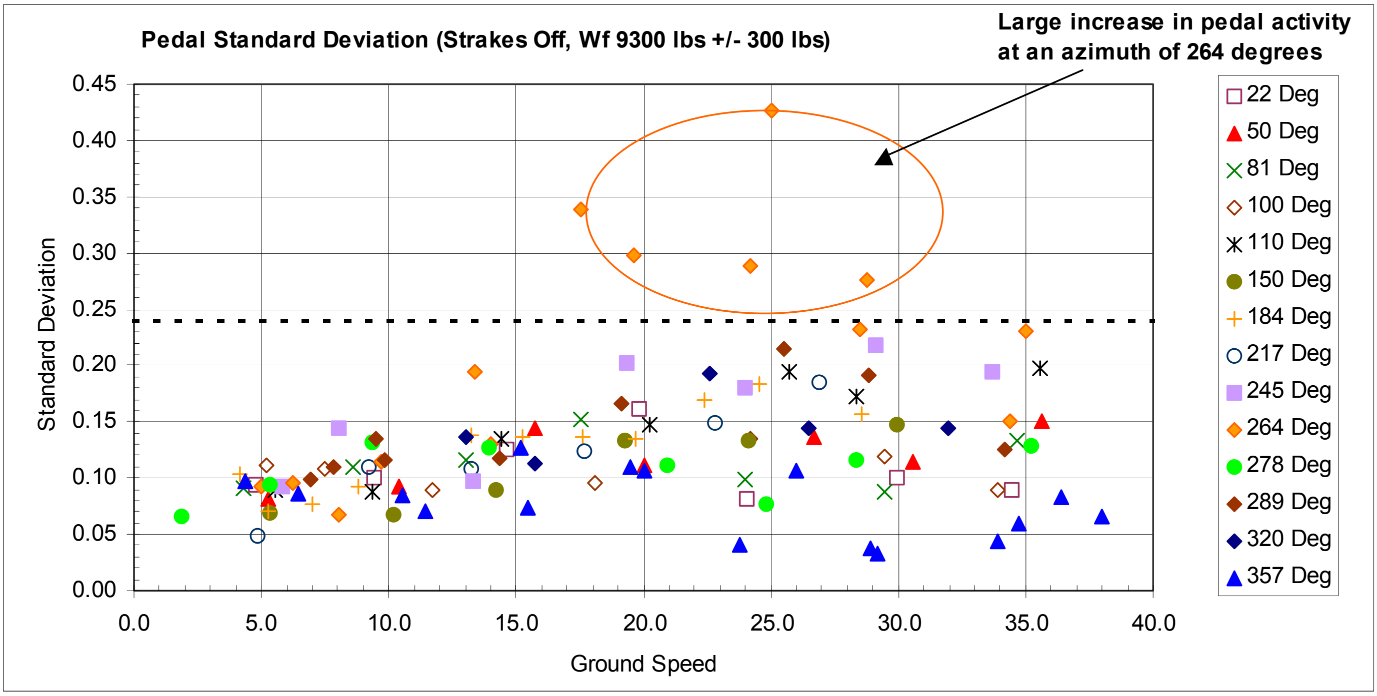

Figure 9: Pedal Standard Deviation - Strakes Off

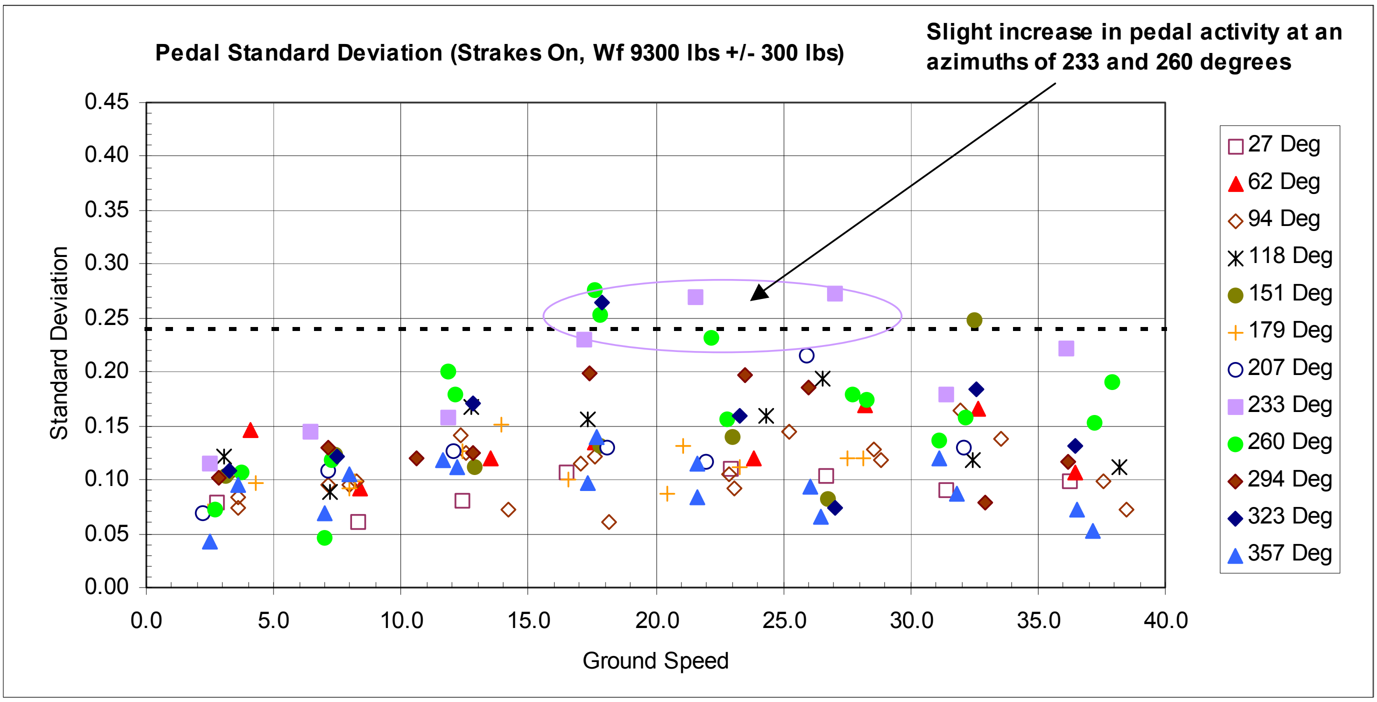

Figure 10: Pedal Standard Deviation - Strakes On

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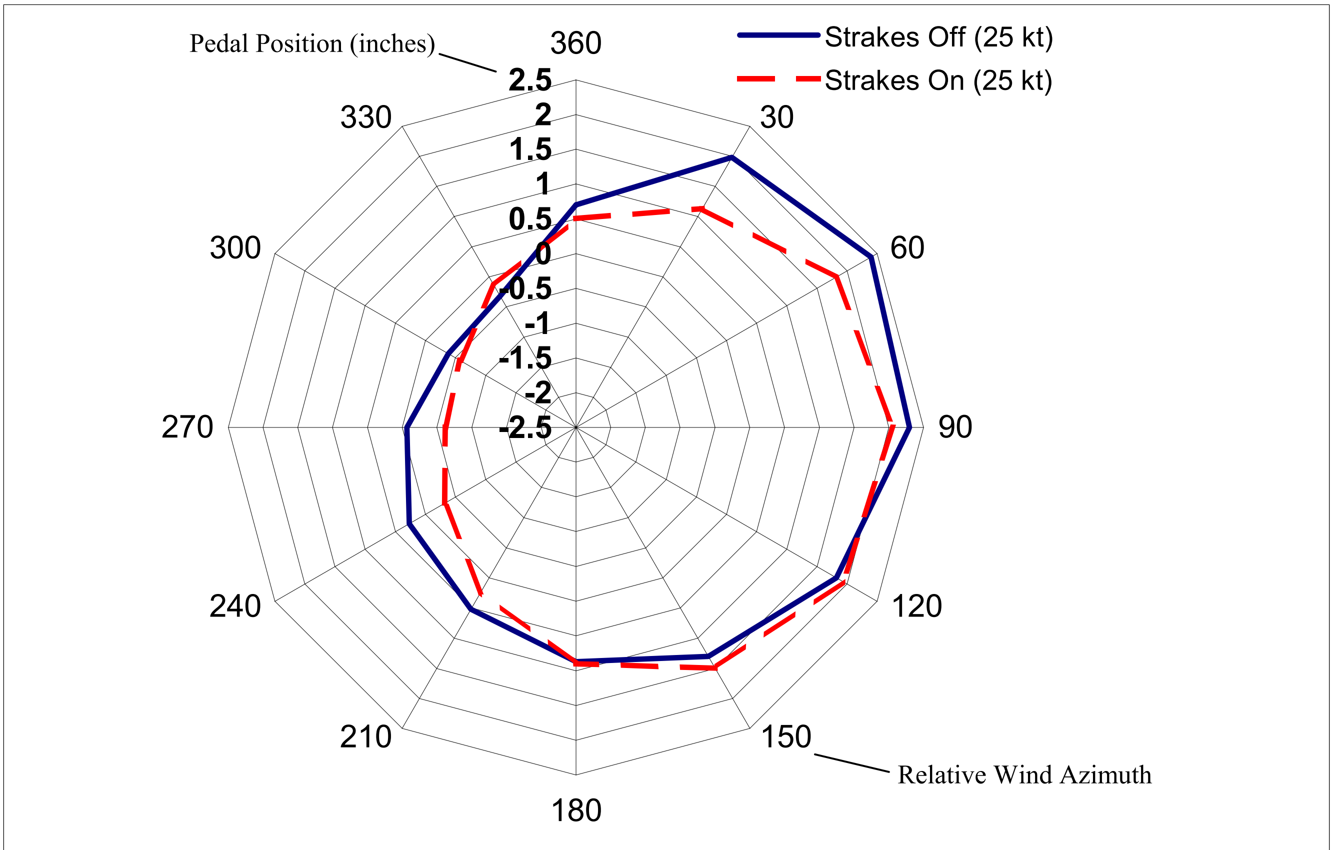

Figure 11: Control Margins in the low speed regime