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DEVELOPMENT OF THE ROOIVALK HORIZONTAL AND VERTICAL STABILIZERS

BY

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Abstract

The design and development of the horizontal and vertical stabilizers of the Rooivalk attack helicopter was complicated by a number of diversified, contradicting and sometimes limiting requirements. These requirements ranged from a need for structural simplicity and commonality with other helicopters already in service with the South African Air Force to high levels of low-speed agility and good directional stability.

During the design of the horizontal and vertical stabilizers of the Rooivalk, and their subsequent development based on flight test results, an attempt was made to find the most suitable compromise amongst all the contradicting requirements. During the development programme, the priorities given to each of the requirements were reviewed based on knowledge gained on the operational implementation of the aircraft within the 'multidimensional' modern battlefield. Those reviewed priorities were incorporated into the final configuration of the stabilizers.

A number of detailed aerodynamic problems, resulting from the very complex interactional aerodynamic environment in which the stabilizers operates, were also resolved during the development process.

The initial design and subsequent aerodynamic development programme of the vertical and horizontal stabilizers of the Rooivalk attack helicopter form the subject of this paper. Included will be the analytical and experimental work done during the initial design of the stabilizers, as well as the test results from the flight tests of each subsequent stabilizer configuration tested. The final configuration, with the resulting flight envelope, is also included.

1. Vertical Stabilizer Design

1.1 Summary of Vertical Stabilizer Design Drivers

Considerations which influenced the design of the stabilizers are stated below:

- **Sideways flight capability**

  The South African Air Force User Requirement (Ref. 2) calls for the Rooivalk to hover and to fire its weapons in wind speeds of 25 knots from any direction. In addition, it also calls for compliance to MIL-F-83300 requirements, without being specific.

  In MIL-F-83300 a hovering capability in steady winds up to 35 knots from any direction is called for. In the Flying and Ground Handling Qualities Development Specification (Ref. 1), Atlas has set a target of 30 knots for Rooivalk sideways flight capability, as it was felt at the time that it would be difficult to meet 35 knots and significant tail rotor loss capability at the same time.

- **Tail rotor loss capability**

  A requirement was set for Rooivalk to survive a direct hit on the tail rotor. The requirement calls for sufficient anti-torque to be provided by the vertical stabilizer in level flight at acceptable side-slip angles to enable the aircraft to fly out of a combat zone, or at least to descend at sufficiently low rates to allow a survivable crash landing. The resulting anti-torque required from the fin was derived, and this was used as a target value during the wind-tunnel evaluation of various vertical stabilizer configurations.

- **Lateral-directional dynamic stability**

  Another important design driver has been the requirement for Rooivalk to have adequate lateral directional stability with the Automatic Flight Control System (AFCS) off. This stems from the requirement for attack-class helicopters to have sufficient directional stability remaining for weapons aiming, following AFCS failure, to enable completion of a mission. This implies that the airframe static-directional stability at zero side-slip has to be neutral or positive, although a moderate degree of negative stability may be tolerated.

- **Yaw rate response**

The required yaw rate response throughout the flight envelope, as stipulated in the Flying and Ground Handling Qualities Development Specification (Ref. 1) is 15 °/s within 1,5 s after yaw control input.

1.2 Design of the Vertical Stabilizer

The design of the vertical stabilizer was determined by geometric constraints, predetermined performance targets and a preliminary sizing exercise carried out using vortex lattice methods. Most significant of the design criteria was the decision to use the Oryx/Super Puma tail rotor, drive shafts and gearboxes.

Performance targets were determined by desirable directional stability (Dutch Roll) characteristics, limitations on sideways drift during power-off landing, sideways flight capability (discussed later in detail) and the requirement of tail rotor loss survivability.

Having determined these constraints, it was further decided that a ventral fin would be desirable in addition to a dorsal fin. A ventral fin has the advantages of contributing to directional stability in descending flight and counteracting the rolling moment caused by the dorsal fin in side-slip, thereby improving the Dutch Roll characteristics.

Five dorsal fin configurations and five ventral fin configurations were tested in various combinations, together with a horizontal stabilizer. The effects of an endplate attached to the horizontal stabilizer, and the effects of three different strakes attached to the ventral fin were also investigated.

Many combinations were tested, the improvements in each case being considered in a range of combinations with other components. In all cases tested in the design of the vertical stabilizer, curves for yawing moment coefficient vs. side-slip angle were obtained for a range of pitch attitudes.

The geometry of the ventral fin, was dictated largely by the requirements for mounting of the tail undercarriage and the clearance which would be needed for a hard landing. These constraints set the span limit and trailing edge limit and resulted in the choice of a symmetric aerofoil section, NACA 0015. The undercarriage was mounted behind the ventral fin. The initial results fell short of the target values set.

To improve the performance of the ventral fin a modification in the tail undercarriage was introduced, the strut being mounted inside the fin, minimizing aerodynamic interference and reducing strut drag. The aspect ratio was maximized for the given area. To allow the strut to pass through the fin trailing edge the NACA 0015 section was truncated. The C_n vs. β curve slope was significantly increased.

An endplate was mounted on the tip of the horizontal stabilizer. For nose-up and level attitudes there was little improvement, although the endplate could be used to improve directional stability in climbing flight, if required.

Three different strake configurations, fitted to the ventral fin, were tested. Fitting strakes to the dorsal fin was not considered, as tail rotor blockage could increase, and access to the intermediate tail gearbox would be impeded. The strakes were supposed to improve the lift generated by the ventral fin at high side-slip angles by creating a strong chordwise vortex. Performance was poor. The third strake was smaller and displayed better performance than the preceding designs. Performance improvement was still not sufficient to warrant the increased complexity of implementation.

The final vertical stabilizer configuration had much improved directional stability characteristics compared with the Oryx, while the sideforce and rolling moment characteristics of the two configurations were not significantly different.

Having finalized the vertical stabilizer configuration, an analysis was carried out using a simulation program to determine the Dutch Roll characteristics of the aircraft. Simulations were done for three representative aircraft masses and moments of inertia, and the decoupled lateral-directional dynamic stability root-locus plots in level flight at a range of forward speeds were obtained. At low forward speeds level 2 of MIL-F83300 Dutch Roll requirements are met, while at higher speed, level 1, requirements are met with AFCS off. (Low speed: 50 km/h to 100 km/h, higher speed:> 100 km/h).

1.3 Out-of-wind Hover Capability Analysis

After the dorsal and ventral fin configurations were finalized, an analysis was done to determine the sideways flight capability of the helicopter. Both the left and right sideways flight capability were investigated.

The limitation during right sideways flight would be the onset of the vortex ring state and the performance would be similar to that of the Oryx (as the Oryx tail rotor was being used). The left sideways flight capability of a helicopter is limited by the reduction in thrust-producing capability of the tail rotor due to tail rotor blockage by the dorsal fin.

The left sideways flight capability of the Rooivalk was analysed with a mathematical model developed from research work done by Boeing Vertol (Ref. 11). An experimental programme was simultaneously initiated to measure the decrease in tail rotor thrust due to tail rotor blockage.

The mathematical model takes into account the aircraft mass, airframe aerodynamic characteristics, tail rotor aerodynamic characteristics and tail fin/tail rotor geometry. At the beginning of the exercise, the design criteria of 25 knots left sideways flight capability was set. The mathematical analysis showed that with the tail empennage configuration used at that time, the tail rotor thrust loss at hover OGE would be 22.5%. The aircraft would not be able to meet the design specification of 25 kts left sideways flight. Calculations showed the maximum allowable blockage loss at hover to be 16%. It became clear that further refinement of the tail empennage would be required.

An experimental programme was initiated utilizing a whirl rig, a full-scale Puma tail rotor and a full-scale model of the tail empennage.

Of the two geometric variables affecting the tail rotor blockage, namely the tail rotor/tail fin separation distance and the tail fin surface area blocking the rotor disk area, only the latter would be available for modification. The tail rotor/tail fin separation distance is fixed because of the decision to use an Oryx tail rotor and drive shafts. During the tests the tail rotor thrust and the tail fin force were measured using loadcells. After testing various configurations with various portions of the fin cut away, a final configuration was arrived at. This configuration has removable tail fin fillets in the bottom trailing edge. These fillets can be removed to reduce the tail rotor blockage if problems are encountered during flight-testing.

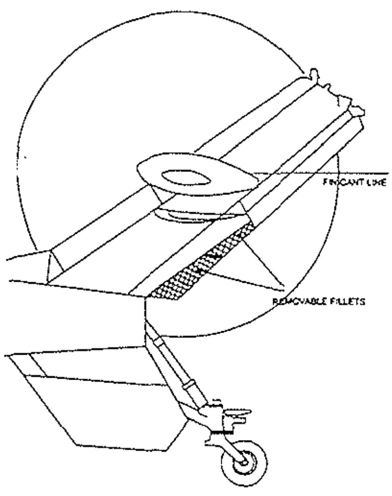

Figure 1: **Vertical Stabilizer Configuration 1: Geometry**

The fillets are placed at the bottom trailing edge of the fin where the loss in directional stability would be minimized, were they to be removed. They are also positioned in the 70% - 100% tail rotor radius area, where they would be most effective for reducing the blockage.

This is similar to the cut-away on the tail fin of the AH-64 Apache, where tail rotor problems were also encountered (Ref. 3). Experimental results showed this final configuration to have a tail rotor thrust loss due to blockage of 14.5% in hover.

As a final measure to reduce the tail rotor blockage, the effective separation distance between the tail rotor and the top half of the tail fin was increased by canting the top section away from the tail rotor by 11°. By incorporating 7° twist in the top section, the effect on directional stability of the aircraft was minimized. With this vertical stabilizer configuration the design requirement of 25 knots sideways flight to the left and right would be met. This final configuration, configuration 1, is shown in Figure 1.

2. Horizontal Stabilizer Design

A number of fundamental design decisions were made before the testing of various horizontal stabilizer configurations began. It was decided that four primary objectives should be met, namely: minimum complexity, longitudinal stability characteristic similar to that of the Oryx, conformance to the phugoid response stability requirement as given in MIL-H-8501A (level 2 at least is desirable) and satisfactory short period stability and static longitudinal stick stability characteristics.

The requirement for minimum complexity resulted in the decision that the horizontal stabilizer should be structurally fixed.

The T-tail (YAH-64 Apache prototype), the mid-mounted asymmetric (Oryx) and the tailboom-mounted symmetrical (Sikorsky S-76) were considered in determining the configuration to be used.

The mid-mounted asymmetric configuration was chosen, primarily because it was successfully implemented on the Oryx. As the same drive train is used, the design of the tail configuration is less complex if a similar configuration is used. Although the cantilever arrangement of the asymmetric configuration is structurally more difficult to design, it has advantages over both the T-tail and tailboom-mounted symmetrical configurations. The potential problems of the T-tail configuration which result from tail shake, vortex formation at the intersection with the vertical surface and increased tail rotor blockage due to the endplate effect are all reduced or removed. Compared to the tailboom mounted symmetrical configuration the mid-mounted asymmetric configuration with is less suseptable to abrupt pitch changes during transitional flight (resulting from main rotor downwash passing over the horizontal stabilizer). Having decided upon the mid-mounted asymmetrical tail configuration, various designs were tested, keeping in mind the requirements for simplicity, similarity to the Oryx and phugoid response.

An inverted cambered section was required to increase maximum lift coefficient for low-speed forward flight and steep climb, while minimizing drag in cruise and reducing nose-down moment at negative stabilizer angles of attack, maintaining static stability in autorotation. A NACA 5415 section was chosen and the Oryx planform was used as a baseline for sizing. A number of modifications to the horizontal stabilizer were tested in the wind-tunnel in order to find the most suitable design.

The effects of adding a leading-edge slat, increasing the aspect ratio, adding an end plate, and a gurney flap were investigated.

Target values for the design and sizing of the horizontal stabilizer in terms of the pitching moment characteristic were determined from design criteria given for the short-period stability parameter and static longitudinal stick stability. Relationships between Cooper Harper Rating (CHR) and short-period characteristics and between pitching moment slopes and short-period characteristics were investigated. It was found that a CHR of less than 3½ for short-period response would be achieved if pitching moment slopes for the entire airframe were negative. For static longitudinal stick stability it was determined that, since the Oryx and the aircraft to be designed in this exercise were to have the same rotor system and identically placed horizontal stabilizers, the static longitudinal stick stability would be similar if pitching moment slopes versus angle of attack curves were similar.

For various vertical stabilizer configurations tests were carried out with and without a leading edge slat. In all cases, the effects of the leading edge slat on pitching moment coefficient were found to be negligible and the leading edge slat was thus discarded.

Two configurations with increased aspect ratios were tested. By increasing the span it was hoped that the lifting surface would extend beyond the area of screening caused by the engine cowlings. In each case, the increase resulted in a more negative pitching moment slope and thus greater stability, which was an important design aim. From the sizing and planform point of view, the horizontal stabilizer with the largest aspect ratio was chosen. Other optional additional devices which might improve stabilizer performance were then evaluated.

Endplates were evaluated in an attempt to increase both directional stability and the effective aspect ratio, and thus the efficiency. Improvements in the pitching moment characteristics were obtained in all cases with endplates fitted, but due to increased complexity and the possibility of vibrations, they were not implemented.

A gurney flap was evaluated in the hope that the pitching moment slope would be increased. The entire pitching moment vs. Speed curve was shifted downwards when the gurney flap was added, but the effect on the slope was insignificant and it was thus considered unnecessary.

Having selected the final horizontal stabilizer configuration, it remained to determine whether the phugoid response military standards (MIL-H-8501A) were met by this configuration. Simulation runs were carried out using a simulation program for three aircraft masses which would be representative in this design exercise. The resulting decoupled longitudinal dynamic stability root locus plots were obtained for a range of forward speeds. At speeds above 54 KTAS, the design would meet level 2 requirements and above 65 KTAS level 1 requirements would be met with AFCS off. The design showed unstable longitudinal dynamic characteristics below 54 KTAS, but as static stick stability remained positive, this instability was considered to be tolerable.

3. Development of the Vertical Stabilizers

3.1 Evaluation of the First Dorsal Fin Configuration

Early, preliminary out-of-wind hover tests, with the original dorsal fin fitted and both removable fillets in place (the maximum tail rotor blockage condition), clearly indicated that the aircraft would not be able to hover in sidewinds in excess of 20 KTAS with a 10% yaw pedal control margin remaining. It was decided to remove the two removable fillets for future flight testing and do a full evaluation of the out-of-wind hover capability of the aircraft in this configuration, with the fillets removed. (This configuration is regarded as the first configuration tested.)

The out-of-wind hover capability of the aircraft was evaluated out-of-ground effect, at a nominal aircraft referred mass of 8819 kg. The results are shown in figure 2.

A speed of 25 knots was reached with 11% yaw pedal control margin remaining in the critical left sideways flight direction. This result implied that the aircraft would be able to meet the User Requirement (Ref. 2) in terms of the required hovering capability in wind speeds of 25 knots from any direction. However, the aircraft did not meet the requirement of 35 knots set out in MIL-F-83300 or the required speed of 30 knots as set out in the Rooivalk Flying and Ground Handling Specification. It was also doubtful if the aircraft, in this configuration, would be able to attain the hovering capability in wind speeds of 25 knots at aircraft masses in excess of the test mass.

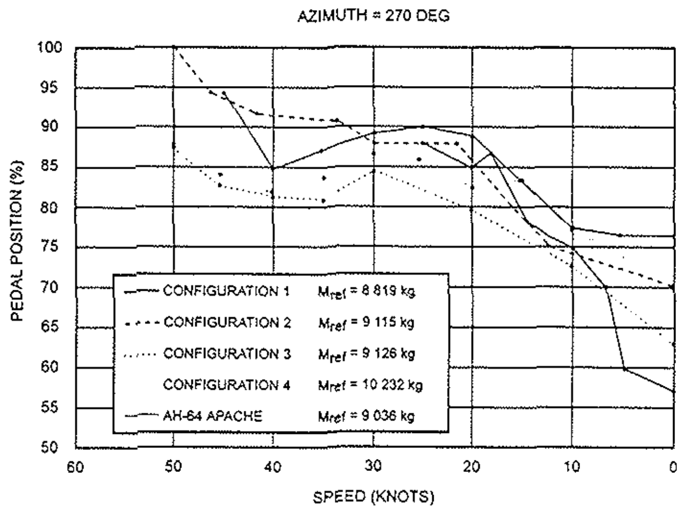

Figure 2: Yaw Pedal Position vs. Sideways Speed 270° Azimuth

The lateral directional dynamic stability of the aircraft in this configuration was also evaluated. The Dutch roll characteristics of the aircraft with AFCS roll and yaw channels disengaged, were evaluated in level, climbing and descending flight at speeds between 40 knots and 120 knots, and at a nominal mass of 7 100 kg.

Results of these tests are presented in Figure 3 in the form of the roots of the characteristic equation of motion of the Dutch-roll mode. The data is shown in relation to the Rooivalk medium-to-long period lateral-directional oscillatory requirements.

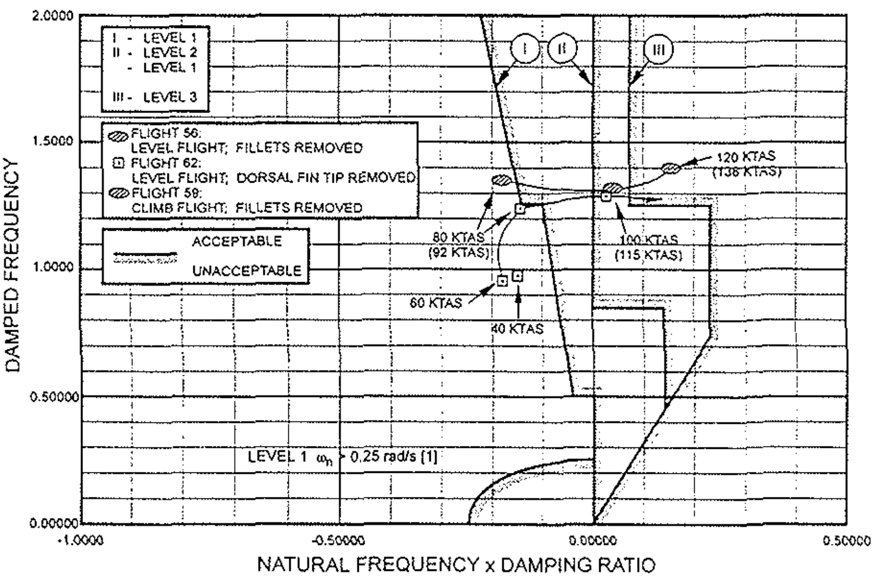

Figure 3: Configuration 1: Lateral-Directional Dynamic Characteristics

The aircraft in this configuration, was able to meet Level 1 Dutch roll requirements with AFCS off at 80 knots, level flight. This implied that the aircraft would be able to maintain Level 1 flying qualities during mission flight phases such as terrain following and ground attack in this speed range, following AFCS roll and yaw channel failure.

At speeds above 80 knots, level flight, the Dutch roll characteristics with AFCS off deteriorated with increase in speed. At 120 knots, the aircraft did not meet Level 3 flying qualities requirements. This implied that mission flight phases such as terrain following, if required to be flown at this speed, would probably have to be terminated in the event of AFCS failure.

It was also found that the Dutch roll mode could not be excited in descending flight, due to the high directional stability of the aircraft in this condition. The ventral part of the vertical stabilizer was partly intended to enhance directional stability when the aircraft would have a nose-up incidence to the flow, such as in descending flight, since part of the dorsal fin is then in the wake of the fuselage.

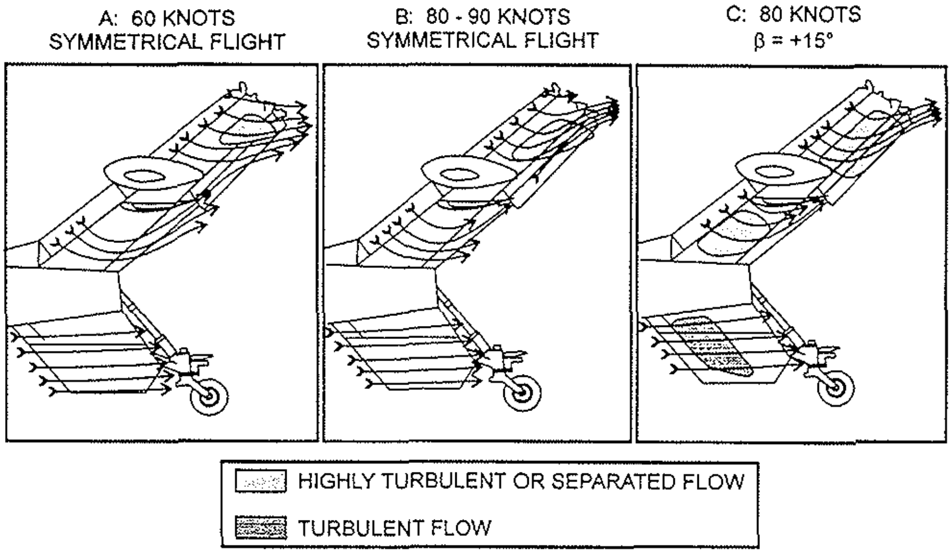

Figure 4: Surface Flow over Vertical Stabilizers

In an attempt to gain a better understanding of the flow mechanisms involved on the dorsal and ventral fins, the surface flow on the post side (curved side) of the dorsal and ventral stabilizers were investigated by using wool tufts stuck to the surface of the stabilizers. The results are shown in figure 4.

It is evident from these results (Figure 4a and 4b) that the flow remained attached over the ventral fin in symmetrical flight through the speed range of 60 to 90 KTAS. This is to be expected, given the thick, truncated airfoil sections used on the ventral fin to accommodate the tail landing-gear. (NACA 0015, truncated at approximately 64% chord).

The flow over the dorsal fin is dominated by two strong vortices, one vortex which probably extended from the intermediate tail rotor gearbox fairing, up along the spar of the bottom half of the fin to the horizontal stabilizer root, and the second vortex extending from the tail rotor gearbox fairing to the tip of the fin. See Figure 4a. It is suspected that the vortex over the top part of the fin separated from the surface, with the result that a bubble was characterized by highly turbulent and/or separated flows. The approximate position and size of the bubble is indicated on Figures 4a and 4b. It seemed that the size of the bubble increased with forward speed up to 90 KTAS. Unfortunately, tuft data at higher speeds was not available for analyses.

In right side-slip at angles of 15° at approximately 80 KTAS, the tufts seemed to indicate that the vortex on the upper surface separated earlier from the surface, resulting in a large area of separated flow over the upper surface, as indicated in Figure 4c. It also appeared that the vortex over the bottom part of the surface separated from the surface, resulting in a region of highly turbulent air over the bottom surface. The flow over the ventral fin remained fully attached, but a region of turbulent flow was evident. No unwanted flight control excursions were reported as the vertical stabilizer progressively stalled as these angles of side-slip were reached, which confirmed the benign nature of the stall indicated earlier by one-twelfth scale model wind-tunnel tests.

The ability of the aircraft to fly with an autorotating tail rotor following the loss of drive to the tail rotor was also investigated. The results showed that the aircraft should be able to fly with an autorotating tail rotor at speeds higher than the minimum power speeds, but at speeds lower than 90 knots the side-slip angle will be higher than the required maximum of 20°.

Based on the results obtained, it was concluded that the out-of-wind hover capability of the aircraft should be improved, whilst care should be taken not to decrease the positive attributes of the vertical stabilizer, such as the directional stability, tail rotor loss capability and tail rotor off-loading in forward flight. It was decided, however, that the out-of-wind hover capability of the aircraft should be given priority over the other characteristics, should a trade-off be required.

Based on the results obtained from the tuft flow visualization tests, an elegant solution seemed possible. It was proposed that the trailing edge of the top, canted, section of the dorsal fin be removed up to the rear spar and be replaced with a blunt, rounded, trailing, edge cap. The proposed modification is shown in Figure 5.

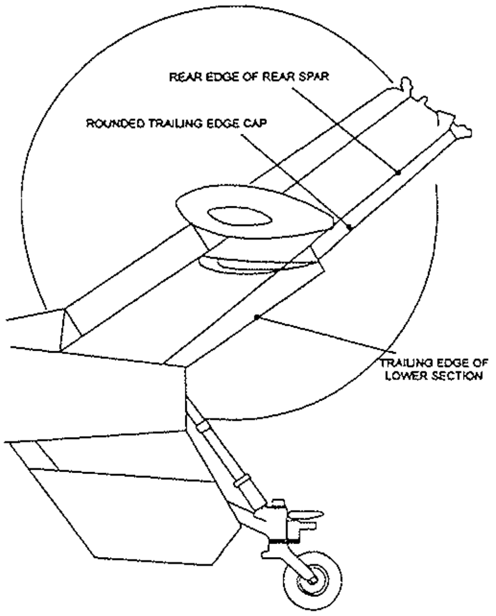

Figure 5: Vertical Stabilizer 2: Geometry

The area removed from the trailing edge of the top section of the dorsal fin would be very effective in reducing the tail rotor blockage. 15% of this area was swept by the primary load area of the blades (70% to 90% of the blade radius).

Surface flow patterns derived from the tuft behaviour indicated that the surface flow in the area under consideration was actually aligned with the trailing edge section of the fin, contributing very little to the sideforce produced by the stabilizer. It was also believed that the removed area would not significantly influence vortex-dominated flow upstream of the trailing edge. It was believed, therefore, that removal of this trailing edge area would not significantly influence the tail rotor off-loading or the directional stability of the aircraft.

3.2 Evaluation of the Second Dorsal Fin Configuration

After the trailing edge of the tip was removed (configuration 2, see figure 5) another comprehensive flight test programme was carried out to evaluate the out-of-wind hover performance and stability characteristics of this configuration.

The out-of wind hover capability and the aircraft yaw response at various speeds were tested in all azimuth directions: only the left sideways flight (270° azimuth) and flight into the critical azimuth direction (295° azimuth) will be discussed here. Left sideways flight is the critical direction of sideways flight as far as tail rotor blockage and interactional aerodynamic effects are concerned.

Using left sideways flight capability as a measure of out-of-wind hover performance, it appears that the modified dorsal fin enhanced the performance considerably. Unfortunately, data beyond a speed of 25 knots is not available for the aircraft with the original dorsal fin to allow direct comparisons to be made. However, from Figure 2 it can be seen that with the original fin and an aircraft referred mass of 8 819 kg, an 11% margin remained at only 25 knots left sideways speed, whereas with the trailing edge modification incorporated and an aircraft referred mass of 9 115 kg, a 10% margin was reached at 34 knots, and flight up to 50 knots has been demonstrated.

At this stage the out-of-wind hover performance of the Rooivalk was compared to that of the AH-64 Apache. In Figure 2 left sideways flight data for the AH-64 Apache (actually right sideways data transposed for a clockwise main rotor), is presented. The Apache data is for an aircraft referred mass of approximately 9 036 kg, and is for flight in-ground effect (approximately 20 feet wheel height), which is generally a less demanding condition for sideways flight. The data have been obtained from Reference 4. It can be seen that the Apache speed versus yaw pedal characteristics are similar to those of Rooivalk out-of-ground effect.

An additional yaw agility requirement was set in the User Requirement Document (Ref. 2) that the aircraft should be able to attain a yaw rate of 15 °/s, 1,5 s after application of the yaw pedal input, throughout the low-speed flight envelope.

With the aircraft in configuration two status, the yaw pedal margins in left sideways and left forward quartering flight were found to be not adequate to produce the required yaw rate response of 15 °/s, 1,5 s after pedal input (see figure 6). From an operational viewpoint, out-of-wind hover and out-of-wind hover manoeuvring could be associated with operations in- and out-of-ground effect. However, certain conditions in-ground effect may, in fact, constitute more severe flight conditions, for instance when the main rotor wake is deflected by the ground surface to interfere with the tail rotor.

It appears that all the Apache out-of-wind hover and hover manoeuvring trials were performed in ground effect (wheel height 20 feet).

It appears that the Apache, which is regarded as an agile aircraft, just meets the 15 °/s yaw rate specification at 35 knots sideways flight in-ground effect.

The lateral-directional dynamic stability of the aircraft in configuration 2 status was evaluated and, as expected, no major deviations in the stability characteristics compared to configuration one, were found.

In addition to the out-of-wind hover capability and the directional stability characteristics of the aircraft, additional characteristics such as yaw pedal speed stability, lateral stick stability and yaw pedal activity were also investigated.

The yaw pedal speed and lateral stability of the aircraft in configuration two status was found to be acceptable. With the rounded trailing edge fitted to the top part of the dorsal fin, the pedal activity was found to be unacceptably reduced when compared to configuration 1, but still unnacceptable.

In an attempt to improve the yaw response of the aircraft, it was decided to reduce the blockage of the lower dorsal fin. It is proposed that the trailing edge be removed up to the rear spar, and replaced by a rounded trailing edge with much reduced side area, similar to that of the dorsal fin tip. The trailing edge of the tip and lower dorsal fin would therefore continue in a straight line down to the root of the fin (see Figure 8). The reduction in swept fin area as well as the rounded trailing edge should both contribute to a reduction in tail rotor blockage with a corresponding increase in yaw pedal margins and yaw response.

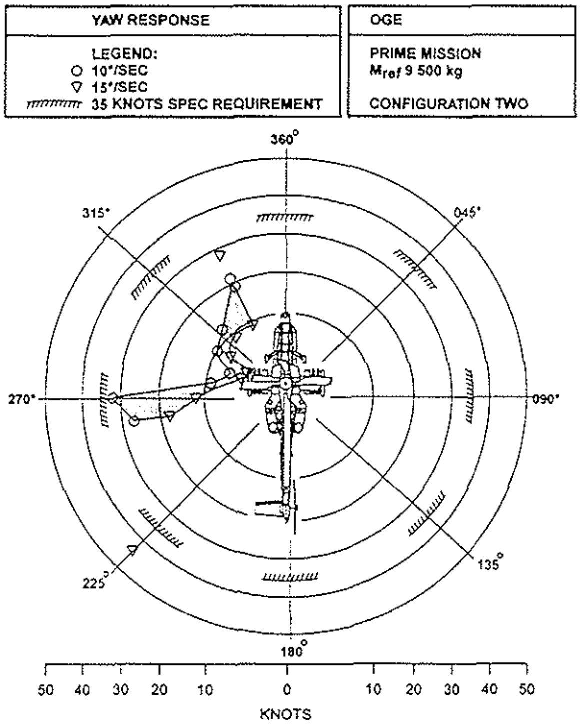

Figure 6: Vertical Stabilizer Configuration 2: Out-of-wind Hover Envelope and Yaw Rate Envelope

During an operational evaluation held in simulated battlefield conditions it was found that the ground clearance between the bottom surface of the ventral fin and the ground was inadequate when the aircraft was operating in rough terrain. The ground clearance was increased by reducing the span of the ventral fin by 300 mm. This modification was incorporated as part of configuration 3 (see Figure 7).

3.3 Evaluation of the Third Dorsal Fin Configuration

After the results from the tests with the aircraft in configuration 2 status were evaluated, it became clear that the aircraft was now able to meet the specified out-of-wind-hover envelope. The aircraft was, however, not able to comply with the minimum yaw rate/yaw acceleration requirements, requiring that the aircraft must be able to attain a yaw rate of 15 °/s, 1,5 s after application of the yaw pedal control input.

The emphasis of the flight-test evaluation shifted accordingly from the out-of-wind hover capability to the yaw response capability of the aircraft. An analysis of the yaw control margin required to attain the minimum acceptable yaw rate/acceleration revealed that, depending upon aircraft mass, a yaw control margin of at least 22% to 26% is required during left sideways flight. This proved that the yaw rate/acceleration requirement is much more severe than the 10% yaw control margin required by the out-of-wind hover capability requirement.

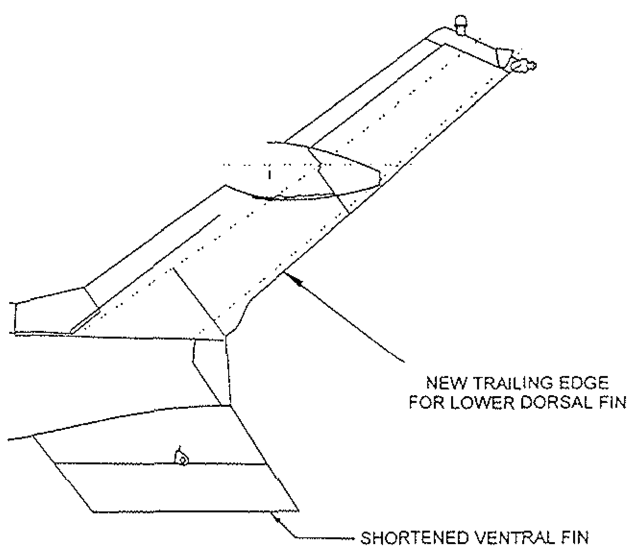

Figure 7: Vertical Stabilizer Configuration 3: Geometry

The tests were conducted in all azimuth directions. Only the results from the tests in the 270° azimuth (left sideways flight) and 295° azimuth (critical azimuth in front quarter flight) will be discussed.

In the 270° azimuth (left sideways flight), a speed of 50 knots was reached with a pedal margin of 12,4% remaining (See Figure 2). In the critical azimuth direction (295° azimuth) the test was terminated at 42 knots with 18% pedal margin remaining.

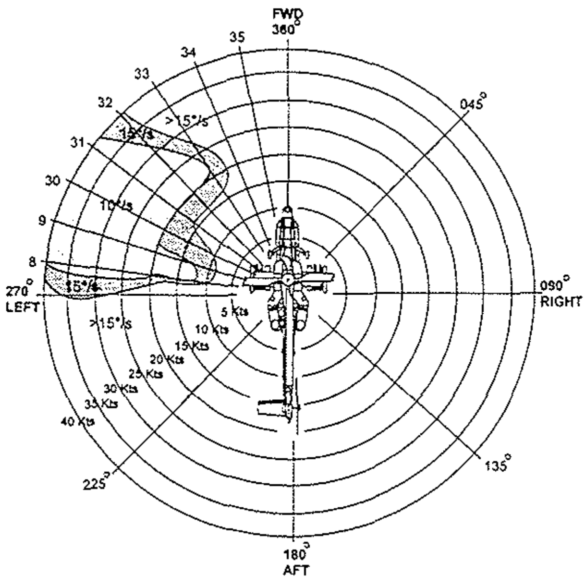

Figure 8: Vertical Stabilizer Configuration 3: Out-of-wind Hover Envelope and Yaw Rate

The results obtained from the yaw response tests in left sideways (270° azimuth) were very encouraging. The aircraft was able to exceed the required yaw rate of 15 °/s after 1,5 s at all speeds up to 40 knots. The only exception is at the 32 knot test-point where a yaw rate of 14 °/s was reached.

The yaw rates attained in the critical azimuth (294° azimuth) were below the required yaw rate of 15 °/s after 1,5 s. At 20 knots sideways speed, a maximum yaw rate of only 9 °/s was reached whilst only 8 °/s was possible at 30 knots and 42 knots. The aircraft was very heavy at 9 593 kg average referred mass, which is 433 kg heavier than the prime mission referred mass of 9 160 kg. An investigation into the effect of aircraft mass on maximum yaw rate attainable indicated that the aircraft should be able to attain a maximum yaw rate of at least 10 °/s after 1,5 s at the prime mission referred mass of 9 160 kg. The yaw control response envelope attainable with the aircraft in configuration 3 status is shown in Figure 8.

The out-of-wind hover performance and the yaw response envelope of the aircraft with the configuration 3 vertical stabilizer fitted either exceeded the required performance or was close enough to the specified performance to be regarded as acceptable.

The lateral stick-speed stability and the yaw pedal-speed stability remained essentially positive, with only minor areas of neutral stability. The lateral stick-speed stability and the yaw pedal-speed stability were satisfactory.

The unacceptably high yaw pedal fluctuation during right sideways flight with the aircraft in configuration 2 status was much reduced, indicating that the strength of the vortices being shed into the tail rotor was much reduced by rounding and smoothing the trailing edge of the dorsal fin. The yaw pedal activity encountered during flight to the right (90° azimuth) and right aft quarter (135° azimuth) was still unacceptably high. These fluctuations were then thought to be caused by the flow separation point on the trailing edge being unstable, resulting in unsteady vortices being shed into the tail rotor disc. The position of the separation point on the trailing edge was fixed by attaching a small vertical strip to the trailing edge. This solved the problem, the pedal activity in right sideways flight being reduced to a very acceptable level.

3.4 Design Requirements Reviewed

At this stage of the programme a decision was made to review the design requirements and priorities. The various requirements such as directional dynamic stability, tail rotor loss capability, out-of-wind hover capability and yaw response were evaluated against the operational environment in which the aircraft was intended to operate.

A survivability analysis showed that the aircraft was most likely to lose the tail rotor at low altitude in hover or at low speed. In this environment the tail rotor loss capability, which is essentially a high-speed capability, would be of little practical value. In light of this it was decided to discard the tail rotor loss capability as a design requirement.

It was decided that priority should be given to increasing the aircraft's ability to operate at low speed in high winds and to maximize the low-speed agility of the aircraft. It was decided that increased agility would maximize the effectiveness and survivability of the aircraft within the battlefield area where it would be more vulnerable.

It was decided that the required stability criteria could be relaxed in favour of increased agility. This decision was based on the fact that if dynamic stability is lost through reduction of the vertical stabilizer area it could be regained by 'tuning' the dual-dual architecture digital autopilot. The very high reliability of the autopilot made the possibility of having to abort a mission because of autopilot failure so remote that the airframe dynamic stability criteria could be relaxed.

3.5 Evaluation of the Fourth, Final Dorsal Fin Configuration

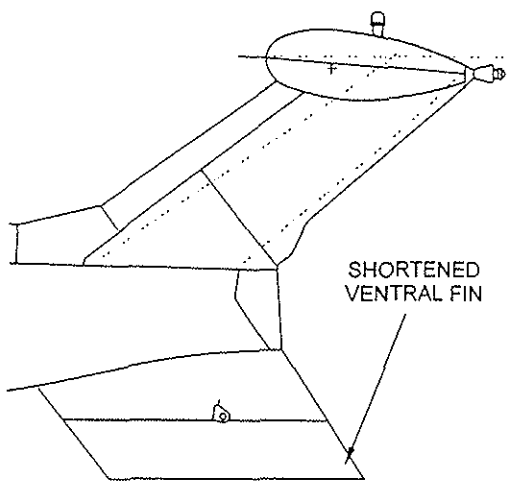

Figure 9: Vertical Stabilizer Configuration 4: Geometry

Based on the decision to optimize the low-speed agility of the aircraft, it was decided to test the out-of-wind hover performance and the yaw agility of the aircraft with the top, canted, section of the dorsal fin removed. This configuration, configuration 4, is shown in Figure 9.

The yaw response of the aircraft in this configuration was improved compared to the yaw response of the aircraft in configuration 3 status. This is mainly due to the increase of between 10% to 15% in pedal margin remaining (with both aircraft at identical reference mass, Configuration 4 having the larger margins). The yaw rate to percentage yaw pedal displacement ratio being virtually identical for both configurations. The yaw response envelope of the aircraft in configuration 4 status is shown in Figure 10. The yaw response of the aircraft in this configuration exceeded the required yaw rate of 15 °/s after 1,5 s except for a very small area around the critical azimuth (295° azimuth) where a yaw rate in excess of 10 °/s was attainable.

The lateral directional dynamic stability (Dutch roll mode), with both the roll and yaw channels of the AFCS disengaged, was significantly reduced by the removal of the canted top section of the dorsal fin. However, the test pilots still found this characteristic acceptable, even though the stability roots for speeds in excess of 130 knots and higher are outside the level 3 boundary of the specification, as shown in Figure 11. The roll to sideslip and roll rate-to-yaw rate to ratios were not seriously affected by the removal of the canted top section of the dorsal fin. The roll reversal characteristics of the aircraft were also investigated and found to have deteriorated, compared to the roll reversal characteristics of the aircraft in configuration 3 status. In view of the gains made in low-speed handling qualities, the degradation in dynamic stability and roll reversal characteristics were acceptable to both test pilots.

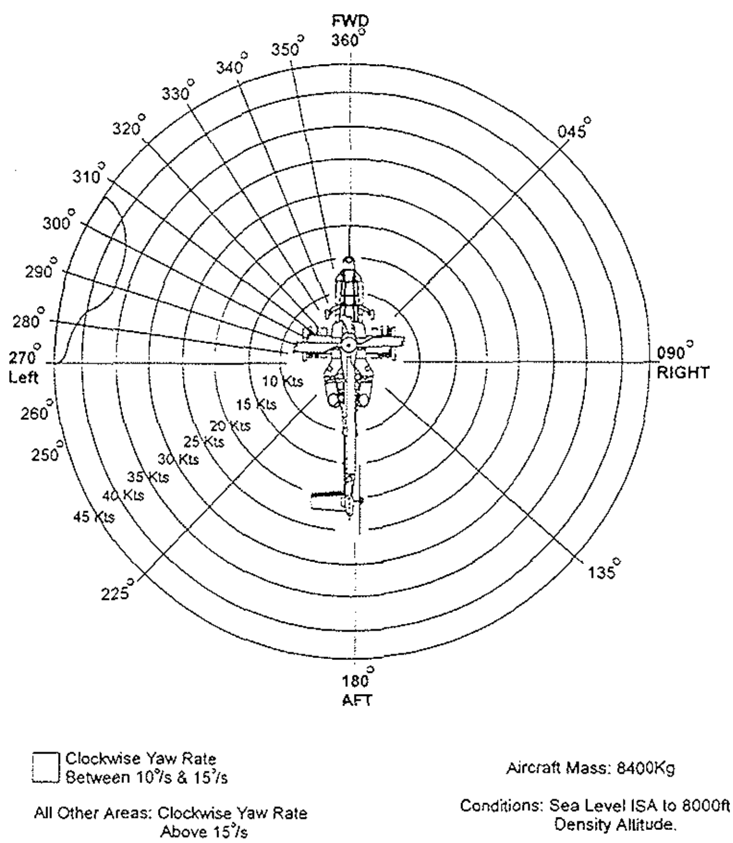

Figure 10: Vertical Stabilizer Configuration 4: Out-of-wind Hover Envelope and Yaw Rate Envelope

Configuration 4 was accepted as the final, production vertical stabilizer configuration. The out-of-wind hover envelope was extended to 45 knots throughout the mass range of the aircraft and for all ambient conditions.

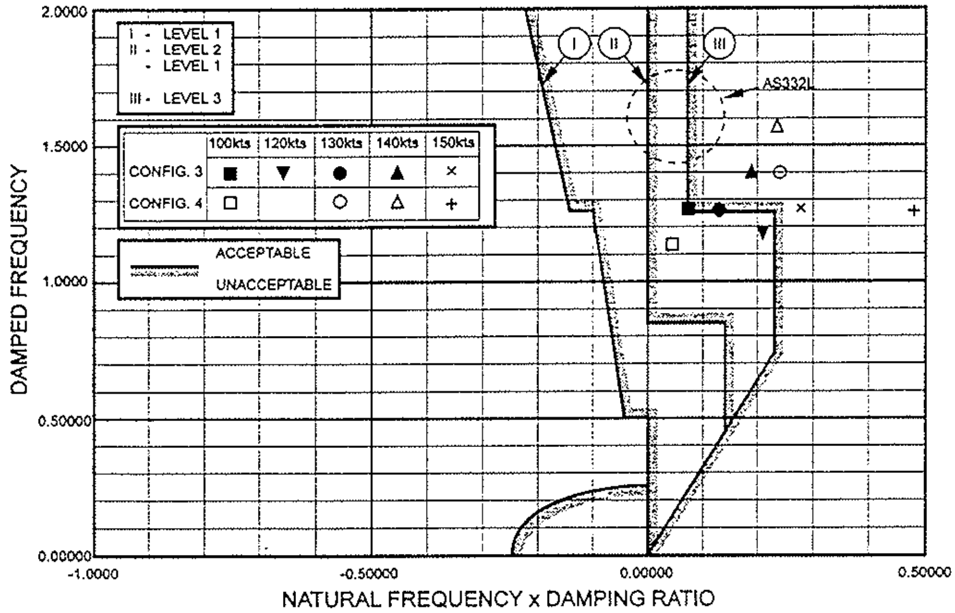

Figure 11: Vertical Stabilizer Configuration 4: Lateral-Directional Dynamics Stability Characteristics

4. Development of the Horizontal Stabilizer

The results of the flight-test evaluation are briefly summarized. No detailed discussions of the results are included. All tests were conducted with the C of G in the neutral, or slightly aft of neutral position.

The pitch attitude of the aircraft was measured throughout the speed envelope. The pitch attitude varied from 6° nose up at hover to 9° nose-up at 40 knots. At speeds higher than 40 knots, the pitch attitude reduced to 2° nose-up at 120 knots. This data illustrates the absence of any large, undesirable pitch attitude changes during transition. This confirms the correct placement of the horizontal stabilizer relative to the main rotor in that no strong main rotor wake/stabilizer interaction effects are present. The pitch attitude of the aircraft during autorotation and maximum power climbs were also satisfactory.

The longitudinal stick travel between full power climb and autorotation were found to be approximately 2,5 inches, well within the 3 inches required by MIL-H-8501A. The longitudinal stick margin during maximum power climb was 25% and during autorotation 45% (at 55 knots). This is sufficient.

The longitudinal static stability was found to be adequate, with the slope of the longitudinal stick vs. speed curves being positive throughout the speed range tested. The longitudinal dynamic stability, with the AFCS pitch channel disengaged, was found to be adequate, well within the level 2 boundary required, with the mode easy to control, and the period being 23 seconds.

The results showed that the design as far as size and position of the horizontal stabilizer are concerned, was satisfactory.

Replacing the Rooivalk horizontal stabilizer with the Oryx horizontal stabilizer would have a number of advantages. Using the Oryx stabilizer would result in a mass saving of 2,7 kg. It would also reduce manufacturing costs and simplify logistics; the stabilizers then being a common component between two aircraft currently in service with the South African Air Force.

In view of the advantages to be gained from using the Oryx stabilizer on the Rooivalk, a Oryx stabilizer was evaluated. The influence of the Oryx stabilizer on longitudinal trimmability, static stability and manoeuvring stability was found to be negligible. On the other hand, a significant reduction in longitudinal dynamic stability occurred. With neutral C of G and the AFCS pitch channel disengaged, the phugoid characteristics deteriorated to a level worse than level 3, which, according to MIL-F-83300, is not acceptable.

The fact that the test pilots still regarded the degraded phugoid acceptable, combined with the fact that the phugoid characteristics only deteriorated lower than level 3 with the AFCS pitch channel disengaged, led to the Oryx stabilizer being adapted for the production Rooivalk aircraft (see Figure 12).

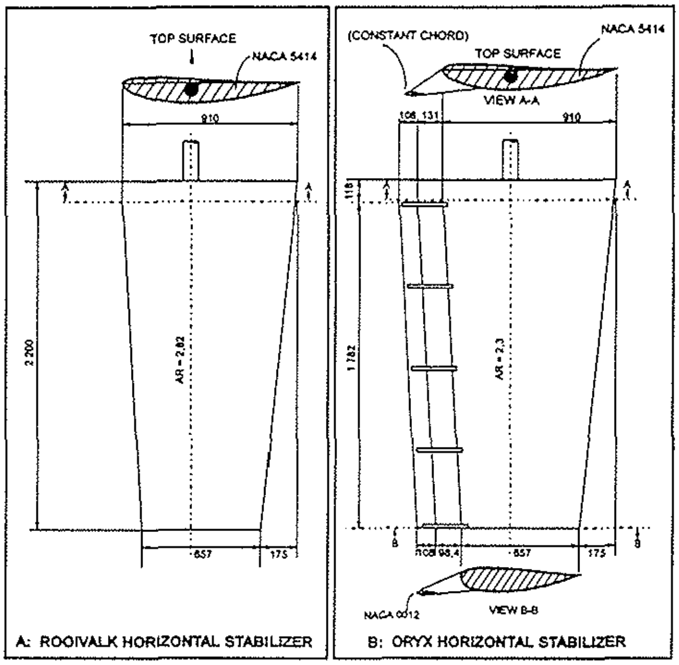

Figure 12: Horizontal Stabilizer Configurations

5. Conclusion

The aerodynamic designs and development of the vertical and horizontal stabilizers of the Rooivalk Attack Helicopter followed the classical path of initial design according to requirements and thereafter being developed/modified by lessons learnt and experience gained through flight-testing and operational testing of the aircraft in its intended operational environment.

The end result is an aircraft with good flying qualities throughout the flight envelope that compares very favourably with its competitors, such as the AH-64 Apache.

6. References

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