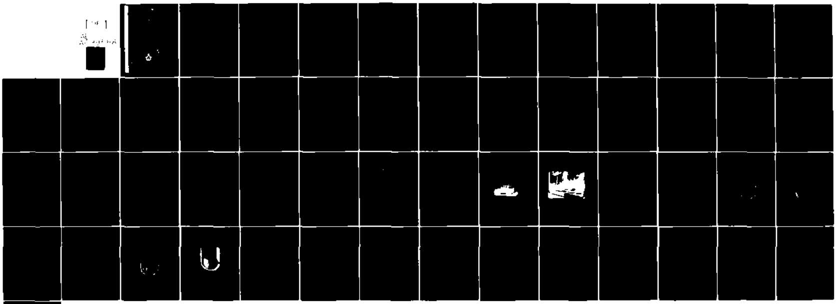
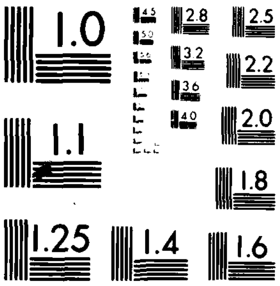
AD-A099 588 AIRCRAFT RESEARCH AND DEVELOPMENT UNIT EDINBURGH (AUS--ETC F/G 1/3
BELL 206B-1 DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT.(U)
MAY 81 L R WARD
UNCLASSIFIED ARDU-TI-721
NL



END
DATE
FILMED
6 81
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

ARDU-TI-721

12

LEVEL II

AR-002-461

DEPARTMENT OF DEFENCE

ROYAL AUSTRALIAN AIR FORCE

AIRCRAFT RESEARCH AND DEVELOPMENT UNIT

EDINBURGH, SOUTH AUSTRALIA

TECHNICAL INVESTIGATION NO 721

BELL 206B-1 DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

COPY NO 45

MAY 1981

1. ~~This document is the property of the Australian Government and the information it contains is released for Defence purposes only and must not be disseminated beyond stated distribution without prior approval.~~
2. ~~The document and the information it contains must be handled in accordance with appropriate security regulations applying in the country of lodgement.~~
3. ~~This information may be subject to privately owned rights.~~
4. ~~When no longer required this document should be returned to ARDU/DISB.~~

ACTION AUTHORITY

This report is for the communication of information and is not an authority. Any action required within the RAAF will be authorised by Headquarters Support Command.

⑨ Technical investigation,

Security classification of this page UNCLAS

DOCUMENT CONTROL DATA SHEET

1 DOCUMENT NUMBERS

AR Number: AR-002-461

Report Number: ⑭ ARDU-TI-721

Other Numbers:

2 SECURITY CLASSIFICATION

a. Complete Document: UNCLAS

b. Title in Isolation: UNCLAS

c. Summary in Isolation: UNCLAS

3 TITLE

⑥ Bell 206B-1 Directional Control in Low Airspeed Flight.

4 PERSONAL AUTHOR(S):

Flight Lieutenant ⑩ L.R. Ward

5 RECLASSIFICATION AND CONTROL REVIEW AUTHORITY

6 DOCUMENT DATE:

⑪ May [redacted]81

7 CORPORATE AUTHOR(S):

Aircraft Research and
Development Unit

8 REFERENCE NUMBERS:

a. Task: TI 721

b. Sponsoring Agency: DAIRENG-AF

9 COMPUTER PROGRAM(S):
(Title(s) and language(s))

⑫ 54

10. RELEASE LIMITATIONS:

Approved for Public Release

Security classification of this page UNCLAS

015600

Security classification of this page UNCLAS

11. **ANNOUNCEMENT LIMITATIONS** *(of the information on these pages)*:

Unlimited

12. **DESCRIPTORS:**

Bell 206B-1
OH-58
Kiowa
Helicopters
TAK Helicopter Rotors
Stability
Control
Flight Tests
Azimuth

13. **COSATI CODES:**

0103

14. **SUMMARY OR ABSTRACT:**

(if this is security classified, the announcement of this report will be similarly classified)

Following a number of incidents associated with directional control of the Bell 206B-1 helicopter, Aircraft Research and Development Unit was tasked to conduct a limited investigation to determine critical wind azimuths and the conditions conducive to loss of directional control.

The flight tests defined areas of critical wind azimuths and speeds where insufficient directional control margins and deficient directional handling qualities existed which were likely to substantially limit helicopter operations at high gross weight and density altitude. Lateral and directional control inputs in left sideward flight were hindered due to interference of the pilot's left thigh and restricted clearance between the collective lever and cyclic stick. Insufficient aft longitudinal control margins were likely during flight in rearward azimuths with extreme forward CGs. Inaccurate and unreliable airspeed indications in the low airspeed flight regime were found to be unsatisfactory.

Although dynamic flight tests for loss of directional control proved inconclusive, a study of relevant reports, articles and flight test data revealed several factors which, in some combination, may result in loss of directional control of the helicopter. Of these factors, operation of the tail rotor in the vortex ring state was considered most likely to be the 'trigger' for loss of directional control.

Several recommendations are made pertaining to helicopter operations, changes to the Flight Manual and further flight tests.

Security classification of this page UNCLAS

AIRCRAFT RESEARCH AND DEVELOPMENT UNIT

BELL 206B-1 DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT

Project Officer:

Ward.

(L.R. WARD)
Flight Lieutenant

Approved By:

(A.A. VILCINS)
Squadron Leader
OIC Flight Test Squadron

(R.G. GREEN)
Group Captain
Commanding Officer

ARDU File Reference: 2535/2/721/Tech

HQSC File Reference: 3000/7/1-721

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification________

By________
Distribution/________
Availability Codes

Dist	Avail and/or Special	
A		

AIRCRAFT RESEARCH AND DEVELOPMENT UNIT

TECHNICAL INVESTIGATION NO 721

BELL 206B-1 DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT

SUMMARY

Following a number of incidents associated with directional control of the Bell 206B-1 helicopter, Aircraft Research and Development Unit was tasked to conduct a limited investigation to determine critical wind azimuths and the conditions conducive to loss of directional control

The flight tests defined areas of critical wind azimuths and speeds where insufficient directional control margins and deficient directional handling qualities existed which were likely to substantially limit helicopter operations at high gross weight and density altitude. Lateral and directional control inputs in left sideward flight were hindered due to interference of the pilot's left thigh and restricted clearance between the collective lever and cyclic stick. Insufficient aft longitudinal control margins were likely during flight in rearward azimuths with extreme forward CGs. Inaccurate and unreliable airspeed indications in the low airspeed flight regime were found to be unsatisfactory.

Although dynamic flight tests for loss of directional control proved inconclusive, a study of relevant reports, articles and flight test data revealed several factors which, in some combination, may result in loss of directional control of the helicopter. Of these factors, operation of the tail rotor in the vortex ring state was considered most likely to be the 'trigger' for loss of directional control.

Several recommendations are made pertaining to helicopter operations, changes to the Flight Manual and further flight tests.

LIST OF CONTENTS

LIST OF TABLES

BELL 206B-1 HELICOPTER DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT

INTRODUCTION

1. On 24 February 1980, Bell 206B-1 helicopter A17-042 sustained Category 5 damage (unrepairable) resulting from impact with trees and the ground following loss of directional control. The results of the subsequent Court of Inquiry were reported in Reference A which concluded that the accident was caused by a loss of airspeed and/or a very strong localized wind gust possibly associated with a developing 'willy-willy'. References B and C also described incidents associated with directional control of the helicopter. Discussions with Bell 206B-1 pilots indicated that a number of unreported incidents of loss of directional control of the helicopter had also occurred. Due to the lack of information on this phenomenon and its flight safety implications, Reference D tasked Aircraft Research and Development Unit (ARDU) to investigate the Bell 206B-1 directional flight control system and low airspeed flight directional control characteristics to determine:

a. critical wind azimuths, and

b. the conditions conducive to loss of directional control of the helicopter.

ARDU was also to provide recommendations for practical operating or technical methods for avoiding loss of directional control of the helicopter. Reference E was an interim report published to expedite dissemination of the initial findings. This final report amplifies Reference E and completes the reporting requirements of Reference D.

CONDITIONS RELEVANT TO THE TESTS

Test Aircraft

2. The Bell 206B-1 is a five place, light observation helicopter configured with two bladed teetering head main and tail rotors driven by an Allison 250-C20 turboshaft engine derated to 400 SHP (sea level standard day). During normal operation, the transmission is limited to 317 SHP input. Designed maximum gross weight of the helicopter is 3,200 lb (or 3,600 lb when carrying external loads). A detailed description of the helicopter is given in Reference F, Section 1 (Description and Operation). A description of the directional flight control system is given in Annex A. Longitudinal, lateral and collective control is by a positive mechanical, irreversible (hydraulically boosted) flight control system which incorporates adjustable friction devices on the cyclic and collective. A force trim system consisting of magnetic brakes and force gradient springs is installed in the cyclic control circuits. The system is designed to provide artificial control feel and control centring. The helicopter used for the investigation (A17-004) was considered representative of operational aircraft and had accumulated a total of 1,492 flight hours at the commencement of the flight tests. The helicopter was equipped with a needle bearing tail rotor yoke and the tail rotor was rigged in accordance with Reference G. Throughout the flight tests, the helicopter was configured with high skid landing gear and all doors on. Defence Kit Passive (armour plating) was not fitted.

Test Limitations

3. The flight tests were conducted within the limits defined in Reference F, Section 5 (Operating Limitations), except that a dispensation was given to permit step pedal inputs and rapid pedal reversals.

Weather, Time and Place of Tests

4. The helicopter was evaluated during eight flights totalling 10.1 hours in visual meteorological conditions at RAAF Base Edinburgh during the period 9 October to 20 November 1980. Calm air (winds less than 3 knots) and approximately sea level standard day conditions prevailed during the tests.

Instrumentation and Test Equipment

5. The general arrangement of instrumentation installed in the helicopter for the flight tests is shown in ARDU Drawing No KA17ID010 (Contractor's Ref No 80056000) which is reproduced in Annex B, Figure 1.

6. Pedal Position. Pedal position was transduced from the control tube shown in Annex A, Appendix 1, Item 8, and displayed by an indicator mounted on the instrument panel coaming. The recorded pedal positions were converted to percentage travel from full left by use of the calibration curve shown in Annex B, Figure 2. This curve was based on static measurements. When measured under dynamic conditions (flight idle), negligible difference was observed. The calibration of the tail rotor blade pitch angle (Annex B, Figure 3) was based on static measurements of the chord of a vertical tail rotor blade versus indicated pedal position, cross-plotted with Annex B, Figure 2. Zero blade pitch was defined when the blade chord was parallel to the helicopter longitudinal axis.

7. Cockpit Data. Cockpit data was recorded on:

a. cine film (by a Photosonic 1VN camera mounted on the left of the centre pillar),

b. a voice tape recorder connected into the intercommunication system, and

c. prepared data cards.

8. Pace Vehicle. The pace vehicle shown in Annex B, Figure 4 was used to provide accurate reference speeds during the flight tests. The vehicle was equipped with the following items:

a. Calibrated 'fifth wheel' accurate to 0.1 knot.

b. Azimuth indicator capable of being set at 30 degree increments.

c. Radio for communications with test aircraft.

d. Anemometer with threshold speed 2 knots for checking ambient wind conditions.

e. Hand-held cine camera for filming helicopter behaviour during dynamic tests.

During the flight tests, the aircraft formated on the pace vehicle at the desired true airspeed and relative azimuth. Pace vehicle speed was maintained within ± 0.5 knot of that desired and corrections for ambient wind were applied where appropriate.

9. Ballast. The cargo platforms were modified with racks (as shown in Annex B, Figure 5) to accept lead ballast. This enabled the helicopter gross weight to be maintained within ± 25 lb of that desired.

TESTS AND STUDIES MADE

10. The following flight tests and studies of relevant material were made:

a. Critical wind azimuths:

(1) Directional control margins.

(2) Directional handling qualities.

(3) Density altitude effect on directional control margins.

(4) Density altitude effect on directional handling qualities.

(5) Lateral control.

(6) Longitudinal control.

b. Airspeed indications.

c. Loss of directional control - dynamic flight tests.

d. Possible causes of loss of directional control:

(1) Tail rotor vortex ring state.

(2) Tail rotor precessional stall.

(3) Tail rotor RPM droop.

(4) Increasing main rotor torque.

(5) Increasing main rotor speed.

(6) Vertical fin effects.

(7) Insufficient directional control margins.

(8) Main rotor shedded vortex interference.

(9) Ground vortex interference.

(10) Helicopter 'weather-cocking' characteristics.

(11) High gross weight.

(12) High density altitude.

RESULTS AND DISCUSSION

Critical Wind Azimuths

11. The relative wind azimuth, Psi (ψ), is defined as the direction of the wind relative to the helicopter longitudinal axis, measured clockwise (as viewed from above) from the aircraft nose. Tests were conducted from ψ = 0 degrees to ψ = 360 degrees in 30 degree increments, with average gross weights of 2,450 lb, 2,800 lb and 3,200 lb, and at a skid height of approximately 4.5 metres. Handling Qualities Ratings (HQRs), to maintain desired aircraft heading within ± 5 degrees, were assigned at each test point using the Cooper-Harper Scale (Reference H). A relevant extract from this document is a Annex C.

12. A critical combination of relative wind azimuth and speed was defined when any of the following occurred:

a. Pilot workload was unacceptably high (HQR $\geqslant$ 7).

b. Any control travel remaining was less than 10% of total control travel available.

c. Control excursions about trim were unacceptable.

d. Any aircraft limit was reached (torque, TOT, etc).

The 10% control margin in Paragraph 12.b was considered the minimum allowable for adequate control; that is, sufficient control power would remain to overcome disturbances caused by wind gusts which could be expected in the operational environment. This was validated during the flight tests.

13. Directional Control Margins. The trimmed pedal positions as a function of relative wind speed and direction for gross weights of 2,450 lb and 3,200 lb are shown in Annex D, Figures 1 and 2. The data for 2,800 lb is not presented since it was similar and lay between that for 2,450 lb and 3,200 lb. Significant results from this data were as follows:

a. The increased main rotor torque (Q_{MR}) that was required at 3,200 lb gross weight compared to 2,450 lb gross weight is reflected by a general shift to the left of the trimmed pedal position curves.

b. The 10% directional control margin (from full left pedal) occurred at right sideward airspeed components which were less than those currently defined in Reference F, Section 5 (Operating Limitations).

c. Significant left pedal trim requirements persisted in relative azimuths of ψ = 210 to 300 degrees for gross weight 3,200 lb. Pedals level equated to 43% of pedal travel from full left and zero tail rotor blade pitch, as defined in Paragraph 6, occurred at 60% of pedal travel from full left.

The area in which directional control margins were insufficient (less than 10% of pedal travel remaining from full left pedal) defined critical combinations of wind speeds and azimuths in which directional control of the helicopter could be lost if wind gusts are encountered. As an example, a helicopter hovering at 3,200 lb gross weight in a steady wind from ψ = 90 degrees at 32 knots requires a trimmed pedal position of 10% (Annex D, Figure 2). A wind gust to 38 knots requires retrimming the pedal position to 0% (full left pedal) to maintain heading. This leaves no margin to control the right yaw which would probably be induced by the gust, and directional control of the helicopter would therefore be lost for the duration of any gust to 38 knots or greater. Similar analysis can be applied to any point within the critical area. A simplified plot of this critical area is shown by the appropriate cross-hatched area of Annex D, Figure 6. This figure is recommended for inclusion in Reference F, Section 6 (Flight Characteristics) in the Hover Capabilities paragraph on page 6-2. Operation of the helicopter in this area under the conditions given should be avoided, particularly in confined areas, due to insufficient directional control margins.

14. Directional Handling Qualities. The directional handling qualities of the helicopter varied markedly as a function of gross weight, relative wind azimuth and speed, as shown by the data in Annex D, Figures 3 to 5. In general, the higher HQRs were assigned as a result of the pilot experiencing difficulty in establishing and maintaining pedal trim, reflected by significant pedal control excursions. In Figure 3, the area of HQR = 4 in the azimuths ψ = 210 to 260 degrees at speeds greater than 20 knots was probably an under-rating due to the abrupt improvement in handling qualities which occurred in that area with increasing speed. The data is therefore more accurately represented by Figures 4 and 5. The area in which directional control difficulties were experienced coincided with that described in Paragraph 13.c and was more thoroughly investigated at gross weight 3,200 lb by stabilizing at speeds in 2 knot increments at azimuths of ψ = 240, 270 and 300 degrees. This data is presented in Annex D, Figures 7 to 9, which show the following:

a. There is a flattening or slight reversal and discontinuity in the apparent pedal trim position versus airspeed gradient in the region 10 to 25 knots (approximately).

b. Increased pilot workload is reflected by large pedal control excursions about the apparent trim point in the same 10 to 25 knot region (the excursions shown have been 'averaged').

When flying in this region (ψ = 210 to 300 degrees, airspeed 10 to 25 knots) the helicopter would frequently, and unpredictably, commence an uncommanded right yaw which required large left pedal inputs of up to 30% of total available travel to control. The left pedal stop was occasionally contacted during these inputs. The yaw excursions were accompanied by a marked increase in high frequency vibrations through the tail rotor pedals and airframe. Since the flight tests were conducted in calm air (Paragraph 4) wind gusts were able to be discounted as the cause. The control difficulties experienced, requiring unacceptably high pilot workload for adequate directional control, were therefore attributed to operation of the tail rotor in the vortex ring state. The simplified plot of the critical area in which directional instability may be experienced is shown by the appropriate cross-hatched area of Annex D, Figure 6, which (as also stated in Pararagaph 13) is recommended for inclusion in Reference F, Section 6 (Flight Characteristics) in the Hover Capabilities paragraph on page 6-2. Operation of the helicopter in this area under the conditions given should be avoided, particularly in confined areas, due to directional instability. The note pertaining to the Hover Capability paragraph on page 6-3 of Reference F, Section 6 (Flight Characteristics) is incorrect and should be deleted if Annex D, Figure 6 is included or amended as recommended if this figure is not included.

15. Density Altitude Effect on Directional Control Margins. Paragraph 5.24.1 and Figure 5-6 of Reference I show the considerable adverse effect increased density altitude has on directional control margins for the US Army OH-58A helicopter. Although conducted in approximately sea level standard day conditions, the ARDU flight tests show that similar effects can be expected for the Bell 206B-1 helicopter. If the Bell 206B-1 data follows that of the US Army OH-58A, pedal control margins would be a function of the ratio W/σ where:

W = gross weight, and

σ = atmospheric density ratio (ambient density/standard day sea level density).

The data in Annex D, Figures 1 and 2 therefore represents (approximately) W/σ = 2,450 lb and 3,200 lb respectively. If the data correlates with that of Reference I, that given in Annex D, Figure 2 would be representative of, for example, the Bell 206B-1 operating at a gross weight of 2,450 lb and density altitude 8,900 ft, that is W/σ = 3,200 lb. Therefore, although gross weight is low, the area in which directional control margins are sufficient is substantially reduced. The data published in Reference F, Appendix 1 (Performance Data), Figure A5-3, shows the maximum gross weight for hovering Out of Ground Effect (OGE) and In Ground Effect (IGE) dependent on ambient atmospheric conditions. This data shows that the helicopter is capable of hovering (for example) at 12,000 ft, standard day, at the following gross weights (neglecting headwind corrections):

a. OGE: 2,800 lb, and

b. IGE: 3,200 lb.

Such performance is often required during survey operations and other similar tasks in mountainous tropical areas. In addition, helicopter control often becomes critical in these areas since the landing pads are generally subjected to winds of largely varying speed and direction which are difficult to judge due to the usual dearth of wind indicators. In this example, the conditions yield W/σ = 4,040 lb (OGE hover) and W/σ = 4,620 lb (IGE hover). Under these conditions the area in which directional control margins are sufficient is likely to be severely limited; however, extrapolation of the data presented in this report to such conditions could prove erroneous. Validation of such extrapolation and provision of data for W/σ in excess of 3,200 lb could only be obtained reliably by further flight tests at high density altitude and gross weight.

16. Density Altitude Effect on Directional Handling Qualities. Directional handling qualities can also be expected to vary with density altitude. The growth of the area of deficient handling qualities and their deterioration with increasing W/σ is shown by the data in Annex D, Figures 3 to 5 which represent (approximately) W/σ = 2,450 lb, 2,800 lb and 3,200 lb respectively. In high density altitude environments, the possibly large area of directional instability is likely to seriously endanger helicopter operations. As with density altitude effects on directional control margins (Paragraph 15), validation of such extrapolation and provision of data for W/σ in excess of 3,200 lb could only be obtained reliably by further flight tests at high density altitude and gross weight.

17. Lateral Control. Lateral control of the helicopter was qualitatively evaluated during the critical wind azimuth testing. In general, the helicopter response to lateral control inputs was rapid, smooth and predictable. Control excursions (at the handgrip) averaged approximately ± 10 mm about the trim point. For the essentially mid lateral CGs tested, control margins were adequate except for the region ψ = 240 to 300 degrees and at speeds in excess of 30 knots. In this region, the substantial left cyclic stick displacements from the neutral (calm air hover) position required for trim, combined with the mid-range collective lever setting, restricted the available clearance between the two controls. As a result, when flying in this region, the cyclic stick would occasionally contact the inside left thigh of the pilot, constraining his leg between the cyclic stick and collective lever. This hindered lateral and directional control inputs. The problem would be exacerbated by left CGs and

large pilot thighs. An anthropometric study of the COH-58A helicopter (Reference J) concluded that the restricted clearance between the collective lever and the cyclic stick when the cyclic stick was deflected full left constituted a flight safety hazard for larger pilots engaged in 'nap of the earth' flying. The report recommended that an engineering evaluation be conducted to investigate means of moving the pilot's collective lever further left and that the co-pilot's collective be removed and stowed at all times except during training flights. ARDU considers the restricted clearance between the collective lever and the cyclic stick unsatisfactory but acceptable, providing the following caution is included in Reference F, Section 6 (Flight Characteristics) in the Control Operation paragraph on page 6-2:

CAUTION

> Left lateral cyclic control travel may be limited by the pilot's left thigh due to the restricted clearance between the collective lever and the cyclic stick. Such interference will limit helicopter left-skid-up slope landing capabilities, manoeuvring roll control and left sideward flight capabilities in the ψ = 240 to 300 degrees azimuths. The co-pilot's controls should be stowed whenever inexperienced personnel occupy that station to prevent inadvertent interference.

18. Longitudinal Control. Longitudinal control of the helicopter was qualitatively evaluated during the critical wind azimuth testing. The helicopter response to longitudinal control inputs was rapid, smooth and predictable. Positive static longitudinal stability was displayed during flight in the ψ = 0 and 180 degrees azimuths; however, a slight discontinuity was noted in the longitudinal cyclic stick position versus relative airspeed gradient in rearward azimuths (ψ = 150 to 210 degrees) at approximately 15 to 20 knots. In this region, the discontinuity manifested itself as a large (approximately 40 mm) aft retrimming requirement and a 3 degree nose-up change in pitch attitude. Although noticeable, the discontinuity did not greatly affect aircraft control and control excursions (at the handgrip) averaged approximately ± 10 mm about the trim point. For the mid-range CGs tested (108.8 to 109.7 inches) control margins were adequate; however, aft longitudinal control margins may be sufficiently reduced to define a critical area in the ψ = 150 to 210 degree azimuths at speeds in excess of approximately 25 knots when the helicopter is loaded to extreme forward CGs as shown by the annotated area in Reference I, Figure 5-6 for the OH-58A helicopter. For the conditions tested, longitudinal control of the Bell 206B-1 helicopter in low airspeed flight was satisfactory; however, further testing would be required to confirm that a critical area of insufficient longitudinal control margins exists in the ψ = 150 to 210 degrees azimuths at speeds greater than 25 knots when the helicopter is loaded with extreme forward CGs. This would require approximately five hours additional flying time and the development of a non-standard modification to enable variation of helicopter longitudinal CG.

Airspeed Indications

19. During the critical wind azimuth testing, the airspeed indications shown in Table 1 were noted. Due to rotor wash and other factors the pitotstatic systems of most helicopters are considered to give inaccurate and unreliable airspeed indications in the low airspeed flight regime. The data in Table 1 confirms this for the Bell 206B-1. The indications could be expected to vary with gross weight, density altitude, yaw rate and skid height but, for the conditions tested, the indications in the relative azimuths of ψ = 150 to 210 degrees are significant. Some combinations of wind gusts, skid height and yaw

rate could produce much higher readings in these azimuths. In Paragraph 18 and Annexes C and L of Reference A, reasonable significance is given to the airspeed indicator reading of 40 knots at the onset of the uncontrolled right yaw. If this reading was generated by a wind gust from behind the helicopter or by rearward movement of the helicopter, large and possibly uncontrollable yawing moments could also have been generated, initiating the loss of directional control. The unreliable airspeed indications also constitute a hazard which may cause disorientation and loss of control during instrument flight conditions (especially instrument take-offs) and are probably one of the reasons that intentional flight under instrument conditions is prohibited by Reference F, Section 7 (All Weather Operation). The inaccurate and unreliable airspeed indications in the low airspeed flight regime are unsatisfactory and the following caution is recommended for inclusion in Reference F, Section 1 (Description and Operation), under the Airspeed Indicator paragraph on page 1-21:

CAUTION

> Airspeed indications are inaccurate and unreliable in the low airspeed flight regime, especially in rearward azimuths where positive indications may be displayed although helicopter movement is rearward relative to the ambient air.

TABLE 1 - INDICATED AIRSPEEDS IN LOW AIRSPEED FLIGHT

Relative Azimuth (degrees)	True Airspeed (KTAS)					
	10	20	30	35	40	50
0	0	0	29	-	33	48
30	0	0	0	-	0	22
60	0	0	0	0	0	-
90	0	0	0	0	-	-
120	0	0	0	0	-	-
150	0	0	20	25	-	-
180	0	0	19	25	-	-
210	0	0	0	17	-	-
240	0	0	0	0	-	-
270	0	0	0	0	-	-
300	0	0	0	-	0	-
330	0	0	22	-	26	-

Loss of Directional Control - Dynamic Flight Tests

20. Limited flight tests at 2,800 ± 25 lb gross weight were conducted to explore the conditions conducive to loss of directional control of the helicopter. The tests attempted to simulate the conditions under which directional control losses had been reported (that is, when turning the helicopter to the right with reference to a point on the ground in the presence of wind). Two test methods were employed as shown in Figure 1. In the circular flight path test method, the helicopter was stabilized approximately 60 metres abeam the pace vehicle at the desired test airspeed and a skid height of approximately 18 metres. The pilot then attempted to perform a constant radius turn with reference to the pace vehicle. In the varying azimuth test method, the helicopter was initially stabilized behind the pace vehicle at the desired airspeed. The pilot then attempted to yaw the helicopter around the pace vehicle, with the nose pointing at the vehicle. During these tests the aircraft was subjected to wind from varying azimuths coupled with a right yaw rate. To enable limiting conditions to be approached safely, a build-up technique was employed. After each run, aircraft control during the preceding manoeuvre was assessed to determine an appropriate increase in relative wind speed (pace vehicle speed) and/or aircraft yaw rate for the next run. The helicopter was tested in wind speeds up to 30 knots combined with yaw rates up to approximately 40 degrees/second. The only limit attained during the manoeuvres was a minor overtorque to 78 psi which occurred after approximately 270 degrees of right turn at approximately 30 degrees/second with 30 knots of relative wind during a circular flight path test manoeuvre. Aircraft behaviour during the manoeuvres was predictable from the critical wind azimuth testing, in that symptoms of tail rotor operation in the vortex ring state were present whenever the relative wind passed through azimuths around $\psi = 270$ degrees. Strong 'weather-cocking' moments were also encountered as the helicopter passed through the rearward ($\psi = 180$ degrees) relative wind azimuth and large left pedal control inputs were required to prevent the yaw rate accelerating substantially in this area. However, at no time during the tests did loss of control appear imminent and, although valuable qualitative assessments of aircraft control were made, this phase of the investigation proved inconclusive. This was considered to be due to the multitude of variables which could have affected aircraft behaviour during the tests and the limited scope of the investigation.

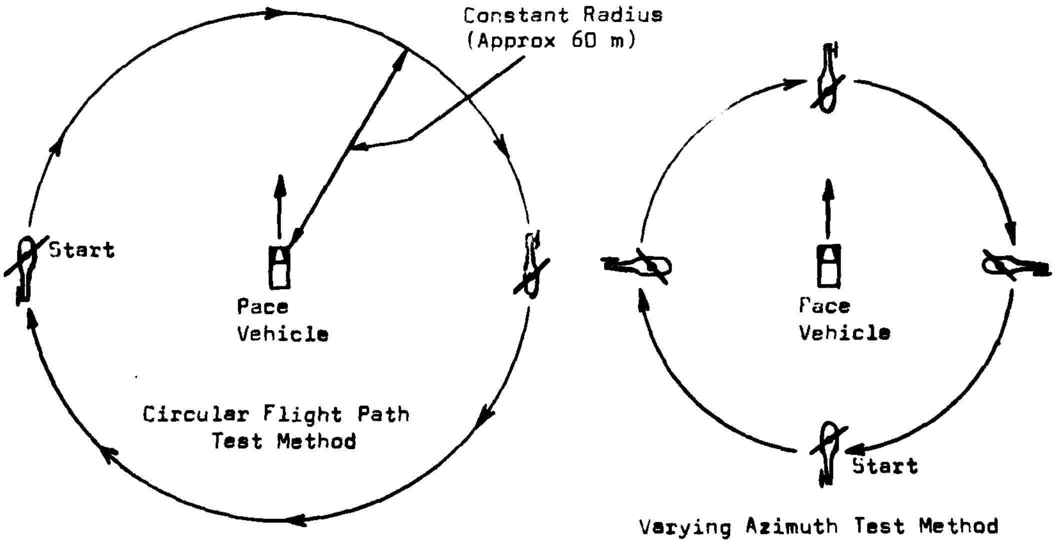


Figure 1 - Test Methods for Loss of Directional Control

Possible Causes of Loss of Directional Control

21. Although dynamic flight tests for loss of directional control proved inconclusive (Paragraph 20), a study of relevant reports, articles, flight test data and the results of flight tests conducted under this investigation revealed several factors which, in some combination, may result in loss of directional control of the helicopter. These are discussed in the following paragraphs.

22. Tail Rotor Vortex Ring State. The directional instability experienced during the critical wind azimuth testing was attributed to operation of the tail rotor in the vortex ring state (Paragraph 14), which may be encountered with winds from the left (ψ = 240 to 300 degrees) or when making hover turns to the right. Operation of the tail rotor in the vortex ring state is regarded as the 'trigger' for loss of direction control of the helicopter and a detailed discussion of the phenomenon is given in Annex E. The recovery techniques for loss of directional control due to loss of tail rotor effectiveness cannot be explicitly stated due to the multitude of circumstances where loss of control may occur and the uncertainty of the cause. However, if operation of the tail rotor in the vortex ring state is considered to be the cause of a loss of directional control, recovery should be accomplished by introducing RIGHT pedal and reducing main rotor torque, if possible, and gaining forward airspeed. If terrain clearance permits, the most expeditious means of recovery may be to 'chop' the throttle and enter autorotation, then re-introduce power when forward airspeed has been gained and the right yaw controlled. The height required to complete such a manoeuvre is unknown and the ultimate course of action must be based on pilot judgement of the relevant factors. The recovery actions outlined in this paragraph are recommended for inclusion in Reference F, Section 3 (Emergency Procedures) under the Anti-Torque System Malfunctions heading on page 3-4.

23. Tail Rotor Precessional Stall. The following discussion of tail rotor precessional stall is paraphrased from Reference K:

> 'A tail rotor is a gyroscope which must be precessed whenever the helicopter has a yawing rate. The moment required to precess a gyroscope is applied 90 degrees ahead of the direction of precession. For a fan or propeller this moment is carried structurally, but for a flapping tail rotor it must be produced aerodynamically. As the aircraft yaws, the tail rotor tip path plane axis lags the tail rotor mast or control axis. This produces an equivalent cyclic feathering or differential blade angle-of-attack from one side of the rotor to the other. As a consequence, one side of the disc will be loaded more highly than the other. If stall is encountered, the additional precessional moment must be produced by the unstalled side of the disc where it substracts from the basic thrust. This significantly reduces the thrust capabilities of the rotor. Stall due to precession is most likely to occur whenever there is a combination of high tail rotor thrust and yaw rate. This occurs when stopping a nose right hovering turn. Precessional stall can be delayed by increasing the airfoil $C_{L_{max}}$, the blade Lock number, or the tail rotor blade tip speed'.

Reference K also provides typical calculated stall boundaries for hovering turns at altitude for three Bell helicopters. This data is reproduced in Figure 2. The stall boundary shown for the UH-ID is cited as an acceptable minimum for future designs. The Bell 206B-1 stall boundary would be expected to be close to that shown for the Bell 206A (in the same ambient conditions), due to the similarity of the two helicopters. Although probably providing a reasonable margin from the cited acceptable minimum stall boundary, tail rotor stall due to precession cannot be discounted as a possible contributory cause of loss of directional control of the Bell 206B-1 helicopter due to its higher density altitude and gross weight hover capabilities compared to the Bell 206A.

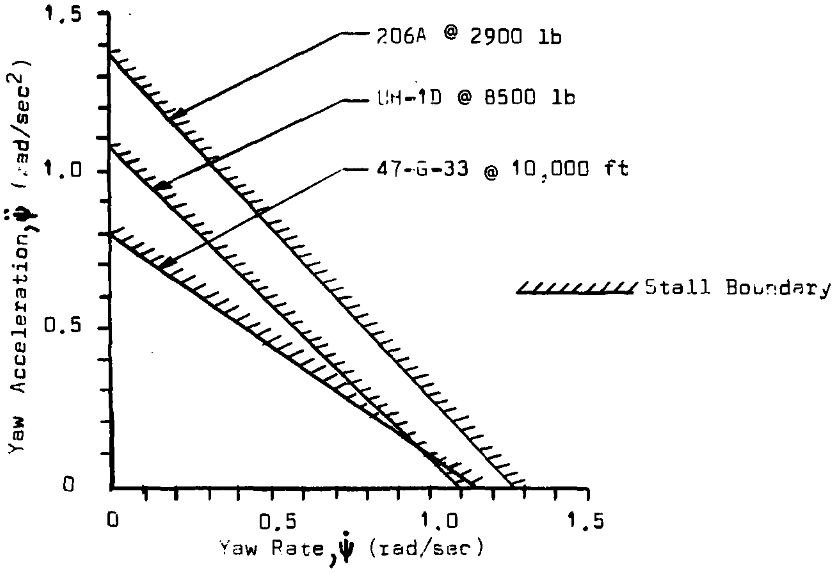


Figure 2 - Typical Calculated Stall Boundaries at Altitude

24. Tail Rotor RPM Droop. In a simplified analysis, the aerodynamic thrust produced by a rotor blade is given by the equation:

$$\text{Thrust} = C_T \rho (\Omega R)^2 A_D$$

Where:

C_T = thrust coefficient (a function of blade design, blade angle and relative wind)

ρ = ambient air density

Ω = rotational velocity

R = rotor radius

A_D = area of rotor disc

Hence, tail rotor thrust varies as the square of rotational velocity. Any reduction or 'droop' in tail rotor rpm will therefore rapidly decrease thrust. This could result in loss of directional control of the helicopter if the tail rotor pedal position required for trim is at or near full left pedal prior to the rpm drooping. These conditions are likely to be encountered during high density altitude/gross weight operations such as vertical take-offs, external load pick-ups and hoisting. If these operations are attempted at the upper limit of aircraft capability, rpm droop can be expected as maximum available engine power is attained. High torque and high density altitude also dictate large left pedal trim requirements which could be exacerbated by winds from right azimuths (Paragraphs 13 and 15). If increased tail rotor pitch (left pedal) is used to compensate for the loss of thrust due to rpm droop, full left pedal travel may be reached. Increasing the tail rotor pitch also increases the power demand on the engine (already lacking sufficient power output) causing further rpm droop. With a combination of high torque, full left pedal and reducing tail rotor thrust due to decreasing tail rotor rpm, the aircraft cannot maintain the desired heading and an uncommanded right yaw will result. The resulting right yaw will tend to increase tail rotor blade section angles-of-attack possibly leading to stall (Paragraph 23) or to operation of the tail rotor in the vortex ring state (Paragraph 22). These would further reduce the tail rotor thrust, causing the uncommanded right yaw to accelerate. Therefore, extreme caution should be exercised when performing low airspeed manoeuvres at the upper limit of helicopter capabilities where left pedal control margins are minimal and a requirement for additional power may cause rpm droop.

25. Increasing Main Rotor Torque. In the low airspeed flight regime, the primary purpose of the tail rotor is to produce sufficient thrust to compensate for main rotor torque and to provide yaw acceleration when desired. An increase in main rotor torque requires a corresponding increase in tail rotor thrust to maintain equilibrium (no yaw); therefore, an increase in the amount of left pedal is required. This effect has been discussed in Paragraph 13.a. If insufficient left pedal control margin remains before an increase in main rotor torque is made, the left pedal control stop will be contacted as power is applied. This will result in an uncommanded right yaw, the rate being dependent on the main rotor torque applied. Recovery should be effected by reducing main rotor torque.

26. Increasing Main Rotor Speed. Additional torque must be applied to the main rotor to overcome its inertia and accelerate it to the speed previously set by the pilot if a transient main rotor rpm droop is experienced. For equilibrium (no yaw) increased tail rotor thrust is required to compensate for the additional torque during main rotor acceleration. For the Bell 206B-1 helicopter, since the tail rotor drive is mechanically connected to the main rotor drive, the increasing tail rotor thrust required may be produced by the increasing tail rotor speed as the main rotor accelerates. However, if the increasing thrust due to tail rotor acceleration is insufficient, additional tail rotor pitch (left pedal) would be required. If insufficient left pedal control margin remains, directional control of the helicopter could be lost for the duration of the main rotor acceleration. Significant transient main rotor rpm droop and reacceleration during power application is commonly encountered when operating the Bell 206B-1 helicopter due to its poor engine/rotor governing characteristics. Accelerating main rotor speed is, therefore, a possible contributory cause of loss of directional control following a transient main rotor rpm droop.

27. Vertical Fin Effects. The Bell 206B-1 helicopter is configured with a 'pusher' type tail rotor which operates in close proximity to the vertical fin. The thrust and efficiency losses which result are discussed in Reference K as follows:

> 'A pusher tail rotor when producing thrust causes air to flow along the surface of the fin, creating negative pressures on the fin and tail boom on the side adjacent to the rotor. The negative pressures integrated over the area affected must be subtracted from the tail rotor thrust to obtain the net thrust. In addition, a tail rotor efficiency loss is experienced due to fin blockage in front of the rotor. The fin force is a function of thrust, fin size and shape, and separation distance between the fin and rotor. It is sensitive to wind velocity and main rotor wake'.

> 'Flight tests with the pusher configuration have also shown a sensitivity of the fin force to wind direction. With a steady wind from the left, the fin force, as defined by pressures measured on the fin surfaces, showed an increase in comparison to the model and zero wind flight data. Furthermore, the adverse pressures extended over a larger portion of the tail boom. Thus, with a left wind, a higher tail rotor thrust is required to overcome the larger adverse fin and boom forces. This increase in tail rotor thrust required can become significant under critical operating conditions'.
>
> 'The "tractor" configuration with the blade moving aft at the top has been shown to be free from the adverse wind effects, so it can be used with confidence. The inherent high fin sideload losses associated with the "tractor" tail rotor, however, are severe, and efforts to eliminate the "pusher" problems could well be worthwhile'.

Vertical fin effects are therefore considered a contributory cause of loss of directional control of the helicopter in the low airspeed flight regime. Reconfiguring the aircraft with a 'tractor' type tail rotor rotating top aft is a possible method of alleviating some of the associated problems but is considered impractical due to high developmental costs and time and the uncertainty of the result.

28. Insufficient Directional Control Margins. Directional control of the helicopter can be lost when directional control margins are insufficient. The factors affecting directional control margins and the consequences of insufficient margins are discussed in Paragraphs 13, 15 and 24 to 26. Directional control travel of the Bell 206B-1 helicopter is limited by stops in the directional control circuit (see Annex A). Available tail rotor blade pitch is, therefore, dependent on the rigging of the control system, which will vary slightly between aircraft. However, actual tail rotor thrust is dependent on blade section angle-of-attack which is, in turn, dependent on ambient conditions as well as blade pitch. The effect of increasing the available control travel to provide increased margins and tail rotor blade pitch cannot, therefore, be accurately predicted and such a modification would require exhaustive flight testing with sophisticated instrumentation to define the optimum rigging.

29. Main Rotor Shedded Vortex Interference. In translating flight, the main rotor of a helicopter sheds two vortices (rotating in opposite directions). These vortices are predicted by circulation theory and are of the same type that extend from the wingtips of fixed-wing aircraft. Such vortex formations are very powerful and have been observed following helicopter flight through smoke or agricultural dust. Reference L states that formation of the vortices (shown in Figure 3) is evident in a 20 knot wind and they are fully formed at 35 knots. At 20 knots, the vortices angle downward at about 45 degrees but this angle is dependent on the height of the main rotor above the ground plane. With wind from the azimuths of ψ = 40 to 90 and 270 to 320 degrees, the vortices can be expected to interfere with the tail rotor airflow. The precise interference cannot be predicted since many variables affect the behaviour of the vortices. Some of the factors are:

a. Main rotor height above the ground plane.

b. Main rotor thrust (and hence induced flow).

c. Tail rotor thrust.

d. Tail rotor placement with respect to the main rotor, horizontal and vertical stabilizers.

e. Direction of rotation of the tail rotor.

Reference M supports the findings of Reference L, that a main-rotor-tip vortex system causes tail rotor thrust perturbations at moderate and high velocities at azimuth angles near ψ = 45 and 315 degrees. Main rotor shedded vortex interference with tail rotor airflow is, therefore, a possible contributory cause of loss of directional control of the Bell 206B-1 helicopter.

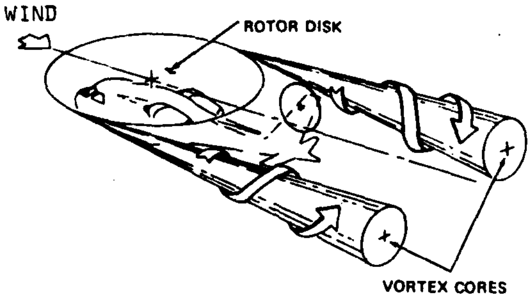


Figure 3 - Wingtip Vortices Produced by Main Rotor

30. Ground Vortex Interference. Several investigations of tail rotor performance in various conditions have been made (References K to N). Amongst other aerodynamic phenomena involved, the formation of the basic recirculation vortex caused by a crosswind acting on the flow field of a main rotor in ground effect has been found to be significant. This 'horseshoe-shaped' recirculation vortex, known as the 'ground vortex', is illustrated in Figure 4 for relative azimuth ψ = 210 degrees approximately. Although initial formation of the vortex is by the same mechanism discussed in Paragraph 29, the presence of the ground seems to have an amplifying effect on the vortex and many of the directional control problems experienced by several main rotor/tail rotor configured helicopters during flight in relative azimuths ψ = 150 to 210 degrees (approximately) have been attributed to the interference effects of the ground vortex. These adverse effects include an increase in the adverse vertical fin force, a decrease in tail rotor thrust and an increase in tail rotor torque required. The adverse effects are the result of immersion of the tail rotor and vertical fin in the ground vortex. When rearward airspeed is sufficiently increased, the free-stream flow diminishes the ground vortex and carries it away from the tail rotor and vertical fin; as a result, there is an abrupt change in tail rotor blade pitch required. The changing position of the vortex may also explain the slight discontinuity noticed in longitudinal control (Paragraph 18). Due to the accompanying adverse effects, ground vortex interference is considered a possible contributory cause of loss of directional control of the Bell 206B-1 helicopter.

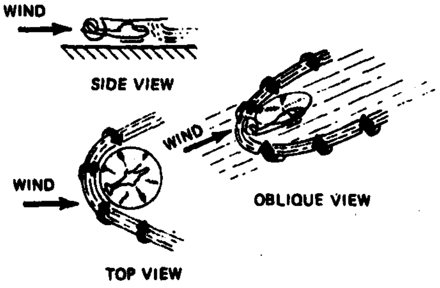
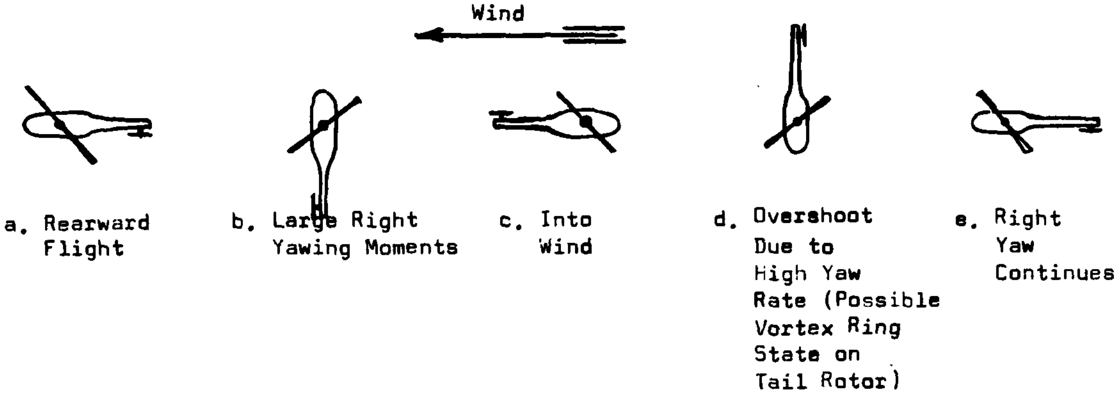


Figure 4 - Helicopter Ground Vortex

31. Helicopter 'Weather-Cocking' Characteristics. The Bell 206B-1 helicopter is designed to be directionally stable in forward flight (relative azimuth $\psi = 0$ degrees). If a sideslip excursion is experienced in forward flight, moments are generated by the tail rotor and vertical fin to restore the helicopter to the balanced forward flight condition. If a sideslip excursion is large, the restoring moments are also correspondingly large. In the low airspeed flight regime, many pilots would argue that neutral directional stability would be an advantage since minimal directional control retrimming requirements for compensation of gust disturbances would result. A compromise is, therefore, required in which the helicopter exhibits acceptable directional control characteristcs in both forward flight and the low airspeed flight regime. The data in Annex D, Figures 3 to 5 shows that signficantly higher pilot workloads are required for trimmed flight in rearward azimuths compared to forward flight azimuths. These are attributed to the helicopter being less directionally stable (in fact unstable) when flying in rearward azimuths. The large yawing moments generated during excursions from flight in rearward azimuths are also reflected by the 'wine-glass' shape of the curves in Annex D, Figures 1 and 2. For example, with reference to Annex D, Figure 2, flight at $\psi = 180$ degrees and 30 knots requires a pedal trim position of approximately 38%. If an excursion of relative wind to azimuth $\psi = 200$ degrees is experienced, a large pedal trim change to 50% is required for equilibrium. This does not account for the extra right pedal that would be required to arrest the left yaw rate which would probably be initiated by such a disturbance. Recoveries from flight in rearward azimuths, where the helicopter was allowed to yaw left or right to align itself into the relative wind, demonstrated that very large yawing moments were produced by the extreme sideslips acting on the tail rotor and vertical fin. These were also noted during dynamic flight tests (Paragraph 20). The high yaw rates generated in these manoeuvres were almost sufficient to cause pilot disorientation and virtual loss of directional control of the helicopter occurred until established in forward flight. Analysis of the nose-right (right yaw) recovery reveals a sequence of conditions which could lead to total loss of directional control. This is illustrated in Figure 5. Initially, the helicopter is in 'stabilized' rearward flight (Figure 5a). The pilot, wishing to orientate the helicopter into the wind, allows the helicopter to commence a nose-right yaw. As the helicopter begins the right yaw, large right yawing moments accelerate the yaw (Figure 5b). The pilot, at this stage, may introduce substantial left pedal in an attempt to control the right yaw and stabilize the aircraft into wind (Figure 5c). However, the yaw rate (and consequently the rotational inertia of the helicopter) may be sufficient to cause the helicopter to overshoot the into-wind orientation and conditions conducive to formation of the vortex ring state on the tail rotor would then prevail (Figure 5d). During yawing recoveries, it was also noted that high power settings were required to prevent the helicopter settling. The high power setting would aggravate the right yaw and the pilot may find the helicopter still yawing right as shown in Figure 5d although he has applied full left pedal. High density altitude and gross weight would also tend to increase the right yaw rate. If the helicopter rotates sufficiently (Figure 5e) conditions prevail for the complete sequence to be repeated and the uncontrolled right yaw will continue. The 'weather-cocking' characteristics of the helicopter are considered a possible contributory cause of loss of directional control. Therefore, caution should be exercised when yawing the aircraft right into wind when the wind is initially in the rearward azimuths, as such a maneouvre may initiate an uncontrollable right yaw.



a. Rearward Flight

b. Large Right Yawing Moments

c. Into Wind

d. Overshoot Due to High Yaw Rate (Possible Vortex Ring State on Tail Rotor)

e. Right Yaw Continues

Figure 5 - Possible Sequence Leading to Loss of Directional Control

32. High Gross Weight. The effect of gross weight on directional control of the helicopter has been discussed in Paragraphs 13 to 16, 23, 24 and 31. In general, operations at high gross weights demand high main rotor torque and consequently high tail rotor thrust and large left pedal trim requirements which reduce the control margins available. High gross weight is, therefore, considered a contributory cause of loss of directional control.

33. High Density Altitude. The effect of density altitude on directional control of the helicopter has been discussed in Paragraphs 15, 16, 23, 24 and 31. In general, operations at high density altitudes dictate higher power requirements and increased angles-of-attack for thrust generation. Control and power margins are reduced and high density altitude is, therefore, considered a contributory cause of loss of directional control.

CONCLUSIONS

Critical Wind Azimuths

34. The flight tests revealed that insufficient directional control margins and deficient directional handling qualities exist within the currently defined low airspeed flight envelope. Areas of critical wind azimuths and speeds were defined as denoted in Annex D, Figure 6 (Paragraphs 13 and 14).

35. Helicopter operations at high gross weight and density altitude are likely to be substantially limited due to the growth of the areas of insufficient directional control margins and deficient directional handling qualities with increasing W/σ (Paragraphs 15 and 16).

36. The restricted clearance between the collective lever and cyclic stick hindered lateral and directional control inputs in left sideward flight due to the interference of the pilot's left thigh. This was considered unsatisfactory but acceptable providing the caution given in Paragraph 17 is included in Reference F (Paragraph 17).

37. Aft longitudinal control margins may be sufficiently reduced to define a critical area in the ψ = 150 to 210 degree azimuths at speeds in excess of approximately 25 knots when the helicopter is loaded with extreme forward CGs (Paragraph 18).

Airspeed Indications

38. The inaccurate and unreliable airspeed indications in the low airspeed flight regime are unsatisfactory (Paragraph 19).

Loss of Directional Control

39. Although dynamic flight tests for loss of directional control proved inconclusive (Paragraph 20), a study of relevant reports, articles and flight test data revealed the following factors which, in some combination, may result in loss of directional control of the helicopter:

a. Tail rotor vortex ring state (Paragraph 22).

b. Tail rotor precessional stall (Paragraph 23).

c. Tail rotor rpm droop (Paragraph 24).

d. Increasing main rotor torque (Paragraph 25).

e. Increasing main rotor speed (Paragraph 26).

f. Vertical fin effects (Paragraph 27).

g. Insufficient directional control margins (Paragraph 28).

h. Main rotor shedded vortex interference (Paragraph 29).

i. Ground vortex interference (Paragraph 30).

j. Helicopter 'weather-cocking' characteristics (Paragraph 31).

k. High gross weight (Paragraph 32).

l. High density altitude (Paragraph 33).

RECOMMENDATIONS

Critical Wind Azimuths

40. The simplified plot of critical wind azimuths and speeds given in Annex D, Figure 6 is recommended for inclusion in Reference F, Section 6 (Flight Characteristics) in the Hover Capabilities paragraph on page 6-2 (Paragraphs 13 and 14).

41. Avoidance of helicopter operations in the critical areas denoted in Annex D, Figure 6, is recommended (Paragraphs 13 and 14).

42. If data is required for W/σ in excess of 3,200 lb, further flight testing in a high density altitude environment is recommended (Paragraphs 15 and 16).

43. The caution given in Paragraph 17 is recommended for inclusion in Reference F, Section 6 (Flight Characteristics) in the Control Operation paragraph on page 6-2 (Paragraph 17).

44. Further flight testing is recommended to confirm that a critical area of insufficient longitudinal control margins exists in the $\psi \approx 150$ to 210 degrees azimuths at speeds greater than 25 knots when the helicopter is loaded with extreme forward CGs (Paragraph 18).

Airspeed Indications

45. The caution given in Paragraph 19 is recommended for inclusion in Reference F, Section 1 (Description and Operation), under the Airspeed Indicator paragraph on page 1-21 (Paragraph 19).

Loss of Directional Control

46. The recovery actions for loss of directional control due to operation of the tail rotor in the vortex ring state, as outlined in Paragraph 22, are recommended for inclusion in Reference F, Section 3 (Emergency Procedures) under the Anti-Torque System Malfunctions heading on page 3-4 (Paragraph 22).

47. It is recommended that extreme caution be exercised when performing low airspeed manoeuvres at the upper limit of helicopter capabilities where left pedal control margins are minimal and application of additional power may cause rpm droop (Paragraph 24).

48. If increasing main rotor torque is considered the cause of an uncontrolled right yaw, recovery should be effected by reducing main rotor torque if possible (Paragraph 25).

49. It is recommended that caution be exercised when yawing the aircraft right into wind when the wind is initially in the rearward azimuths (Paragraph 31).

REFERENCES

A. Report of Court of Inquiry Appointed to Inquire into the Accident Involving Army Helicopter A17-042 at BOURKE NSW on 24 February 1980

B. Flightfax Magazine of 25-31 August 1978, pages 2 to 5, 'OH-58 Tail Rotor Stall'

C. Aircraft Incident Message SAA A1780004 of 14 March 1980

D. Headquarters Support Command 3000/7/1-721 (5) of 8 September 1980

E. Aircraft Research and Development Unit 2535/2/721/Tech (19) of 4 February 1981

F. Defence Instruction (Air Force) AAP 7210-010-1, Flight Manual, Bell 206B-1 Helicopter, amended to AL 5 of June 1980

G. Special Technical Instruction Bell 206B-1/143, Revised Tail Rotor Rigging Procedure for 206-001-811 Series (Needle Bearing) Yokes, of 14 July 1980

H. National Aeronautics and Space Administration Technical Note D-5153 of April 1969, 'The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities'

I. Change 5 to TM55-1520-228-10, Operator's Manual, Army Model OH-58A Helicopter, of 26 March 1980

J. Defence Research Board, Canada, Defence and Civil Institute of Environmental Medicine, Technical Memorandum No 879 of October 1972, 'Anthropometric Survey of COH-58A "Kiowa" Helicopter'

K. Journal of the American Helicopter Society, Volume 15, No 4, October 1970, pages 2 to 15, 'Tail Rotor Design, Part 1 - Aerodynamics'

L. American Helicopter Society, 29th Annual National Forum, May 1973, Preprint No 764, 'Tail Rotor Performance in Presence of Main Rotor, Ground and Winds'

M. American Helicopter Society, 30th Annual National Forum, May 1974, Preprint No 802, 'Tail Rotor Thrust on a 5.5 Foot Helicopter Model In Ground Effect'

N. National Aeronautics and Space Administration Technical Note D-6118 of March 1971, 'A Wind-Tunnel Investigation of Helicopter Directional Control in Rearward Flight In Ground Effect'

PROJECT PERSONNEL

Project Pilot: Flight Lieutenant L.R. Ward, BSc, tp.

Project Engineer: Flight Lieutenant M.J. Tobin, Dip MEng, tpe.

DIRECTIONAL FLIGHT CONTROL SYSTEM
BELL 206B-1 HELICOPTER

General

1. The directional flight control system of the Bell 206B-1 helicopter is a positive mechanical, fully reversible type. Tail rotor pedals are provided for the pilot's and copilot's stations which are arranged side-by-side. A mechanical system of control tubes, bellcranks and a pitch change mechanism transmits movements of the tail rotor pedals to the tail rotor mounted on the aft left side of the tailboom. A vertical fin is mounted opposite the tail rotor on the tailboom. The system is illustrated in Appendices 1 to 3.

Mechanical System

2. A schematic of the mechanical system is shown in Appendix 1. The tail rotor pedals are adjustable fore-and-aft by turning the knob shown in Appendix 1, Item 3. The pedal assemblies are mechanically connected by control tubes to a central bellcrank (Appendix 1, Item 12) so that movement of one set of controls results in corresponding movement of the other set. The central bellcrank incorporates an adjustable friction clamp (Appendix 1, Item 11) designed to provide a breakout friction force of 3 to 5 pounds at each pedal, and a non-adjustable pedal stop in the mounting to limit left and right pedal travel. Movement of the central bellcrank is transmitted to an assembly on the tail rotor gearbox via a series of control tubes, bellcranks and walking beams. Rigging of the tail rotor controls is achieved by adjusting the lengths of the control tube and rod assembly shown in Appendix 1, Items 8 and 4 respectively. Tail rotor blade pitch control is then accomplished by means of the bellcrank, rod and lever assembly, mounted on the gearbox, actuating a control tube through the hollow rotor drive shaft to the pitch (feather axis) control crosshead and pitch links (Appendix 1, Items 5 and 6 respectively).

Tail Rotor

3. The tail rotor is a two bladed, semi-rigid, teetering head type rotating clockwise as viewed from the left of the aircraft. Slight pre-coning is incorporated. Each of the two symmetrical aerofoil section aluminium alloy blades (Appendix 2, Item 2) is mounted in a forged aluminium alloy yoke (Appendix 2, Item 8) by means of two spherical bearings (Appendix 2, Item 3) which provide for pitch change movement. The blades have a chord of 157 mm and the total diameter of the assembly is 1575 mm. Designed operating rotational speed is 2645 RPM at 103% N2 engine RPM. The yoke and blade assembly is mounted on the output shaft of the 90 degree gearbox by means of a splined trunnion (Appendix 2, Item 10) to provide for blade flapping. A 45 degree delta-three hinge is incorporated by mounting the trunnion and control crosshead at 45 degrees to the blade pitch change axis. The delta-three hinge is designed to aid rotor stability and disturbance damping. Washers (Appendix 2, Item 23) are installed on the tail rotor pitch horns (Appendix 2, Item 4) to compensate for aerodynamic blade pitch forces.

Vertical Fin

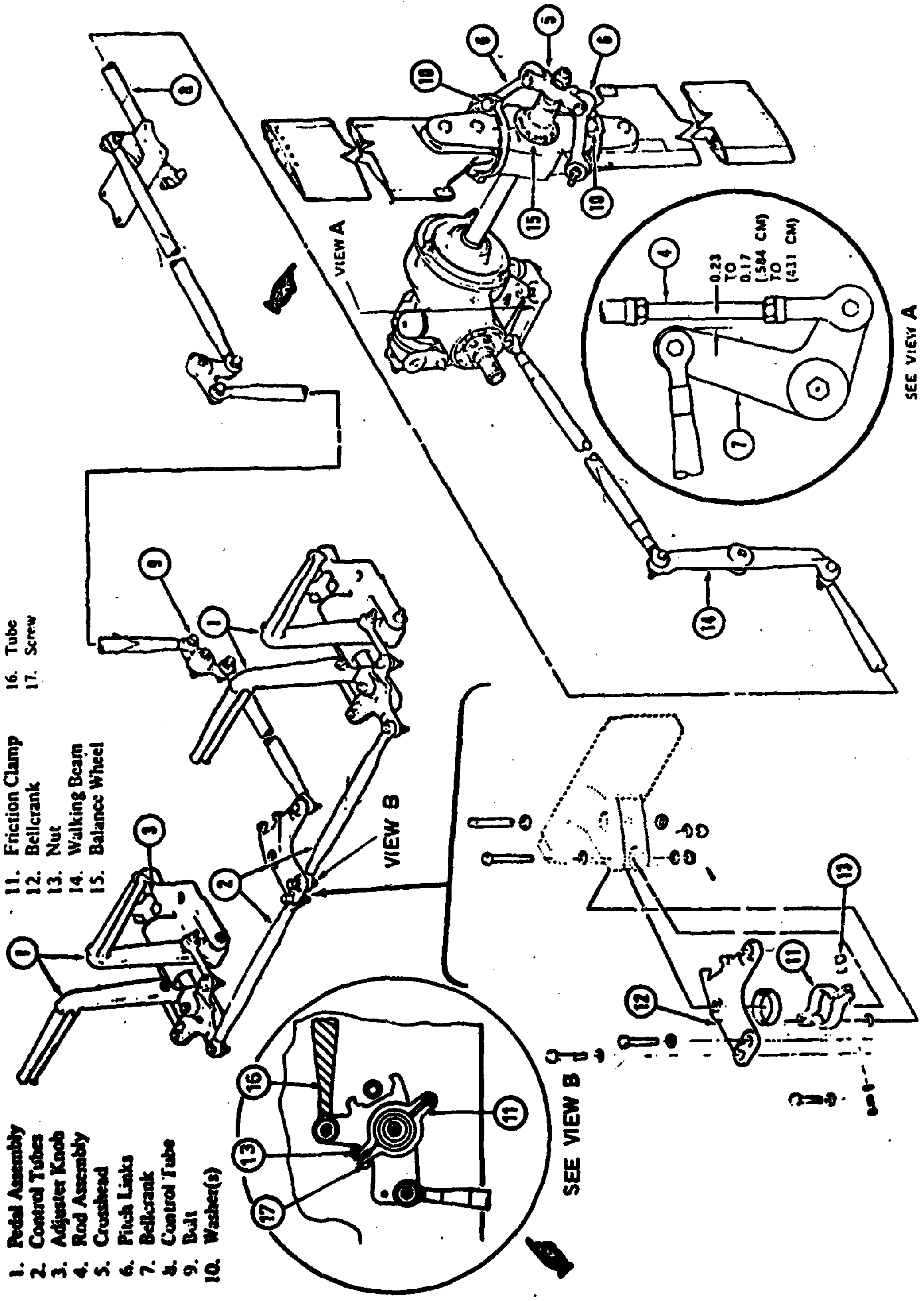
4. The vertical fin is shown in Appendix 3. The fin is constructed from aluminium honeycomb and incorporates a symmetrical aerofoil section. The upper and lower surfaces are swept and tapered and the chord of the fin is canted approximately 5.5 degrees (leading edge right) to the helicopter longitudinal axis. The fin is designed to increase directional stability and unload the tail rotor during forward flight.

Appendices:

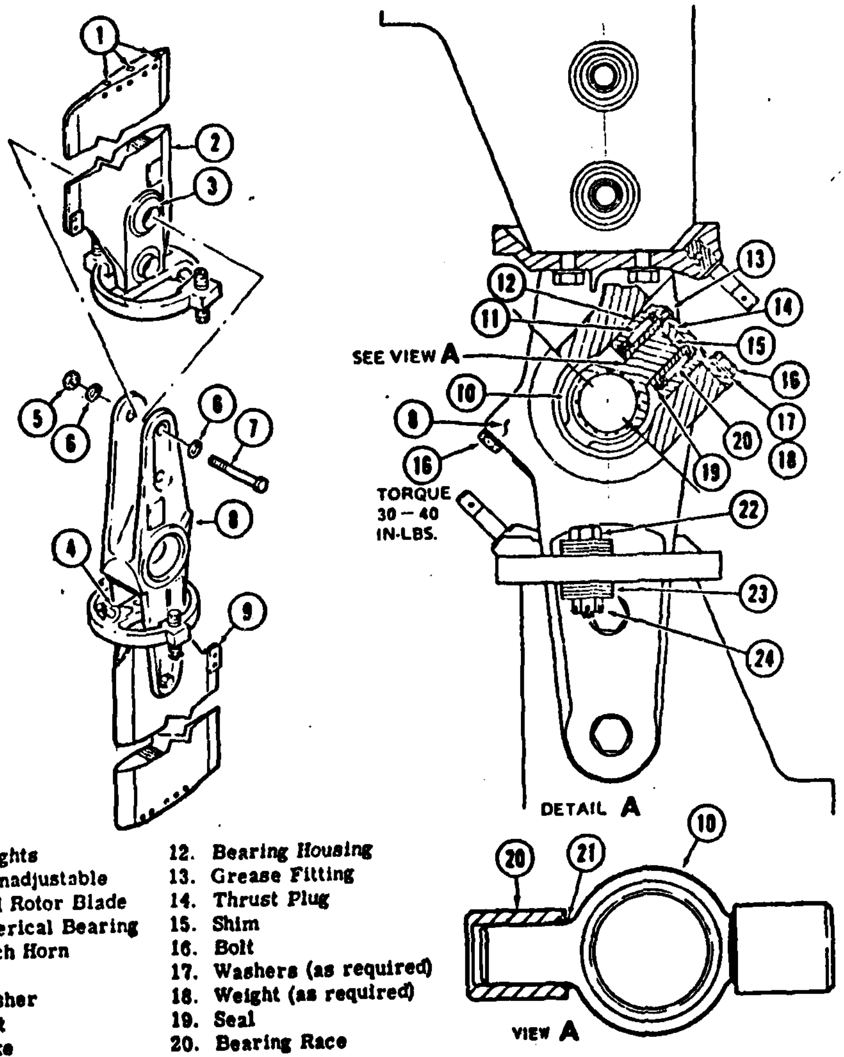
1. Bell 206B-1 Helicopter Directional Flight Control Mechanical System
2. Bell 206B-1 Helicopter Tail Rotor Hub and Blade Assembly
3. Bell 206B-1 Helicopter Horizontal and Vertical Stabilizers

APPENDIX 1 TO
ANNEX A TO
REPORT NO TI 721

BELL 206B-1 HELICOPTER
DIRECTIONAL FLIGHT CONTROL MECHANICAL SYSTEM



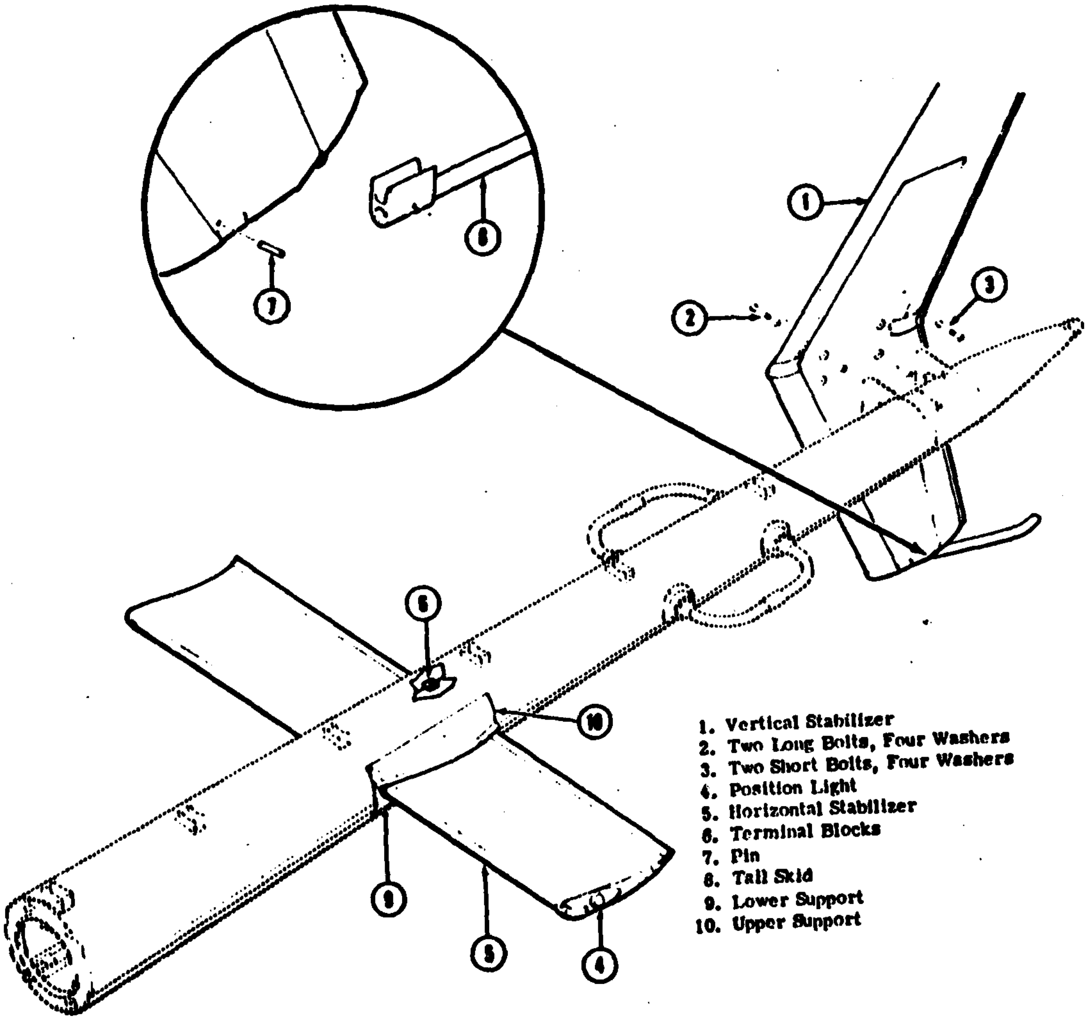
BELL 206B-1 HELICOPTER
TAIL ROTOR HUB AND BLADE ASSEMBLY



1. Weights (nonadjustable
2. Tail Rotor Blade
3. Spherical Bearing
4. Pitch Horn
5. Nut
6. Washer
7. Bolt
8. Yoke
9. Balance Weight
10. Trunnion
11. Bearing
12. Bearing Housing
13. Grease Fitting
14. Thrust Plug
15. Shim
16. Bolt
17. Washers (as required)
18. Weight (as required)
19. Seal
20. Bearing Race
21. Sealant
22. Bolt
23. Washer
24. Nut

APPENDIX 3 TO
ANNEX A TO
REPORT NO TI 721

BELL 206B-1 HELICOPTER
HORIZONTAL AND VERTICAL STABILIZERS



1. Vertical Stabilizer
2. Two Long Bolts, Four Washers
3. Two Short Bolts, Four Washers
4. Position Light
5. Horizontal Stabilizer
6. Terminal Blocks
7. Pin
8. Tail Skid
9. Lower Support
10. Upper Support

ANNEX B TO
REPORT NO TI 721

INSTRUMENTATION AND TEST EQUIPMENT

Figure 1 - General Arrangement of Helicopter Instrumentation

Figure 2 - Indicated Pedal Position Vs % Pedal Travel

Figure 3 - Tail Rotor Blade Pitch Vs % Pedal Travel

Figure 4 - Calibrated Pace Vehicle

Figure 5 - Modified Cargo Platforms

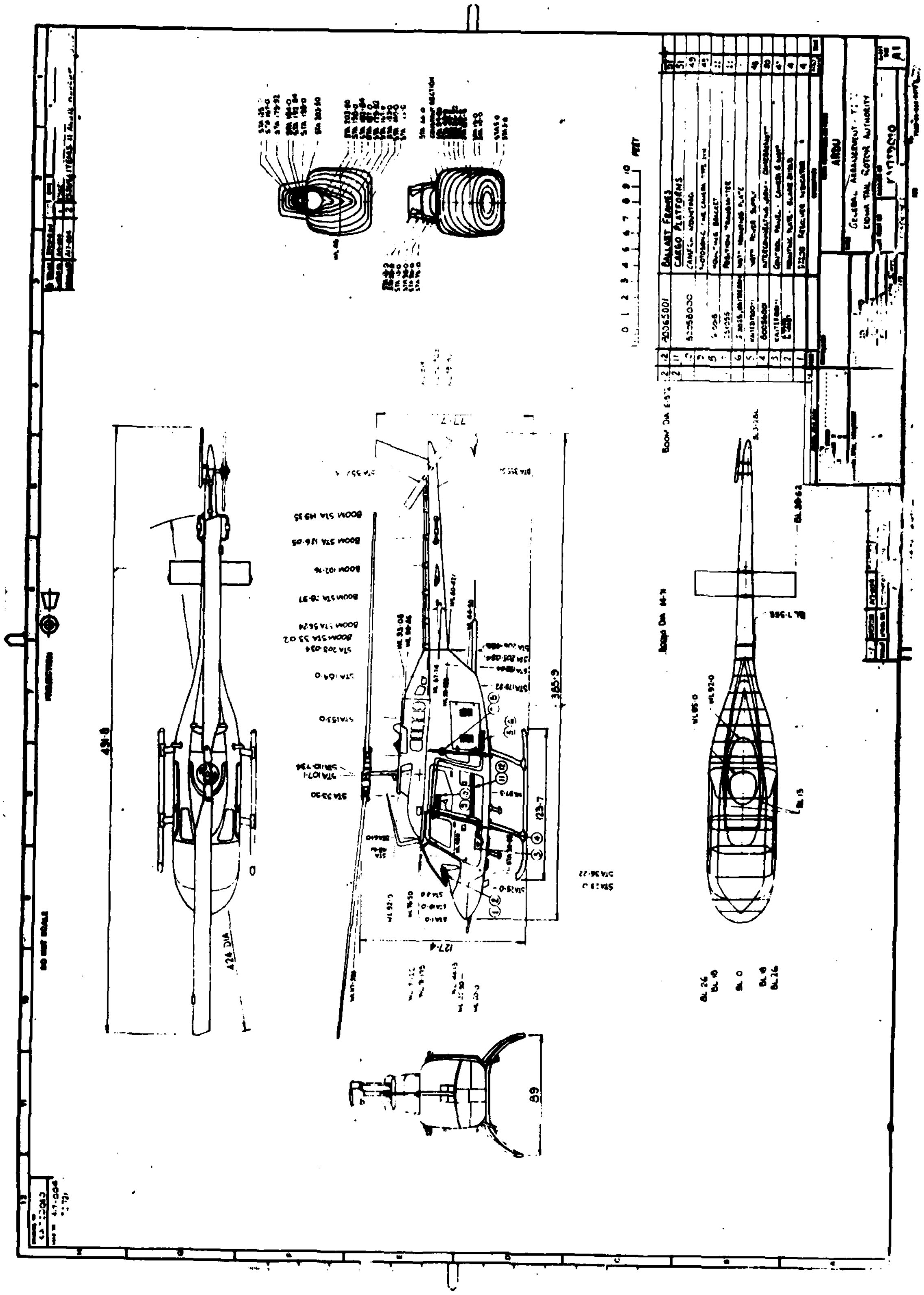


Figure 1 - General Arrangement of Helicopter Instrumentation

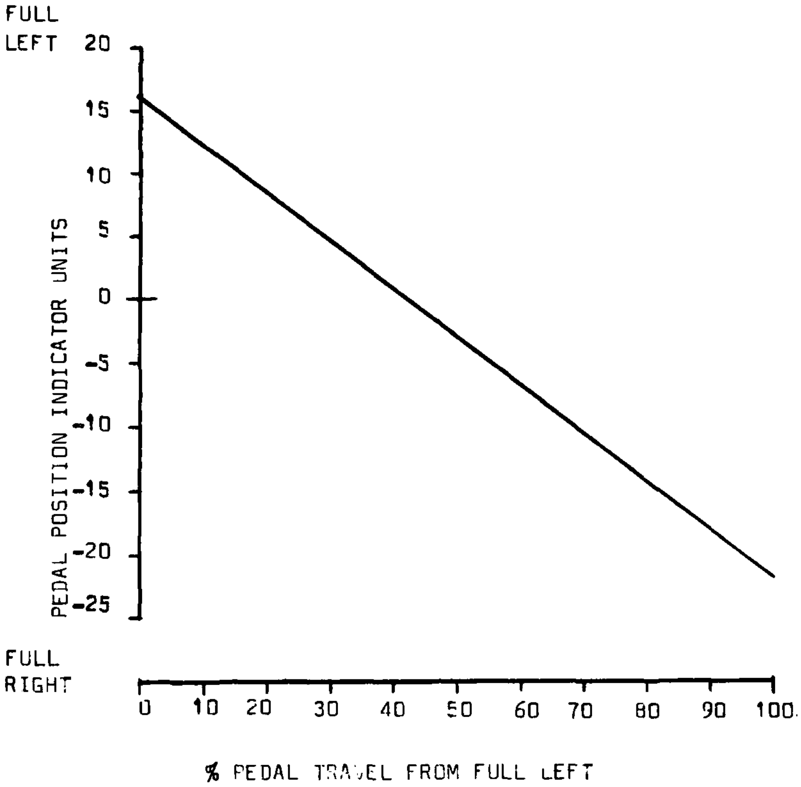


Figure 2 - Indicated Pedal Position Vs % Pedal Travel

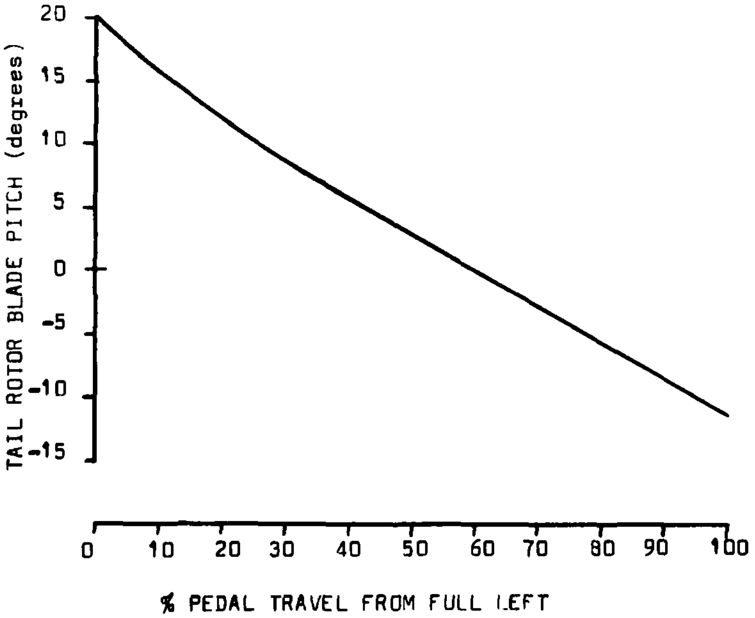


Figure 3 - Tail Rotor Blade Pitch Vs % Pedal Travel

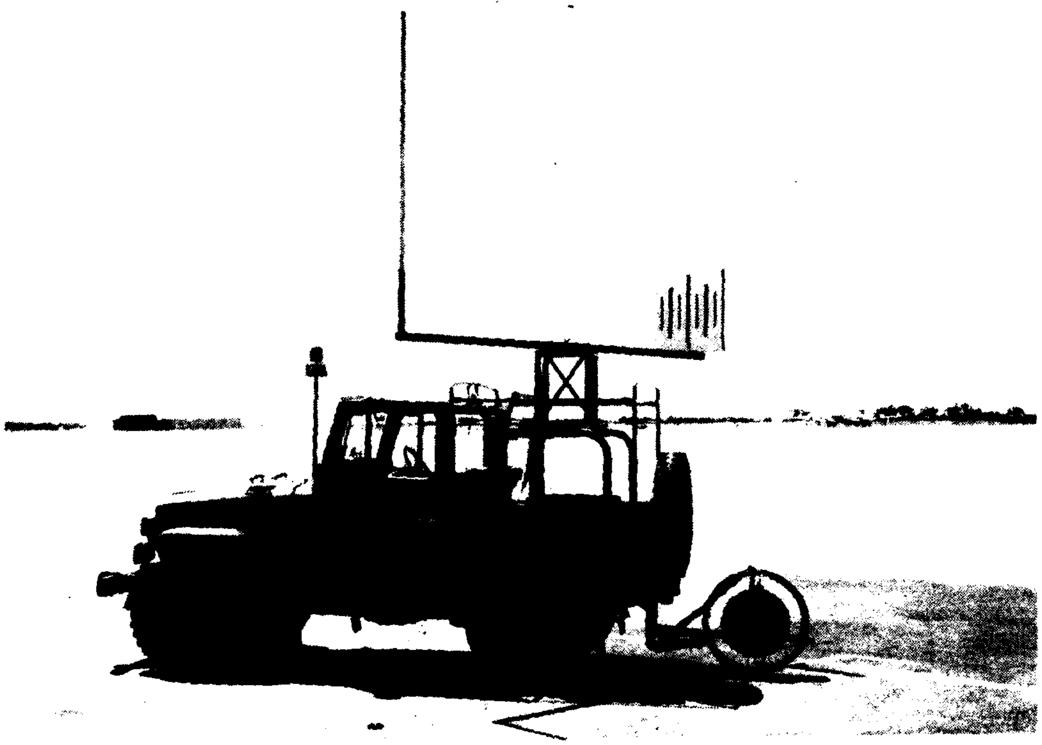


Figure 4 - Calibrated Pace Vehicle

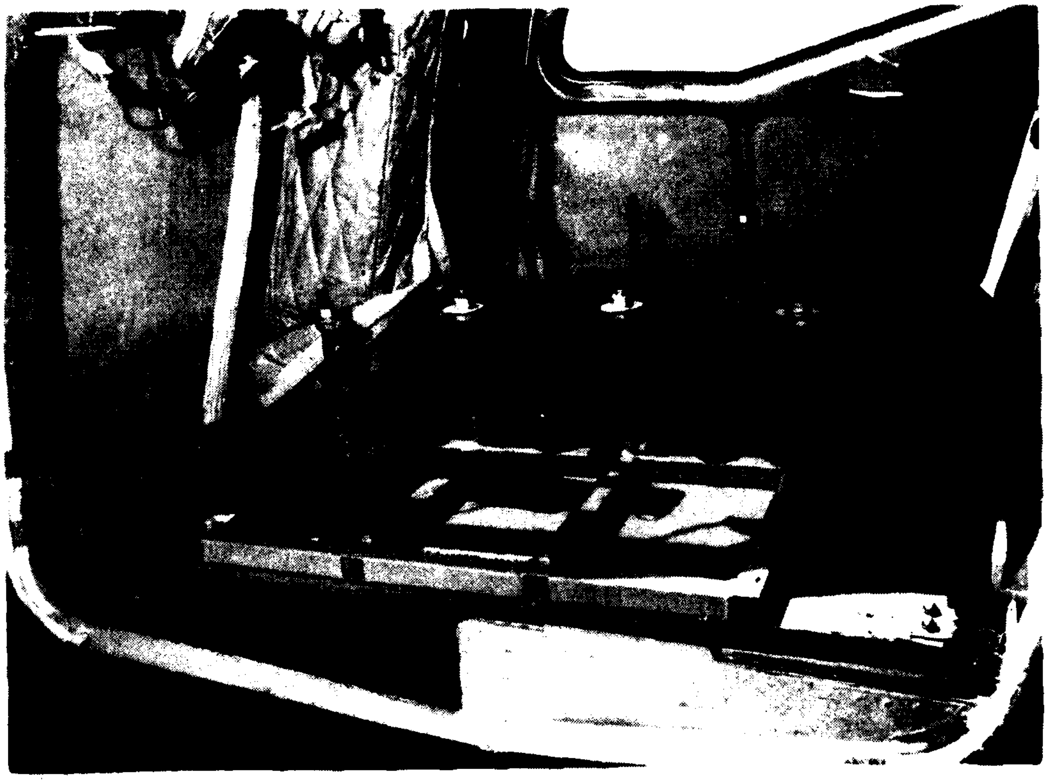
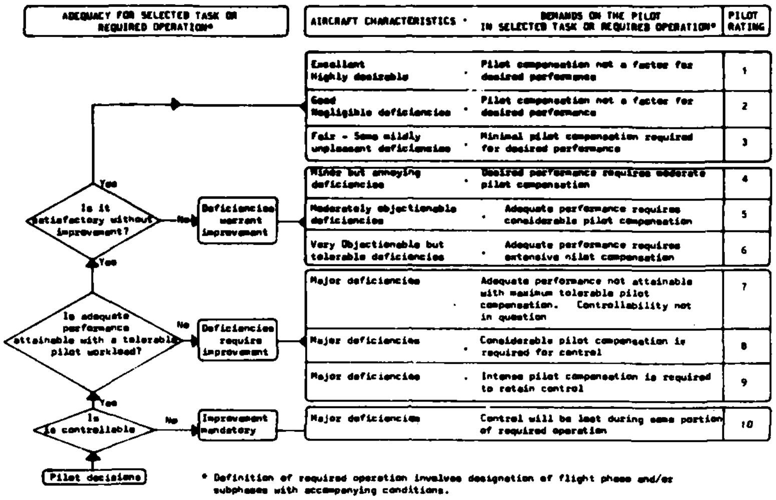


Figure 5 - Modified Cargo Platforms

HANDLING QUALITIES RATINGS
(EXTRACT FROM NASA TN-D-5153)



AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very Objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

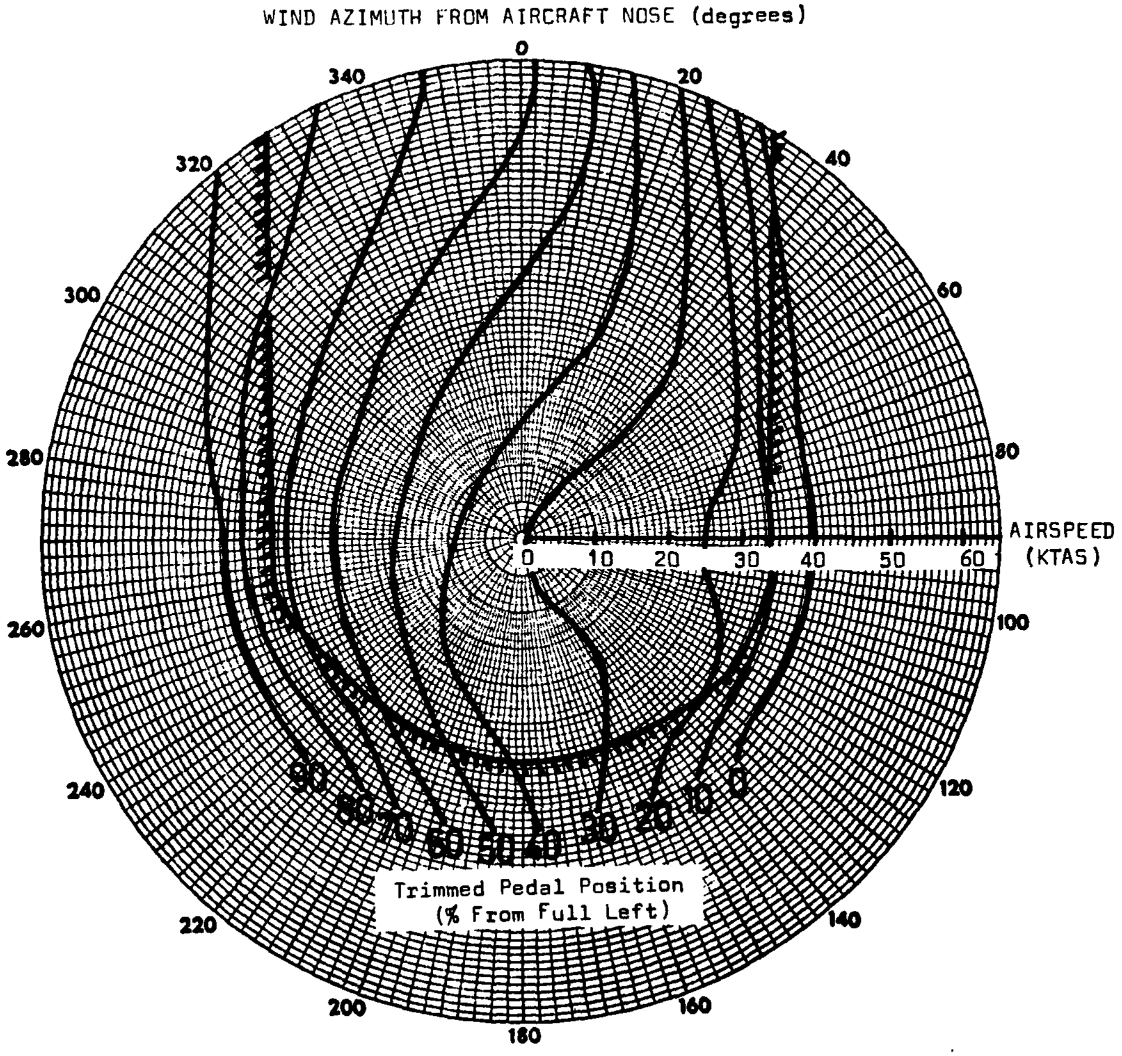
The integrated physical and mental effort required to perform a specified piloting task.

DIRECTIONAL CONTROL DATA

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
2,450	2,450	-100	+18.5	354	108.8	4.5



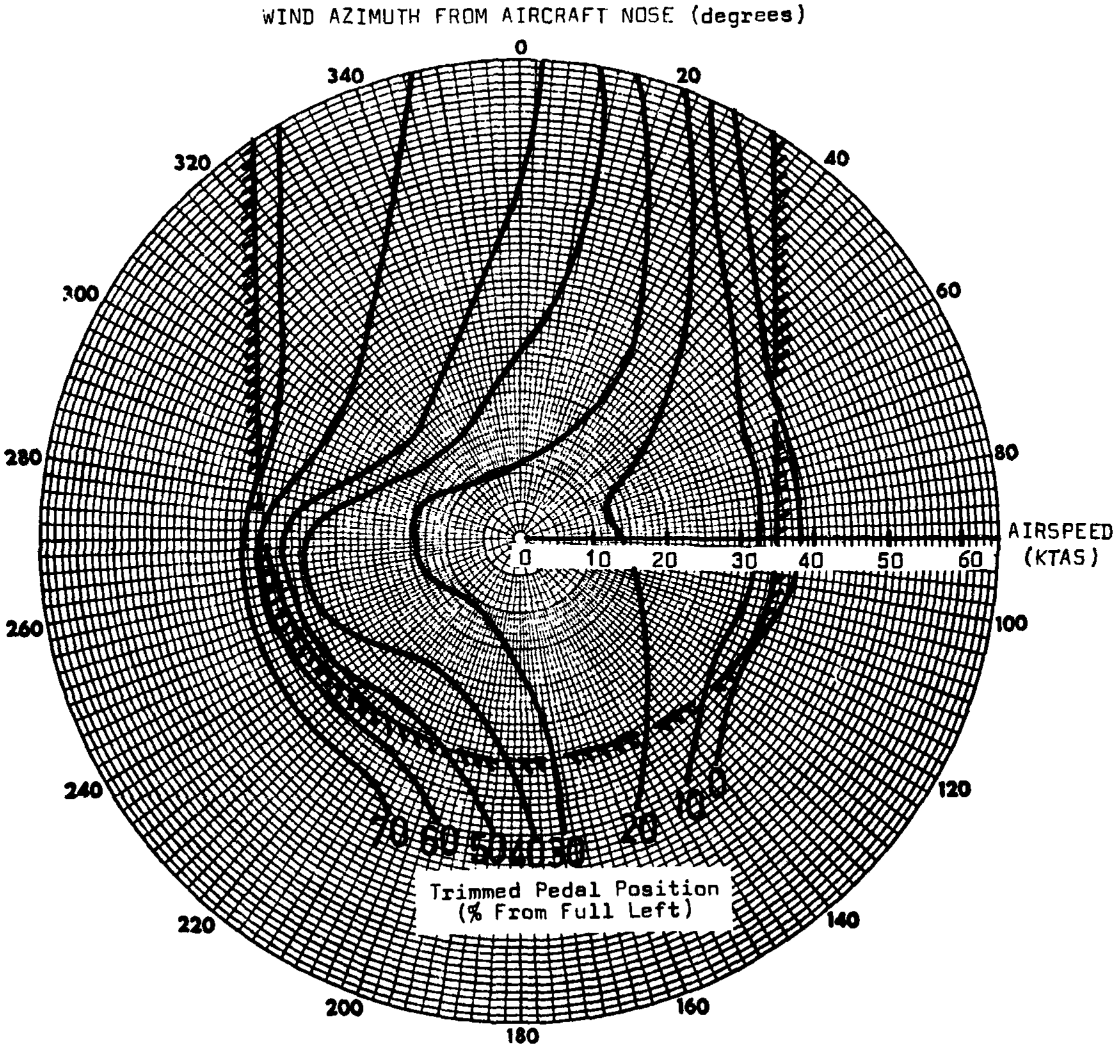
▨ Flight Manual Airspeed Limits

Figure 1 - Low Airspeed Flight Directional Control Requirements (2,450 lb Gross Weight)

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
3,146	3,200	-180	+12	354	109.2	4.5



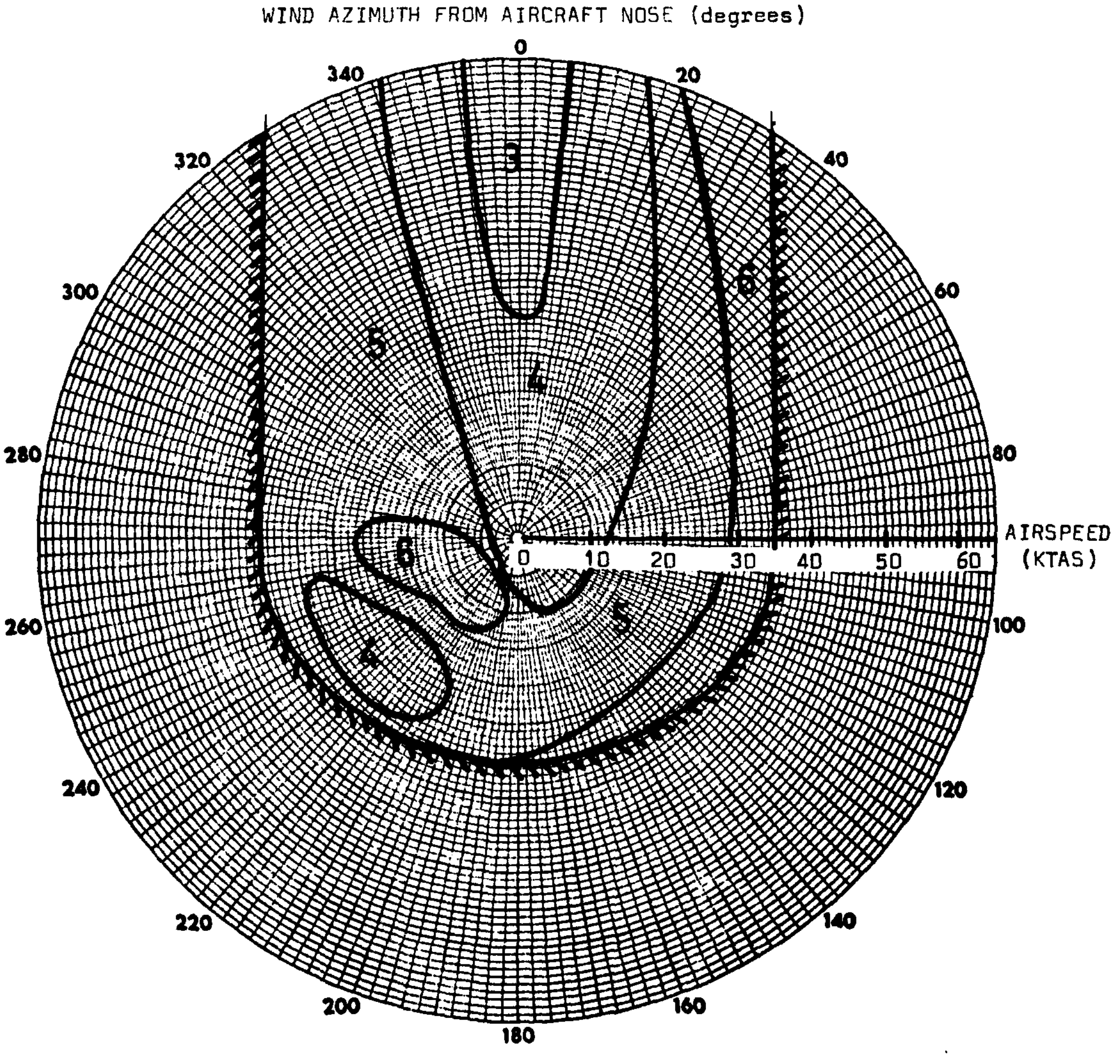
ттттт Flight Manual Airspeed Limits

Figure 2 - Low Airspeed Flight Directional Control Requirements
(3,200 lb Gross Weight)

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
2,450	2,450	-100	+18.5	354	108.8	4.5



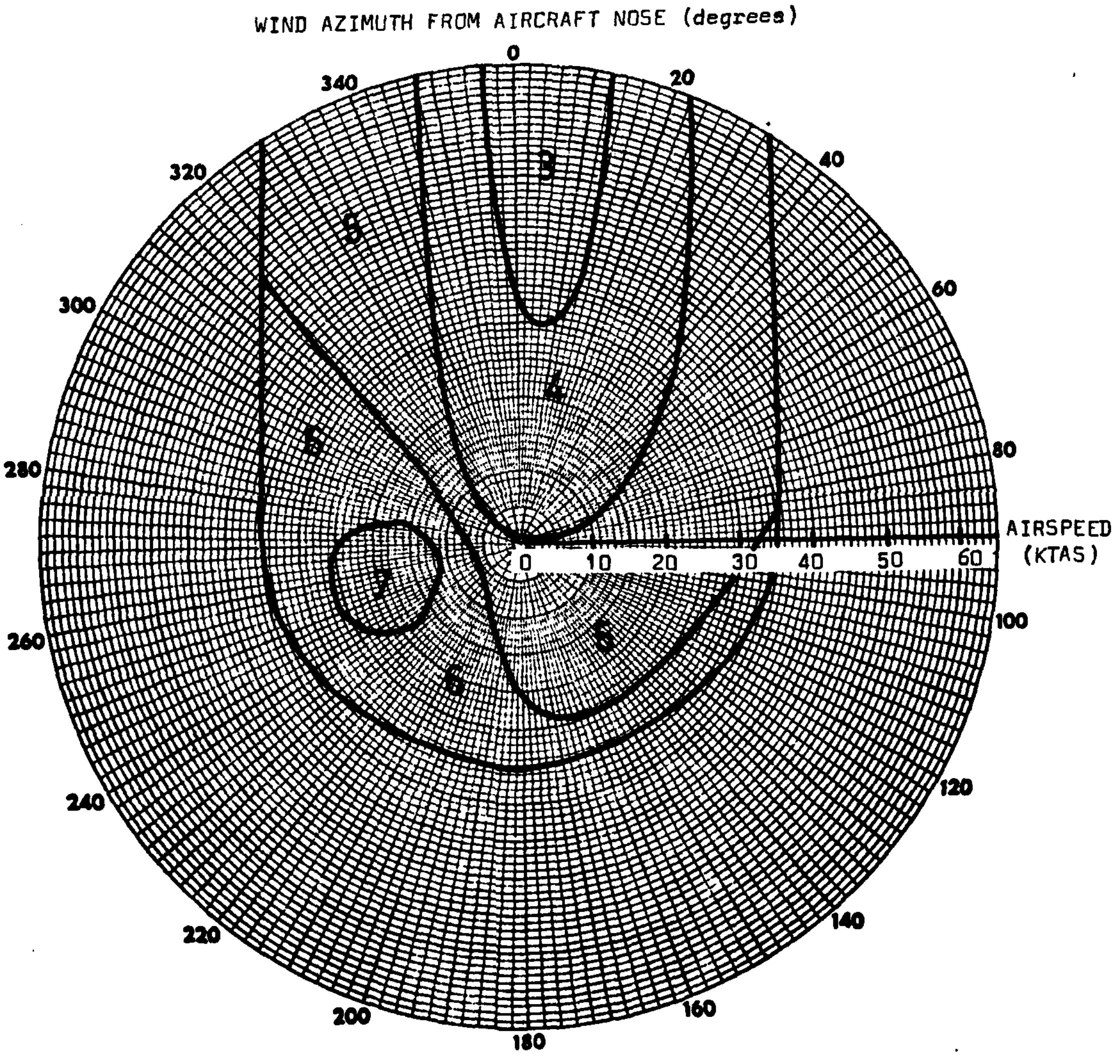
//// Flight Manual Airspeed Limits
HQR assigned on workload to maintain heading within ± 5 degrees

Figure 3 - Low Airspeed Flight Handling Qualities Ratings (2,450 lb Gross Weight)

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
2,796	2,800	-170	+16.5	354	109.7	4.5



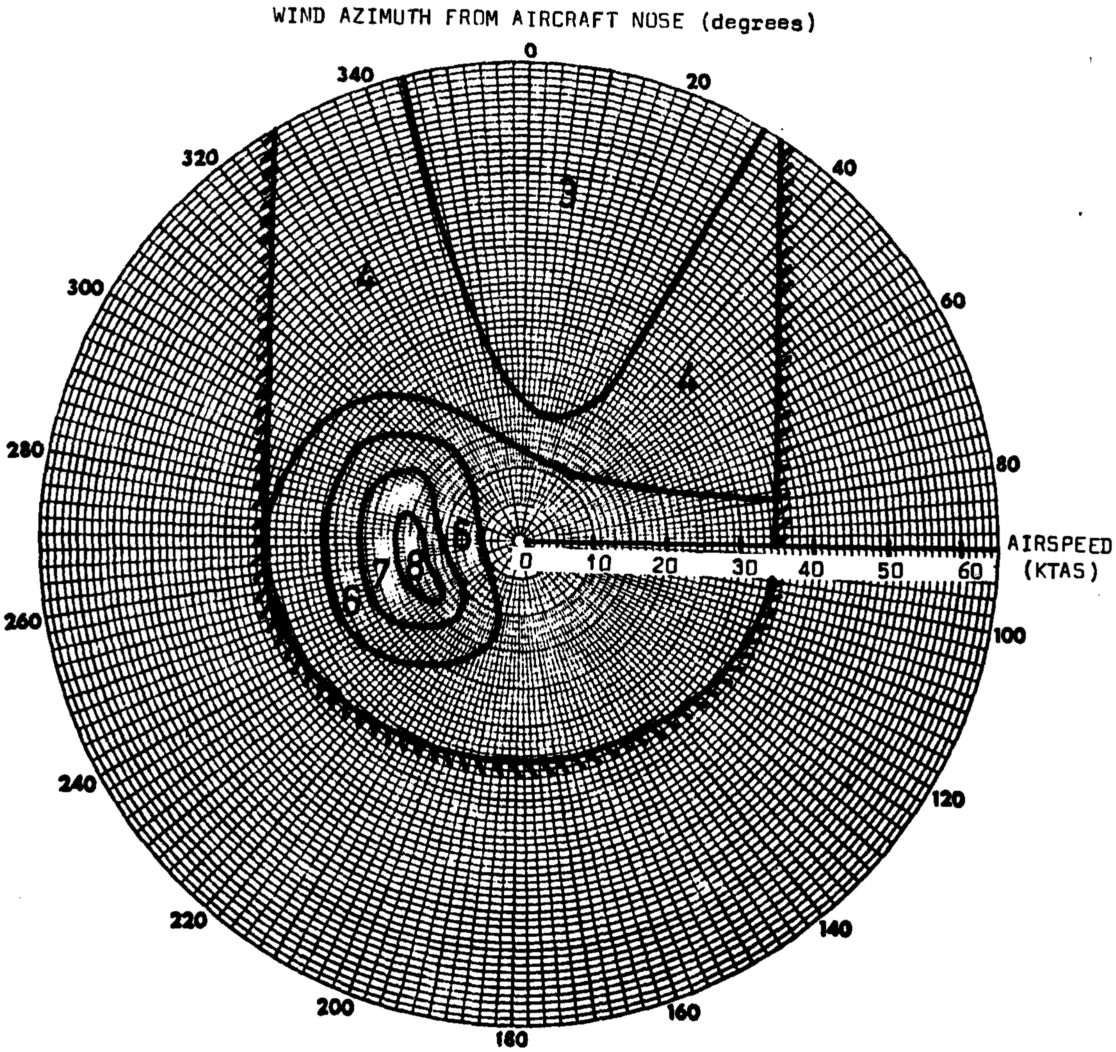
//////// Flight Manual Airspeed Limits
HQR assigned on workload to maintain heading within ± 5 degrees.

Figure 4 - Low Airspeed Flight Handling Qualities Ratings (2,800 lb Gross Weight)

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
3,146	3,200	-180	+12	354	109.2	4.5



/////// Flight Manual Airspeed Limits

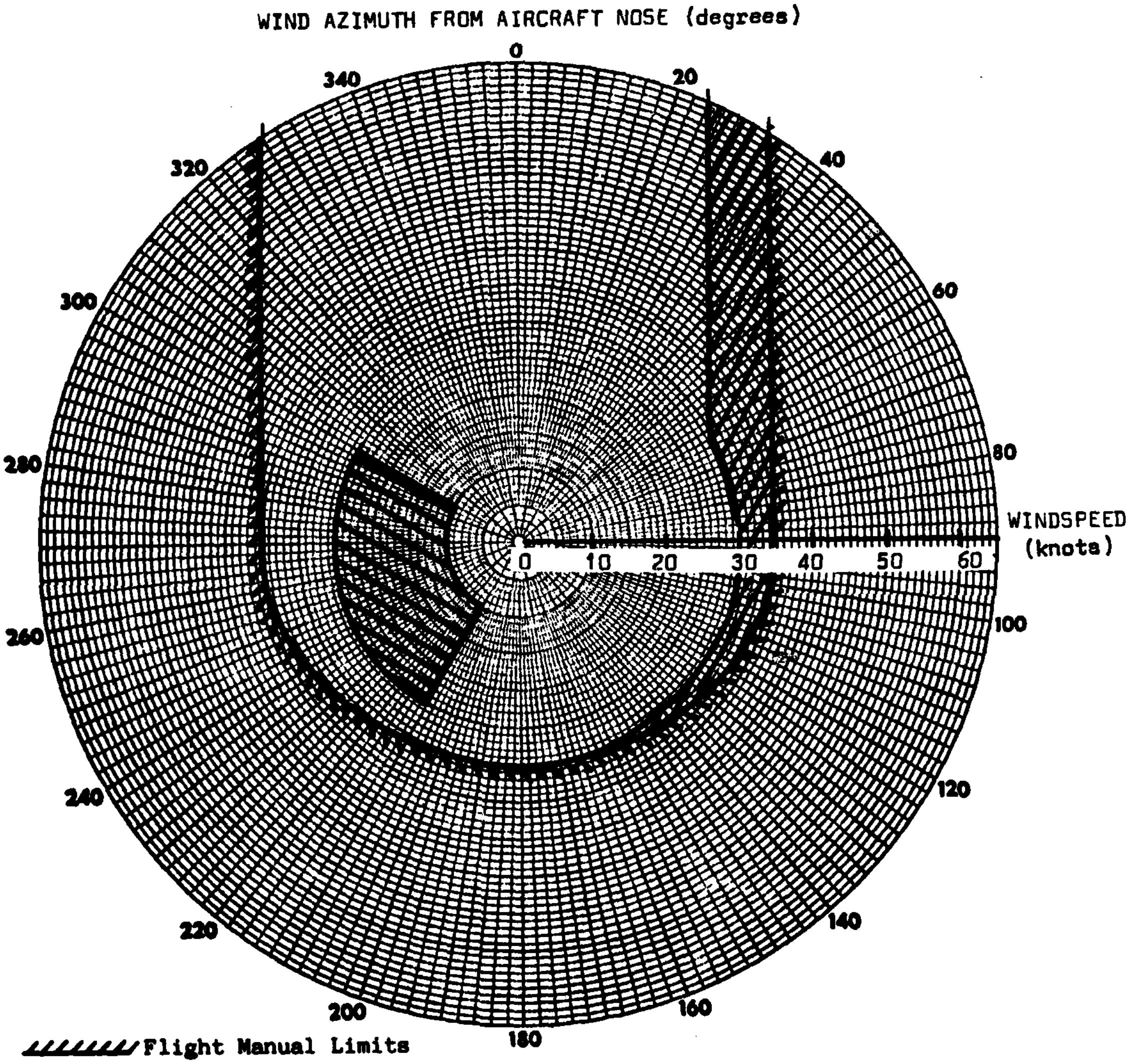
HQR assigned on workload to maintain heading within ± 5 degrees

Figure 5 - Low Airspeed Flight Handling Qualities Ratings (3,200 lb Gross Weight)

BELL 206B-1 HELICOPTER
ALLISON 250-C20 ENGINE

CONDITIONS

Configuration	Gross Weight	Pressure Altitude	Ambient Temperature	Rotor Speed	Skid Height
High Skids Doors On	3,200 lb	S.L.	+15°C	354 rpm	4.5 m



⫽⫽⫽⫽⫽⫽ Flight Manual Limits

▨ Area in which directional control margin may be less than 10% of total control travel.

▧ Area in which unacceptable pilot workload is required to maintain desired heading within ± 5 degrees due to directional instability.

Caution: Valid only for the conditions given. During operations at high density altitudes and gross weights, the area in which directional control margins are adequate is likely to be severely limited and the area of directional instability greatly increased.

Figure 6 - Critical Wind Speeds and Azimuths

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
3,194	3,200	-60	+15	354	109.2	4.5

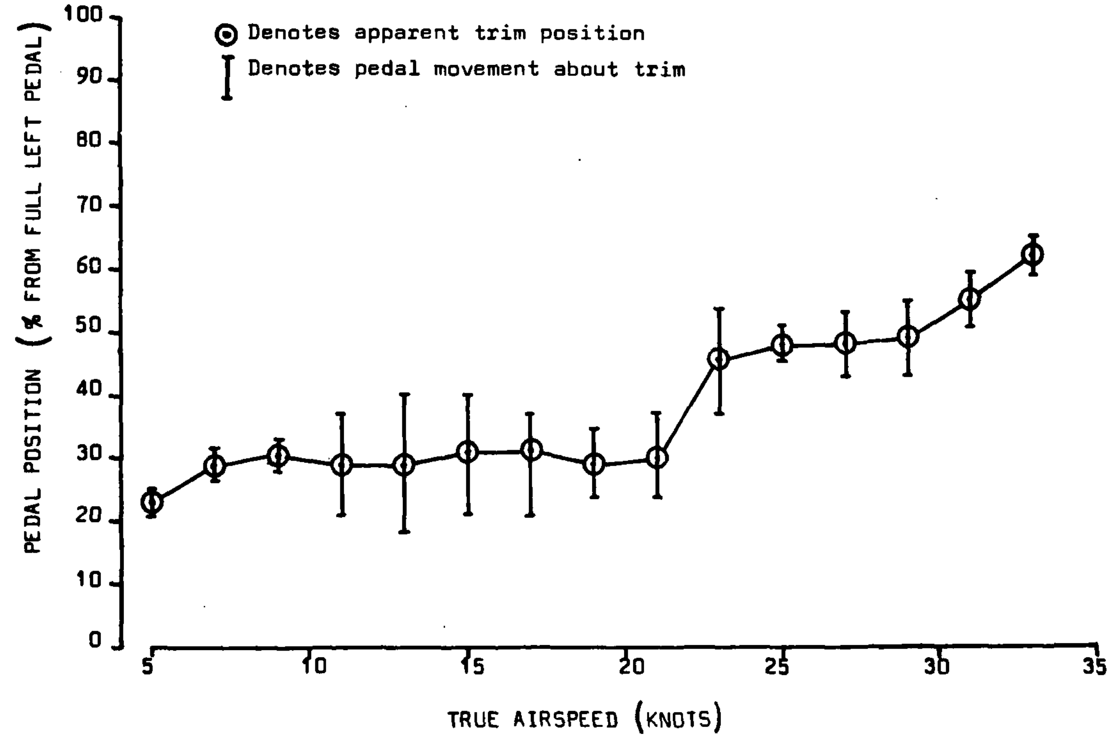


Figure 7 - Pedal Positions For Wind Azimuth ψ = 240 Degrees

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKIDE LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (^{o}C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
3,194	3,200	-60	+15	354	109.2	4.5

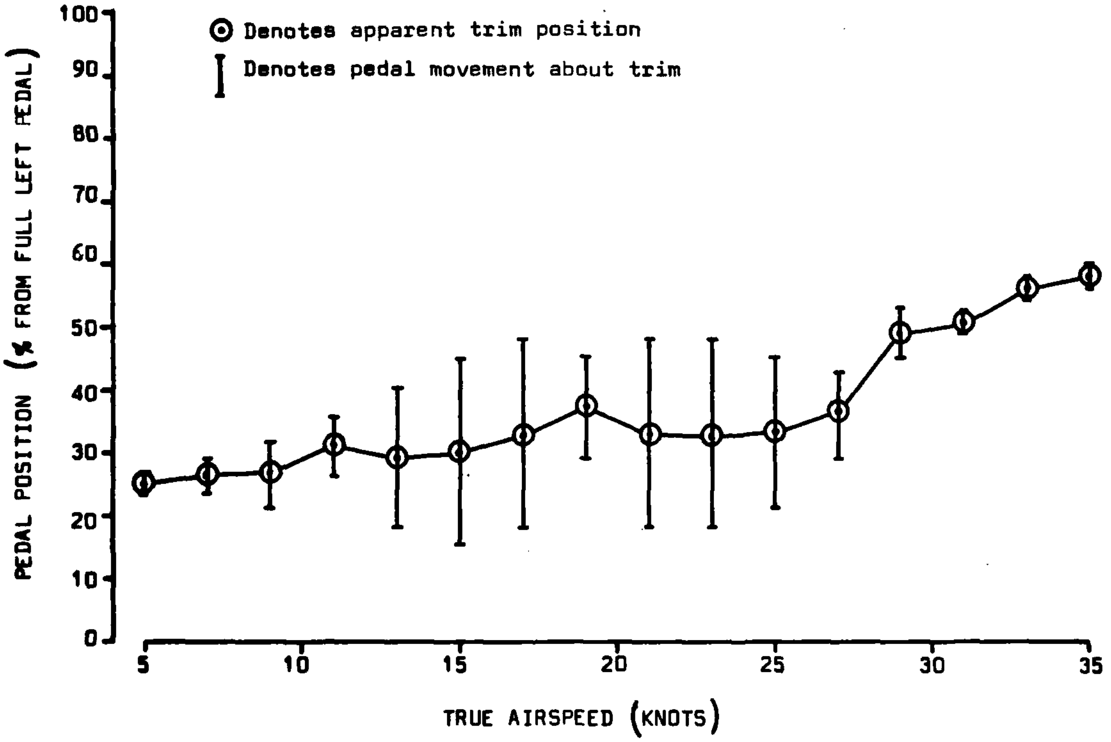


Figure 8 - Pedal Positions For Wind Azimuth ψ = 270 Degrees

BELL 206B-1 A17-004
ALLISON 250-C20 ENGINE
CONFIGURATION: DOORS ON, HIGH SKID LANDING GEAR

AVERAGE CONDITIONS

W/σ (lb)	Gross Weight (lb)	Pressure Altitude (ft)	Ambient Temperature (°C)	Rotor Speed (rpm)	Long CG (in)	Skid Height (m)
3,194	3,200	-60	+15	354	109.2	4.5

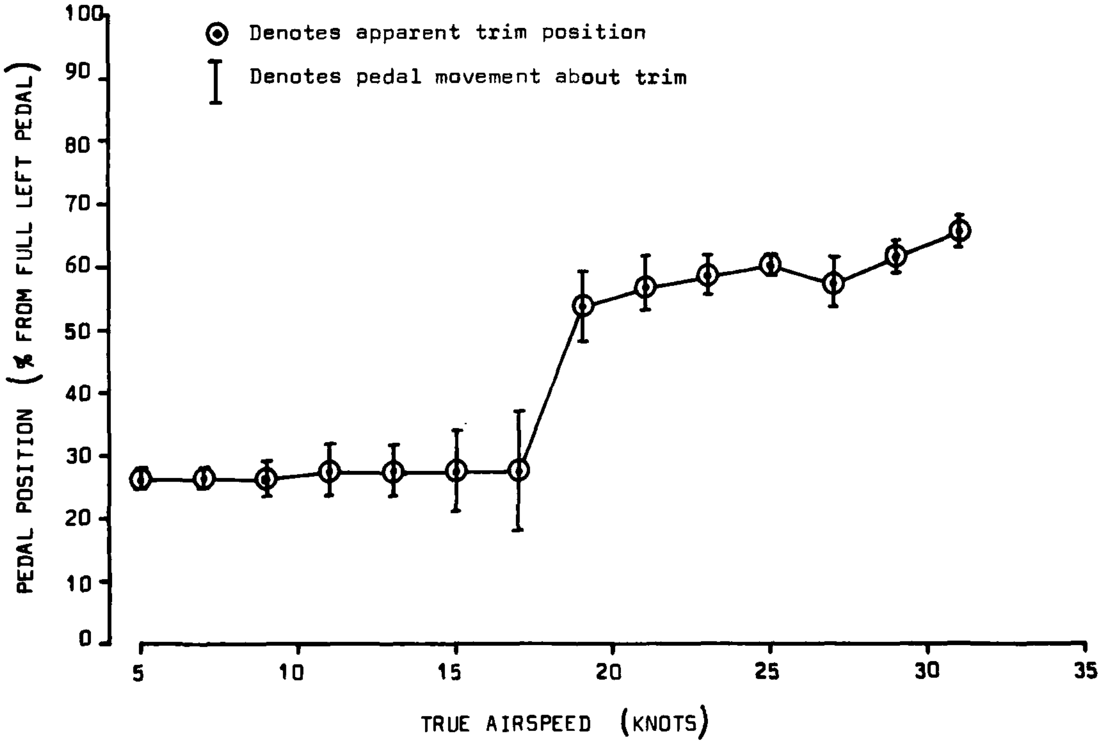


Figure 9 - Pedal Positions for Wind Azimuth ψ = 300 Degrees

TAIL ROTOR VORTEX RING STATE

Introduction

1. The following discussion is largely based on an article which appeared in the July 1980 edition of Rotor and Wing International. The article was written by R.W. Prouty, Chief, Stability and Control Analysis, Hughes Helicopters. The article dealt mainly with the vortex ring state sometimes encountered on main rotors but made mention of, and has application to, tail rotors. The directions of airflow, forces and moments in the discussion are applicable to helicopters with main rotors turning counter-clockwise as viewed from above.

Conditions of Flow

2. Appendix 1 shows the possible flow conditions around a tail rotor in various steady sideward flight cases. In this simplified analysis, the Tail Rotor Thrust (T_{TR}) is assumed to be constant and directed to the right to balance main rotor torque. In practice, T_{TR} will vary with changing aerodynamic forces on the fuselage and vertical fin and with main rotor torque.

3. Appendix 1, Figure 2 shows the airflow pattern when the helicopter is hovering in still air. The ambient air is calm but, in producing a thrust to the right, an airflow called 'induced flow', is directed to the left through the tail rotor. The airflow pattern is comparable to that around the main rotor of a helicopter in an OGE hover.

4. Appendix 1, Figure 1 shows the airflow pattern in right sideward flight. The ambient air is now moving left relative to the tail rotor. In producing the T_{TR}, increased tail rotor blade pitch (left pedal) is required compared to Figure 2 due to the induced flow being in the same direction as the ambient air flow. The airflow pattern is comparable to that around the main rotor of a helicopter in a vertical climb.

5. Appendix 1, Figure 3 shows the airflow pattern when the helicopter is moving slowly left up to approximately 10 KTAS. Although the ambient flow is moving right relative to the tail rotor, the induced flow still dominates the flow in the vicinity of the tail rotor and, except for a decrease in rotor power, conditions will be similar to hover. The airflow pattern is comparable to that around the main rotor of a helicopter in a slow power-on vertical descent.

6. Appendix 1, Figure 4 shows the airflow pattern when the helicopter is moving left at approximately 10 KTAS to 25 KTAS. The ambient flow is approximately the same as the induced flow through the tail rotor. In this condition, the tip vortices cannot move away from the tail rotor disc and some of the air becomes trapped in a smoke-ring shaped body enclosing the outer rim of the rotor. This is known as the 'vortex ring state' which can cause directional control problems due to accompanying effects which will be discussed later. The airflow pattern is comparable to that around the main rotor of a helicopter in a high-powered vertical descent sometimes referred to as 'settling with power'.

7. Appendix 1, Figure 5 shows the airflow pattern when the helicopter is moving left at greater than the velocity of the induced flow, making the net flow to the RIGHT through the rotor. The tail rotor is now slowing the airflow passing through it a little and actually is extracting energy from the airflow. The condition is known as the windmill-brake state and the airflow pattern is comparable to that around the main rotor of a helicopter in vertical autorotational descent.

Behaviour of the Vortex Ring

8. The unsteadiness of the flow in the vortex ring state has been observed during wind-tunnel tests of model rotors using smoke for flow visualization. Appendix 2 shows a sequence of events based on an interpretation of cine photography of the smoke during such tests. Unsteadiness starts at about one-quarter, peaks at three-quarters, and disappears at 1¼ times the hover-induced velocity through the rotor. Depending on rotor disc loading, the state may be entered when moving left 300 fpm (3 KTAS) to 600 fpm (6 KTAS) and persist up to 1,500 fpm (15 KTAS) to 3,000 fpm (30 KTAS). There is some evidence that flow from the azimuths of ψ = 250 and 290 degrees is worse than flow from the true left sideward flight (ψ = 270 degrees) azimuth. At azimuths outside the area of ψ = 270 ± 50 degrees, enough 'fresh' air is introduced into the system to blow the tip vortices away from the rotor and free it from the conditions conducive to the vortex ring state.

9. According to the concept illustrated in Appendix 2, the rotor is continuously pumping air into a large 'bubble' to the left of the rotor. This bubble fills up and bursts every second or two, causing large-scale disturbances in the surrounding flow field. The bubble appears to erupt first from one side and then another so that not only does the rotor thrust vary, but the rotor flaps erratically.

Effects of the Vortex Ring State

10. A characteristic of the vortex ring state (besides unsteadiness of the flow) is the high power required to maintain rotor thrust. This is sometimes referred to as 'power settling' in the context of the main rotor of a helicopter making a vertical descent under power. Figure 1 shows the power and collective pitch required to maintain constant main rotor thrust in vertical descent for a typical helicopter. Not only does the power required increase in the vortex ring state, but so does the collective pitch - apparently due to local blade stall during flow fluctuations. Transposed to the tail rotor, the conditions conducive to vortex ring formation may be encountered during right hover turns or left sideward flight.

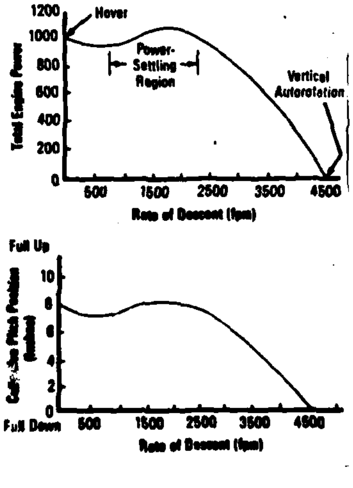


Figure 1 - Power and Pitch Required in Vertical Descent for Typical Helicopter

11. To produce a right turn in a hover, the tail rotor thrust is decreased by reducing its collective pitch with right pedal and the main rotor torque is permitted to yaw the helicopter. For a slow right turn started with a small pedal displacement, the tail rotor is placed in a condition corresponding to a main rotor in a low rate of descent. As the turn rate increases, tail rotor thrust also increases to a point where it again balances the main rotor torque and the helicopter settles on a constant yaw rate - indicative of a positively damped (stable) system.

12. For a larger right pedal step input, the higher yaw rate may put the tail rotor into the vortex ring state where the collective pitch required to maintain a constant thrust is increasing rather than decreasing. Conversely, for collective pitch held constant after the step, the tail rotor thrust decreases rather than increases and the yaw rate suddenly increases. This is indicative of a negatively damped (unstable) system. In an attempt to control the sudden increase in right yaw rate, the pilot may apply left pedal, but the initial response could be to deepen the vortex ring state, and the yaw rate might still increase. If right pedal is applied, the flow may stabilize as illustrated in Appendix 1, Figure 5.

13. Tail rotor vortex ring state may also manifest itself as an inability to maintain heading in left sideward flight or, alternatively, while hovering over a spot with wind from the left (ψ = 270 degrees azimuth). The critical left speed range for tail rotors of most current helicopters is 10 KTAS to 25 KTAS as illustrated in Appendix 1. Flight tests of several main rotor/ tail rotor configured helicopters have demonstrated a difficulty in establishing pedal trim position in left sideward flight. The pedal position/relative-air-speed gradient appears to be flat or with a slight reversal. Wind-tunnel tests of rotors operating in various vertical airflows have given experimental data which can be used in calculating the steady state power and control (blade pitch) angles throughout the sideward flight speed range including the vortex ring state. This is illustrated in Figure 2. The vortex ring state causes a reversal tendency in the steady-state tail rotor blade pitch (θ_{TR}) versus sideward flight velocity plot. For higher thrusts and disc loadings, the vortex ring state and, consequently, the reversal, occurs at higher speed due to the increase in tail rotor induced flow velocity. The pedal reversal is aggravated by operation IGE. During steady-state sideward flight, just as the helicopter 'loses its ground cushion' there is an increase in main rotor torque required. This requires additional tail rotor thrust, and hence more tail rotor blade pitch or left pedal. This effect is shown in Figure 3.

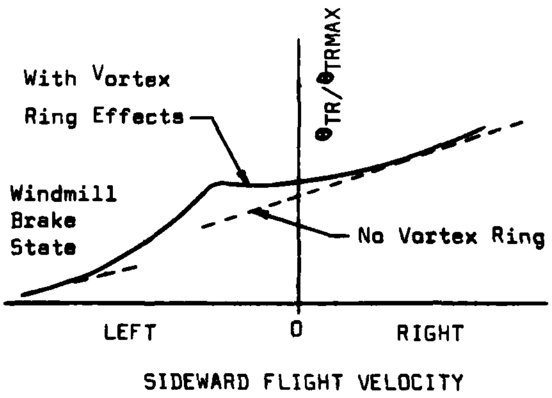


Figure 2 - Tail Rotor Pitch (θ_{TR}) in Sideward Flight

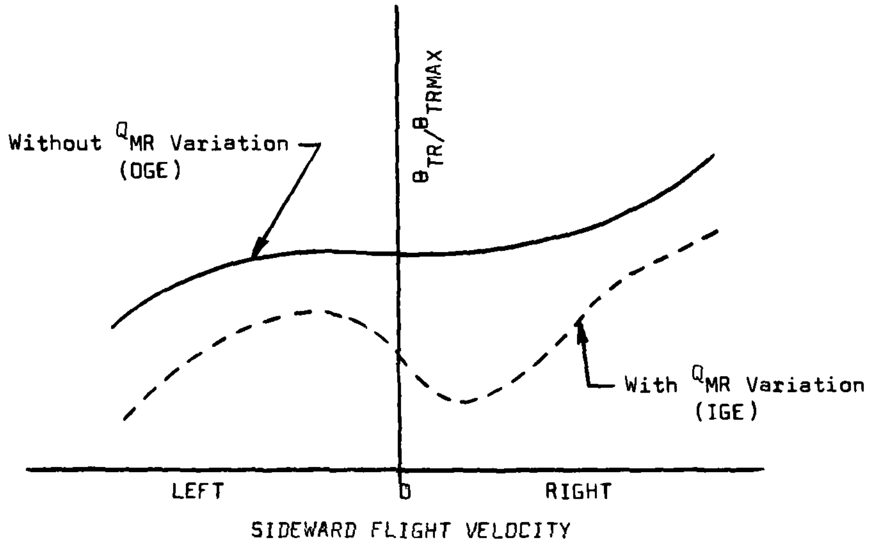


Figure 3 - Effect of Main Rotor Torque (Q_{MR}) Variation

14. Under certain conditions, other phenomena, such as the aircraft 'weather-cocking' characteristics and sideload produced by the main rotor wake acting on the boom, can affect the pedal reversal tendency but are usually of minor importance.

Appendices: 1. Tail Rotor Vortex Ring State - Flow Visualization

2. Vortex Ring Behaviour

TAIL ROTOR VORTEX RING STATE - FLOW VISUALIZATION

T_{TR} = Tail Rotor Thrust

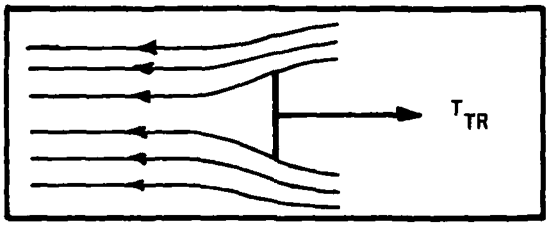


Figure 1.
Right Sideward Flight

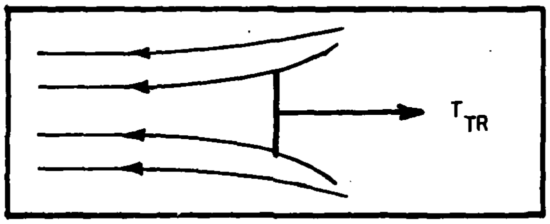


Figure 2.
Hover

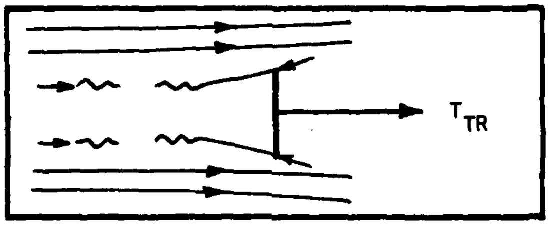


Figure 3.
Left Sideward
Flight ~10 KTAS

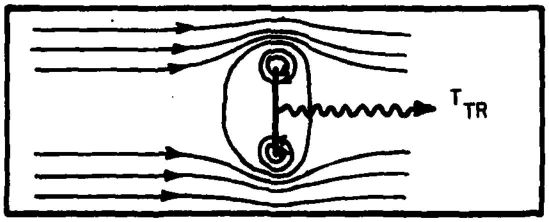


Figure 4.
Left Sideward
Flight ~10 to 20 KTAS

Possible Vortex
Ring Condition

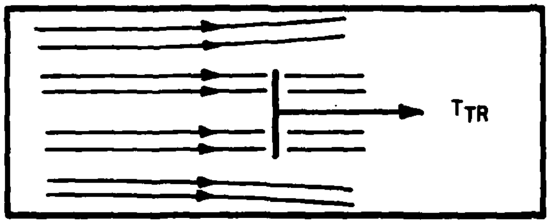


Figure 5.
Left Sideward
Flight ~25 KTAS

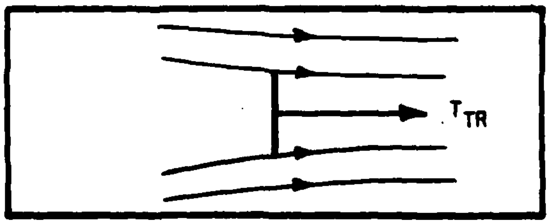


Figure 6.
Left Sideward
Flight >25 KTAS

VORTEX RING BEHAVIOUR

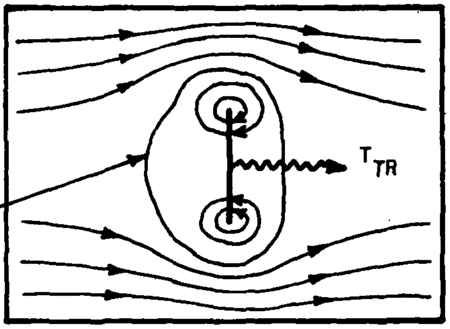


Figure 1. Bubble Formed

Boundary of Bubble

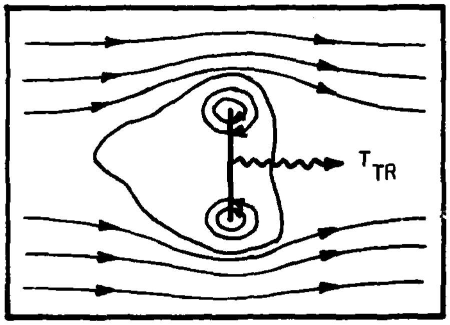


Figure 2. Bubble Grows

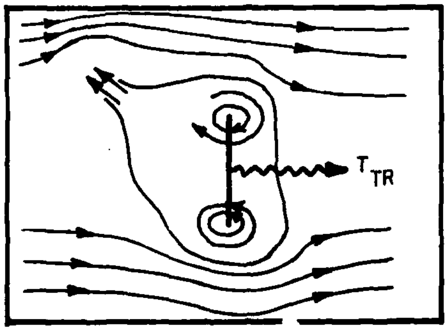


Figure 3. Bubble Bursts

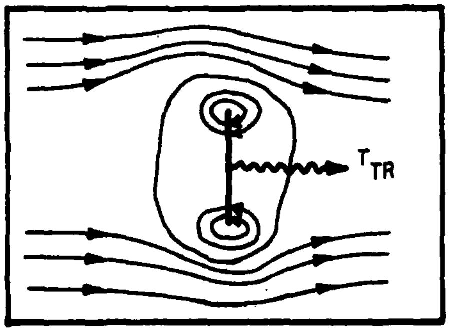


Figure 4. Bubble Reforms

AIRCRAFT RESEARCH AND DEVELOPMENT UNIT

TECHNICAL INVESTIGATION NO 721

BELL 206B-1 DIRECTIONAL CONTROL IN LOW AIRSPEED FLIGHT

DISTRIBUTION EXTERNAL

Department of Defence		Copy No
Air Force Office:	TP4-AF	1
	DAFS	2-3
	DRR-AF	4
	DGAFHS	5
Army Office:	DAVN	6-7
	HQ AVN CEN OAKEY	8-11
	NO 1 AVN REGT OAKEY	12-13
	AVN SCHOOL OAKEY	14-17
	NO 171 COMM AND LIAISON SQN OAKEY	18-20
	NO 162 RECCE SQN TVL	21-23
	NO 161 RECCE SQN HOLSWORTHY	24-26
	NO 5 BASE WKS SHOP OAKEY	27
Navy Office:	AMAFTU RAN NOWRA	28-29
Defence Science and Technology Organization:	CSLT	30-31
	DISB	32-50

Operational Command

Headquarters Operational Command (SOOPS)	51
Headquarters RAAF AMBERLEY (EXECO)	52
No 9 Squadron RAAF AMBERLEY	53-54
No 12 Squadron RAAF AMBERLEY	55-56
Headquarters RAAF FAIRBAIRN	57
No 5 Squadron RAAF FAIRBAIRN	58-60
Headquarters RAAF TOWNSVILLE	61
No 35 Squadron RAAF TOWNSVILLE	62-63

Support Command

Headquarters Support Command (AIRENG3)	64-66
RAAF Academy RAAF POINT COOK (Library)	67
RAAF Institute of Aviation Medicine RAAF POINT COOK	68-69

Civil Establishments

Aeronautical Research Laboratories MELBOURNE	70-72
Defence Research Centre SALISBURY (Library)	73

DISTRIBUTION INTERNAL

Commanding Officer	74
OIC TEST A	75
Project Officer	76-77
Senior Research Scientist	78
Library	79
Report Production Flight (Master)	80
Spares	81-90

END

DATE
FILMED

6-81

DTIC