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PRELIMINARY EVALUATION OF A DIFFUSER-THRUSTER FOR USE AS A HELICOPTER ANTI-TORQUE SYSTEM

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PRELIMINARY EVALUATION OF A DIFFUSER-THRUSTER FOR USE AS A HELICOPTER ANTI-TORQUE SYSTEM

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ABSTRACT

A preliminary experimental investigation was carried out to determine the suitability of a diffuser thruster (DT) for use as a helicopter anti-torque system. Tests results obtained on a hover test stand and a static rig are used to compare the performance of a DT with those of a conventional tail rotor, fenestron and circulation controlled tail boom fitted with a thruster. Based on the results obtained to date it is shown that the power coefficient of the DT compares favourably with that of a conventional tail rotor. It is noted that the DT cannot enter the vortex ring state associated with conventional tail rotors and the fenestron.

NOTATION

A	=	cross section of flow
A_R	=	$A_3/A_1 = A_2/A_1$ = area ratio
C_p	=	$\dfrac{P(\rho A_3)^{1/2}}{T^{3/2}}$ = power coefficient
C_{PR}	=	$(P_2 - P_1)/q_1$ = pressure recovery coefficient
C_{PR_i}	=	$1 - 1/_{AR}{}^2$ = ideal pressure recovery coefficient
D	=	tail boom diameter
ΔH	=	total head loss
η	=	fan efficiency
G	=	$\rho V A$ = mass flow
k	=	ratio of flow areas of downstream free stream and the outlet area of the thruster
K_D	=	$\dfrac{P_{t_1} - P_{t_2}}{q_1}$
K_T	=	$\dfrac{P_{t_2} - P_{t_4}}{q_2}$
L	=	Distance between thruster and main rotor shaft
P	=	power
P_s	=	static pressure
P_t	=	total head
q	=	dynamic head
Q	=	boom torque
ρ	=	air density
t	=	total circulation controlled slot thickness
T_R	=	main rotor thrust
V	=	uniform velocity

1. INTRODUCTION

While conventional helicopter tail rotors (CTR) have played a major role in the practical application of the helicopter since 1939 they suffer from a number of disadvantages. These include mechanical complexity in that they require a drive to the aft end of the helicopter, vibration, noise, are dangerous to personnel and they are the cause of approximately 15% of all helicopter accidents [1]. Also during some manoeuvres the tail rotor can lie in the wake of the main rotor giving rise to aerodynamic interactions and consequent mechanical vibrations. Due to the contraction of the wake the axial velocity of the air in the wake is increased compared to that in the rotor plane giving rise to increased energy consumption. In the case of untwisted rotor blades the axial velocity varies approximately linearly with blade radius resulting in a further increase in the energy consumption of the tail rotor.

In sideways flight the tail rotor can be engulfed in a vortex ring necessitating large movements of the controls to effect a change in the thrust of the tail rotor.

The fenestron rotor which is housed in a shroud offers a number of advantages compared to the conventional tail rotor [2]. The shroud results in reduced noise levels, offers protection from damage and eliminates the trailing vortices from the blade tips. Elimination of the trailing vortices avoids the contraction of the wake resulting in lower axial velocities in the wake and reduced power consumption compared to a conventional tail rotor with the same diameter. It does however have the mechanical disadvantages of the CTR such as complexity and vibration. As is the case with a conventional tail rotor in sideways flight the rotor can be engulfed in a vortex ring.

The NOTAR (No Tail Rotor) [3] system comprised of a circulation controlled tail boom (CCTB), thruster at the aft end of the tail boom, and fan at the forward end of the tail boom to provide air to the circulation controlled tail boom and thruster, which thereby eliminates a number of mechanical disadvantages of the CTR. The NOTAR system has proved to be a viable anti-torque system [3]. However the circulation controlled section which provides a large portion of the torque in hover loses its effectiveness as the downwash from the main rotor moves off the tail boom [4] and care must be taken to ensure that extraneous flows such as engine exhausts do not affect the flow over the tail boom. Also, the static pressure of the air in the tail boom is of the order of 7 kPa [5] which results in the velocity of the air from the thruster being of the order of 105 m/s. This velocity is high compared to that typically found in the wake of a CTR and a fenestron and results in comparatively high power requirements for the thruster. The overall power requirements of an anti-torque system comprised of a circulation controlled tail boom appears to be of the order of 50% higher than that of a CTR [5].

An attempt has been made to determine whether it would be possible to develop an anti-torque system which is not subject to problems identified above. To this end tests were carried out on an anti-torque system shown in figure 1 which is comprised of:

i) a fan located at the entrance to the tail boom.
ii) a tail boom to duct air from the fan to it's aft end
iii) a diffuser located at the aft end of the duct to reduce the speed of the air, and
iv) a thruster fitted to the outlet of the diffuser which turns the air through approximately 90 deg and ejects it sideways with a nearly uniform exit velocity to generate a thrust and consequently the torque required to balance that applied to the main rotor.

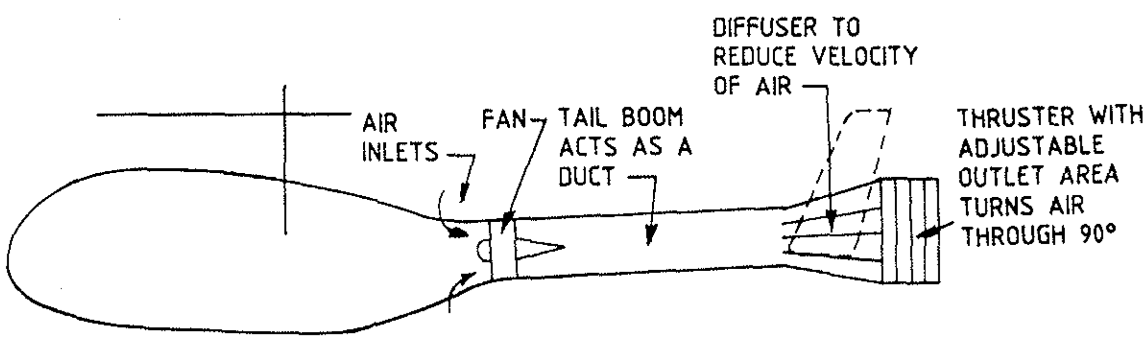


Figure 1: General Arrangement of a Diffuser-Thruster

One of the characteristics of both the CCTB based system and the DT is the large volume of air which is passed down the tail boom. The use of this air to cool the engine exhaust has been considered and provides one of the possible motivations for the development of the DT as an anti-torque system. A typical arrangment of a helicopter fitted with a DT to cool the engine exhaust gases is presented in figure 2.

A preliminary evaluation of fitting a DT to a Alouette helicopter has indicated that the DT carries a small mass penalty but has minimal effect on the centre of gravity due to the removal of the tail rotor and its drive system.

It is accepted that a number of problems are associated with the current design of the DT. For example torque

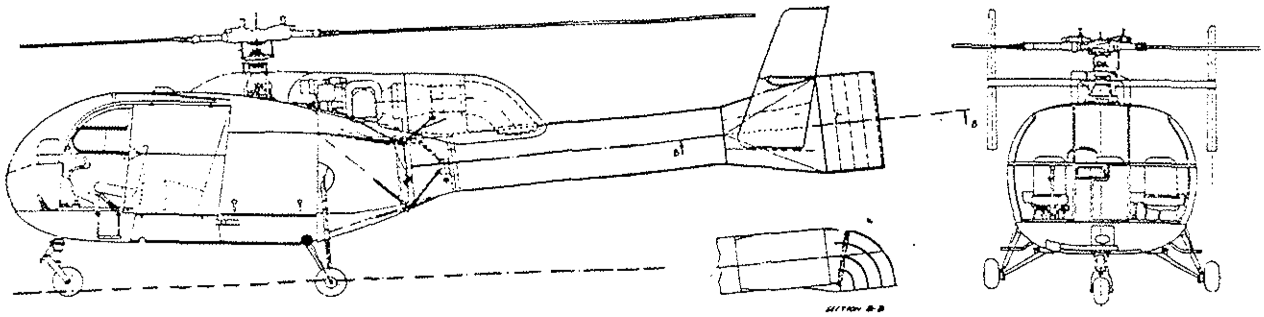


Figure 2: Helicopter fitted with a DT used to cool the Engine Exhaust Gases

control needs to be solved and in particular the negative torque capability which may be required during autorotations cannot be developed with the current design. Also, if it is used to cool the engine exhaust gases the full flow will be required throughout the flight which will complicate control of the torque. The objective of the current test programme is to characterise some of the more pertinent operational parameters.

2. ANALYTICAL BACKGROUND

An analytical background for assessing the performance of a DT may be obtained by considering the flow through the DT with the geometry presented in figure 3. This DT is referred to as DTTH.

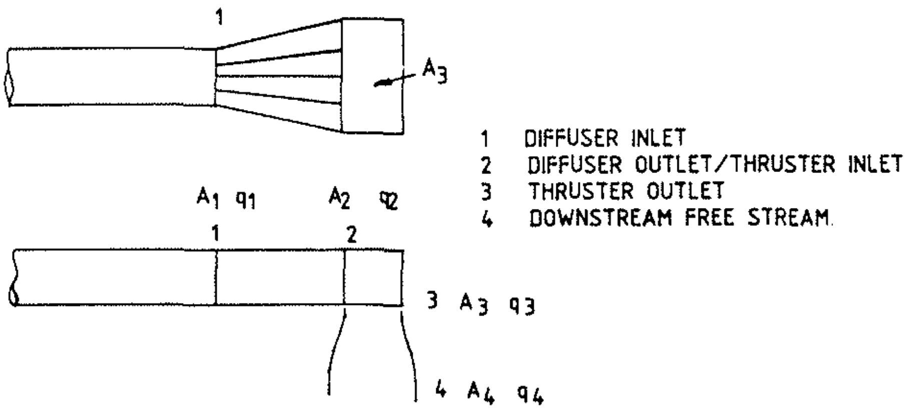


Figure 3: Model used for Analysis

For purposes of the analysis it is assumed that uniform incompressible flow conditions exist at all cross sections.

The thrust is given by

$$T = GV_4 = \rho A_3 V_3 V_4 \qquad (1.)$$

By definition

$$A_4 = kA_3 \qquad (2.)$$

The loss in total head ΔH_D across the diffuser may be written [8]:

$$\frac{\Delta H_D}{q_1} = C_{PR_i} - C_{PR} = 1 - \frac{1}{A_R^2} - C_{PR} = K_D \qquad (3.)$$

The head loss in the cascade is determined by averaging the losses in the individual flow passages using the data presented in reference [7]. For the geometry used which has four passages the head loss across the cascade is given by:

$$\frac{\Delta H_T}{q_2} = K_T = \sum_{1}^{4} \frac{(K_1 + K_2 + K_3 + K_4)}{4} \tag{4.}$$

Thus the total head loss across the DT is given by:

$$\frac{\Delta H}{q_1} = 1 - C_{PR} - \left(\frac{A_1}{A_2}\right)^2 (1 - K) = K_D + \frac{K_T}{A_R^2} \tag{5.}$$

The power applied to the DT fan is given by:

$$P = G\left\{ \left(\frac{\Delta H}{q_1}\right) \frac{q_1}{\rho} + \frac{V_3^2}{2k^2} \right\} / \eta \tag{6.}$$

Since

$$G = \rho\, A_3 V_3 = \rho A_1 V_1 \tag{7.}$$

and using equations (1) and (6) may be written

$$P = \frac{(Tk)^{3/2}}{(\rho A_3)^{1/2}} \frac{1}{2} \left\{ K_D A_R^2 + K_T + \frac{1}{k^2} \right\} / \eta \tag{8.}$$

The static pressure in the tail boom is given by:

$$P_{s_1} = q_1 \left[K_D - 1 + \frac{1}{A_R^2} (K_T + \frac{1}{k^2}) \right] = \frac{Tk}{2A_3} \left[A_R^2 (K_D - 1) + K_T + \frac{1}{k^2} \right] \tag{9.}$$

A value of C_{PR} for a diffuser with vanes of approximately 0.65 to 0.76 [6] is possible. For this analysis $C_{PR} = 0.76$ is used resulting in $K_D = 0.0492$. Using data from reference 7 the loss coefficient for each of the four channels, for a height to channel width ratio of 7 are: $K_1 = 0.79$; $K_2 = 0.12$; $K_3 = 0.10$; $K_4 = 0.10$ giving an average value of $K_T = 0.278$.

The expansion coefficient k for the jet from the thruster was determined from experimental data using equation 1. It was found that k = 0.799.

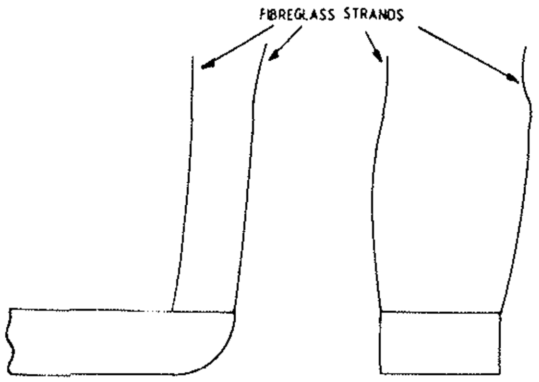
To determine whether the air flowing out of the thruster was expanding fibreglass strands were attached to the thruster. In figure 4 it may be seen that the flow area does increase with distance from the thruster. The apparent discrepancy in k is due to the fact that the velocity of the air flowing out of the thruster is not uniform.

For the calculations for DTTH k was assigned a value of one.

Using equations 8, 11 and the values of K_D and K_T given above and a fan efficiency of 75% the fan power and static pressure in the tail boom are given by

$$P = 1.023 \frac{T^{3/2}}{(\rho A_3)^{1/2}} \tag{10.}$$

and



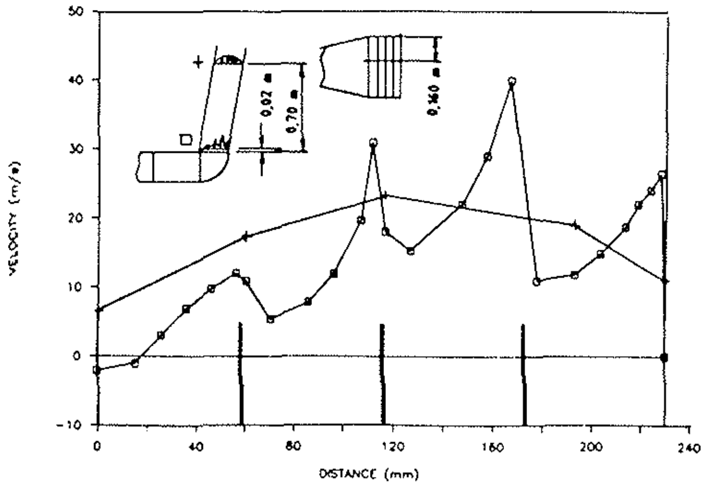


Figure 4: Flow Profiles out of the Thruster

$$P_{s_1} = -1.853 \frac{T}{A_3} = -0.707 q_1 \tag{11.}$$

respectively.

3. EXPERIMENTAL RIGS

Tests on the rotor spin rig clearly indicated, refer to figure 8, that in hover the rotor has limited effect on the torque developed by the DT. Further tests were carried out on a static rig.

a) Diffuser Thruster

Tests have been carried out on three DTs to date. Tests on DT1 were terminated. DT2 and DT3 were similar except that two of the diffuser vanes in DT3 are adjustable. The overall dimensions of DT3 are presented in figure 5.

The ratio of the areas of the tail boom cross section and the thruster outlet is $A_3/A_1 = 2.2894$. This ratio was chosen arbitrarily and the effect on the area ratio on the performance of the DT still has to be confirmed experimentally.

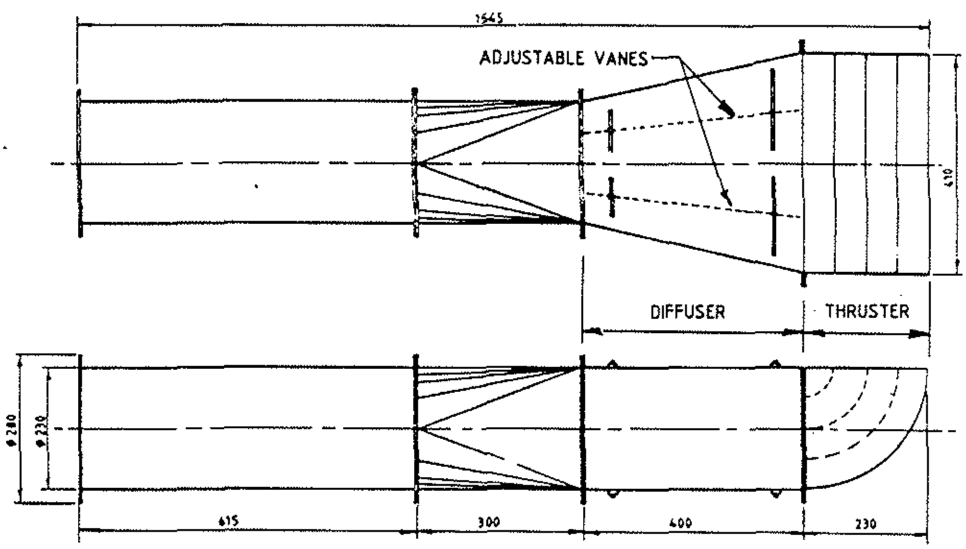


Figure 5: General Arrangement of DT3

b) Rotor Test Rig

The rotor test rig shown in figure 6 is comprised of a rotor test facility [8] fitted with a DT. The DT is supported by means of two vertical and two horizontal load cells located at its ends. Air is supplied to the DT by means of a fan located on the ground and a duct through which the air is conveyed to the DT. A rubber sleeve connects the DT to the duct. The air supply to the DT was varied by means of a plate fitted to the fan inlet.

Parameters measured during the tests included rotor thrust, rotor torque and the horizontal and vertical forces acting on each end of the thruster. The air flow, static, total and dynamic pressures were measured by means of pitot tubes. The ranges and standard deviations of the transducers are presented in table 1.

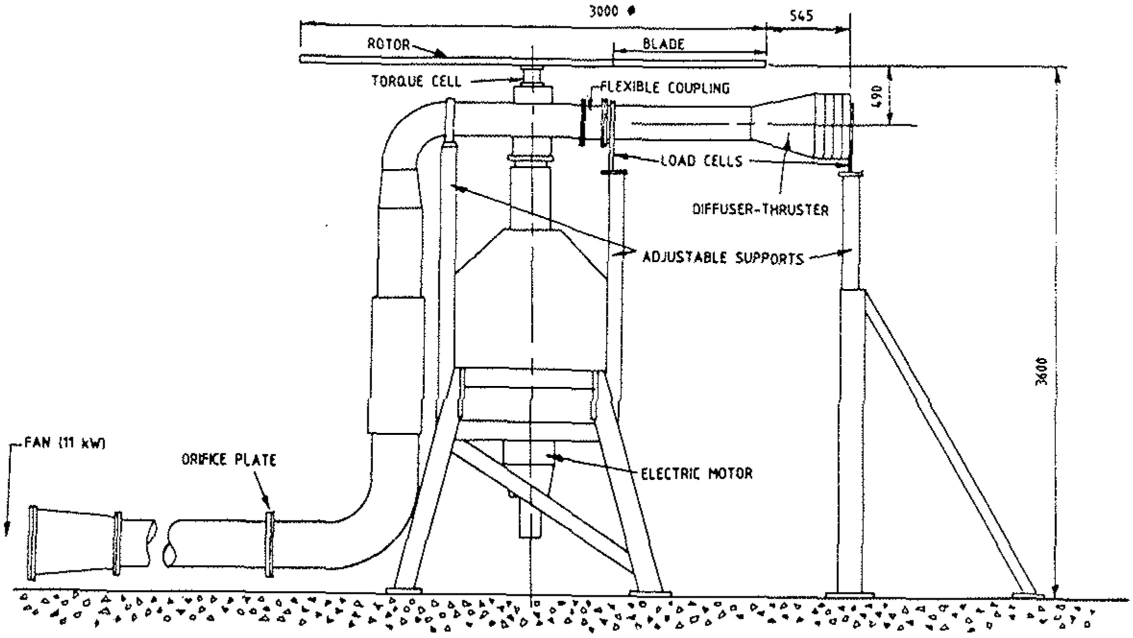


Figure 6: General Arrangement of Rotor Test Rig

Table 1: Range and Standard Deviations of Transducers

COMPONENT	RANGE	STANDARD DEVIATION (% OF FULL SCALE)
Rotational Speed (rev/min)	2000	0.25
Rotor Thrust (N)	5000	0.80
Rotor Torque (Nm)	380	0.48
Thruster Load Cells (N)	100	1.4
Tail Boom Pressure (N/m^2)	5000	0.25
Thrust (static rig) (N)	85	0.47

All readings were collected by means of a computer controlled data acquisition system. Zero readings were taken prior to each test. Each data point was averaged from 10 readings with each data set being recorded at one second intervals.

c) Static Test Rig

The static test rig is shown in figure 7. It is comprised of a fan and duct with the DT connected to the end of the duct by means of a rubber sleeve. The air flow to the DT was varied by means of a plate fitted to the fan inlet. The DT is supported on two pivots at its inlet end and on a load cell at its thruster end. The load cell was calibrated by placing weights at the centre of the outlet of the thruster and hence gave a direct reading of the thrust acting on the DT. A honeycomb flow straightener was placed inside the rubber sleeve to increase the uniformity of the flow entering the DT and to prevent the rubber sleeve from collapsing inwards due to the negative pressure inside the DT.

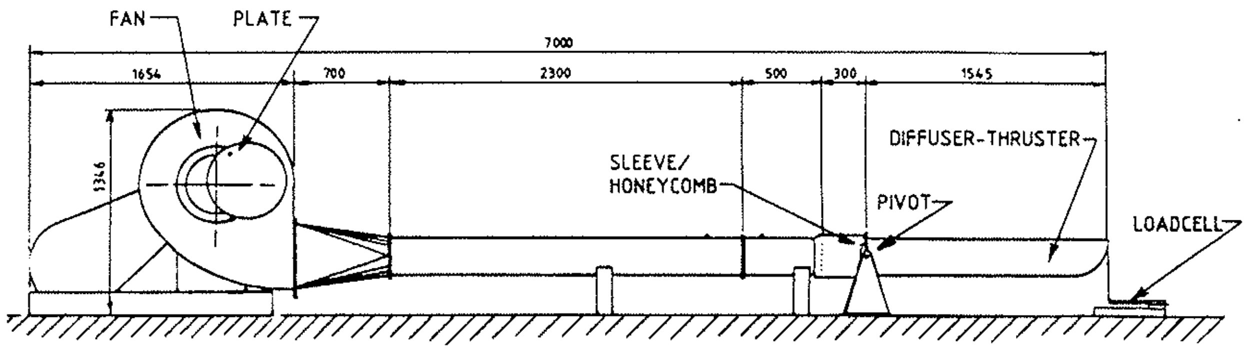


Figure 7: General Arrangement of the Static Test Rig

The air flow, static, total and dynamic pressures were measured by means of pitot tubes.

4. EXPERIMENTAL RESULTS

4.1 Effect of Rotor Downwash on DT

Since in hover the exhaust from the DT lies outside the wake of the rotor it would be expected that the rotor downwash would have no effect on the torque developed by the DT. To determine the effect of the rotor downwash on the torque of the DT a test was carried out on the rotor test rig in which the mass flow through the DT was kept constant and the rotor thrust was altered by varying the speed of the rotor. As shown in figure 8 the rotor thrust in hover had a small effect on the torque developed by the DT.

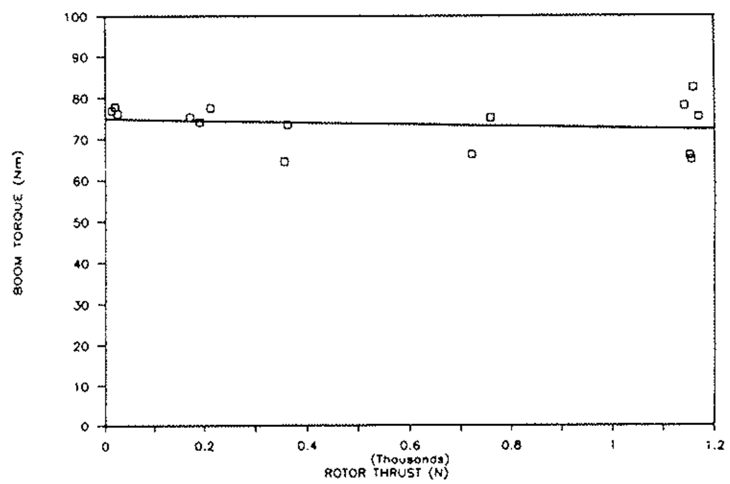


Figure 8: Variation of DT Torque with Rotor Thrust

4.2 Performance of DT2

Data obtained from tests carried out on the rotor test rig and the static test rig are presented in table 2.

Table 2

MODEL/ RIG	q_1 (N/m^2)	THRUST (N)	G (kg/s)	POWER (W)	$T/(A_3 q_1)$	P_{s_1}/q_1	$\frac{P(\rho A_3)^{1/2}}{T^{3/2}}$
DT2/RTR	968	45.2	1.812	1299	.495	-0.450	1.314
DT2/RTR	652	29.2	1.487	733	.487	-0.447	1.376
DT2/RTR	366	16.9	1.114	312	.490	-0.437	1.382
DT3/ST	1505	68.2	2.259	2455	.481	-0.444	1.338

RTR: tests carried out on the rotor test rig ST: tests carried out on the static test rig

As may be seen from the data in table 2 the performance of DT2 and DT3 are similar. For purposes of this analysis the performance of the current DT is based on the average results presented in table 2 giving the thrust as:

$$T = 0.488\, A_3\, q_1 \qquad \textbf{(12.)}$$

the static pressure in the tail boom as:

$$P_{s_1} = -0.445\, q_1 \qquad \textbf{(13.)}$$

and the power absorbed by the fan as:

$$P = 1.354\, \frac{T^{3/2}}{(\rho A_3)^{1/2}} \qquad \textbf{(14.)}$$

To determine the losses occurring in the diffuser and thruster a test was carried out on DT3. For this analysis it was assumed that no losses occurred downstream of the thruster. Relevant data are presented in table 3.

Table 3: Performance of Diffuser and Thruster

LOCATION	q (Pa)	Ps (Pa)	P_t (Pa)
DIFFUSER ENTRANCE	1505	-667	838
DIFFUSER EXIT	653	13.5	633
DIFFUSER WAKE		0	341

The loss coefficients for the diffuser and thruster obtained from data in table 3 are compared with those expected using references 6 and 7 respectively in table 4.

Table 4: Expected and Measured Values of K_D and K_T

	EXPECTED	MEASURED	
K_D	0.1092	0.1362	
K_T	0.278	0.478	
K_T/A_R^2	0.0530	0.194	(referenced to q_1)

4.3 Static Pressure Distribution in the Tail Boom

As one of the possible uses considered for the CCTB based system and DT is cooling of the engine exhaust gases by passing them into the tail boom it is pertinent to investigate the static pressure existing in the tail boom. In the case of McDonnell Douglas' NOTAR it appears that the static pressure could be raised to 7 kPa [5]. For purposes of the present calculation a static pressure of 3.5 kPa is used. The static pressures in the tail boom for the CCTB, DTTH and DT3 are presented in figure 9 where it may be seen that the static pressure depressions in the tail boom for the DTTH and DTB are significant.

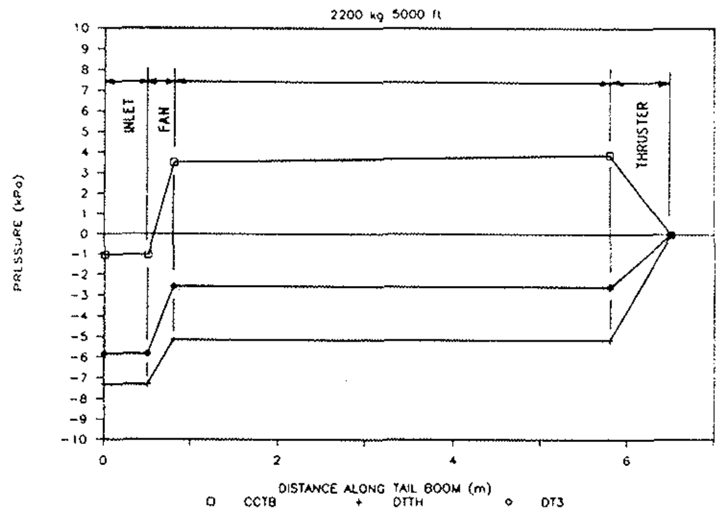


Figure 9: Static Pressure Distribution in Tail Boom

5. COMPARISON OF RESULTS

The performance of the DT as a main rotor anti-torque device is compared with the CTR and a CCTB combined with a thruster. For purposes of comparison the performance of the systems fitted to an Alouette III helicopter are considered. The hover flight condition used for purposes of comparison was:

All up mass	=	2200 kg	CCTB boom pressure	=	3500 Pa
Altitude	=	1524 m ISA	CCTB slot thickness	=	0.028D m
Main Rotor Power	=	365 kW	CTR power	=	42.4 kW
Rotor Speed	=	350 rev/min			

5.1 Conventional Tail Rotor

Data obtained from an Alouette III indicated that the power supplied at the tail rotor drive shaft is given by:

This corresponds to a figure of merit of 0.575 which compares favourably with data presented in reference 2.

$$P = 1.231 \frac{T^{3/2}}{(\rho A_3)^{1/2}} \tag{15.}$$

5.2 Fenestron

Reference 2 gives a figure of merit for a fenestron of 0.76. This gives (2)

$$P = 0.658 \frac{T^{3/2}}{(\rho A_3)^{1/2}} \tag{16.}$$

5.3 Circulation Controlled Tail Boom and Thruster

The analysis is based on data presented in reference 9 and 10. The results presented in reference 9 have been adjusted based on the later experimental work of reference 10.

The torque acting on a circulation controlled tail boom is given by:

$$Q_B = \left\{ 2.017 \left(L_2^2 - L_1^2\right) Pt + 0.05943\ T_R + 0.00561\ T_R\ P^{1/2} \right\} D \tag{17.}$$

The first term on the RHS gives the torque component due to the air flowing through the slots in the absence of rotor downwash. This air adheres to the surface of the tail boom due to the Coanda effect and leaves the boom essentially on the opposite side of the tail boom to that which contains the slots. The second term is due to the rotor downwash in the absence of circulation control air and is a function of the structure of the surface of the tail boom and the point at which flow separation occurs. The magnitude and direction of this component can be altered by the presence of a flap. The third term is due to the combined effects of the rotor downwash and the circulation generated by air flowing through the slits and around the surface of the tail boom.

The torque generated by the thruster was treated in a simplistic fashion with friction losses and the effects of the expansion of the jet from the thruster being ignored. It was taken to be:

$$Q_T = G V_j \tag{18.}$$

Equations (17), (10) and (14) were used to determine the power applied to the fans used for the CCTB and DT systems. The results are plotted in figure 10.

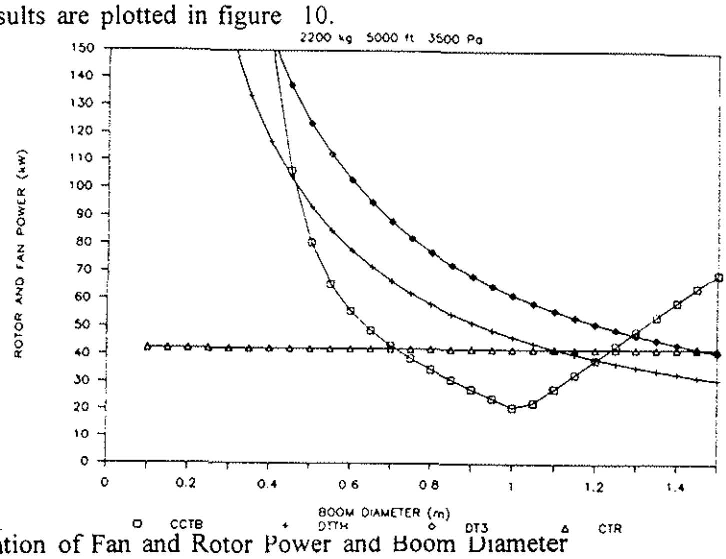


Figure 10: Variation of Fan and Rotor Power and Boom Diameter

5.4 Cooling of the Engine Gases

To obtain an indication of the temperature of the combined engine exhaust and air used for anti-torque that would typically be obtained a calculation was carried out for a tail boom with a diameter of 0.6 m. It was assumed that the engine exhausts 4.5 kg/s of air and fumes at 500°C. The temperature of the ambient air is assumed to be 15°C.

The temperature of the combined gases for the systems of interest are presented in table 4.

Table 4

	Mass Flow (kg/s)	Exhaust Temperature (°C)
CCTB	9.9	166
DTTH	32.9	73
DT3	29.4	79

It is clear that for the helicopter considered large reductions in the temperature of the engine exhaust can be achieved.

5.5 Summary

Since the various torque systems considered operate on different principles direct comparison of all operational parameters in terms of the analysis presented here is not possible. Relevant parameters are compared in table 5.

Table 5: Comparison of Parameters

	$\frac{P(\rho A_3)^{1/2}}{T^{3/2}}$	$\frac{P_{s_1} A_3}{T}$	$\frac{P_{s_1}}{q_1}$	**Temperature of exhaust gases (°C)**
CTR	1.231	-	-	500
Fenestron	0.658	-	-	500
DTTH	1.023	- 1.853	- 0.707	73
DT3	1.354	- 0.913	- 0.445	79
CCTB	-	-	-	166

6. CONCLUSIONS

i) Preliminary experimental results have indicated that the thrust performance of a DT compares favourably with that of a CTR but to ensure that the mass penalty is acceptable its performance will need to be improved.

ii) If the performance of a DT can be based on expected losses in a diffuser and corner vanes then there is much room for improvement of the DT. The experimental data indicates that the flow in the diffuser and thruster can be improved to reduce the losses.

iii) The static pressure depression in the tail boom of a DT combined with the large flow of ambient air would be useful for drawing engine exhaust gases into the tail boom and cooling them to possibly less than 100°C.

8. REFERENCES

1. A. H. Logan, NOTAR, Vertiflite, Vol. 28., No. 3, March/April 1982, pp 20-23.

2. Vuillet, Operational Advantages and Power Efficiency for the Fenestron as Compared to a Conventional Tail Rotor, Vertiflite, Vol. 35, No. 5, July/August 1989.

3. A.C. Haggerty, McDonnell Douglas Helicopter Company Independent Research and Development - Preparing for the Future, NASA CP 2495, NASA/Army Rotorcraft Technology Conference, Ames Research Center, March 1987, pp 1450-1481.

4. S.A. Hanvey, No Tail Rotor (Circulation Control Tail Boom), 26th Annual Symposium of The Society of Experimental Test Pilots, 25 September 1982.

5. R. Prouty, NOTAR: Refining the Design, Rotor and Wing, March 1993, pp 41-42.

6. D. L. Cochran and S. J. Kline, Use of Short Flat Vanes for Producing Efficient Wide-Angle Two-Dimensional Subsonic Diffusers, NACA TN 4309, September 1958, p 135.

7. Industrial Ventilation - A Manual of Recommended Practice, Committee on Industrial Ventilation, Edward Brothers Inc., Fifteenth Edition, 1978.

8. A. Nurick, W. Green and S.A.H. Poprawa, Commissioning of a Helicopter Rotor Test Facility, Research Report No 86, School of Mechanical Engineering, University of the Witwatersrand, October 1985.

9. A. Nurick and C. Groesbeek, Experimental and Computational Investigation of a Circulation Controlled Tail Boom, Paper B05, 18th European Rotorcraft Forum, Avignon, France, 15-18 September 1992.

10. A. Nurick, Unpublished Results.