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Response Characteristics of a Helicopter Tail Boom Thruster

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A.Nurick, T.M. Bergh

University of Witwatersland
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Response Characteristics of a Helicopter Tail Boom Thruster

Alan Nurick Tristan M Bergh
University of the Witwatersrand, Johannesburg

The response of a thruster attached to the aft end of a helicopter tail boom to variations in its outlet area was investigated on a scaled rig. The time dependent thrust was related to the initial and final static thrust and outlet area, tail boom length, air total pressure and pertinent geometric dimensions. It is shown analytically that for the case of a single outlet the response increases with static pressure in the tail boom and decreases with an increase in length of the tail boom. The thrust was found to oscillate at the natural frequency of the tail boom with the oscillation being excited by the operation of the clamshells and the air flow in the tail boom. Identification of thrust variations attributed to changes in the outlet area of the thruster was achieved by fitting a Fourier series to the experimental thrust and clamshell displacement data. It is shown that the response can be predicted with good accuracy using a simple analysis.

Notation

A = thruster outlet cross-sectional area

A_B = tail boom cross-sectional area

A_R = A/A_B = area ratio

A_t = A_1/A_0

G = mass flow

K_G = static mass flow coefficient

K_T = static thrust coefficient

L = length of column of air in tail boom

P_t = total pressure

t = time

T = thrust

ρ = air density

τ = $t\,(T_0/\rho A_0 L^2)^{1/2}$ = dimensionless time

Γ = T/T_0 = dimensionless thrust

Subscripts

0 = conditions prior to change of thruster outlet area

1 = conditions at changed thruster outlet area

1 Introduction

An anti-torque system comprised of a thruster fitted to the aft end of a helicopter circulation controlled tail boom located in the downwash of the main rotor was proposed by Velazquez in 1971 [1]. Such anti-torque systems have been installed on the McDonnell Douglas MD520N [2], MD Explorer [3] and MD 660 [4] helicopters and on the Ka-26 helicopter [5]. Raitch [6] discussed and summarised the results of a number of investigations carried out by Sikorsky Aircraft [7], Kaman Aerospace [8] and Vought helicopter [9] on the performance of anti-torque systems not incorporating a tail rotor. It was noted that for anti-torque systems in which air was blown down a tail boom and exhausted sideways into the atmosphere an intolerable lag existed between the call for a yaw moment change and the realisation thereof due to the inertia of the air in the tail boom.

It has been shown [10] that it is possible to reduce the power of a thruster by lowering the exit velocity of the air and increasing the outlet area to maintain the required thrust. The behaviour of thrusters has been characterised by means of dimensionless parameters which define the thrust, power, mass flow and static pressure in the tail boom [11]. In this work it was shown that for a given thruster with no diffuser the power required for a given thrust is proportional to the square root of the total pressure per unit mass of the air in the tail boom. It has been shown [12] that by exhausting the engine gases into the tail boom that not only is it possible to cool the engine exhaust gases before they are exhausted into the atmosphere but the power of the exhaust gases can contribute significantly to the power required to drive the thruster at the aft end of the tail boom thereby reducing the power of the cold air fan. It has also been shown [13] that the overall power of an anti-torque system comprised of a circulation controlled tail boom and thruster may be reduced by approximately 15% if a dual flow system is used in which air at a comparatively high pressure of 3500-7000 Pa is fed to the circulation control slots and air at a lower pressure of approximately 2000 Pa is fed to the thruster.

An anti-torque system comprised of a circulation controlled tail boom, thruster, engine exhausting into the tail boom, dual flow and some diffusion referred to as CIRSTEL (Combined Infra-Red Suppression and Tail Rotor Elimination) is currently being developed in South Africa as a demonstrator. The demonstrator has been designed to replace the conventional tail rotor on an Alouette III helicopter as shown in figure 1.

The performance of the CIRSTEL system has been evaluated and optimised [14] using available experimental data [10,11,12,13,15,16]. It has been found that the power required by the cold air fan at the forward end of the tail boom is approximately the same as that of the replaced tail rotor. However the total pressure of the air in the tail boom for the optimised design is approximately 2000 Pa and it may be expected from Raitch [6] and the analysis presented below that the yaw response of a tail boom with a single outlet on the thruster could be low.

To quantify and gain an understanding of factors contributing to the response of a thruster to a variation of its outlet area a test rig has been constructed with features which will allow various thrust control algorithms to be investigated. Control of the thrust of a thruster may be achieved by varying its outlet area by means of a rotating can [2], slide gates [11] and other devices. An objective of the experimental programme is to identify geometric and flow parameters which affect the response of the thrust to a rapid variation of the thruster outlet areas and to subsequently develop control algorithms which would increase the manoeuvrability of the helicopter.

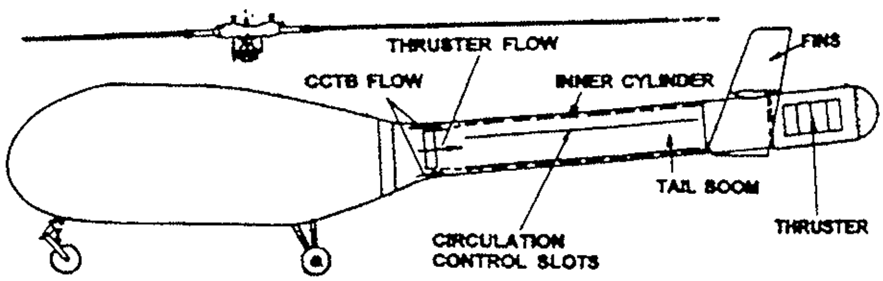

Figure 1 General Arrangement of a CIRSTEL Anti-Torque System Fitted to an Alouette III Helicopter

2 Analytical Background

The analysis is aimed at predicting the change of thrust due to a variation of the thruster outlet area. It is assumed that the instantaneous flow parameters are given by the static relationships [11] and dynamic effects are small. The relationships are developed to give an initial basis for comparison of the performance of a thruster with the experimental data it being accepted that dynamic effects may, if necessary, be included at a later stage once a clearer understanding of their behaviour is obtained.

The static thrust of a thruster is given by:

$$T = K_T \, P \, A \tag{1}$$

The mass flow is given by:

$$G = K_G \, (\rho A T)^{1/2} = \rho A_B V \tag{2}$$

If the thruster outlet area is altered then the system curve for the thruster will vary as indicated in figure 2 it being assumed that the change in static pressure due to a change in the system resistance is small.

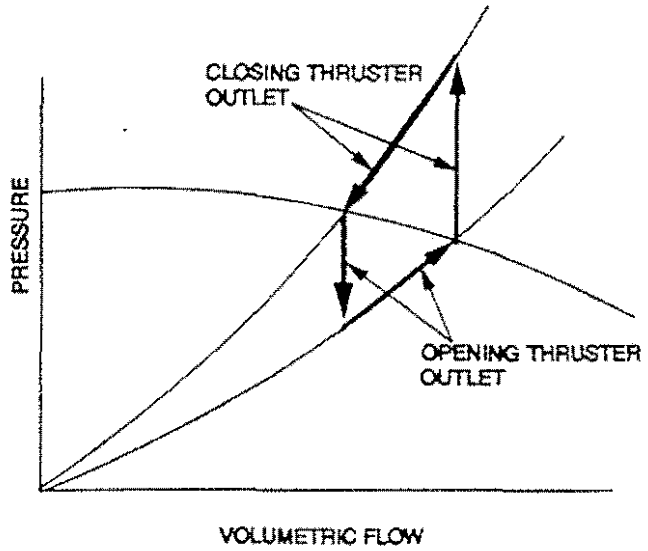

Figure 2 Effect of Changing Thruster Outlet Area

The acceleration of the column of air in the thruster is given approximately by:

$$\rho \ L \ A_B \ \frac{dV}{dt} = A \ (P_0 - P_1) \tag{3}$$

where the suffix 0 refers to the initial conditions and the suffix 1 to the final conditions pertaining to the final setting of the thruster.

Substituting equations (1) and (2) into equation (3) gives:

$$\rho \ A_B \ \frac{dV}{dt} = \frac{K_G^2}{2} \ (\frac{\rho \ A_1}{T})^{1/2} \ \frac{dT}{dt} \tag{4}$$

Thus equation (3) may be written:

$$L \ \rho \ A_B \ \frac{dV}{dt} = L \ \frac{K_G^2}{2} \ (\frac{\rho \ A_1}{T})^{1/2} \ \frac{dT}{dt} = A_1 \ (P_0 - P) \tag{5}$$

Substituting equation (1) into equation (5) and rearranging gives:

$$(\frac{\rho \ A_1 \ L^2}{T^3})^{1/2} \ \frac{dT}{dt} = \frac{2}{K_G^2 \ K_T} \ (\frac{T_0}{T} \ \frac{A_1}{A_0} - 1) \tag{6}$$

or

$$(\frac{\rho \ A_0 \ L^2}{T_0^3})^{1/2} \ \frac{dT}{dt} = \frac{2}{K_G^2 \ K_T} \ (\frac{A_0}{A_1})^{1/2} \ (\frac{T}{T_0})^{3/2} \ (\frac{T_0}{T} \ \frac{A_1}{A_0} - 1) \tag{7}$$

The following dimensionless variables may be defined:

Time:

$$\tau = \frac{t}{L} \left(\frac{T_0}{\rho A_0}\right)^{1/2} \tag{8}$$

thruster area ratio:

$$A_t = \frac{A_0}{A_1} \tag{9}$$

and, thrust ratio:

$$\Gamma = \frac{T}{T_0} \tag{10}$$

Substituting equations (8),(9) and (10) into equation (7) gives:

$$\frac{d\Gamma}{d\tau} = \frac{2}{K_G^2 K_T} A_t^{1/2} \Gamma^{3/2} \left(\frac{1}{A_t \Gamma} - 1\right) \tag{11}$$

indicating that Γ is a universal function of τ for a given A_t apart from the dependence of K_G and K_T on A_R. Equation (11) may be integrated to give the thrust at any time due to a random variation of the outlet area A.

As indicated by equation (11) the dimensionless rate of change of thrust is a function of the thrust and area ratios. The thrust ratio for a particular manoeuvre will be given and is independent of the thruster outlet area or total pressure of the air. The area ratio will also be constant as the area is, for a given thrust proportional to the total pressure of the air in the tail boom and thus the area ratio will be approximately fixed for a given thrust ratio. It follows that since τ is proportional to $(T/A)^{1/2}$ the response for a given thrust ratio will, by equation (1), be proportional to $(P_J)^{1/2}$. Also, the response of the thrust alone, ignoring the effect of the length of the tail boom on the lever arm on the torque is inversely proportional to the length of the tail boom. Thus to increase the response of the thrust to variations in the outlet area of the thruster the pressure of the air in the tail boom should be as high as possible and the length of the air column in the tail boom should be as short as possible. Alternatively the change in thrust should be accomplished without having to accelerate or decelerate the column of air in the tail boom which should effectively reduce L to zero.

The initial rate of change of the thrust following a rapid change of the thruster area is given by:

$$\frac{d\Gamma}{d\tau} = \frac{2}{K_G^2\ K_T} A_t^{1/2} \left(\frac{1}{A_t} - 1\right) \tag{12}$$

at which time $\Gamma=1$.

3 Experimental Rig

A general arrangement of the thruster response rig is presented in figure 3.

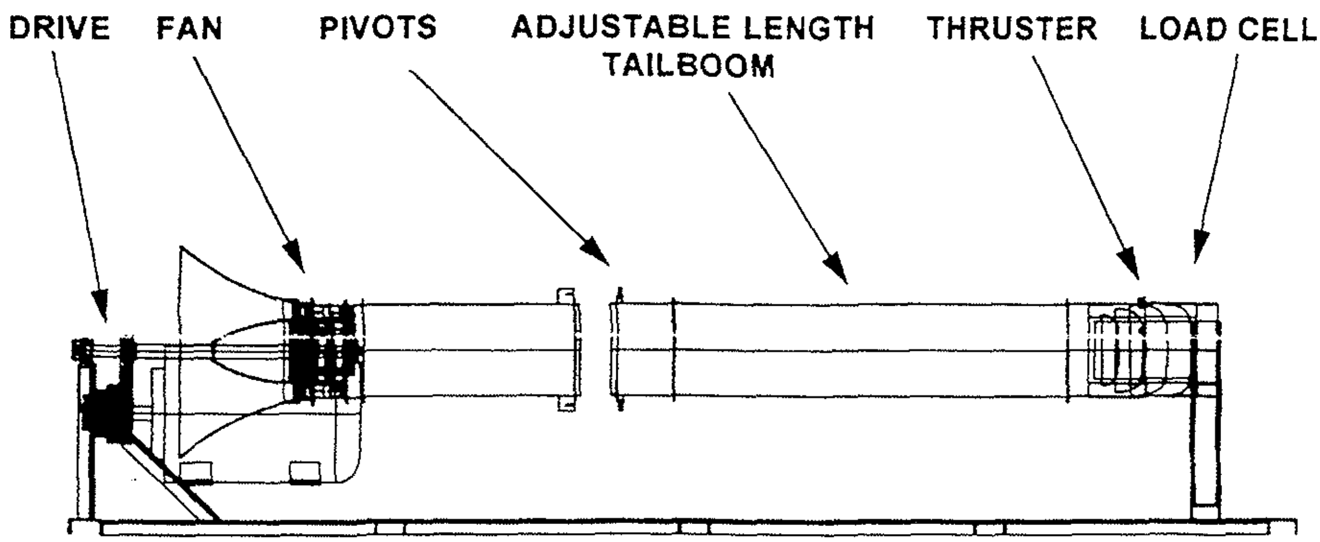

Figure 3 General Arrangement of Response Test Rig

The test rig was designed to simulate as closely as possible the geometry of a CIRSTEL anti-torque system excluding the dual and engine exhaust flow to ensure that the mass and geometry of air in the test rig was similar to that of a full scale helicopter. The dual flow system and engine exhaust gas mixer were excluded to simplify the test rig and to ensure that effects extraneous to the acceleration of a column of air and the consequent thrust were not included.

The test rig is comprised of an inlet duct, variable speed fan (speed changes by changing pulley sizes), different lengths of tail boom with a diameter of 301.6 mm and thruster a through which the air is exhausted to atmosphere in a direction parallel to the ground. The tail boom is supported on two plain spherical bearings which allow it to swing in a horizontal plane. It is restrained from moving by a load cell which is used to measure the thrust. The load cell is fixed to the rig by a plain spherical bearing on each of its ends to prevent transverse loads from affecting the thrust measurements. The aft end of the tail boom is restrained from vertical movement by means of a rod with plain spherical bearings on its ends which allows the tail boom to move freely in a horizontal direction. The moveable aft end of the tail boom is connected to the fixed forward end by means of a rubber tube.

The thruster has two outlets which are located on opposite sides of the tail boom as shown in figure 4. Only one outlet was used for the tests presented.

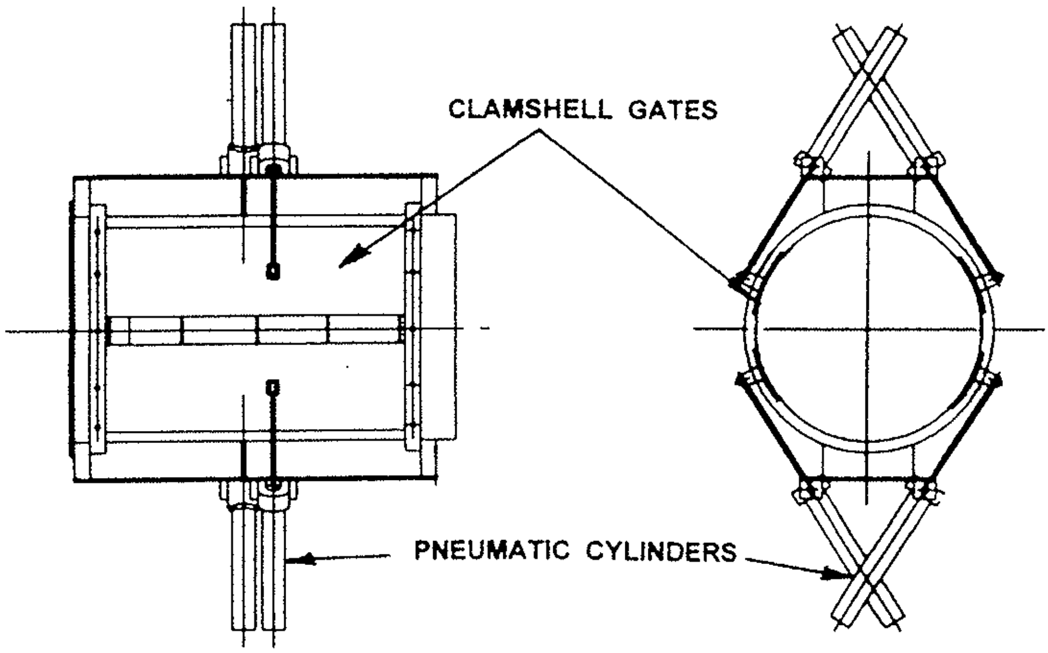

Figure 4 Cross-section of Tail Boom Aft End with Clamshell Gates

Flow from each of the outlets is controlled by means a pair of clamshell gates which slide in grooves on either side of the outlet. Each clamshell of a pair moves in opposite directions about the midpoint of the outlet. The use of the two clamshells gates on each outlet ensures that the air exhausts from the thruster in a direction parallel to the rotor disc plane thereby eliminating thrust components in a direction normal to the rotor disc plane.

The clamshells on each side of the thruster may be controlled independently. This was done to meet the requirements of the CIRSTEL anti-torque system in which two parameters need to be controlled viz the thruster thrust and the temperature of the gas mixture exiting into the atmosphere. It has been shown [11] that the thrust is a function of the difference in cross-sectional areas of the two outlets while the mass flow and hence temperature is a function of the sum of the areas of the two outlets. Also, the use of two outlets as opposed to a single outlet will allow a wider range of algorithms relating thrust response to variations in outlet area to be tested. The clamshells are moved by means of pneumatic cylinders. The flow of air to the pneumatic cylinders is controlled by solenoid valves which are opened or closed by the computer used to drive the data acquisition system. In the case of the test rig the distance over which the clamshells are moved is controlled by stops fitted to the thruster. The distance moved by each of the clam shells is measured by means of a linear displacement transducer.

The thruster thrust was measured by means of a calibrated load cell located at the thruster.

All data were collected by means of a computer controlled HPE1313A 64 channel high speed scanning analogue to digital converter. The channels were scanned at a rate of 1000Hz. Sample measurement frequency is 10000 Hz. All data were stored on disc and analysed at some convenient time.

Table 1 Standard Deviations of Instrumentation

Parameter	Range	Standard Deviation
Thruster thrust	1000 N	0.37 N
Clam shell displacement	100 mm	0.25 mm
Tail boom pressure	5000 Pa	5 Pa

4 Test Procedure

An initial set of tests was carried out to determine K_T and K_G to characterise the static performance of the thruster. The tests were carried out at different area ratios A/A_B as it has been demonstrated [11] that these coefficients are functions of the area ratio. For each of the tests the thrust and mean static and total pressures per unit mass were measured at the inlet to the thruster.

For each dynamic test the flow through the thruster and the position of the thruster outlet plates are preset. The thruster outlet plates are then moved rapidly in a controlled manner to a new preset position. The position of the thruster outlet plates, thrust and static and total pressures at a number of locations within the tail boom are recorded with respect to time using a computer based data acquisition system All relevant initial flow parameter settings are recorded.

5 Results and Discussion

K_T and K_G

Values of K_T and K_G obtained for the thruster are presented in figure 5. As it is not the objective of the research presented here to optimise the performance of the thruster no further comment is passed on the values of K_T and K_G obtained from the tests. They are used as measured for the particular thruster used for the response tests. In the response tests the area ratio A_R limits used were 0.157 and 0.556. For the analyses mean constant values of K_T=1 and K_G=0.9 were used in equation (7).

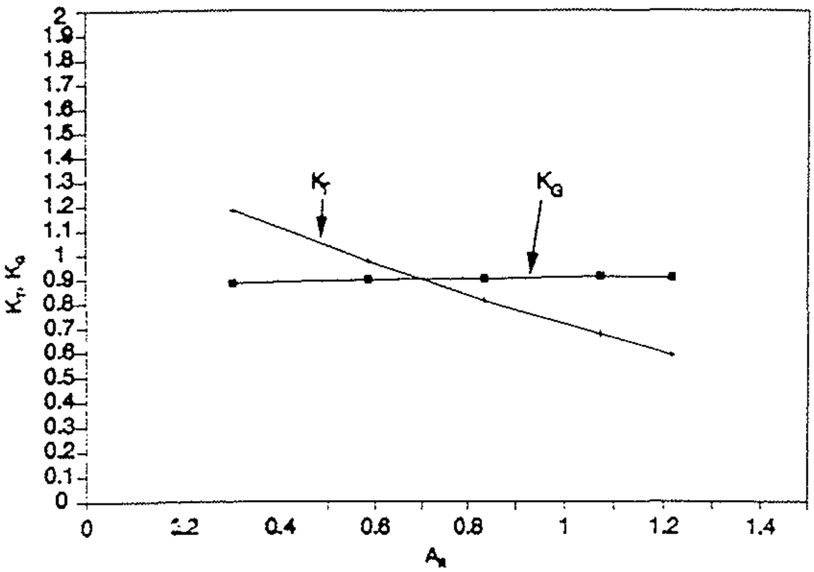

Figure 5 Variation of K_T and K_G with Area Ratio A_R

<u>**Thruster Response**</u>

To determine the effects on the load cell of the impact of the clamshell gates on the limit plates a test was carried out with no air flow with the clamshell gates being moved using the pneumatic cylinders. The results are given in figure 6.

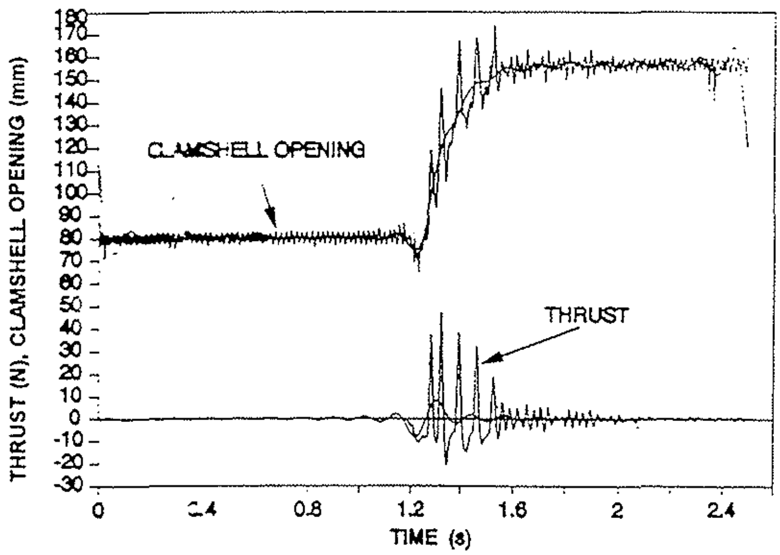

Figure 6 Variation of Clamshell Opening and Thrust with Time (No Flow)

As may be seen in figure 6 movement of the clamshell gates and the resulting impact on the stops results in an oscillating component being added to both the clamshell displacement and load cell. A frequency analysis indicated that the frequency of both oscillating components was 27 Hz and it appeared that this was the natural frequency of the tail boom in horizontal plane about the pivots supporting the tail boom. The mean thrust during the movement of the clamshell gates was zero.

The response of the thrust to a variation of the thruster outlet area was determined by moving the clamshell gates rapidly and measuring the resulting thrust. Results obtained for the case where the clamshell gates were opened rapidly are presented in figure 7.

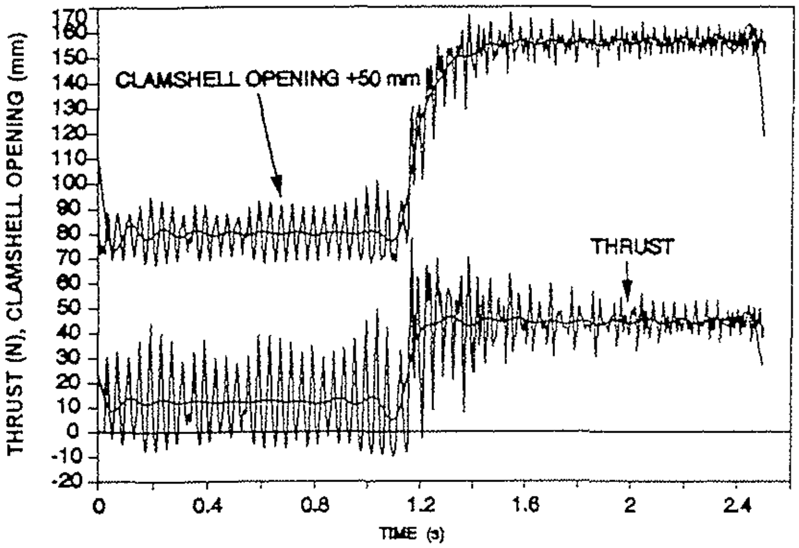

Figure 7 Variation of Clamshell Opening and Thrust with Time

As indicated by the data in figure 7 both the clamshell displacement and thrust readings have a superimposed oscillating component. It was found that the frequency of both these oscillating components was 27 Hz. These superimposed oscillations existed prior to and following the movement of the clamshell gates indicating that both the flow of air in the tail boom and the movement of the clamshells excites the natural oscillation of the tail boom. Also, the magnitude of the superimposed oscillation is greater at the lower flow rates indicating that the stability of the flow from the axial fan could be a function of the slope of the pressure versus volume flow characteristic of the fan. For clarity 50 mm has been added to all the displacement readings. In an attempt to eliminate the 27 Hz components from the displacement and thrust readings a Fourier series with less terms than that corresponding to the 27 Hz was fitted to the data. The resulting curves are included in figure 7. The thrust before and after the movement of the clamshell gates was similar to the static values.

To ensure that the superimposed oscillations obtained were not due to noise from the electric motor used to drive the fan a test was carried out in which one end of the load cell was disconnected. It was found that the output from the load cell during the entire test was virtually zero.

In figure 8 the Fourier representation of the measured thrust is compared with that predicted using equation (7) in which it is assumed that the clamshell plates are opened instantaneously. As may be seen in figure 8 good agreement was obtained between the measured and predicted variation of thrust.

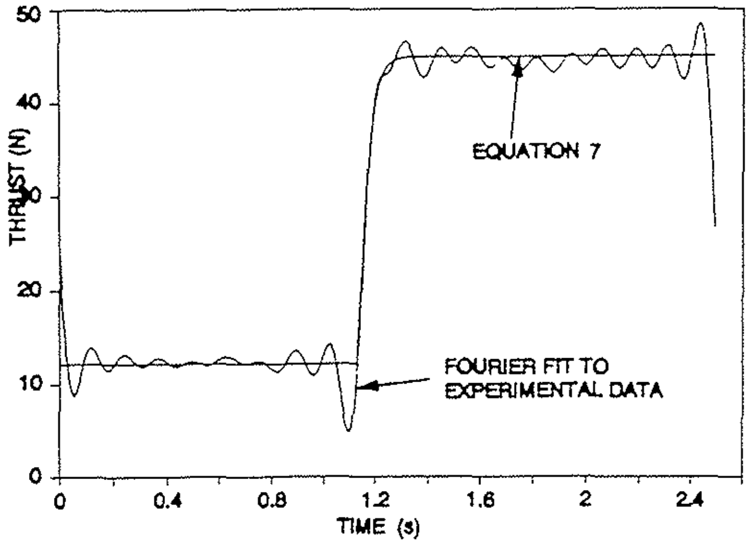

Figure 8 Variation of Thrust with Time (Clamshell Gates Opening)

Results obtained for the case where the clamshell gates were closed are presented in figures 9 and 10,

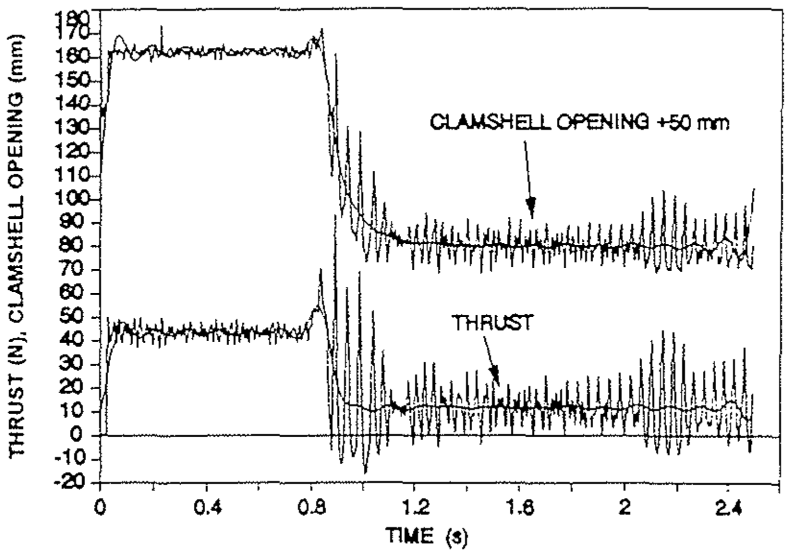

Figure 9 Variation of Clamshell Opening and Thrust with Time

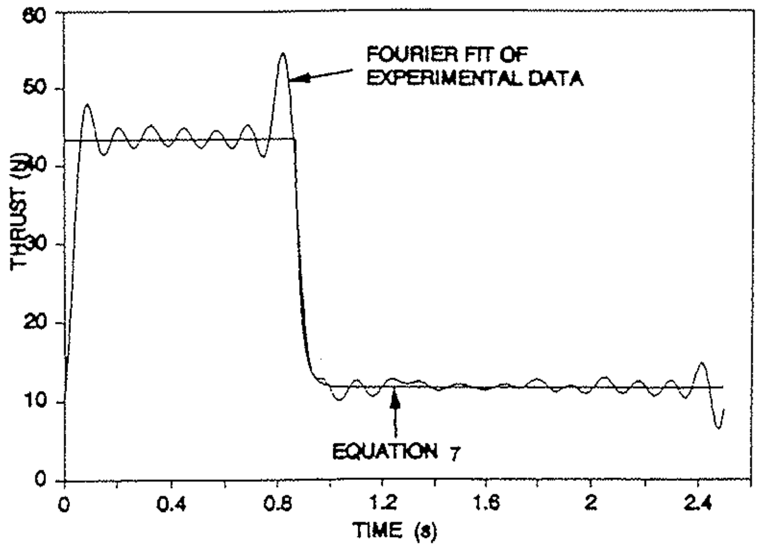

Figure 10 Variation of Thrust with Time

Similar results were obtained for the case where the clamshell gates were closed. Again it was found that the magnitude of the imposed oscillations was greater at the lower fan flow.

6 Conclusions

i a test rig has been developed which may be used to investigate and characterise response characteristics of a helicopter thruster fitted with dual outlet controls

ii thruster response may be predicted using a simple analytical model

ii thruster response is proportional to the square root of the total pressure per unit mass of the air in the tail boom

iii thruster response is inversely proportional to the length of the column of air which needs to be accelerated

7 Further Work

Ultimately the objective of the response research is to ensure that control algorithms are developed which will ensure that the manoeuvrability of a helicopter fitted with a CIRSTEL anti-torque system will be satisfactory. Further research will be aimed at investigating additional control algorithms in which a single thruster outlet is used and more particularly control laws in which the two outlets are used simultaneously.

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