SYSTEM ANALYSIS AND OPTIMISATION OF THE CIRSTEL TAIL BOOM

R. Heise, T.W. von Backström
Department of Mechanical Engineering
University of Stellenbosch
South Africa

Abstract

This paper details the development and results of a one-dimensional numerical model to simulate the CIRSTEL (Combined Infra-Red Suppression and Tail Rotor Elimination) equipped helicopters in hover. The model was used to perform a simple numerical optimisation of the system, with the objective of minimising the power requirement of the system. The model can be adapted to optimise other performance parameters such as the thruster exhaust temperature. Total pressures required for the system from the twin-flow-fan were the main variables used in the optimisation process. Secondary variables were the geometric dimensions of the tail boom. Previously the analysis methods used for the system did not allow for a numerical optimisation routine. Also, the effect the tail boom had on the engines has previously not been considered in sufficient detail. The current model thus incorporates an engine model to check and define parameters that minimise any effects the system may have on the engine. Two case studies were completed with the model, namely on a single- and twin-engine light helicopter of similar size.

Symbols

A	Area [m^2]
C_D	Drag coefficient / Discharge Coefficient
c	Chord length [m]
D	Drag [N]
d	Tail Boom Diameter [m]
F	Force [N]
f	Loss Factor
$\dot{m}$	Mass Flow [kg/s]
n	Area Ratio
P	Total Pressure [Pa]
p	Static Pressure [Pa]
Q	Torque [Nm]
R	Main Rotor Radius [m]
T	Thrust [N]
V	Velocity [m/s]
v_i	Induced Velocity [m/s]
W	Power [kW]
ρ	Density [kg/m^3]

Subscripts

B	Blade
c	Climb
Core	Core Section
CCS	Circulation Control Section
e	Engine
MR	Main Rotor
t	Blade Tip
TR	Thruster

Introduction

The CIRSTEL tail boom is a single rotor helicopter anti torque and control system. It relies on the Coanda effect to create circulation around the helicopter tail boom when exposed to the rotor downwash which results in a sideways-directed lift force to counter the main rotor torque. Additionally a tail thruster adds extra torque and allows for directional control. The system is similar to the NOTAR system, but inducts the engine exhaust gases into the tail boom for infra-red suppression and potential energy savings.

The Numerical Model

The CIRSTEL tail boom system consists of 5 main components; the Circulation Control Section (CCS), the core section with the mixer/nozzle, tail thruster, a fan and finally the helicopter engine, as this forms an integral part of the system. The twin flow fan supplies air to both the core and circulation control section. The CCS has two Coanda slots through which the air vents to set up a circulation around the tail boom in the presence of the main rotor downwash. In the core section the engine exhaust gases are mixed with fresh air supplied by the fan and exit the tail boom via the tail thruster. Refer to Figure 1 for a general layout of the tail boom.

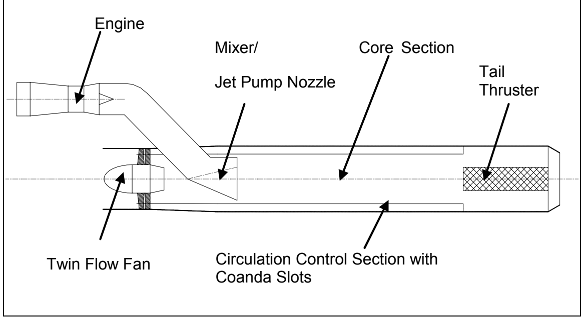

Figure 1 Schematic of the CIRSTEL Tail Boom

The model simulates each of the components individually, and then inter-links the individual component outputs to give the global performance of the tail boom.

1. Main Rotor

Added to the model of the five components is a routine that models the helicopter main rotor and conventional tail rotor performance. The tail rotor is simulated for comparison purposes to evaluate the tail boom relative to an equivalent tail rotor

The main rotor is modelled using a suitably modified momentum theory to include the effects of a finite number of blades and tip losses. The required thrust can be increased by a small amount to compensate for the extra downwash induced drag on the fuselage. To account for a non-uniform induced velocity and tip losses an empirically determined correction factor of κ = 1.18 is used to modify the average downwash velocity, as described by Seddon[1]. For the rotor blades NACA 0012 blade profile (Riegels[2]) data was used when calculating the power required to overcome blade drag. In none of the consulted literature total downwash velocities of (V_c + v_i) are used to predict the profile drag; generally the climb and induced velocities are ignored. For the current application the following equation is derived. Starting with the incremental power of a blade section,

$$dW_D = \frac{1}{2}\rho C_D V^3 c dr \qquad 1$$

the equation can be integrated for the whole blade length and number of blades to give, after some simplification:

$$W_D = \frac{1}{8}\rho C_D A_B \left(V_t^2 + \left(V_c + v_i\right)^2\right)^{\frac{3}{2}} \qquad 2$$

Gessow et al[3] do state that the commonly used equation is limited to hover and low-speed climb. The above equation however provides better answers when compared to published performance data of helicopters. From the calculated power the amount of torque acting on the fuselage is determined, and the performance of an accompanying conventional tail rotor can be determined using the same momentum theory

2. Engine

To date the engine has never been completely included in any analysis of the CIRSTEL system. (Lippert et al[4]) As an integral part of the system the modelling of the engine is critical to monitor the effects on the engine caused by the tail boom, primarily as the turbine backpressure can change with the design of the mixer. By increasing the backpressure on the turbine the surge margin is reduced, and a reduction in delivered power will occur as well. The current model allows for the design to be optimised such that the backpressure on the engine is reduced to zero.

The engine is modelled as a single shaft, constant speed engine with a diffuser after the turbine. The exit area of the diffuser is the same as that of the mixer and is thus one of the design and optimisation parameters. Since the engine is a constant speed unit the volume flow through the engine is constant. Hence the mass flow can be determined from the ambient atmospheric conditions once a mass flow is known at given atmospheric conditions. The standard thermodynamic relationships for the compressor and turbine are used, with the combustor exit total temperature fixed at a specified 1100K for this study. A pressure ratio for the compressor is determined for the selected engine along with the section efficiencies.

The engine is tied into the rest of the tail boom by the value of the static pressure at the exit of the diffuser/mixer, which is the static pressure in the core section of the boom. For the turbine performance the diffuser exit dynamic pressure can be determined from the known mass flow, density, exit area and diffuser efficiency, which then together with the static pressure gives the exit total pressure of the engine. A problem arises in determining the exhaust density, which again is dependent on the static pressure in the tail boom and thus forming a circular reference. To curb the problem an exit density is guessed with which the calculations are continued. In the solving phase of the program the error between the guess and calculated value is then kept zero by changing the guessed density.

Finally the engine power output is determined, and modified to include gearbox losses. The shaft power available is then compared to the total demand from main rotor and fan and the gearbox rating. If required the total takeoff weight can be modified to keep within the limits of the engine and gearbox.

3. Core Section with Mixer

The core section with its mixer where the engine exhaust gases are injected is essentially a jet pump. This effectively unloads the fan if carefully designed and thus allows an effective power reduction mechanism over conventional systems. Control volume momentum analysis is used to set up a quasi one-dimensional model of the mixer and duct. To make the equations useful for the design of the current tail boom, they were derived such that the entry and exit streams can have different densities and the total pressures of each stream can be specified. Total pressures are used in the equations as the total pressures in the sections of the tail boom drive the solution.

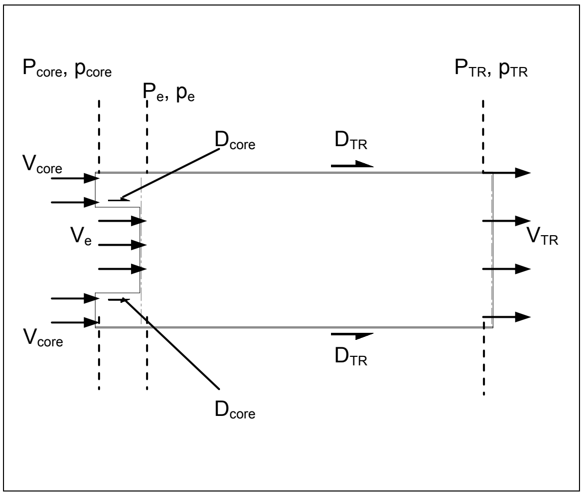

Figure 2 Control Volume for the Core Section

Figure 2 shows the control volume of the core section for purposes of the momentum analysis. The duct has a constant diameter, thus the mixer exit opening occupies a fraction n of the cross-sectional area A, with the fan duct area being (1-n)A. The sum of forces on the control volume can then be written as

$$\begin{aligned}\sum F &= D_{TR}+D_{core}+D_e+Ap_{TR}-nAp_e-(1-n)Ap_{core}\\ &= \dot{m}_{core}V_{core}+\dot{m}_e V_e-\dot{m}_{TR}V_{TR}\end{aligned} \qquad 3$$

At the entrance and exit to the control volume the streams will exhibit some momentum deficiencies due to wall friction and form drag. These are accounted for in the D_x terms and take on the form of

$$\begin{aligned}D_x &= f_x \rho_x V_x^{\,2} A\\ &= f_x \dot{m}_x V_x\end{aligned} \qquad 4$$

Here the loss factor f is equivalent to half the drag coefficient based on the cross-sectional area of the flow. The losses in the duct that are accounted for in the D_{TR} term are effectively duct friction losses and are calculated using pipe flow theory. Losses in the engine air are estimated to be f_e = 0.05 for a 95% diffuser efficiency. From Hoerner[5] the drag coefficient of the mixer is estimated to be C_D = 0.2 which would make f_{core} = 0.1. This value was later adjusted to f_{core} = 0.12 when comparing results to some limited experimental data (Bouwer et al[6]). After some simplification the final result of the momentum analysis yields the following equation:

$$\begin{aligned}A(P_{TR}-P_{core}) &= \dot{m}_{core}V_{core}\left(\frac{1-2n}{2(1-n)}-f_{core}\right)\\ &\quad+\dot{m}_e V_e\left(1-f_e\right)-\dot{m}_{TR}V_{TR}\left(\frac{1}{2}-f_{TR}\right)\end{aligned} \qquad 5$$

This is the desired function with the section mass flows as the required variables with the core fan total pressure as the output. This equation can now easily be applied for the system calculations.

The experiments done by Bouwer et al[6] were for a fixed value of the mixer/duct area ratio, thus that data cannot easily be used for design purposes. That data was however used to calibrate the current equations. Care has to be taken when interpreting the results by Bouwer as it can predict unrealistic total pressures from the fan at low mass flow ratios as insufficient data is available in that region.

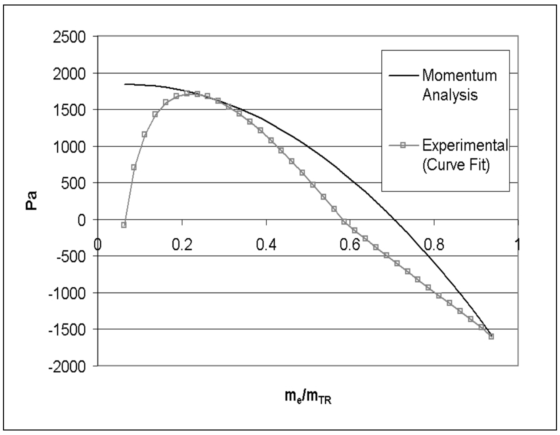

Figure 3 Momentum Analysis and Experimental Result Comparison for the Core Section

Figure 3 compares the experimental data to the results obtained by the momentum equation, all to achieve a total exit pressure of 1200 Pa and 1.6kg/s mass flow, with a nozzle area ratio n = 0.469. The figure shows the pressure contribution the fan has to deliver to achieve the desired exit pressure for a range of engine mass flow fractions of the total required exit mass flow. As can be seen from the figure the theoretical results follow the experiment relatively well for mass flow ratios larger than 0.2. At the lower values the experimental curve-fit indicates a negative pressure rise required from the fan to achieve the desired total pressure rise at the thruster end of the duct, which is unrealistic as the fan at that ratio has to virtually deliver the entire pressure rise on its own.

4. *Tail Thruster*

The performance of the tail thruster is based on the theory developed by Nurick[7] for a clamshell thruster, with experimentally determined thrust and power coefficients that are used for the calculations. Thrust of the thruster is a function of the thrust coefficient, exit area and the total pressure supplied to the thruster. Similarly the mass flow is dependent on the power and thrust coefficient, exit area, density and total pressure. Here the total pressure is calculated from the momentum theory for the core section. Once the total core section mass flow is known the amount the fan has to contribute can be calculated by subtracting the engine mass flow form the total flow.

As shown by Nurick(7) the static pressure can be determined from the thruster coefficients, geometry and total pressure alone. The density in the tail boom can not be calculated because the specified total pressure influences the static pressure, mass flow and hence the mixed air flow temperature in the duct, which are all needed to calculate the density. This results in a circular reference, and again a density is guessed from which the calculations are continued, and this guessed density is then adjusted during the solving phase to equal the actual value. Knowing the two mass flows entering the core section the mixture temperature can be calculated, from which finally the actual mixture density can be calculated.

5. *Circulation Control Section*

Fonternel et al(8) give a summary for the theory on the circulation section, while more recently Nurick(9) conducted further investigations specifically for the CIRSTEL system. The torque the circulation section provides in hover is a function of the supplied total pressure, main rotor thrust and the tail boom geometry. A similar geometry is used in the simulations as the geometry used by Nurick, for which the produced torque is given by

$$Q_{CCS} = 0.101\left(\frac{P_{CCS}}{T_{MR}/\pi R^2}\right)^{\frac{1}{2}} T_{MR} d \qquad 6$$

This equation is valid for a round and flap-less tail boom. Two Coanda slots are used for this boom; one at a location of 60º from the top, with the second slot located 120º form the top of the tail boom. The Coanda slots extend to the radius of the main rotor with a total length of 2.75m. To calculate the mass flow through the two Coanda slots, they are modelled as a nozzle with a discharge coefficient of C_D = 0.802. The discharge coefficient is derived from experimental data (Nurick(9)).

6. *Fan*

A unique fan is used for the CIRSTEL system in that it has the ability to supply each section of the tail boom with a separate air stream of the required pressure and mass flow quantity. As part of the general research effort into the CIRSTEL system such a fan has been tested experimentally. Results from these tests are incorporated into the current simulation program in that it has been shown that the two sections of the fan do not influence each other significantly, regardless at which operating point each section is working. Secondly the fan efficiencies determined during the experimental trials are used here to determine the power requirements of the fan. Since the required mass flow and total pressure rises are known, and hence the required fan power, the corner stone for the fan design is provided as well.

7. *Global Tail Boom Performance*

The torque each of the circulation control and tail thruster sections develops is added to give the total delivered torque of the tail boom. The total power required by the fan is also the sum of the two sections and is an important result to monitor. This value is required for monitoring of the total power requirement of the helicopter and to compare to the power demand of the conventional tail rotor to highlight any power savings or differences. Finally the total mass flow requirement of the fan is required for the design of the air intakes for the fan.

Optimisation Method

As well as facilitating an easy design process, the program was also designed to be utilised with a numerical optimisation scheme. Added to that, by monitoring the performance of the individual components during the optimisation process, the most critical components could also be identified. Standard numerical optimisation techniques, such as the simplex method (Vanderplaats(10)) with constraints, were employed to find optimum dimensions and parameters for this tail boom. For simplicity the current program was written for a spreadsheet, which allowed a better visibility and control of the parameters during the search for convergence.

The objective of the optimisation process is to minimise the power required by the fan, while the tail boom still delivers the required torque to balance and control the helicopter. Primary constraint on the optimisation process is thus the percentage of main rotor torque the tail boom has to counter, including the reserves required for manoeuvring. Once an optimum for a selected design point is found, the solution has to be checked for other parts of the hover envelope by scaling the fan with the appropriate fan scaling laws.

Any reductions in the total power requirement over the standard tail rotor have their obvious advantages; if the requirement increases the feasibility of the system reduces, though the tactical and safety advantages of the system remain.

Input variables used are primarily the geometric features of the tail boom, such as boom diameter, mixer area and thruster exit area. The total pressures in the two conduits of the tail boom drive the solution, as these have the most direct influence on the performance of the boom and the fan. The fraction each of the two sections delivers of the total torque can also be limited.

Optimisation Constraints

Two helicopter design configurations were studied, namely a single and a twin engined helicopter in the light utility helicopter class. Both helicopters have the same overall dimensions with a main rotor diameter of 11m. The single engine helicopter is modelled as having an engine based on the Artouste IIIB delivering 500kW, while the twin has engines each delivering 480kW, which in turn are based on the Arrious 2K1 engine. For the single engine helicopter the power limit is the engine output, while for a twin the limit is usually defined by the main rotor gearbox rating. Accordingly the limit is set in the program. As a design point the maximum take off weight is selected at atmospheric conditions of 85 000 Pa and 25ºC for both versions. The upper design limit chosen is a maximum all up weight which can be maintained with available power plus an extra margin of the fan power to allow for manoeuvring.

Engine performance degrades with altitude and temperature, which was also included in the analysis. Due to the nature of the CIRSTEL system the backpressure on the engine can change from normal atmospheric conditions, which in turn will change the engine output due to a difference in the pressure drop across the turbine. These effects of the changing backpressure were also included in the analysis of the system. A higher backpressure on the turbine will reduce the power output and reduce the surge margin. A lower pack pressure would thus seem to be a better solution, but this can lead to an over-loading of the engine, and thus the backpressure should be kept close to zero during solving.

Further constraints that were experimented with are the thruster exit area and tail boom diameter. These variables however quickly converged to unrealistic values; the tail boom diameter increased to a size that could not be installed on a helicopter and the thruster exit area also ended up as being too large to practically fit on the tail boom. These two dimensions thus had to be fixed to practical values and did not form part of the numerical optimisation process. For both test cases the dimensions were identical for these geometric features. The exit area of the mixer was chosen such that the engine(s) would experience a close to zero backpressure, yet the mixer performed sufficiently as a jet pump nozzle for both test cases. When allowing the optimisation routine to size the nozzle area the tendency is to reduce the area and increase the backpressure on the engine unless the backpressure is explicitly constrained. Further, a larger nozzle exit area is more desirable to allow for better mixing of the hot gasses inside of the core section duct.

The fraction of the torque delivered by the circulation control section is limited to below 48%; this is to ensure an effectiveness of the tail boom at slow speed flight, when the effectiveness of this section is reduced due to the decrease in downwash from the main rotor and more reliance is on the tail thruster. Since the circulation control section is more efficient at creating torque the fraction it contributes is always close to the maximum limit. A secondary effect of this limit is the temperature of the gasses exiting the thruster; by increasing the workload of the core section more cold air is demanded from the fan, and thus the thruster temperature is reduced.

Optimisation Results

In both test cases the power required by the fan reduced noticeably to that below a conventional tail rotor. The fan power was below 5.3% and 8.7%, for the single and twin respectively, of the main rotor power, as opposed to the 9 to 10 % of the conventional tail rotor. The reduction in power can mainly be attributed to the jet pump effect in the core section and the ability to optimise the tail thruster and circulation control section separately. The jet pump has a dominating effect on the performance of the tail boom, and is thus a critical component in the design of the system. Table 1 gives the detailed results of the simulations for the two case studies.

The relatively small power saving for the twin stems from the high engine compressor pressure ratio of 9.5 versus the pressure ratio of

5 used for the single. Resultantly it has a small mass flow through the engine for the power the engine produces and the fan then has to supply enough air to power the tail thruster. This can also be seen by the low thruster exit temperature of 151ºC. The power saving is thus a trade off, amongst others, between the type of engine used and the thruster exit temperature required that has to be considered at the start of the design process.

Table 1 Optimisation Results for 110% of Main Rotor Torque

	Single 2070kg T/O mass	Twin 3500kg T/O mass
Total Fan Power [kW]	17.7	52.8
Equivalent Tail Rotor Power [kW]	27.2	61.2
% Saving	34.8%	13.7%
Thruster Gas Temperature [ºC]	167	151
Total Torque [Nm]	9159	16634
Total Pressure Supplied to Thruster [Pa]	2126	3765
Total Pressure Supplied to CCS by the Fan [Pa]	1720	3552
Total Pressure Supplied to Core Section by the Fan [Pa]	1377	2890
% Contribution by Circulation Control Section	46.3%	47.7%
Tail Boom Diameter [m]	0.720	0.720
Tail Thruster Area [m^2]	0.4655	0.4655
Core Section Diameter [m]	0.650	0.650
Nozzle Area (Fraction of Core Section)	0.235	0.230
Mass Flow Fraction	0.281	0.249

Finally the thruster exhaust temperature was reduced to well below the 170ºC threshold for both test cases, which will make it difficult for infra-red sensors to pick up. In the calculations complete mixing of the exhaust gas is assumed due to the limitations of the one-dimensional model. Incomplete mixing will not significantly affect the momentum analysis, but a distinct degrading of the IR suppression will occur if incomplete mixing takes place. It is thus imperative that the design of the mixer is carefully considered.

Also worthwhile noting here is that the total pressure in the CCS section is lower than the pressure supplied to the thruster. The fan however has to deliver a higher pressure to the CCS than to the core section; the remainder being made up from the energy supplied by the engine exhaust gas.

Conclusion

The results of this optimisation study show that the system offers a potential power demand reduction over a conventional tail rotor by up to 35%, while reducing the exhaust gas temperature to below 170^{o}C. It is also shown that through careful designing and sizing of the mixer nozzle the effects on the engine can be negligible while still boosting the performance of the tail thruster.

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