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Experimental Investigation of a Helicopter Circulation-Controlled Tail Boom

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Results of an experimental investigation to characterize the performance of a model helicopter circulation-controlled tail boom in the wake of a hovering rotor are presented. The tail boom had a circular cross section, two slots, and a removable flap. A method for predicting the torque of a tail boom using results obtained in a wind tunnel is presented. The effects of slot width, slot length, boom pressure, rotor thrust, and distance between the rotor and tail boom on the torque were determined. Results are compared with those predicted using two-dimensional data obtained in a wind tunnel. It is shown that the torque acting on a tail boom in hover is characterized, as is a circulation-controlled cylinder in a wind tunnel, by three flow phenomena that may be combined to describe the torque.

Nomenclature

C_T	=	rotor thrust coefficient, $T/(\pi\rho R_o^4\omega^2)$
C_μ	=	$(\rho V^2 t)_{\text{jet}}/(0.5\rho U^2 D_c)$
D_c	=	tail boom diameter
G	=	mass flow
H	=	distance between the tail boom centerline and rotor disk plane
k	=	ratio of wake radius to that in the rotor disk plane
L	=	lift
L_1	=	distance of forward end of slots from rotor shaft
L_2	=	distance of aft end of slots from rotor shaft
l	=	distance along tail boom
P	=	pressure in tail boom
Q	=	torque about rotor shaft
R	=	correlation coefficient
R_o	=	main rotor radius
T	=	rotor thrust
t	=	sum of widths of slots
U	=	wake velocity
x	=	dimensionless radius, r/R_o
ν	=	mean rotor disk loading, $T/(\pi R_o^2)$
ρ	=	air density
σ	=	standard deviation
ω	=	rotational speed of rotor

Subscripts

calc	=	calculated
i	=	inner radius
meas	=	measured
o	=	outer radius of the wake or rotor
w	=	in the wake at the centerline of the tail boom

Introduction

IN 1800 Young[1] described the attachment of a jet to an adjacent convex surface. The effect was rediscovered in about 1910 by Coanda and has since been known as the Coanda effect. The Coanda effect has been implemented on a model wing of the Gruman A6-A (Ref. 2) and the British Aircraft Corporation's TSR.2 (Ref. 3). On rotary wing aircraft, it has been implemented on the lifting rotor of the Kaman circulation-controlled (CC) helicopter[4] and the stopped rotor of the U.S. Navy/Defense Advanced Research Projects Agency X-Wing.[5] One of the earlier proposals for a circulation-controlled tail boom was that of Velazquez, who in 1971 proposed a helicopter antitorque system comprising a CC tail boom (CCTB) located in the downwash of a helicopter rotor.[6] The use of a CCTB and thruster as an antitorque system has been implemented on the McDonnell Douglas Helicopter Systems (MD) MD520N (Ref. 7), the MD Explorer helicopters,[8] and the Ka-26 (Ref. 9).

Wind-tunnel investigations have been carried out on elliptical[10–14] and circular[15–20] (CC) airfoils. Generally the performance of CC airfoils was related only to the slot momentum coefficient C_μ. Nurick and Groesbeek[21] showed from tests carried out on a CCTB on a whirl tower[22] that CC flows are related to parameters other than the slot momentum coefficient alone. Dionisio and Nurick[23] demonstrated that the lift on a CC airfoil can be related to the sum of the effects of 1) asymmetric flow due to nonsymmetries in surface conditions, 2) momentum changes of the circulation control air and external flow, and 3) lift augmentation due to induction of circulatory flow by the slot wall jet in the presence of an external flow.

Logan[24] investigated the performance of a CCTB with one slot, in and out of ground effect. Jet velocities were varied from 37 to 68 m/s, slot widths from 4.3 to 19 mm, and the angular position of the slot from 90 to 150 deg from the leading edge or top of the tail boom. It was found that the maximum side force occurred with the slot at 140 deg and it reduced rapidly when the ratio of the slot jet velocity to the freestream velocity dropped below 4, or C_μ below 0.4. The tail boom force was correlated with the velocity ratio and C_μ. In flight tests,[24] premature separation of the flow from the tail boom occurred with a single slot, but was prevented using end plates.

Morger and Clark[25] carried out an analytical and experimental investigation of the flow on a CCTB to obtain a method, other than fences, of controlling the premature separation,[24] which was achieved by removing a flat section on the top of the tail boom. Van Horn[26] prevented premature separation by using a second slot located at 70 deg.

The objective of the research presented here was to investigate CCTB flowfields and to relate them to those of a cylinder in a two-dimensional flow in a wind tunnel.

Analytical Background

Dionisio and Nurick[22] showed that the lift of a two-dimensional CC cylinder (CCC) may be written as

$$\delta L = K_1\rho U^2 D_c\delta l + K_2 Pt\delta l + K_3\rho U^2(P/\rho U^2)^{\frac{1}{2}} D_c\delta l \qquad (1)$$

where the first term on the right-hand side (RHS) of Eq. (1) is due to flow asymmetries due to surface conditions, the second to momentum changes of the air flowing in the slot jets and to the

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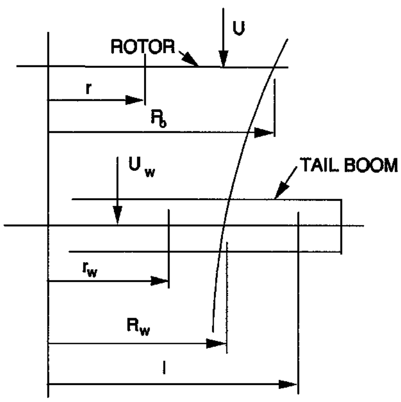

Fig. 1 Rotor wake notation.

freestream, and the third to the lift augmentation of the external flow by the CC air.

In terms of the notation given in Fig. 1, the torque acting on the tail boom is given by

$$Q = K_1 \int_{R_{w1}}^{R_{w2}} \rho U^2 D_c r_w \, dr_w + K_2 \int_{L_1}^{L_2} Ptl \, dl + K_3 \int_{R_{wi}}^{R_{wo}} \rho U (P/\rho)^{\frac{1}{2}} D_c r_w \, dr_w \tag{2}$$

where the first and third terms on the RHS have been integrated across the wake along the centerline of the tail boom and the second term across the length of the slots.

From continuity of flow in the wake,

$$2\pi \rho r \, dr U = 2\pi \rho r_w \, dr_w U_w \tag{3}$$

Put

$$r_w = kr \tag{4}$$

$$U_w = U/k^2 \tag{5}$$

The rotor thrust, from momentum considerations, is given by

$$T = 4\pi\rho \int_{r_i}^{r_o} U^2 r \, dr \tag{6}$$

which by Eqs. (4) and (5) is

$$T = 4\pi\rho k^2 \int_{R_{wi}}^{R_{wo}} U_w^2 r_w \, dr_w \tag{7}$$

The mass flow of air through the rotor is

$$G = 2\pi\rho \int_{r_i}^{r_o} Ur \, dr = 2\pi\rho \int_{r_{wi}}^{r_{wo}} U_w r_w \, dr_w \tag{8}$$

which by Eqs. (7) and (8) is

$$Q = K_1 D_c [T/(4\pi k^2)] + (K_2/2)\left(L_2^2 - L_1^2\right) Pt + (K_3/2\pi)(P/\rho)^{\frac{1}{2}} D_c G \tag{9}$$

Put

$$U = U_T f(x) \tag{10}$$

where

$$x = r/R_o \tag{11}$$

Here $f(x)$ defines the dimensionless axial velocity profile of the wake.

Thus, the mass flow is given by

$$G = 2\pi\rho R_o^2 U_T \int_0^1 x f(x) \, dx \tag{12}$$

and rotor thrust by

$$T = 4\pi\rho R_o^2 U_T^2 \int_0^1 x f^2(x) \, dx \tag{13}$$

Combining Eqs. (12) and (13) gives

$$G = T^{\frac{1}{2}} (\pi\rho)^{\frac{1}{2}} R_o F \tag{14}$$

where

$$F = \frac{\int_0^1 x f(x) \, dx}{\left[\int_0^1 x f^2(x) \, dx\right]^{\frac{1}{2}}} \tag{15}$$

F should be approximately constant for hovering rotors varying from approximately 0.667 for a linearly varying velocity field to 0.707 for a uniform velocity field.

Substituting Eqs. (14) and (15) into Eq. (9) gives

$$Q/TD_c = K_1 \big/ 4\pi k^2 + (K_2/2)\left(L_2^2 - L_1^2\right)(P/T)(t/D_c) + \left[K_3 \big/ (4\pi)^{\frac{1}{2}}\right](P/T)^{\frac{1}{2}} R_o F \tag{16}$$

If the mean disk loading is given by

$$\nu = T \big/ \pi R_o^2 \tag{17}$$

then Eq. (16) may be written as

$$Q/TD_c = K_1 \big/ 4\pi k^2 + (K_2/2)\left(L_2^2 - L_1^2\right)(P/T)(t/D_c) + (K_3 F/2\pi)(P/\nu)^{\frac{1}{2}} \tag{18}$$

An objective of the experiments was to quantify the constants K_i, $i = 1, 2, 3$, where the downwash or CC air only were used and where both were used and to compare the values of the K_i with those obtained in two-dimensional wind-tunnel tests.

Experimental Equipment

Tests were carried out on a test rig fitted with a CCTB,[22] shown in Figs. 2 and 3. The rotor had five untwisted blades, a diameter of 3.0 m, and was driven by a variable speed electric motor. Collective pitch was set manually.

The CCTB was supported at its ends by load cells used to measure forces in directions normal and parallel to the rotor disk plane. The tail boom was restrained from moving axially by means of a double universal coupling, which allowed the forward end of the tail boom to move in a transverse direction without significant forces being imposed on the load cells.

The tail boom had an outer diameter of 0.229 m and two slots each with the same width,[22] which could be varied by spacers. The geometry of the slot outlets differed from those of the cylinder used in the wind-tunnel tests in that the upper lip had a thickness of 3 mm whereas those of the wind-tunnel model terminated in a sharp point. The width of the flap, shown in Fig. 3, was 40 mm.

Tests have been carried out on CCCs[19] and on CCTBs[26] in which the widths of the slots differed. For these tests, the widths of the slots were the same because the objective of the tests was not to optimize the performance, but to relate its performance to flow parameters and to compare the results with those obtained on a circular cylinder in a wind tunnel. In the two-dimensional tests, the widths of the two slots were also the same.

Air was fed to the tail boom from a fan located on the ground and was varied using a damper. The distance between the tail boom and rotor disk plane was variable. The airflow was measured using

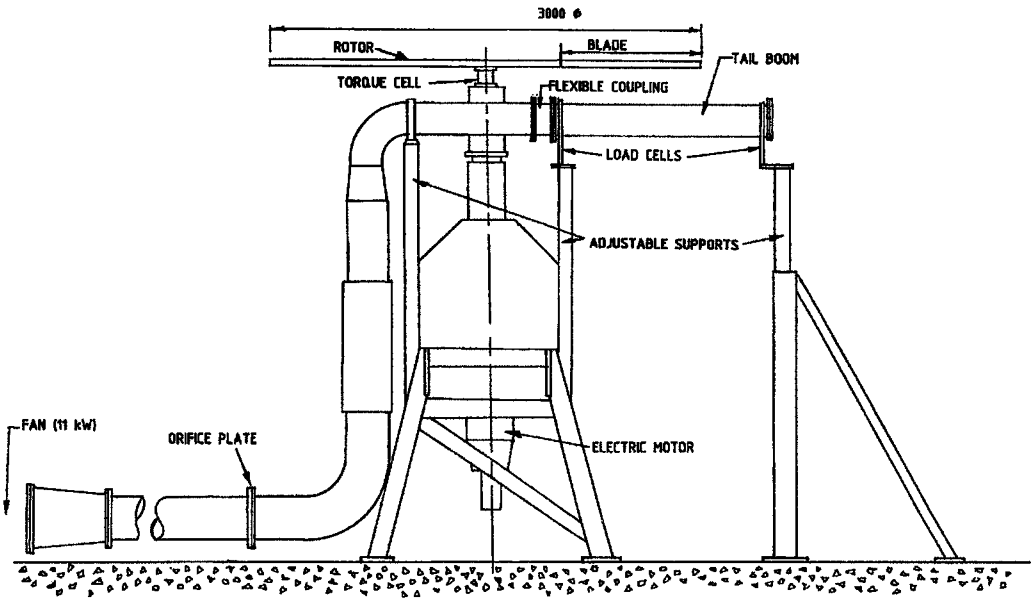

Fig. 2 General arrangement of rotor test rig.

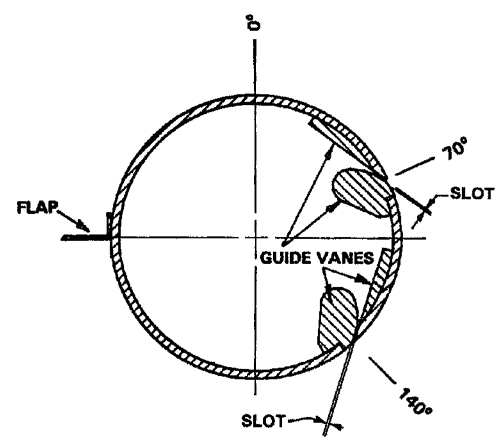

Fig. 3 Cross section of tail boom.

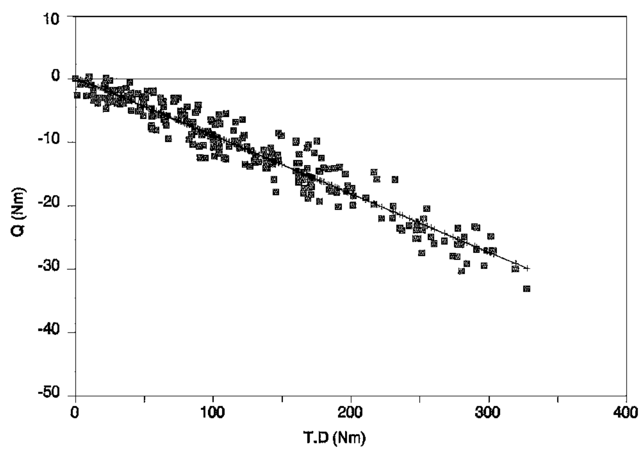

Fig. 4 Variation of tail boom torque with parameter TD_C (external flow only, no flap).

Table 1 Instrumentation details

Parameter	Transducer	Range	σ, %FS
Rotor speed	Tachometer	2000 Hz	0.25
Rotor thrust	Two load cells	5000 N	0.5
Rotor torque	Shaft torque cell	500 Nm	0.25
Boom pressure	Differential pressure transducer	5000 Pa	0.25
Boom torque	Four load cells	150 Nm	1.2

Table 2 Parameter range of tests to determine K_1

Parameter	Range
D, mm	229
θ_c, deg	10–20
H/R_o	0.286–0.498
T, N	0–1500

a calibrated orifice plate. Details of the instrumentation and their inaccuracies are given in Table 1.

All data were recorded on disc in engineering units, each data point being averaged from 10 readings taken over a period of 10 s.

Results and Discussion

K_1 was determined with the CC airflow zero and various downwash velocities and K_2 where the CC airflow was varied and zero downwash. All three constants were determined where both rotor downwash and the CC air were used simultaneously. Tests were carried out with and without the flap.

Torque due to Rotor Downwash Only

The torque with zero CC air is dependent on the direction in which the rotor downwash is deflected by surface conditions or irregularities on the tail boom. These irregularities comprised the two jet slots and the flap, when it was fitted. The parameter ranges of the tests are presented in Table 2.

The tests with the flap fitted were carried out with $H/R_o = 0.286$ only. Data obtained for that test are presented in Fig. 4 for the case of no flap and in Fig. 5 with the flap fitted to the tail boom. The constants are presented in Table 3, where they are compared with the two-dimensional[23] values.

The wake contraction k, given in Ref. 27, is a function of the thrust coefficient C_T. For the tests, C_T varied from 0.011 to 0.027, and the corresponding contraction ratios varied from 0.78 to 0.82, respectively. For the analysis, a mean value of $k = 0.8$ was used.

In the two-dimensional tests it was found that the lift varied with slot width whereas for the CCTB, K_1 was independent of the slot width. This could be attributed to the thickness of the lip on the jet slots of the CCTB and could also account for the larger values of K_1 obtained for CCTB without a flap compared to the wind-tunnel tests.

Table 3 Coefficients K_1 for downwash only

Tests	$K_1/4\pi k^2$	K_1	R	σ
Wind tunnel, maximum $T = 80$ N				
No flap, mm				
$t = 2$	——	−0.071	0.783	1.69 N
$t = 6$	——	−0.139	0.960	1.20 N
$t = 10$	——	−0.222	0.932	2.00 N
With flap, mm				
$t = 2$	——	0.734	0.9999	0.31 N
$t = 6$	——	0.618	0.9995	0.56 N
$t = 10$	——	0.446	0.998	0.81 N
Rotor tests				
No flap, mm				
$t = 3$	−0.0918	−0.739	0.967	2.09 Nm
With flap, mm				
$t = 2$	0.0605	0.487	0.990	1.10 Nm
$t = 4$	0.0600	0.483	0.994	0.90 Nm
$t = 8$	0.0600	0.483	0.994	0.90 Nm

Table 4 Parameter ranges for tests to determine the effect of slot length on K_2

Parameter	Range
L_2, mm	1190–1985
L_1, mm	585
P, Pa	500–3500
t, mm	3

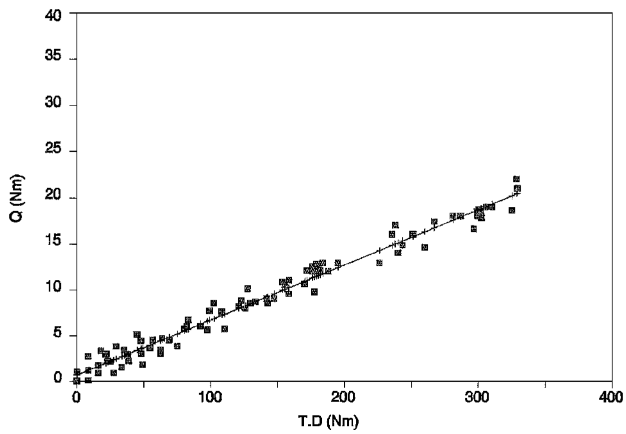

Fig. 5 Variation of tail boom torque with parameter TD_C (external flow only, with flap).

The data, shown in Figs. 4 and 5, indicate that irregularities on the surface of a cylinder will give rise to a lift force, and for a cylinder fitted with a flap, K_1 is similar to that obtained in wind-tunnel tests.[23]

It appears that the torque generated by the downwash only is adequately described by the first term on the RHS of Eq. (18).

Torque due to Circulation Control Air Only

Air leaving the slots adheres to the surface of the cylinder and flows around it leaving the surface at some angle that will be a function of the momentum decay and boundary-layer growth. The value of K_2 will depend on the direction of flow of the air when it leaves the surface of the cylinder. Because the cross-sectional area of the tail boom is large compared to the outlet area of the slots, it may be expected that the static pressure in the tail boom will not vary materially along the length of the tail boom, and hence, the velocity of the air leaving the slots should be virtually independent of the length of the boom, for lengths typical of helicopter tail booms.

Tests were carried out to determine whether K_2 is a function of the length of the tail boom and to demonstrate that K_2 is independent of the boom pressure and slot width. The parameter ranges of the tests are presented in Tables 4 and 5. The test for the effect of the variation of slot length on K_2, where $L_2 = 1190$–1985 mm, had the following results: $K_2 = 1.045$, $R = 0.961$, and $\sigma = 1.008$ Nm. Table 6 and Fig. 6 present test results for CC air only.

Table 5 Parameter ranges for tests to determine the effect of pressure and slot width on K_2

Parameter	Range
L_2, mm	1985
L_1, mm	585
P, Pa	500–3500
t, mm	2–8

Table 6 Coefficient K_2 for CC air only

Test	$K_2/2$	K_2	R	σ
Wind tunnel, maximum = 80 N				
No flap				
$t = 2$ mm	——	0.977	0.849	0.493 N
$t = 6$ mm	——	0.993	0.998	0.263 N
$t = 10$ mm	——	1.041	0.999	0.312 N
All	——	0.967	0.993	0.982 N
With flap				
$t = 2$ mm	——	1.205	0.985	0.324 N
$t = 6$ mm	——	1.139	0.997	0.287 N
$t = 10$ mm	——	1.030	0.998	0.307 N
All	——	1.016	0.977	1.286 N
Rotor tests				
No flap				
$t = 3$ mm	0.511	1.022	0.962	1.084 Nm
With flap				2.684 Nm
$t = 2$ mm	0.562	1.123	0.965	7.132 Nm
$t = 4$ mm	0.501	1.001	0.938	3.250 Nm
$t = 8$ mm	0.496	0.992	0.986	3.694 Nm
All	0.516	1.032	0.952	

Table 7 Tests for determination of K_1, K_2, and K_3 for the combined flows

Parameter	Range
D, mm	229
θ_c, deg	10–20
H/R_o	0.286–0.498
P, Pa	1500–4000
t, mm	2, 4, and 8
T, N	0–1500

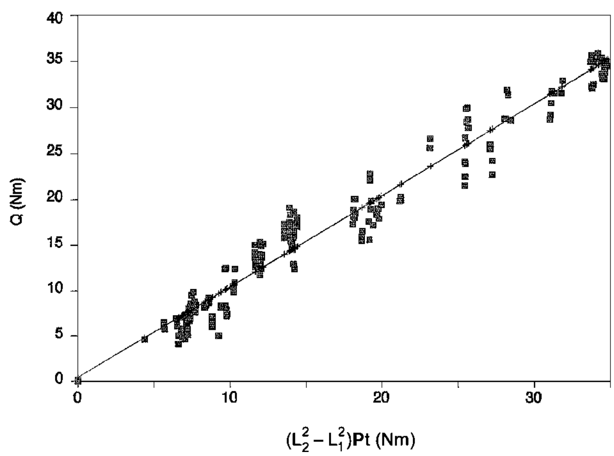

Fig. 6 Variation of tail boom torque with parameter $(L_2^2 - L_1^2)\,Pt$ (CC flow only, with a flap).

The data in Table 6 indicate that for zero downwash, K_2 is independent of the length of the slots, and from the data in Table 7 and Fig. 6, K_2 is independent of the boom pressure and slot width. The presence of a flap has no effect on the torque due to CC air only. The value of K_2 of approximately 1 agrees well with values predicted from a momentum balance across a suitable control volume if it is

Table 8 Values of K_1, K_2, and K_3 for combined flows

Test and analysis method	K_1	K_2	K_3	R	σ
Wind tunnel data					
a) N-K_1IW-K_2IW-K_3C	−0.139	0.967	0.628	0.895	17.7 N
b) N-$K_1$0-$K_2$0-K_3C	0.0	0.0	0.610	0.819	22.7 N
c) N-K_1MW-K_2MW-K_3MW	−0.314	3.555	0.577	0.961	11.0 N
d) F-K_1IW-K_2IW-K_3C	0.600	1.0	0.403	0.924	12.0 N
e) F-$K_1$0-$K_2$0-K_3C	0.0	0.0	0.770	0.540	26.3 N
f) F-K_1MW-K_2MW-K_3MW	0.771	3.215	0.200	0.988	4.8 N
Rotor rig data					
g) N-K_1IW-K_2IW-K_3C	−0.139	0.967	0.589	0.901	10.3 Nm
h) N-K_1IR-K_2IR-K_3C	−0.739	1.022	0.730	0.901	12.8 Nm
i) N-$K_1$0-$K_2$0-K_3C	0.000	0.000	0.715	0.948	7.6 Nm
j) N-K_1MW-K_2MW-K_3MW	−0.314	3.555	0.577	0.792	13.3 Nm
k) N-K_1MR-K_2MR-K_3MR	0.313	−0.128	0.648	0.952	7.4 Nm
l) F-K_1IW-K_2IW-K_3C	0.600	1.0	0.423	0.850	10.8 Nm
m) F-K_1IR-K_2IR-K_3C	0.483	1.032	0.449	0.854	11.2 Nm
n) F-$K_1$0-$K_2$0-K_3C	0.000	0.000	0.778	0.934	10.0 Nm
o) F-K_1MW-K_2MW-K_3MW	0.771	3.215	0.200	0.801	14.6 Nm
p) F-K_1MR-K_2MR-K_3MR	0.580	0.772	0.544	0.954	8.4 Nm

assumed that the flow leaves the tail boom at approximately 270 deg from its top or leading edge.

Thus, the torque generated for zero downwash is adequately described by the second term on the RHS of Eq. (18).

Torque due to the Combined Downwash and CC Air

The lift force will be normal to the downwash. Because of the effects of the rotor vortex field and torque acting on the rotor blades, the air in the wake has angular momentum and the downwash will not be parallel to the rotor shaft. This inclination is small and is ignored because the antitorque component of interest is parallel to the rotor disk plane.

The values of K_1 and K_2 obtained earlier were those for independent downwash and CC flows. Although the individual flow effects should exist when these flows are combined, it is likely that the values of K_1 and K_2 will be affected by flow interaction. It was found, using glass fiber strands, that the point at which the Coanda flow left the surface of the tail boom varied from approximately 180 deg from the first slot at the forward end of the tail boom to approximately 90 deg at the aft end. This angle decreased as the downwash velocity increased with increasing distance from the rotor shaft.

The parameter ranges of the tests are presented in Table 7. The data were analyzed to determine the extent to which the 1) tail boom torque is a function of flow asymmetries, CC momentum, and the lift augmentation due to induction of circulatory flow by the slot wall jet on the external flow, as given by Eq. (18); 2) constants K_1 and K_2 changed when the rotor downwash and CC air were combined; and 3) two-dimensional flowfield of a CC tail boom in the wake of a hovering rotor differs from that of a cylinder in a wind tunnel as defined by the constants K_1, K_2, and K_3.

The analyses were carried out by comparing the measured torque values Q_{meas} with the calculated torque values Q_{calc} determined using various combinations of the constants K_i, $i = 1$–3. The constants were determined using regression techniques. The results of the analyses are presented in Table 8 and Figs. 7–12.

In Table 8 N indicates no flap fitted to tail boom and F indicates flap fitted to tail boom. For $K_i jk$, $i =$ constant subscript (1, 2, or 3); $j = I$ indicates constant obtained when either downwash or CC used, $j = M$ constant obtained from multilinear regression, and $j = 0$ constant assumed to be zero; and $k = W$ indicates from wind-tunnel tests, $k = R$ from rotor rig tests, and $k = C$ constant calculated using regression technique. The results from analyses i–k (Table 8) for a tail boom without a flap are presented in Figs. 7–9, respectively. The results from analyses n–p for a tail boom with a flap are presented in Figs. 10–12, respectively.

Wind-Tunnel Tests

The wind-tunnel results are reproduced from Ref. 23. In addition, K_3 was determined for when K_2 and K_3 were put equal to zero (analyses b and e, Table 8).

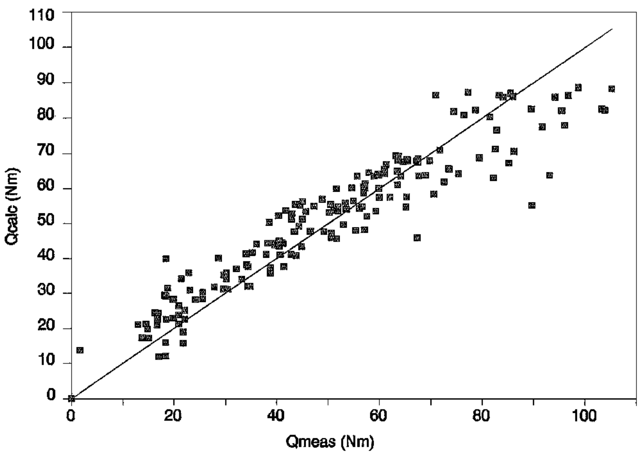

Fig. 7 Variation of the calculated torque with measured torque (K_1 = K_2 = 0, no flap).

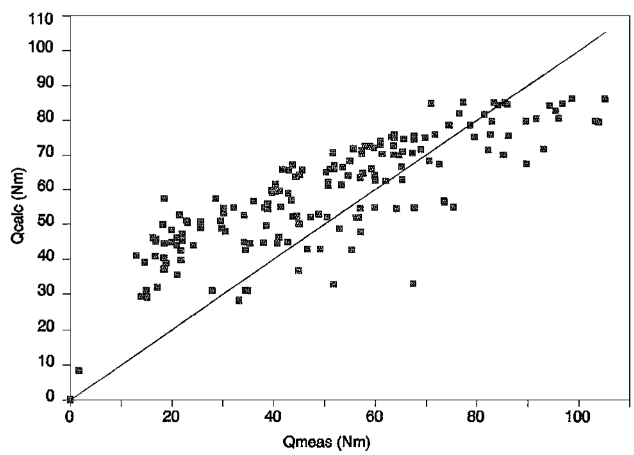

Fig. 8 Variation of the calculated torque with measured torque (K_1 and K_2 from wind-tunnel tests, no flap).

Comparison of analyses a and c from Table 8 shows that for a cylinder without a flap the downwash velocity and the CC air do interact as the constants K_1 and K_2 vary for the two tests, and the correlation obtained when all three constants are fitted to the data improves from 0.895 to 0.961. Comparison of analyses b and c indicates that the lift is a function of all three effects, and the lift due to flow distortion and CC momentum cannot be ignored.

The same trends obtain for a cylinder fitted with a flap. Comparison of analyses d and f show that K_1, K_2, and K_3 need to be altered to obtain good correlation between the calculated and measured lift

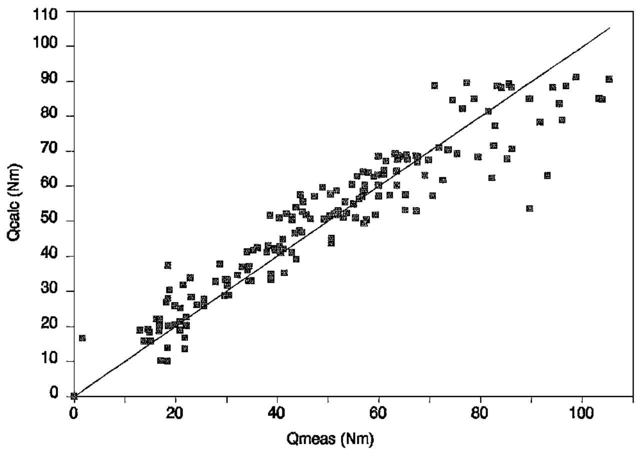

Fig. 9 Variation of the calculated torque with measured torque (K_1, K_2, and K_3 from regression analysis, no flap).

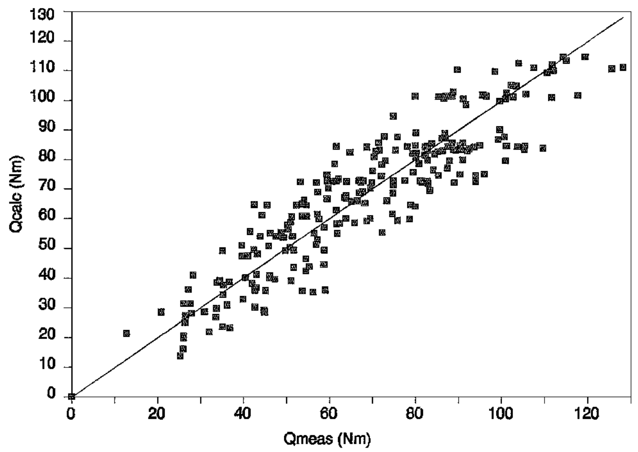

Fig. 10 Variation of the calculated torque with measured torque (K_1 = K_2 = 0, with flap).

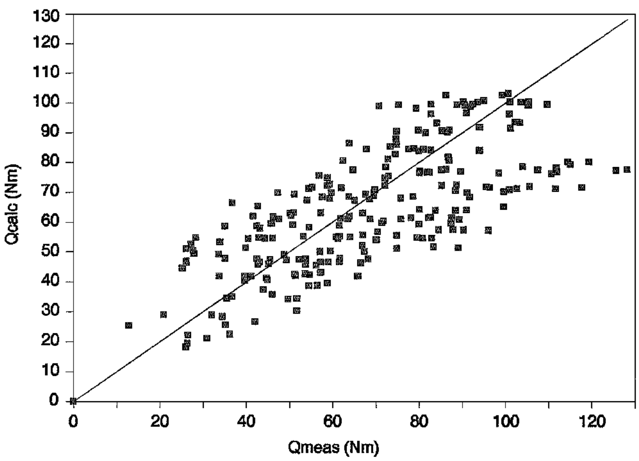

Fig. 11 Variation of the calculated torque with measured torque (K_1 and K_2 from wind-tunnel tests, with flap).

values, that is, the correlation coefficient increases from 0.924 to 0.988 when all three constants are fitted using a multilinear regression. Also, poor correlation is obtained between the calculated and measured lift when it is assumed that the lift is not dependent on the flow distortion and the momentum of the CC air.

Thus, for a CC cylinder in a wind tunnel, the data indicate that, with or without a flap, lift is a function of flow asymmetries and the momentum of the CC air, as well as the circulation augmentation of the CC, or slot jet, on the external flow. Consequently all three

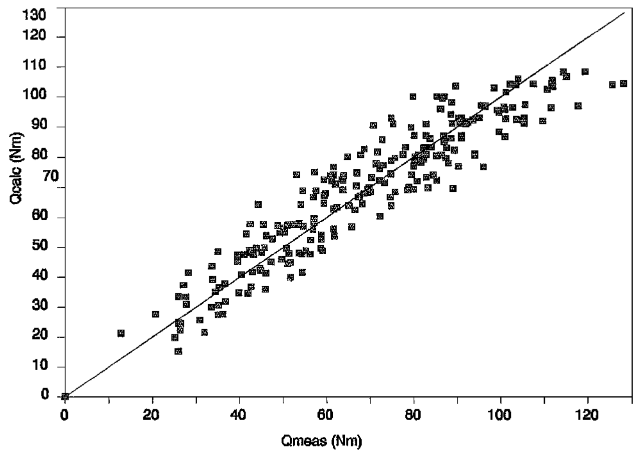

Fig. 12 Variation of the calculated torque with measured torque (K_1, K_2, and K_3 from regression analysis, with flap).

flow effects must be taken into account to predict adequately the lift acting on a CC cylinder in a wind tunnel.

Tail Boom with No Flap

Using the constants K_1 and K_2 obtained from the wind-tunnel tests, for flow asymmetry and momentum flows, and calculating K_3 (analysis g, Table 8) resulted in a correlation coefficient between the predicted and measured tail boom torque values of 0.901. Although the constants K_1 and K_2 obtained in the wind-tunnel tests differed from the equivalent values measured on the rotor rig (analysis h), the correlation coefficients were similar, that is, both are 0.901. When K_1 and K_2 were taken as zero (analysis i), that is, the torque on the tail boom is assumed to be independent of the flow asymmetry and momentum of the CC air, a correlation coefficient of 0.948 was obtained. From these results it appears that whereas the lift on a CC cylinder in a wind tunnel is dependent on the flow distortion and the momentum of the CC air, this is not the case for a CCTB with no flap in the wake of a hovering rotor.

Calculating the tail boom torque using the constants K_1, K_2, and K_3 obtained from the wind-tunnel tests by means of regression (analysis j) gave a correlation coefficient between the calculated and measured tail boom torques of 0.792. A regression on the rotor test rig data (analysis k), gave a correlation of 0.952. Comparing these two sets of data, that is, analyses j and k, indicates that the flowfields of a CC cylinder in a wind tunnel and the wake of a hovering rotor differ significantly. Using results obtained in a wind tunnel to predict the torque on a tail boom gives poor results. In the case of the rotor test rig, the torque components due to the flow distortion and the momentum of the CC air are small. This, combined with the similar correlation coefficients obtained for the cases where it is assumed that K_1 and K_2 are zero (analysis i) and the regression on the rotor test rig data (analysis k), that is, 0.948 and 0.952, respectively, indicates that the torque for a CCC in the wake of a hovering rotor is not, for the tail boom tested, a function of the circulation developed by the CC air and the rotor downwash, although these effects do exist. Rather the torque is due to the circulation augmentation of the slot wall jet and the external flow, that is, the third term on the RHS of Eq. (18).

From the available data it appears that the best prediction of torque for a tail boom with no flap, assuming that the torque is independent of the flow asymmetries and momentum of the CC air, is given by

$$Q/TD_c = 0.101(P/\nu)^{\frac{1}{2}} \tag{19}$$

with a correlation coefficient of 0.948.

Tail Boom with a Flap

For a cylinder with a flap similar coefficients K_1 and K_2 were obtained for the separate asymmetry and CC momentum flows (analyses l and m, Table 8) in the wind tunnel and rotor tests. As would be expected, the correlation coefficients between the calculated and measured tail boom torques for these two cases were similar, that is, 0.850 and 0.854, respectively, with the correlation for both being low.

Where it is assumed that the tail boom torque is independent of the flow asymmetry and momentum of the CC air (analysis n), a correlation coefficient of 0.934 was obtained, which is similar to that for the cylinder without a flap.

Calculating the tail boom torque using the constants K_1, K_2, and K_3 obtained from the wind-tunnel tests on a cylinder with a flap (analysis o) gave a correlation coefficient between the calculated and measured tail boom torques of 0.801. A regression of the rotor test rig data (analysis p) gave a correlation of 0.954. Comparing these two sets of data, that is, analyses o and p, indicates that the flowfields of a CCC in a wind tunnel and the wake of a hovering rotor differ significantly, with the prediction of tail boom torque using results obtained in a wind tunnel being poor. As was the case for the cylinder without a flap, similar correlation coefficients were obtained where it is assumed that K_1 and K_2 are zero (analysis n) and there is the regression on the rotor test rig data (analysis p), that is, 0.934 and 0.954, respectively. Although these comparisons for a tail boom, with and without a flap, are similar, the torque due to the flow asymmetry and momentum of the CC air is not small, and the torque due to these flows should be taken into account. However, as may be seen by comparing the values of K_1 and K_2 for the wind tunnel (analysis f) and the rotor rig (analysis p), the effects of the flow asymmetry and momentum of the CC air is reduced for the tail boom torque.

It appears from the results obtained on a CCC, with and without a flap, that the dependence of the torque on the flow asymmetry and momentum of the CC air is less than would be expected from wind-tunnel results. This could be attributed to some flow characteristic found in the wake of a hovering rotor such as nonsteady flows, the three dimensionality of the flow, and/or the trailing vortices.

The tail boom torque was correlated with the slot momentum coefficient for all of the tests, but the correlation was so poor that the results have not been presented.

From the available data it appears that the torque developed by a tail boom with a flap and the slot geometry given in Fig. 2 is given by

$$Q/TD_c = 0.0721 + 0.386\left(L_2^2 - L_1^2\right)(P/T)(t/D_c) + 0.0577(P/\nu)^{\frac{1}{2}} \tag{20}$$

with a correlation coefficient of 0.954.

Conclusions and Recommendations

1) The torque generated by a CCTB, about the rotor axis is, as is the lift on a CCC in a wind tunnel, composed of three components. These are due to asymmetric flow due to nonsymmetries on the surface of the tail boom, the momentum of the CC air and resulting momentum changes of the downwash, and lift augmentation due to induced circulatory flow by the slot wall jet on the external flow.

2) The external flow, or downwash associated with a helicopter rotor, tends to reduce the dependence of the torque on the flow asymmetry and momentum of the CC air, compared to that predicted from wind-tunnel tests on a CCC. A flap, as tested, tends to retain the dependence of the torque on flow asymmetry and CC momentum, but this dependence is less than that predicted by wind-tunnel tests.

3) The torque of a tail boom for a particular helicopter and tail boom with no flap is a function of the rotor thrust, tail boom pressure, and tail boom diameter. The torque is related essentially to the combined effects of circulation generated by the CC air and the rotor downwash.

4) The torque of a tail boom for a particular helicopter and tail boom with a flap is a function of the rotor thrust, tail boom pressure, tail boom diameter, and slot width.

5) For the range of tail boom geometries and operating conditions tested, the correlation between the tail boom torque and the slot momentum coefficient alone proved to be inadequate.

6) The variation of flow through the jets with boom length is minimal when the rotor downwash is zero. It would be expected, in terms of the structure of the static pressure field, that this would be approximately true when there is rotor downwash.

As a result of this study the following recommendations are made.

1) The research should be continued in a controlled environment to obtain greater clarity of the role played by the slot geometry.

2) The cause of the lack of dependence of the torque on flow asymmetry and momentum effects should be identified. This could possibly be achieved by pulsing the flow in a wind tunnel and/or introducing a vortex in the flow to simulate the trailing vortex from the main rotor blades.

3) There is no proof that a CCTB with a circular cross section is the optimum shape for a CCTB, and the performance of other cross sections should be investigated.

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