THE AERODYNAMIC PERFORMANCE MEASUREMENT OF COAXIAL ROTOR IN HOVER

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Abstract

- *To evaluate the performance of coaxial rotor in hover, the experimental test rig was designed and measurement of thrust, moment and hovering efficiency for the single and coaxial rotor was carried out. With the change of pitch angle, rotating speed, solidity, and stage spacing, the aerodynamic performance of the coaxial rotor was evaluated and compared to single rotor under similar working conditions. The performances of upper rotor and lower rotor were compared with single rotor. Under torque balanced state, the coaxial rotor achieves higher (FOM) figure of merit than the non-balanced state, the optimal pitch angle was obtained with maximum FOM 0.65.*

1 Introduction

The employment of rigid coaxial rotor in high speed compound helicopter helps to enhance the cruising speed significantly, such as X2 and S97 helicopter. The reverse rotation of the rotors aids to balance the torque and roll moment, increasing the flight efficiency by removal of tail rotor. However, compared to traditional coaxial rotors, rigid coaxial rotor is quite close to each other, resulting in a strong flow interaction between them. Particularly in hover, the lower rotor performance declines remarkably due to the downwash of the upper rotor. Vice versa, the performance of upper rotor is also influenced to a certain extent due to the lower rotor suction effect.

In order to investigate the performance of each rotor, to analyze the torque and thrust varying with pitch angle, rotating speed and stage distance, to evaluate the influence factors comparing to the single rotor, the hovering test rig was designed and measurement was carried out for the coaxial rotor.

A review of coaxial rotor research can be found in literature [1]. Generally, the hovering test rig of coaxial rotor can be divided into two types: (1) Two rotor sharing one axis is the most popular type, where meters for each rotor and driving system are located under the experimental rig. This type can be applied for forward flight test. It was accepted by Harrington [2], McCloud and Stroub [3], Nagashima [4], Felker [5], Lee[6], Zeng[7] and Cameron[8]. (2) The second type employs two separate axes to drive the rotors, both rotors and measurement devices are located symmetrically. It was adopted by McAlister [9], Schafroth [10], Bell[11] in their experiments. The second type is not suitable for forward flight test due to strut interference, but the construction is simple with lower cost. Compared to the complicated structure in first type, general motors and meters can be employed. Considering the second type is economical, it was accepted in the test rig of this paper.

This experiment was carried out for single and coaxial rotors separately. Then blade number of rotors, pitch angle, rotating speed and stage distance for the coaxial rotor were changed to measure the thrust, torque and figure of merit of each rotors. Torque coefficient, thrust coefficient and figure of merit are given in equations (1-3).

$$C_Q = \frac{Q}{\rho \pi R^3 (\Omega R)^2} \quad (1)$$

$$C_T = \frac{T}{\rho \pi R^2 (\Omega R)^2} \quad (2)$$

$$FOM = \frac{C_{Tco}^{3/2}}{\sqrt{2} C_{Qco}} \quad (3)$$

The subscript $_{co}$ represents coaxial rotor. The performance of coaxial rotor was calculated by equations (4) and (5). Because the upper and the lower rotor rotate in opposite direction, their torque Q are either positive or negative, the symbol are only considered in the torque balance calculation. In other calculation, the absolute torque value are applied to consider the power consumed by the coaxial rotors, the thrust and torque coefficients are composed of both rotors, see equations (4) and (5).

$$C_{T_{co}} = C_{T_{upp}} + C_{T_{low}} \quad (4)$$

$$C_{Q_{co}} = C_{Q_{upp}} + C_{Q_{low}} \quad (5)$$

The solidity of a coaxial rotor is defined in equation (6), where n is the number of blades.

$$\sigma = \frac{nc}{\pi r} \quad (6)$$

2 Description of the Experiment

The test rig is shown in Fig. 1. The height of the axis is 1.42m from the floor. Two 3kW variable-frequency motors drove rotor via the torque meters. The four bar linkages were fixed under the motors connected with the tension sensors to measure thrust. The pitch angle of the rotor was measured by digital angle meter. The parameter of the test is shown in table 1.

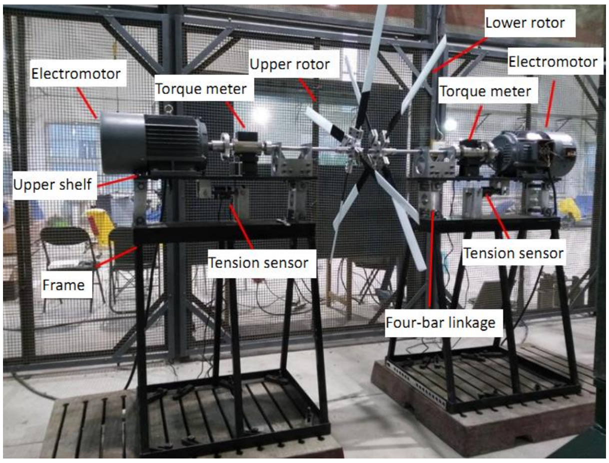

Fig. 1. Test rig for coaxial rotor

Table 1. Rotor Parameters

Parameter	**Coaxial**	**Single**
Number of blades	4	2/4
σ	0.20298	0.050740.10149
Stage distance H/D		0.1374, 0.1676, 0.1964
Diameter (m)	1.4	
Airfoil section	NACA0015	
Chord (m)	0.055	
Ω (RPM)	900, 1100, 1300, 1500	
V_{tip} (m/s)	66, 81, 95, 110	
Pitch angle (°)	6, 9, 12, 15, 18	
Weight, g/blade	285	

The blade is formed by glass fiber composite material in rectangle shape without twist. The pitch angle was adjusted statically, by a digital inclinometer with resolution 0.1°. The measurement range for the torque meter is 20NM. The accuracy of each meter is given in table 2.

Table 2. The measurement range and accuracy of the meters

Tension sensor	Pitch angle	Torque
0.05%	0.1°	0.5%

During the test, the atmosphere temperature and pressure were 23°C and 101.9kPa, and the air humidity was 99%. For each working condition, once pitch angle and stage distance were fixed, thrust, rotating speed, moment were collected three times. The average value was used in the process. The Reynolds numbers at the 3/4 span location of the rotor are 3.49×10^5 , 4.27×10^5, 5.04×10^5 and 5.82×10^5 respectively.

3 Aerodynamic Performance Measurement of Single Rotors

3.1 Single Rotor with Two Blades

In the single rotor measurement, the lower rotor test rig was removed. Two blades and four blades were fixed on the upper rotor separately to evaluate the solidity influence on the rotor. The performance of single rotor is plotted in Fig. 2.

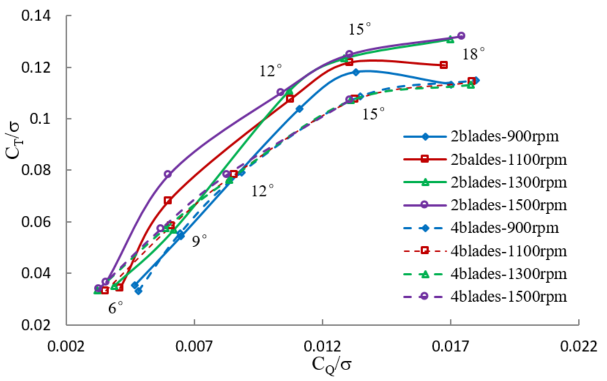

Fig. 2. The C_T/σ-C_Q/σ curve for single rotor

It shows that both C_T/σ and C_Q/σ increase with pitch angle. At pitch angle 15°, the curves of 2 blades turns to the horizontal direction.

Fig. 3 shows the FOM varying with C_T/σ.

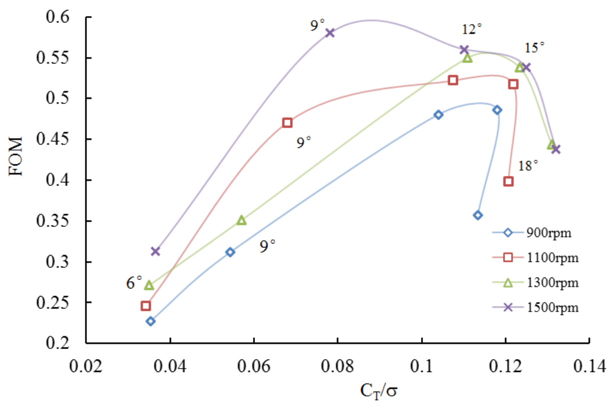

Fig. 3. The FOM-C_T/σ curve for single rotor with 2 blades

At the same rotating speed, there is an optimal pitch angle to obtain the maximum FOM. The optimal pitch angle is 12° for most cases. At same pitch angle, figure of merit increases with rotating speed in most cases. The maximum FOM is 0.58 at 1500rpm when pitch angle is 9°.

3.2 Single Rotor with Four Blades

The C_T/σ and C_Q/σ curve of four blades rotor is also given in Fig.2. The FOM performance of 4 blades is shown in Fig. 4.

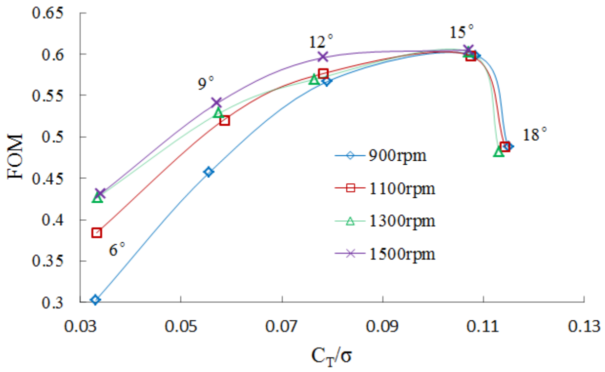

Fig. 4. The FOM-C_T/σ curve for single rotor with 4 blades

Compared to Fig. 3, the FOM of 4 blades is higher than 2 blades under the same rotating speed and pitch angle. Fig. 2 shows that the rotating speed influence on the performance of four blades can be ignored. Fig. 4 shows that the optimal pitch angle for the 4 blades is 15°, the maximum FOM is 0.605, higher than that of the 2 blades (0.58).

4 Aerodynamic Performance Measurement of Coaxial Rotors under Unbalanced Torque

In the measurement of coaxial rotors, four rotor blades were applied. The experimental were conducted in two conditions. Torque of the rotor are balanced and unbalanced.

In real flight, the torque on coaxial rotor is zero to achieve zero pitching moment on the helicopter. In the experiment, dynamic pitch angle adjustment devices are often used to control the torque balance. In view of the static pitch angle adjustment in this experiment, it is laborious and difficult to adjust the zero torque. Actually the identical pitch angle situation is quite close to zero torque condition, as proposed by literature [1, 4, 7], the pitch angle difference between the upper rotor and lower rotor is no more than 1° in torque balanced situation. Therefore, the identical pitch angle was applied in the unbalanced condition. When the revolution was 1300 rpm, the torque on the coaxial rotor was approaching to the measuring range (20NM), so the 1500rpm rotating speed test were canceled.

4.1 Pitch Angle Influence

The pitch angles of the upper and lower rotors were selected according to table 1. In the experiment, the upper and lower rotor rotating speeds were the same.

Considering the tested rotating speed has small influence on the rotor performance in section 3.2, and the best performance of the 4 blades single rotor were achieved when rotating speed is 1300rpm, the data for coaxial rotor at rotating speed 1300 were presented. The performance of each rotor is shown in Fig. 5.

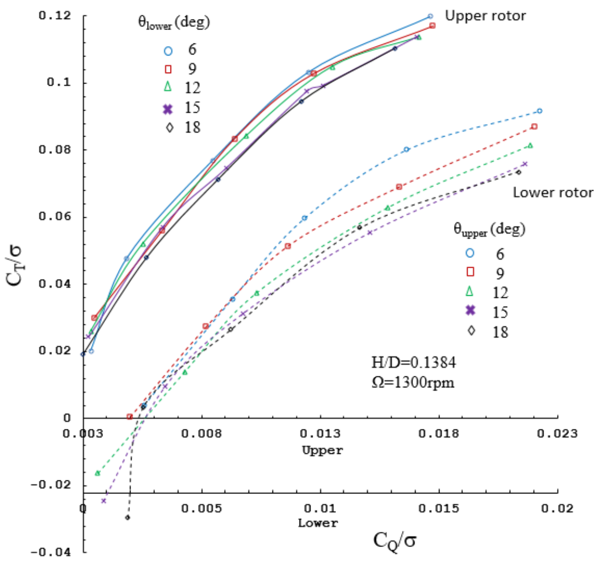

Fig. 5. The C_T/σ-C_Q/σ curve for upper and lower rotors

Fig. 5 shows that the upper rotor has a better performance than the lower rotor. Once the pitch angle of the opposite rotor is fixed, the C_T/σ and C_Q/σ of the other rotor are increased with its own pitch angle. When the pitch angle of the lower rotor is fixed, the change of C_T/σ and C_Q/σ with upper rotor pitch angle is small. While when the pitch angle of upper rotor is fixed, the change of C_T/σ and C_Q/σ with lower rotor pitch angle is big. The figure for both rotors are close to the pattern in literature [1], where the coaxial rotor were measured without torque balance.

To demonstrate the figure of merit for coaxial rotor, Fig.6 shows the FOM varying with C_T/σ. The curve fitting for each rotating speed were applied. Fig. 6 shows that an optimal C_T/σ is related to the maximum FOM for each rotating speed. The maximum FOM is 0.786 from the test point, with pitch angle (15°, 6°). The value is greater than the optimal FOM 0.605 for the single 4 blades rotor. If we focus on the tested point on the fitted curve, the optimal pitch is (12°, 12°).

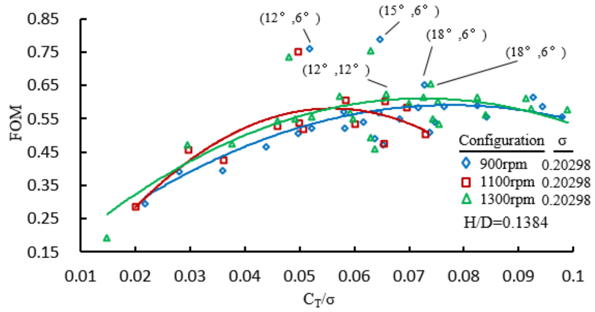

Fig. 6. The FOM-C_T/σ curve for coaxial rotor

Based on the conclusion that the single four blades rotor achieved the optimal FOM under pitch angle 15° in section 3.2, Fig. 7 shows the C_T/σ-Ω performance of upper and lower rotor varying with lower rotor pitch angle, while the upper rotor pitch angle was 15°.

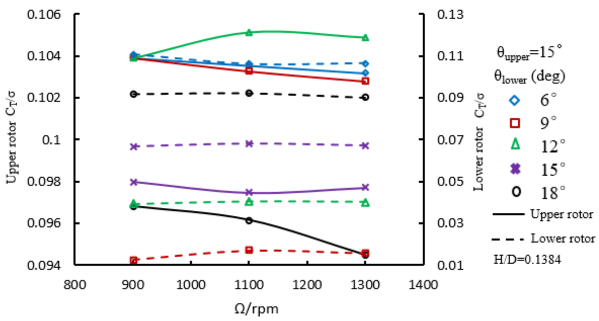

Fig. 7. The C_T/σ-Ω curve for coaxial rotor

Fig. 7 shows that under same rotating speed, the change of upper and lower rotor C_T/σ with lower pitch angle is complicated. Rotating speed has a significant influence on the thrust coefficient of upper rotor, but an ignorable influence on that of the lower rotor.

Similarly, Fig.8 shows the C_Q/σ-Ω performance of upper and lower rotor varying with lower rotor pitch angle, while the upper rotor pitch angle was 15°.

Fig. 8 shows that under same rotating speed, the increase in lower pitch angle results in a complicated change of upper rotor C_Q/σ and a monotone increase of lower rotor C_Q/σ. The rotating speed has a significant influence on the upper rotor torque coefficient while ignorable influence that of the lower rotor.

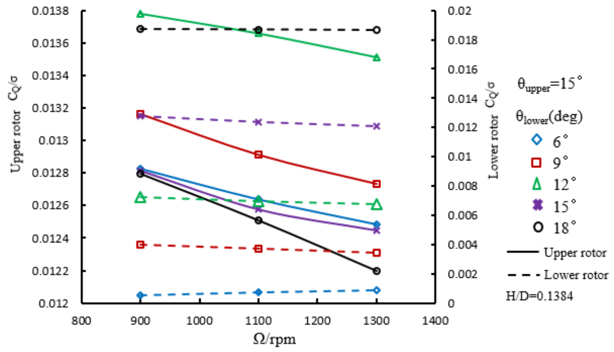

Fig. 8. The C_Q/σ-Ω curve for coaxial rotor

The performance comparison of coaxial rotor with 4 blades single rotor is shown in Fig. 9, taking the identical pitch angle for the coaxial rotor.

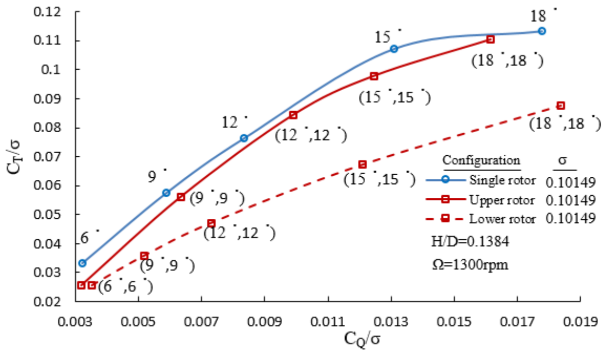

Fig. 9. The C_T/σ- C_Q/σ curve for single and coaxial rotor

It is obviously that single rotor achieves the best performance, then the upper rotor is better than the lower rotor. The performance of the upper rotor is close to the single rotor. The performance decline of the lower rotor is due to the downstream of the upper rotor, resulting in decline of effective angle of attack.

The performance decline of the upper rotor from single rotor is due to the suction effect of the lower rotor, leading to a small decline of effective angle of attack. The interaction from the upper rotor to the lower is strong than the interaction from the lower to the upper. The phenomenon was explained in literature [12].

4.2 Stage Distance Influence

The stage distance influence on the FOM is plotted on Fig. 11. It shows that in the tested stage distance, the performances of the coaxial rotor are nearly identical. This conclusion is different to the general accepted rule, i.e. FOM of the coaxial rotor increases when stage distance decreases. This is because the layout of the test rig differs with the literature [1], the frame of the upper and lower rotor has an obstruct effect when space distance decreases.

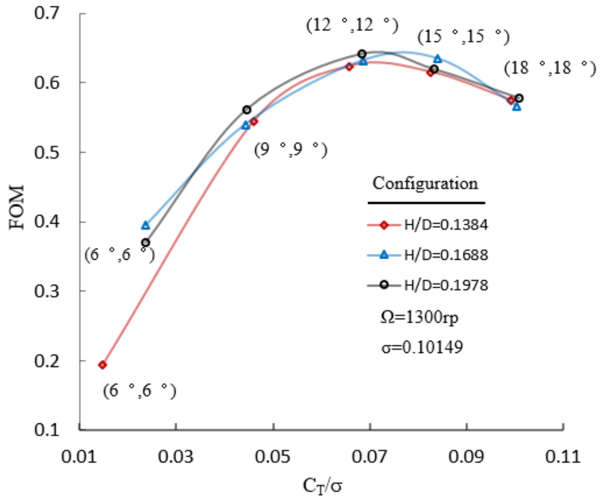

Fig. 10. The FOM- C_T/σ curve for and coaxial rotor under various stage distance

To investigate stage distance influence on each rotor performance, results are compared with whole axial rotor performance under rotating speed 1300rpm.

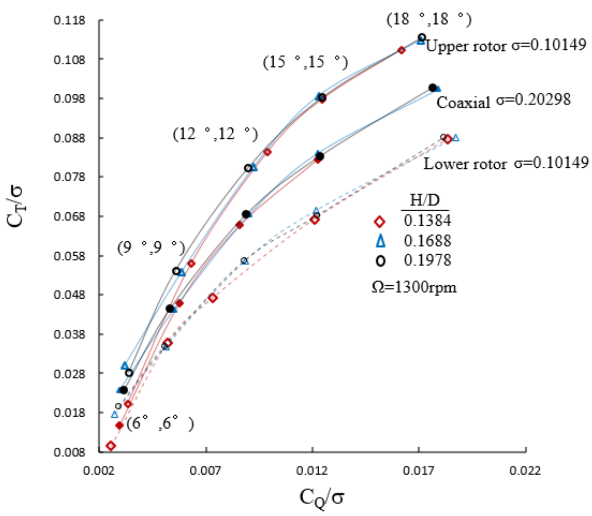

Fig. 11. The C_T/σ- C_Q/σ curve under various stage distance

Fig. 11 shows that the performance of coaxial rotor is nearly independent on the stage distance. The increases of distance improves the upper rotor performance in pitch angle range 6°~12°. When the pitch angle is greater than 12°, the upper rotor performance is independent to stage distance. The pitch angle influence of lower rotor is small, resulting in the total performance nearly unchanged.

5 Aerodynamic Performance Measurement of Coaxial Rotor under Balanced Torque

Further attempts were applied to obtain the torque balanced situation. A group of pitch angle were tested to approach the zero torque, shown in tables 3~5 under stage distance H/D=0.1196. Subscript $_{-b}$ represents balanced result. The upper rotor pitch angle was fixed, the lower rotor angle was adjusted. According to Cameron's proposal [8], even in the dynamic pitch adjust situation, it is quite difficult to achieve zero torque because the torque are very sensitive to pitch angle. So the linear interpolation method was used in this paper to obtain the pitch angle for the lower rotor and to predict the performance of the rotors. The balanced pitch angle and performance result of each rotor are shown in tables 6~8.

Table. 3. Pitch angle test at 900rpm

θ_{upper}(°)	$C_{T\ upper}$	$C_{Q\ upper}$	θ_{lower}(°)	$C_{T\ lower}$	$C_{Q\ lower}$	$C_{Q\ co}$	$\theta_{lower\text{-}b}$(°)
6	0.00280	0.000406	6	0.00216	0.000295	0.000111	7.1
	0.00288	0.000413	7	0.00252	0.000405	0.00000874	
9	0.00515	0.000607	9	0.00347	0.000578	0.0000295	9.3
	0.00539	0.000649	10	0.00479	0.000710	-0.0000614	
12	0.00831	0.00100	12	0.00551	0.000927	0.0000756	12.2
	0.00803	0.000932	12.5	0.00667	0.00104	-0.000108	
15	0.0101	0.00139	15	0.00779	0.00132	0.0000668	15
18	0.0117	0.00168	17	0.00899	0.00166	0.0000219	18.1
	0.0117	0.00190	18	0.00975	0.00189	0.00000118	

Table. 4. Pitch angle test at 1100rpm

θ_{upper}(°)	$C_{T\ upper}$	$C_{Q\ upper}$	θ_{lower}(°)	$C_{T\ lower}$	$C_{Q\ lower}$	$C_{Q\ co}$	$\theta_{lower\text{-}b}$(°)
6	0.00278	0.000365	6	0.00243	0.000278	0.0000870	6.5
	0.00278	0.000323	7	0.00265	0.000398	-0.0000749	
9	0.00503	0.000558	9	0.00356	0.000561	-0.00000356	8.96
	0.00570	0.000596	10	0.00497	0.000699	-0.000104	
12	0.00818	0.000955	12	0.00556	0.000919	0.0000356	12.1
	0.00786	0.000901	12.5	0.00671	0.00102	-0.000123	
15	0.0103	0.00137	15	0.00790	0.00134	0.0000344	15
18	0.0115	0.00166	17	0.00906	0.00167	-0.00000791	16.9
	0.0116	0.00188	18	0.00971	0.00194	-0.0000637	

Table. 5. Pitch angle test at 1300rpm

θ_{upper}(°)	$C_{T\ upper}$	$C_{Q\ upper}$	θ_{lower}(°)	$C_{T\ lower}$	$C_{Q\ lower}$	$C_{Q\ co}$	$\theta_{lower\text{-}b}$(°)
6	0.00205	0.000339	6	0.00258	0.000260	0.0000787	6.6
	0.00268	0.000317	7	0.00289	0.000378	-0.0000614	
9	0.00503	0.000531	9	0.00389	0.000553	-0.0000229	8.8
	0.00569	0.000565	10	0.00515	0.000705	-0.000140	
12	0.00798	0.000910	12	0.00576	0.000917	-0.00000736	11.9
	0.00779	0.000959	12.5	0.00678	0.001003	-0.0000450	
15	0.0101	0.00133	15	0.00789	0.00133	0.00000595	15
18	0.0115	0.00164	17	0.00909	0.00165	-0.0000116	16.7
	0.0116	0.00188	18	0.00975	0.00193	-0.0000510	

Table. 6. Results of balanced torque at 900rpm

θ_{upper}(°)	$C_{T\ upper\text{-}b}$	$C_{Q\ upper\text{-}b}$	$\theta_{lower\text{-}b}$(°)	$C_{T\ lower\text{-}b}$	$C_{Q\ lower\text{-}b}$	$C_{T\ co\text{-}b}$	$C_{T\ upper\text{-}b}/C_{Tco\text{-}b}$	FOM
6	0.00288	0.000414	7.1	0.00255	0.000414	0.005429	0.531	0.342
9	0.00523	0.000621	9.3	0.00390	0.000621	0.009132	0.572	0.497
12	0.00819	0.000974	12.2	0.00599	0.000974	0.014182	0.578	0.613
15	0.01006	0.00139	15	0.00779	0.00139	0.017854	0.563	0.6215
18	0.01174	0.00191	18.1	0.00979	0.00191	0.021532	0.545	0.5838

Table. 7. Results of balanced torque at 1100rpm

θ_{upper}(°)	$C_{T\ upper\text{-}b}$	$C_{Q\ upper\text{-}b}$	$\theta_{lower\text{-}b}$(°)	$C_{T\ lower\text{-}b}$	$C_{Q\ lower\text{-}b}$	$C_{T\ co\text{-}b}$	$C_{T\ upper\text{-}b}/C_{Tco\text{-}b}$	FOM
6	0.00278	0.000343	6.5	0.00255	0.000343	0.00533	0.522	0.401
9	0.00500	0.000557	8.96	0.00351	0.000556	0.00851	0.588	0.499
12	0.00811	0.000942	12.1	0.00582	0.000942	0.0139	0.582	0.617
15	0.01027	0.00134	15	0.00790	0.00134	0.0182	0.565	0.638
18	0.01148	0.00163	16.9	0.00897	0.00163	0.0205	0.561	0.634

Table. 8. Results of balanced torque at 1300rpm

θ_{upper}(°)	$C_{T\ upper\text{-}b}$	$C_{Q\ upper\text{-}b}$	$\theta_{lower\text{-}b}$(°)	$C_{T\ lower\text{-}b}$	$C_{Q\ lower\text{-}b}$	$C_{T\ co\text{-}b}$	$C_{T\ upper\text{-}}/C_{T\ co\text{-}b}$	FOM
6	0.0024	0.000326	6.6	0.00276	0.000326	0.00516	0.584	0.401
9	0.0049	0.000523	8.8	0.00364	0.000524	0.00855	0.574	0.533
12	0.008	0.000900	11.9	0.00556	0.0009003	0.0136	0.590	0.622
15	0.0101	0.00133	15	0.00789	0.00133	0.0180	0.561	0.640
18	0.0115	0.00157	16.7	0.00891	0.00157	0.0204	0.563	0.655

Data in tables 6 and 7 shows that when the torque is balanced, at speed 900rpm and 1100rpm, the pitch angle of the lower rotor is approximately less than 1° greater than that of the upper rotor. This agrees with the proposal in literature [1, 8]. However at speed 1300rpm, table 8 shows that at torque balance situation, the pitch angle of the lower rotor is approximately 1° less than that of the upper rotor. This is the new discovery never proposed by literature.

Tables 6~8 demonstrate that the upper rotor undertook 52.2%~59.0% thrust of the coaxial rotor. It is very close to the conclusion in literature [13] that upper rotor undertook more than 55% thrust of the coaxial rotor.

The comparison of FOM-C_T/σ curve for torque balanced and unbalanced situation is shown in Fig. 12, corresponding C_T/σ-C_Q/σ curve are plotted in Fig. 13.

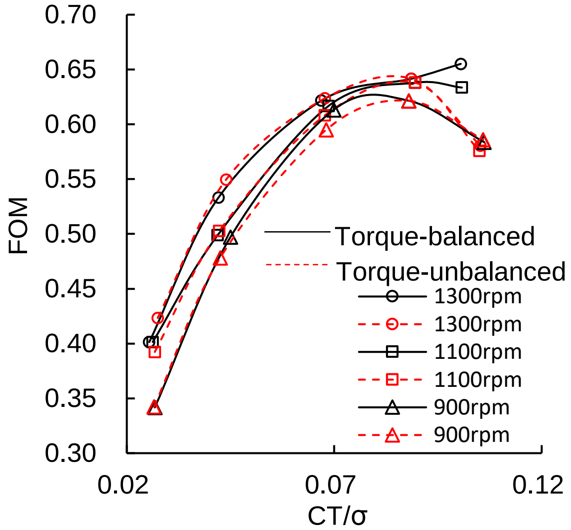

Fig. 12. The FOM-C_T/σ curve for torque balanced and non-balanced conditions

Fig. 12 shows that balance improves the maximum FOM under rotating speed 1300rpm. Under other two rotating speeds, although the maximum FOM is unchanged after balance, the FOMs at other points are improved. The optimal pitch angle is (15°,15°) for rotating speed 900rpm and 1100rpm for both balance and unbalance situation, corresponding maximum FOM are 0.6215 and 0.638. The optimal pitch angle is (18°, 16.7°) for rotating speed 1300rpm under balance situation, the maximum FOM is 0.655. Under unbalanced situation at speed 1300rpm, the maximum FOM is 0.65 at (12°, 12°).

Fig. 13 shows the performance comparison after the balance.

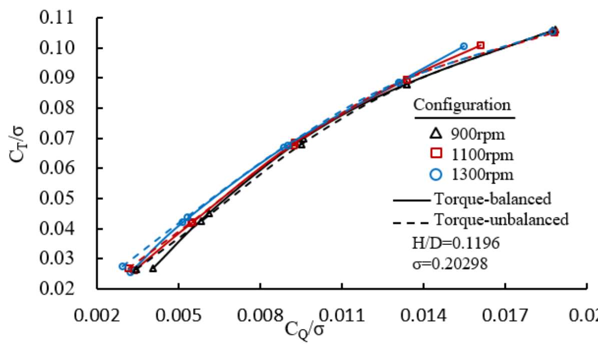

Fig. 13. The C_T/σ-C_Q/σ curve for torque balanced and non-balanced conditions

Fig. 13 shows that when pitch angle is less than 15°, the performance difference between the balanced and unbalanced situation is small. When the angle is greater than 15°, the balanced curves move to the top-left direction of the unbalanced curves, displaying the enhanced performance.

6 Conclusions

The aerodynamic performance measurement of coaxial rotor in hover was conducted. Influence of pitch angle, stage distance, rotating speed, solidity, torque balanced and non-balanced on the rotor thrust, torque and FOM are analyzed.

(1) The optimal FOM for the 4 blade single rotor is 0.605 at 15° under rotating speed 1500rpm. The optimal FOM for 2 blade single rotor is 0.58 at 9° under rotating speed 1500rpm.

(2) The experimental results show that the hovering efficiency of coaxial rotor is higher than that of the single rotor. The optimal FOM of the coaxial rotor is 0.655 at (18°, 16.7°) under torque balanced situation, and 0.65 at (12°, 12°) under unbalanced situation at rotating speed 1300rpm.

(3) Pitch angle is the most sensitive factor for the rotor performance. Rotating speed and stage distance play a small influence on the rotor performance.

(4) In the torque balanced situation, the pitch angle difference between the upper rotor and lower rotor is about 1°, and the performance of the upper rotor is better than the lower. Upper rotor undertook 52.2%~59.0% thrust of the coaxial rotor in torque balanced situation.

Acknowledgments

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