EXPERIMENTAL STUDY OF ROTOR AND SHIP INTERFERENCE IN THE ABSENCE OF AMBIENT WIND

YANG Jiong[1], MA Shuai[2], WU Jie[2], WANG Chang[2], YUE Tingrui[2], LIU Qinglin[2]

(1.China Aerodynamics Research & Development Center, Mianyang, Sichuan,621000, China；

2. China Aerodynamics Research & Development Center, Low Speed Aerodynamics Institute, Mianyang, Sichuan,621000, China)

Abstract: The experimental study and numerical simulation are carried out in this paper which aims at the interaction characteristics of rotor aerodynamic performance under the influence of ship in hovering. Firstly, the position of recirculation region caused by the blocking of the deck rear edge changes obviously when the rotor closes to the deck. The thrust coefficient firstly decreases and then increases, while the pitching moment doesn't change very noticeable. Secondly, the influence of the trailing edge deck can be ignored and the ground effect plays a dominant role when the rotor disc begins to enter the area above the deck. The ground effect significantly enhances with increasing of the projection area of rotor disc on the deck. Finally, the ground effect remains unchanged and the aerodynamic interaction of rotor and the hangar door plays the leading role when the rotor closes to the hangar door. The recirculation region caused by the blocking of hangar door is close to the rotor disk and results in the inflow increase of the rotor disc. The thrust drops sharply and the nose-down pitching moment is increased obviously. The influence of hangar door in two different states is also studied in this paper for the purpose of revealing the flow mechanism of the effect of the hangar door on rotor performance and seeking the effective methods to solve the problem of rotor load mutation.

Key words: Ship-borne helicopter; Flight deck; Hover; Ground effect; Rotor/ship interference; Hangar door

INTRODUCTION

Helicopter shipboard operation is a very dangerous and challenging mission for a pilot. Due to the combination of the significant spatial changes in "time-averaged" aerodynamic loading and temporal aerodynamic loading during the launch and recovery of a shipborne helicopter, the pilot's workload can be very high.

There are two means that be mainly adopted to ensure shipborne helicopter safety: (1) Safe launch and recovery envelope are prescribed for specific aircraft types on different ship classes. Every ship-helicopter combination has its own ship-helicopter operating limits (SHOLS) diagram. (2) Autonomous shipboard operation systems are aimed to improve the performance of helicopter shipboard operations.

A good understanding of the aerodynamic loading characteristics of rotor and the fluid dynamics mechanisms during the launch and recovery of a ship-borne helicopter is fundamental for SHOLS analysis and control law design. Although the flow structures of air passing over the ship's superstructure and landing deck and the consequent unsteady rotor airloads have been widely studied for various atmospheric wind speed and ship's forward speed [1-4], less work solves the interference between helicopter rotor and ship itself without atmospheric wind and ship's movement.

The problem of Interference between helicopter rotor and ship in absence of outer wind involves two distinct fields.1. Recirculation of the wake between the rotor and deck edge or hangar door causing an additionally severe thrust loss of the rotor [5]. 2. Partial ground effect results from a helicopter rotor partially hovering above a ship deck [6]. Despite considerable research has been conducted independently in the two disciplines mentioned above, it still lacks systematic investigation concerning the mechanisms of the aerodynamic interference between rotor and such specific geometry as combination of deck and hangar.

There is another interesting question that needs to be investigated: Since the recirculation between the rotor and hangar door leads a considerable thrust loss of the rotor, does the recirculation can be eliminated or mitigated by opening the hangar door?

Therefore, the main objectives of this experimental research are to: (1) measure and analyze how the

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

aerodynamic performance of helicopter rotor changes during stern approach and landing; (2) examine the overall flow topology of rotor wake as it interacts with hangar door; (3) verify the influence of hangar door open and closed on helicopter rotor aerodynamic performance.

1. EXPERIMENT

Experiments are carried out in a test hall at CARDC. The experimental setup is presented in Fig.1, showing a rotor mounted above ship center line. A simplified ship model that is comprised of hangar and deck is used for the experiments, shown in Fig.2, and the hangar door can be half and full open. A four-bladed rotor model is used under nominal rotation speed of 1500 rpm, and it was suspended from a crane span structure, the height of hub can be adjusted by traverse adjustment. In order to measure the thrust, torque, pitching and rolling moments, a six-component balance was installed on the bottom of model rotor.

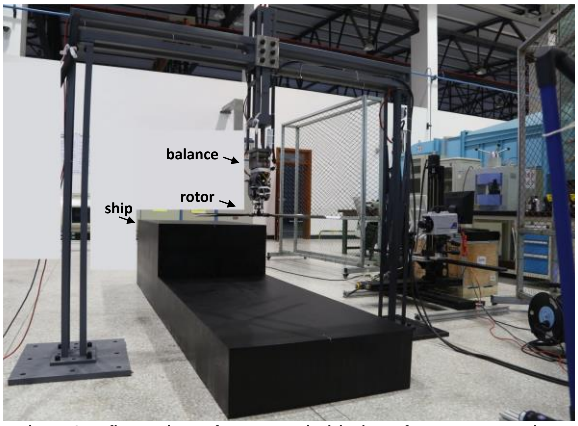


Fig.1 Configuration of rotor and ship interference experiment

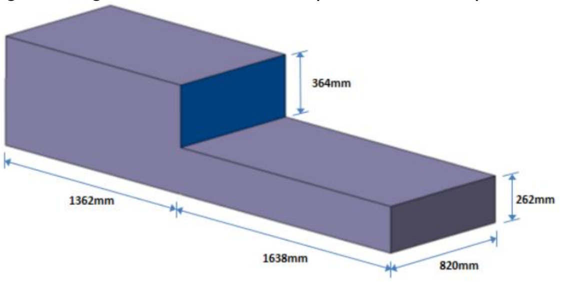


Fig.2. Specifications of ship model

The rotor consists of four untwisted, untampered, uniform blades, 0.98m in radius and 0.056m in chord. It was operated at a rotational frequency of 25 Hz (1500 rpm), yielding a tip Mach number and chord Reynolds number of 0.22 and 2.9×10^5 respectively. Collective pitch angle was set to 10 deg.

The experiment mainly includes load measurement and PIV measurement. The load measurement is to make use of six component balance to acquire the forces or moments of rotor. The PIV measurement is to acquire flow structure and characteristics in the flowfield of interested.

1.1. Definition of axis

Two sets of axis defined as ship body axis and rotor axis respectively are shown in Fig.3.

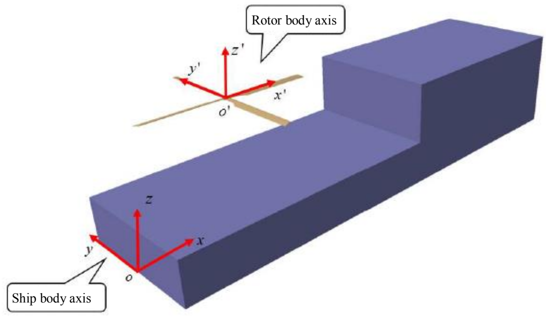


Fig.3 Definition of two sets of axis

The definition of the ship body axis is mainly for the sake of distinct position relation between rotor and ship. The ship body axis original O is located in the symmetry center of stern, with x-axis to point to ship's bow, z-axis to direction upward, y-axis to be decided by the right hand rule.

The definition of the rotor body axis is mainly for the sake of the description of rotor. The rotor body axis original O is located in the center of hub, and the axis direction definitions are the same with the ship body axis.

1.2. Experiment matrix

The rotor performance test matrix consists of a set of different positions of rotor with respect to the ship, and these conditions are equivalent to the process of a shipborne helicopter stern approach and landing (the measurement points are summarized in Table.1, and illustrated in Fig.4). The red dot represents the position of rotor hub center. Table 1 gives the experiment matrix of hub center.

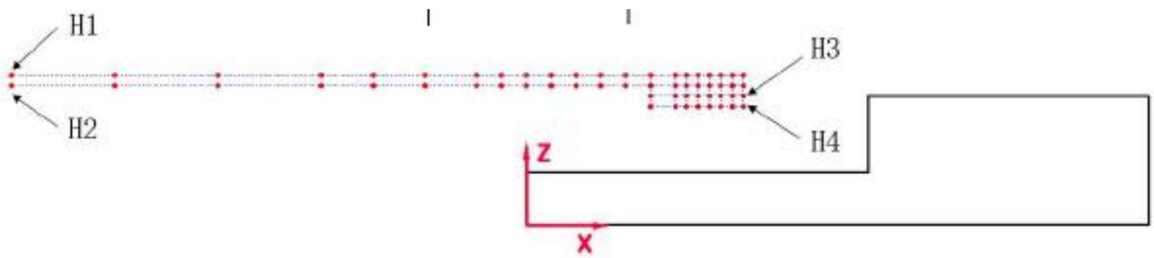


Fig.4. Relative location relationship between the rotor hub center and ship

Table. 1 Experiment matrix showing the rotor hub center coordinate values (ship body axis)

Z (mm)	Index	H1=468 mm	H2=418 mm	H3=368 mm	H4=318 mm
X (mm)	T	-1990	-1990		
	S	-1490	-1490		
	R	-990	-990		
	Q	-740	-740		
	P	-490	-490		
	O	-240	-240		
	N	-120	-120		
	A	0	0		
	B	120	120		
	C	240	240		
	D	360	360		
	E	480	480		
	F	600	600	600	600
	G	720	720	720	720
	H	775	775	775	775
	I	830	830	830	830
	J	885	885	885	885
	K	940	940	940	940
	L	995	995	995	995
	M	1050	1050	1050	1050

Half-open and fully-open status of hangar door can be simulated through changing the model hangar door plate. Table.2 gives the experiment matrix under different status of hangar door half-open and fully-open.

Table.2 Experiment matrix under different status of hangar door half-open and fully-open (ship body axis)

X (mm)	Rotor height			
	H1 (z=730mm)	H2 (z=680mm)	H3 (z=730mm)	H4 (z=580mm)
360	D	D		
480	E	E		
600	F	F	F	F
720	G	G	G	G
775	H	H	H	H
830	I	I	I	I
885	J	J	J	J
940	K	K	K	K
995	L	L	L	L
1050	M	M	M	M

1.3. Experiment facilities

Experiment facilities mainly include: model support device, rotor rig, measurement system, data acquisition system and PIV measurement system.
Model support device is welded by the rectangle steel, mainly include fixed struts and one moveable part to adjust the rotor high.
The main function parameters of the rotor rig can be seen in Table.3. The main functions of rotor rig are manipulating of rotor control and real-time monitoring. The collective pitch, cyclic pitch and rotation of rotor can be manipulated through the control system, and the rotor rotation can be monitored through encoder.

Table.3 The main function parameters of the rotor rig

Main function parameters	Values
Rotation speed	1250～2400rpm
Rotation precision	1%
AoA	-15°～+15°
AoA precision	0.1°

The balance is the core parts of measurement system, and a box type six-components balance is adopted.
The data acquisition of rotor experiment is accomplished by the PXI system which mainly includes PXI acquisition card and conditioning card. The signal of rotor's azimuth angle from encoder is adopted as the exterior trigger. 64 points per rotation are acquired and the total 320 rotations give sample amount of 20480 points.
The core equipment for flow field experiment is the TR-PIV system of LaVision company. In the experiment, viewing field of CCD camera has a size of 600 mm × 600 mm, and laser frequency is 25 Hz.

1.4. Airloads coefficient

Non-dimensional parameters, including thrust coefficient C_T、torque coefficient C_Q、pitching moment coefficient C_{my} and hover efficiency FM, are calculated as follows:

$$C_T = \frac{T}{\frac{1}{2}\rho V_T^2 \cdot \pi R^2} \quad (1)$$

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

$$C_{my} = \frac{My}{\frac{1}{2}\rho V_T^2 \cdot \pi R^2 \cdot R} \quad (3)$$

$$FM = \frac{1}{2}\frac{C_T^{\frac{3}{2}}}{C_Q} \quad (4)$$

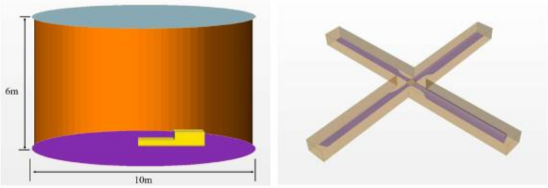
Among them, the R is a rotor radius; The V_T is rotor tip's speed. T, Q and M_y are respectively thrust, torque and pitching moment measured in the experiment.

2. NUMERICAL SIMULATION

Numerical calculation of rotor/ship interference under representative height H1(z=730 mm) is performed. Calculation position index and coordination could be seen in Table.4. Numerical calculation region could be seen in Fig.5. The cylinder background region has the diameter of 10 m. The rotor has the rotation of 1500rpm under direction of counter-clockwise.

Table.4 Position index and coordination (ship body axis)

X (mm)	Position	X (mm)	Position
-1990	T	120	B
-1490	S	240	C
-990	R	360	D
-490	P	480	E
-240	O	775	H
-120	N	940	K
0	A	1050	M



(a) Background region (b) Overlap region

Fig.5 Numerical calculation region

The mesh demarcation can be seen in Fig.5 and Fig.6, among them the amount of background meshes is about 4,500,000, the amount of overlap meshes is about 3,800,000.

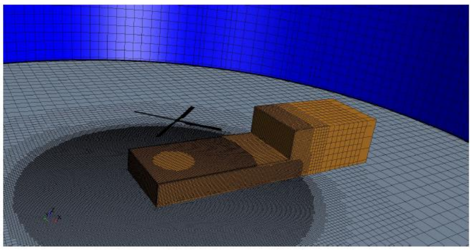


Fig.5 Grids on the surface and boundary

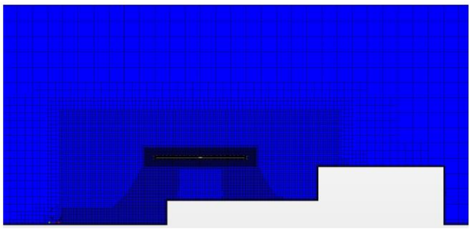


Fig.6 Grids on symmetric center plate

3. RESULT AND ANALYSIS

3.1. Loads measurement result

In the process of landing, the relative position of rotor to ship is continuously changing, the thrust coefficient, torque coefficient, pitching moment coefficient and hover efficiency will appear obvious variation.

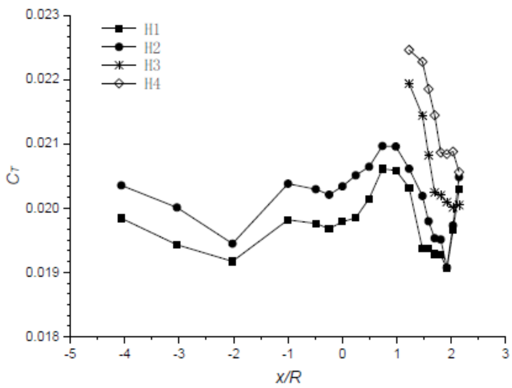


Fig.8 Rotor thrust coefficient versus position

Fig.8 gives the curves of the thrust coefficient versus position, and accordingly the landing process is divided into three regions according to the different relative position(x/R).

(1) The first region, from x/R=-4 to x/R=-1, the rotor is approaching ship stern gradually. The thrust coefficient decreases first and then increases, and gets minimum at x/R=-2.

(2) The second region, from x/R=-1 to x/R=1, the rotor gets into above the deck gradually. From the x/R=-1 to x/R=0, rotor's thrust coefficient decreases slightly, but from x/R=0, the rotor thrust coefficient appears up-trend and gets maximum at x/R=1.

(3) The third region, for x/R>1, rotor completely get into above the deck and gradually gets close to hangar door. From the x/R=1 to x/R=1.8, rotor's thrust coefficients under four heights all appear abrupt decline, the rotor’s thrust loses significantly.

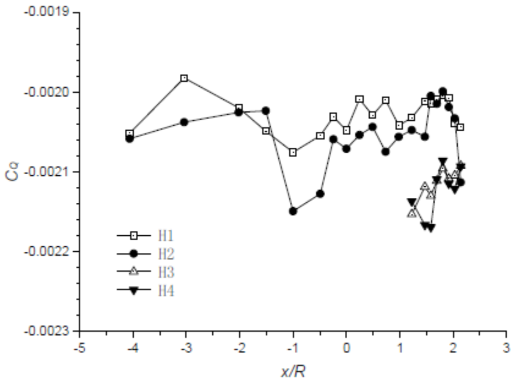


Fig.9 Rotor torque coefficient versus position

Fig.9 gives the curves of the torque coefficient versus position, follows can be seen from the curves:

(1) Under the influence of ground effect or the ship deck effect, the torque coefficient of rotor slightly has increases with the lowering of rotor height.

(2) The rotor torque coefficient varies significantly in two districts: One is from x/R=-1 to x/R=0.5, the rotor is located above the deck stern and mainly be subjected to the steep wall interference influence of the stern; The other one is in the x/R=1.5 neighborhoods, the rotor is close to the ship hangar door and be subjected to its interference.

Fig.10 gives the pitching moment coefficient of rotor under different height versus position. In the x/R<1 district, the rotor is located at H1 height, the influence of the ship stern upon the pitching moment coefficient can be neglect; But when the rotor is located at H2 height, the rotor will be subjected to the obstacle of the ship stern, and will produce a little nose-down moment. When the rotor closes to the hangar door (namely x/R>1 district), under four different heights, the rotor pitching moment coefficient will sharply increase, the rotor will be subjected to large nose-down moment.

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

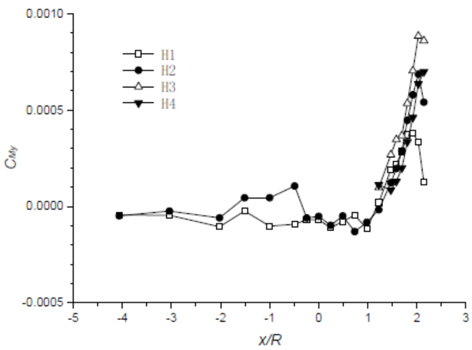


Fig.10 Rotor pitching moment coefficient versus position

From the Fig.11 rotor performance curves, hover efficiency has the same variety trend with thrust coefficient, both all embody the regulation that increases with the lowering of rotor height

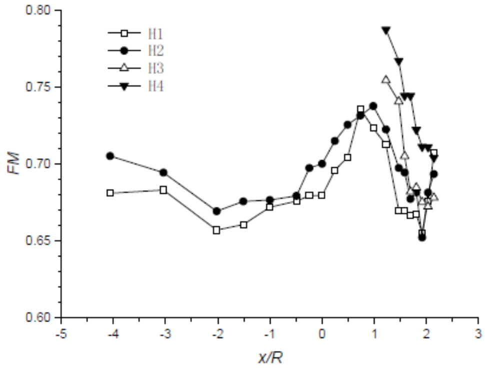


Fig.11 Rotor hover efficiency versus position

Fig.12 and Fig.13 give respectively the rotor thrust coefficient and the pitching moment coefficient curves which contrast numerical and experimental result. Although the values differ but the whole variety trends keep consistent. Experiment and calculation differ most at point S (namely x/R=-3), where the rotor mainly be subjected to interference of the ship stern and the flow is of great unsteady.

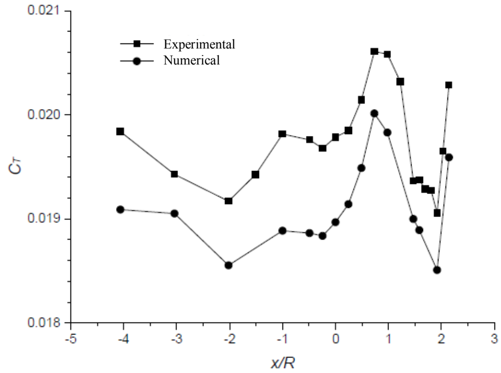


Fig.12 Contrast of numerical and experimental result of rotor thrust coefficient

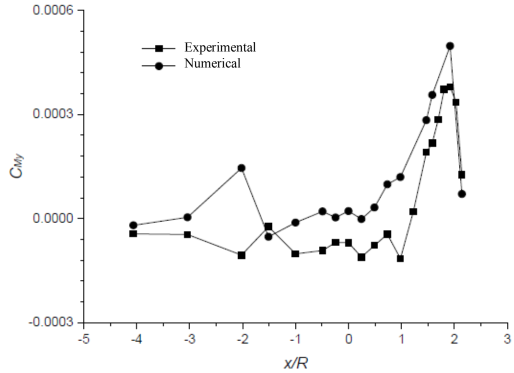


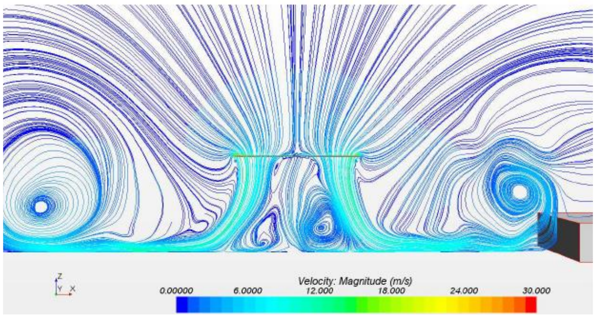
Fig.13 Contrast of numerical and experimental result of rotor pitching moment coefficient

3.2. Flow structure analysis of numerical calculation

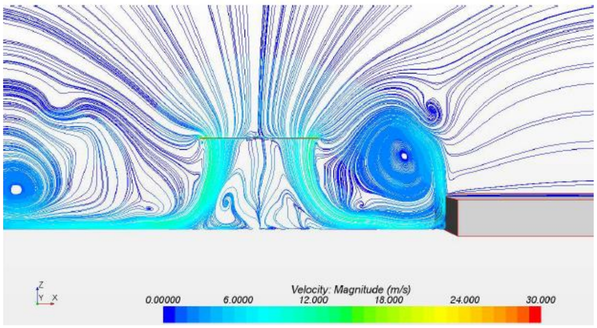
Considering flow structure result from numerical calculation, the interference mechanism from ship upon rotor can be revealed in different three regions.

3.2.1 Rotor approaching stern

The first region is the one before rotor's footprint approaching the stern(Fig.14), where the thrust coefficient decreases as the rotor approximating the edge of stern, owing to additional down-wash increased by the re-circulation introduced by the interference between the rotor and stern edge.

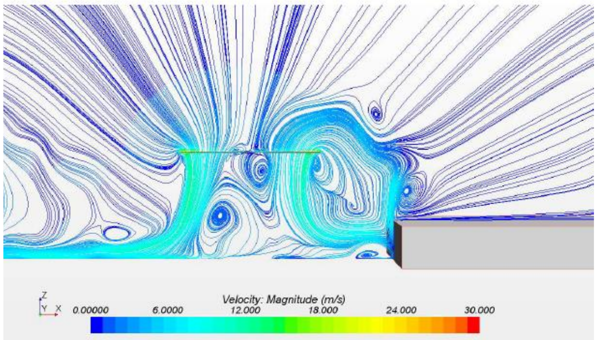


(a) Rotor center located at position T

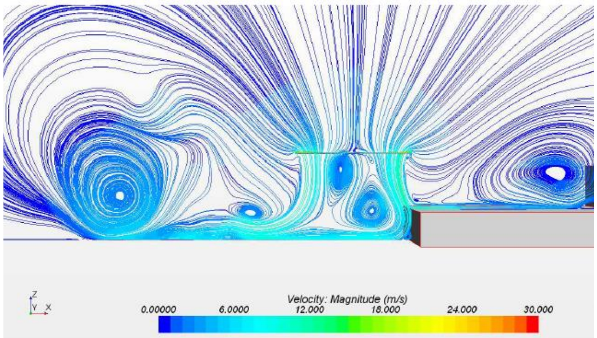


(b) Rotor center located at position S

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018



(c) Rotor center located at position R

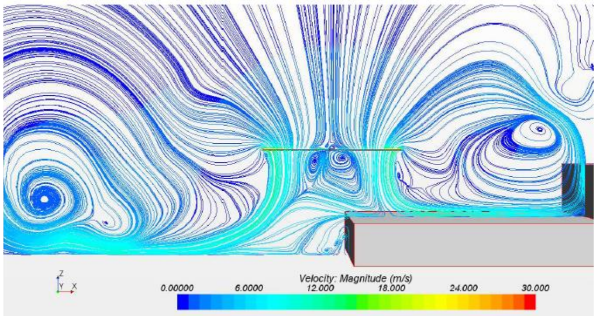


(d) Rotor center located at position P

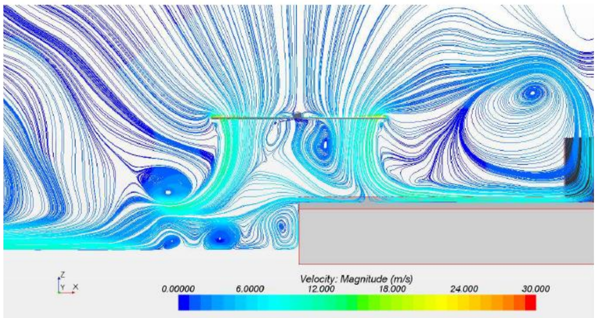
Fig.14 Numerical flow field of rotor/ship interference (rotor approaching stern)

3.2.2 Rotor entering deck

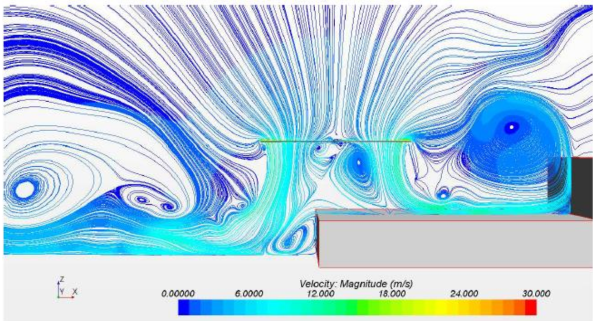
The second region is the one after rotor entering deck from stern (Fig.15), where a gradual increase of the thrust is observed. This phenomenon is caused by the ground effect rising as the footprint of rotor center moving forward.



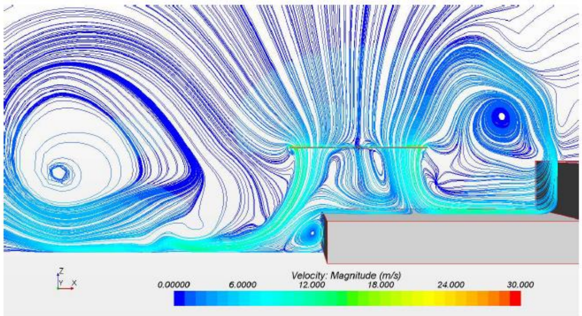
(a)Rotor center located at position N



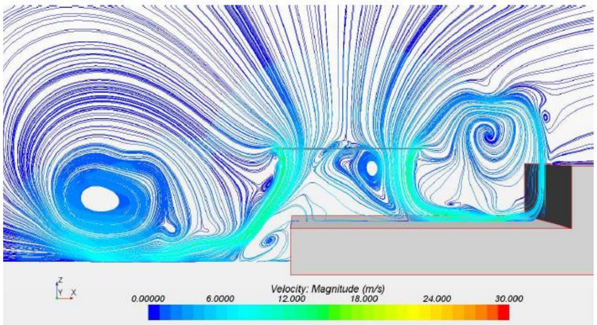
(b)Rotor center located at position A



(c) Rotor center located at position B



(d)Rotor center located at position C

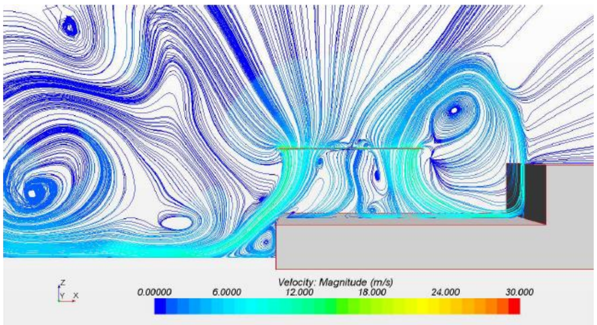


(e)Rotor center located at position D

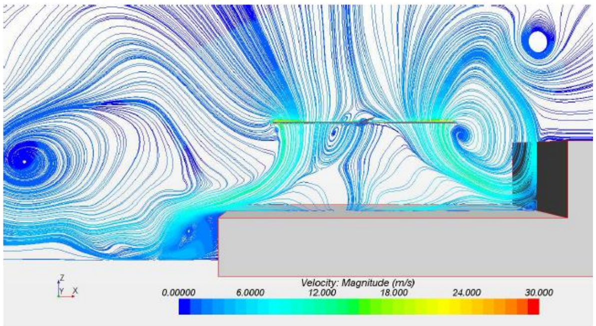
Fig.15 Numerical flow field of rotor/ship interference (rotor entering deck)

3.2.3 Rotor approaching hangar door

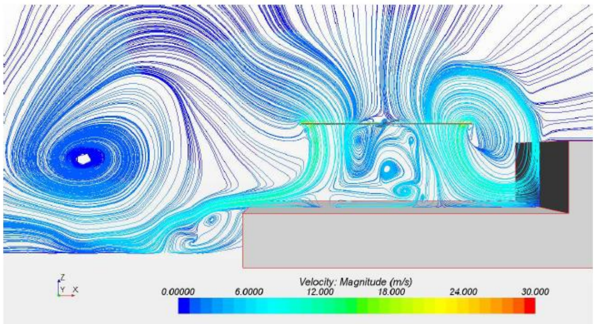
The third region is the one close to the hangar door (Fig.16), and there is a sudden decrease in the trust force. This behaviour is attributable to the re-circulation introduced by the interference between the rotor and hangar door. But in the region further closer to the hangar door, the trust force of the rotor tends to increase.



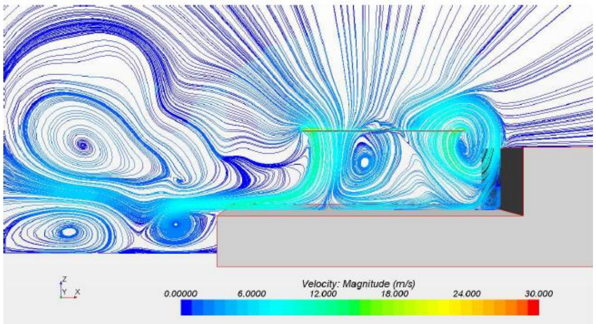
(a)Rotor center located at position E



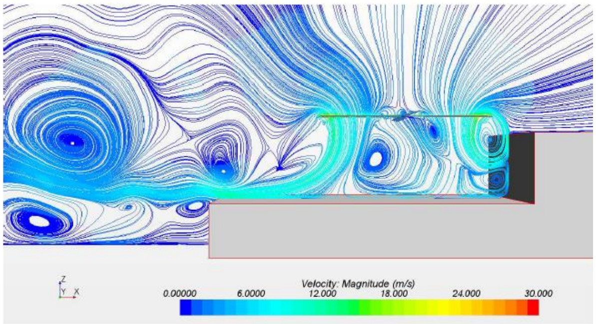
(b)Rotor center located at position G



(c)Rotor center located at position H



(d)Rotor center located at position K



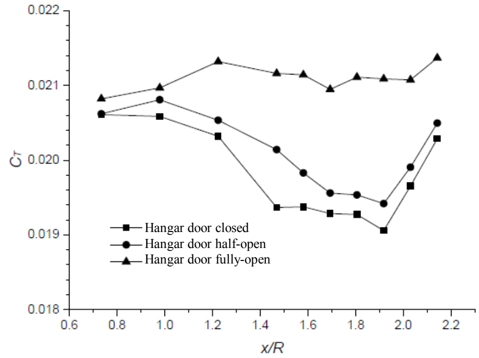
(e)Rotor center located at position M

Fig.16 Numerical flow field of rotor/ship interference (rotor approaching hangar door)

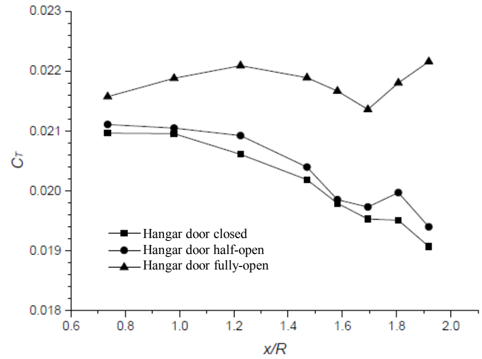
3.3. Hangar door research under status of open and closed

As what is described in previous section: When the rotor is hovering in hangar neighborhood, the rotor will suffer serious thrust loss and large nose-down moment. This section develops the hangar door research that influence the rotor loads under different status of door open and closed.

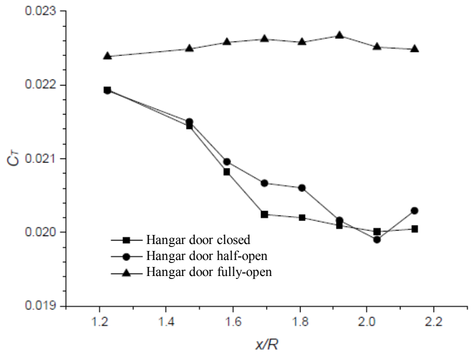
Fig.17 and Fig.18 give respectively the rotor thrust coefficient and pitching moment coefficient versus position under different height of rotor and different status of door open and closed.



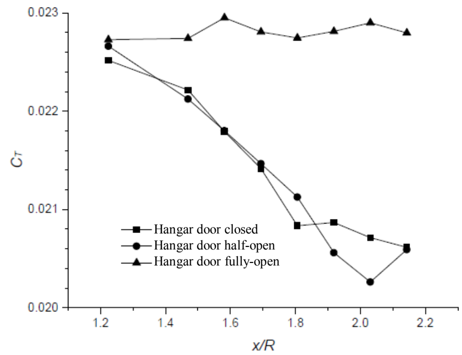
(a) Height of H1



(b)Height of H2



(c)Height of H3

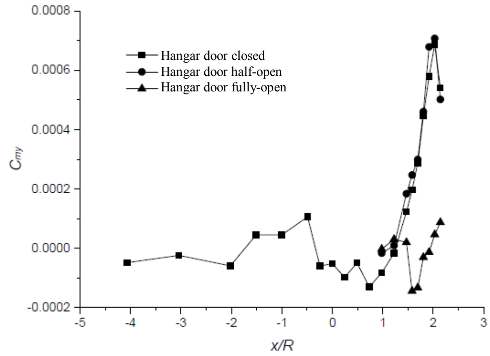


(d)Height of H4

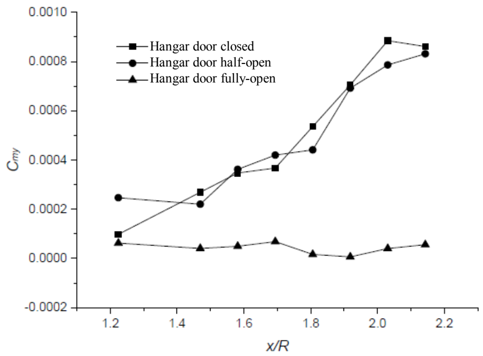
Fig.17 Thrust coefficient versus position under different status of door open and closed

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

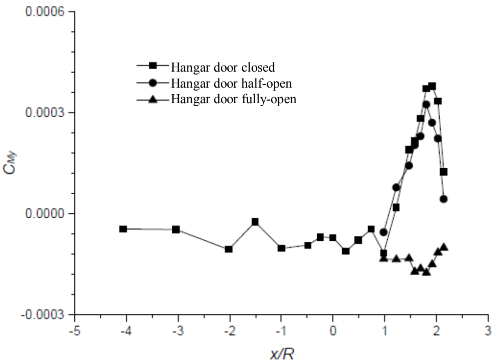
From the Fig.17 we can see: compared with the hangar door close, when the door is half-open the rotor thrust coefficient has a slight improvement under the height of H1 and H2, but has no obvious variety under the height of H3 and H4; When the door is fully-open the rotor thrust has no loss at four heights. Therefore, fully-open of the hangar door could effectively avoid the problem of rotor thrust loss.



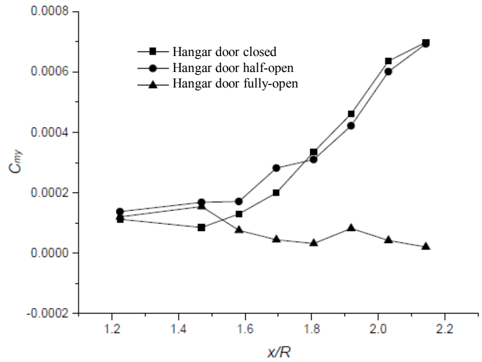
(a) Height of H1



(b)Height of H2



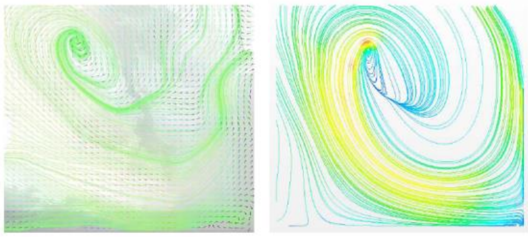
(c)Height of H3



(d)Height of H4

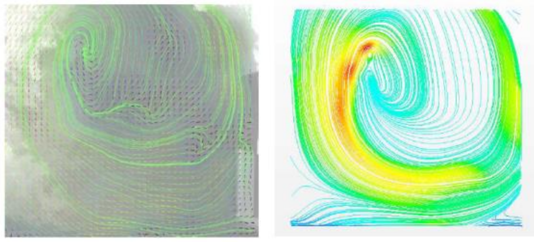
Fig.18 Pitching moment coefficient versus position under different status of door open and closed

From the Fig.18 we can see: compared with the hangar door close, when the door is half-open the rotor pitching moment coefficient has no obvious change under the different heights; But when the door is fully-open the rotor's nose-down moment has no obvious mutate. Therefore, fully-open of the hangar door could effectively avoid the problem of rotor pitching moment mutate, and helpful for the stability of the rotor.



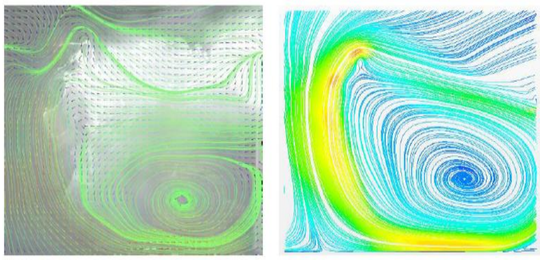
(a)PIV result (b)Numerical result

Fig.19 Comparison of flow field with hangar door closed



(a)PIV result (b)Numerical result

Fig.20 Comparison of flow field with hangar door half-open



(a)PIV result (b)Numerical result

Fig.21 Comparison of flow field with hangar door fully-open

In order to reveal the interference mechanism of hangar door status upon rotor performance, the flowfields that PIV measured and numerical calculated are compared with the rotor center located at position H (x=775 mms). Fig.19~Fig.21 give respectively the result PIV measured and

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

numerical calculated of hangar closed, half-open and fully-open.

From the contrast result we can see: The overall flow topology in the area between the rotor and hangar have good consistency between PIV result and numerical result.

The overall flow topology in the area between the rotor and hangar given in Fig.19~Fig.21 for the three hangar door states explain how the hangar door open-closed action affects the rotor performance. In the hangar door open case, a large vortex is formed by the recirculation between the rotor and hangar door, making a greater contribution to the strength of inflow. The height of this large vortex decline slightly with the hangar door half-open, and it drop far away from rotor plane with the hangar door fully-open.

The effects of the hangar door open on rotor' performance when helicopter is hovering above on deck and close the hangar is shown in Fig.22. There is a mild recover in the trust loss in the case of the hangar door half-open, but the tendency of thrust decreasing is not change. After the hangar door fully-open, the tendency of trust losing has almost disappeared, the distribution of thrust seems more smooth than that in the hangar door closed.

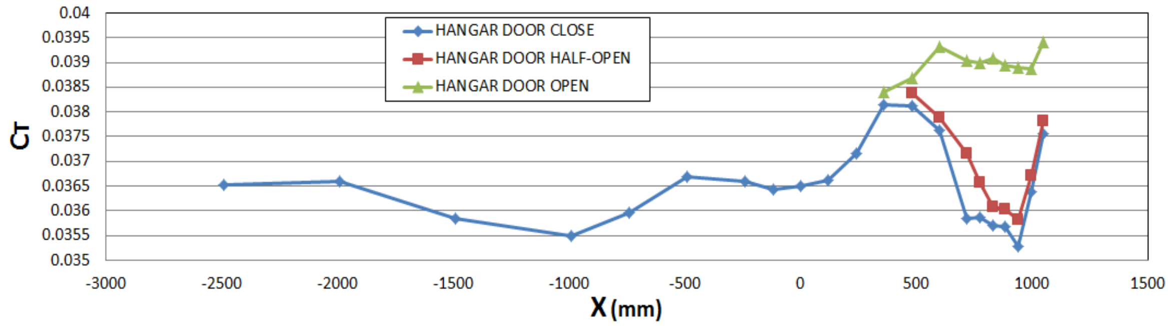


Fig.22. Effect of the hangar door open and closed on the time-averaged rotor thrust coefficient obtained at H1 height

4. CONCLUSION

1） During the ship landing process, the rotor is subjected to interference influence from the ground effect and steep wall effect, its aerodynamic loads change significantly with the rotor position.
2） The position of recirculation region caused by the blocking of the deck rear edge changes obviously when the rotor closes to the deck. The thrust coefficient firstly decreases and then increases, while the pitching moment doesn't change very noticeable. The thrust losing is most serious when the rotor at x/R=-2 and the thrust coefficient decrease by 4%.
3） The influence of the trailing edge deck can be ignored and the ground effect plays a dominant role when the rotor disc begins to enter the area above the deck. The ground effect significantly enhances with increasing of the projection area of rotor disc on the deck.
4） The ground effect remains unchanged and the aerodynamic interaction of rotor and the hangar door plays the leading role when the rotor closes to the hangar door. The recirculation region caused by the blocking of hangar door is close to the rotor disk and results in the inflow increase of the rotor disc. The thrust drops sharply and the nose-down pitching moment is increased obviously.

The influence of hangar door in two different status is also investigated in this paper for the purpose of revealing the flow mechanism of the effect of the hangar door on rotor performance and seeking the effective methods to solve the problem of rotor load mutation. The effect of rotor performance and the flow field structure change insignificantly when the hangar door half opened. Both thrust losing and the nose-down pitching moment of the rotor almost disappear when the hangar door is widely opened. The results show that the recirculation of rotor wake is far away from the rotor disc without blocking of hangar door, and the rotor inflow can be effectively reduced at the same time.

5. OUTLOOK

Further research could be developed from a few aspects as follows:

1） The experiment aspect, a wind tunnel experiment on the foundation of current research could be performed to acquire interference characteristics from ship upon rotor under different wind speed.
2） The numerical calculation aspect, the high precision scheme and dense grid could be combined to better catch rotor wake's characteristics.
3） Experimental and numerical research on different paths of helicopter landing could be performed to provide safety and effective ship landing strategy.

REFERENCES

[1] A. Srinivasan, J. D. Shipman, and N. Sinha. Towards numerical modeling of coupled vstol-ship airwake flowfields. volume 52, 2004. 42nd AIAA Aerospace Sciences Meeting and Exhibit.

[2] Kääriä, C. H., Wang, Y., Curran, J., Forrest, J., and Owen, I., "AirDyn: An Airwake Dynamometer for Measuring the Impact of Ship Geometry on Helicopter Operations," 36th European Rotorcraft Forum, Paris, 7–9 Sept. 2010.

[3] Chen Friedman, Julie Duplessis, Murray Snyder. "Measurements of Dynamic Interface Between Ship and Helicopter Air Wakes", AIAA Applied Aerodynamics Conference,2015.

[4] James S. Forrestm, Ieuan Owen. "Aerodynamic Loading Characteristics of a Model-Scale Helicopter in a Ship's Airwake" JOURNAL OF AIRCRAFT Vol. 49, No. 5, September–October 2012.

[5] Daniele Zagaglia, Michea Giuni, Richard B. Green. "Rotor-Obstacle Aerodynamic Interaction in Hovering Flight: An Experimental Survey", AHS 72nd Annual Forum, West Palm Beach, Florida, May 17–19, 2016.

[6] Hong Xin, V. R. Prasad, David A. Peters. "An Analysis of Partial Ground Effect on the Aerodynamics of a Helicopter Rotor", 38th Aerospace Sciences Meeting & Exhibit, 10-13Januaty2000/Reno,NV.

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018