

Research Article Main Rotor Wake Interference Effects on Tail Rotor Thrust in Crosswind

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Reverse pedal operational property in front crosswind flight condition is a potential hazard for accidents involving loss of tail rotor effectiveness (LTE), which is closely related to the main rotor (MR) wake interference on the tail rotor (TR). As understanding of this interaction is vital for the early warning strategy development, the MR wake influence effect on TR thrust and the effect of helicopter yaw stability are examined in this study. For this purpose, the comparison of TR thrust and flow field with wind azimuth and speed in front crosswind environment was performed by experiment and CFD simulation, respectively. Test campaign was performed at a 5.5 m × 4 m wind tunnel in the China Aerodynamics Research and Development Center using a high-position bottom-blade forward-rotating TR and a counterclockwise rotating MR to address the TR thrust under wind speeds of 8-22 m/s with 50°, 60°, and 70° wind azimuths. The influence of MR disc loading was also contrasted. CFD analysis was used to gain insight into the flow physics responsible for the interference effect. It was conducted with unsteady Reynoldsaveraged Navier-Stokes simulations, where the MR using the actuator disk approach and the TR blade rotation was modeled via a sliding mesh method. Results indicated that the MR disc vortex has a remarkable interference effect on the TR aerodynamic performance characteristic and that the effect is sensitive to the wind speed, wind direction, and MR disc loading. The observed yaw instability is considered to be related to the lesser inflow introduced by the MR disc vortex due to the change in the relative position of the disc vortex filament and TR with the wind azimuth. The increase in TR thrust at moderate wind speeds is due to the increase in leading edge dynamic pressure caused by the opposite swirl direction of the disc vortex contrasted to the TR. The MR disc loading affects the TR thrust due to the change of disc vortex strength and position.

1. Introduction

Given their unique ability of hovering and vertical take-off and landing flight, helicopters are regularly required to perform challenging missions in crosswind environments, particularly in areas with complex environmental winds, such as mountain and ocean areas, especially for rescue missions, emergency services, and military operations. Directional control problems in hovering or low-speed flight when crosswinds are encountered commonly occur with single main rotor (MR) configuration helicopters; these problems are often related to the property of tail rotor (TR) aerodynamic performance [1–3]. The Federal Aviation Administration (FAA) advisory circular 90–95 describes those circumstances as loss of TR effectiveness (LTE), which is a critical low-speed aerodynamic flight characteristic that causes an unanticipated rapid yaw [4]. The National Transportation Safety Board has identified LTE as a contributing factor in several civil helicopter accidents where the pilot has lost control [5]. LTE limits the flight envelope of helicopters in extreme environments. For example, the port and starboard wind boundary of the ship helicopter operational limitations of a ship-borne helicopter is constrained by the pedal margin [6, 7]. Therefore, a better understanding of the thrust generated by TR in crosswind condition is valuable for helicopter flight mission planning, pilot training, and control system development.

The interference effect of MR wake has a significant influence on the performance of TR. If the helicopter is exposed to a large sideslip crosswind from the front, then the TR is located in the downstream of the MR and partly immersed in the MR wake. Under certain velocity conditions, the MR wake will roll into two counterrotating macro disc edge vortices [8], comparable to the tip vortices behind a fixed wing. The interaction with the so-called MR disc vortex in the front-quartering wind region with a slide slip angle of between 45° and 70° can cause a sudden change in the thrust produced by the TR, as demonstrated by Ellin for a flight test using a Lynx helicopter [9]. Maneuvering in the quartering region will require additional pedal activities to counter the sudden change in TR thrust. Moreover, the pedal input pattern implemented for a trimming helicopter versus the wind azimuth variation is nonmonotonic, as shown by a flight test [10]. An investigation of a Bell 206 helicopter LTE accident conducted by the Australian Transport Safety Bureau revealed that as the pilot right-turned the helicopter in quartering crosswind, he initially had a pedal operating to react the change in the TR thrust, responded by the MR disc vortex interference; however, he did not correct the pedal operating in time when the effect of the MR disc vortex weakened, which caused an unanticipated rapid yaw [11]. Given that the MR disc vortex-TR interactions can have a serious threat to operational safety, the FAA advised to offer a warning against LTE [4].

Considerable research related to the MR-TR interaction phenomenon in a crosswind environment has been conducted to derive a TR design guideline in response to directional control problems occurring in some new helicopter development process [12-14]. Boeing performed a wind tunnel test with a counterclockwise (CR) rotating MR and a moveable TR test rig to contrast the TR configuration; it showed that at a speed of 35 kt, the lower and midposition TR produced significant thrust increase dip for near 60° wind azimuth, which could contribute to loss of yaw stability [15, 16]. The HELIFLOW project conducted a wind tunnel experiment subtask named quartering flight. It compared four TR configurations involving two height locations and two rotational directions at 60° wind azimuth. The result indicated that the top blade suffered a sudden thrust recovery after the rotating TR when the wind speed increased to an advance ratio of 0.06 [17, 18]. Brown adopted the vorticity transport model to calculate the TR performance in a 60° sideslip. The study contributed to understanding why reversing the TR rotation can cause significant difference in its thrust [19, 20].

The FAA recently proposed a research program with the aim of detecting proximity to LTE events within helicopter flight data monitoring. A physics-based LTE model is still in the process of being explored to improve the accuracy of detection [21]. Thus, an improved understanding of the TR thrust characteristics in a large sideslip flight and the underlying mechanism that can be used in the physicsbased model development process is urgently needed. The experience that pilots sometimes require to give an opposite pedal movement to maintain a constant heading at a certain



FIGURE 1: MR-TR combined crosswind test configuration in a wind tunnel.

TABLE 1: Rotor characteristics.

Characteristic	MR	TR	
Rotation direction	CR	Bottom blade forward	
Radius	1.5 m	0.29 m	
Blades per rotors	4	2	
Root cutout	0.15 m	0.12 m	
Rotational speed	1400 rpm	7230 rpm	
Chord	0.09 m	0.055 m	
Blade precone	3°	0°	

larger sideslip angle in a narrow speed range [4, 10] implies that the yaw stability in this wind region is special.

Although previous studies have characterized the TR performance associated with MR interference effects for various TR configurations restricted to a certain constant sideslip angle [16–20], literature on the yaw stability characteristic caused by the produced thrust of TR (i.e., the slope of TR thrust versus wind azimuth) in the presence of MR wake interference in a quartering wind region is limited. Studies [22, 23] have examined the TR thrust variation in crosswind directions of 0° –360° at one fixed wind speed. However, the intervals of 30° wind azimuth applied in these studies are excessively large to derive the yaw stability detail and have limited the wind speed region.

In this current work, a wind tunnel test was conducted to quantify the thrust characteristic of a bottom-blade forwardrotating TR at 50°, 60°, and 70° wind azimuths with wind speeds from 8 m/s to 22 m/s, including the interaction effect of a CR MR, to investigate the yaw stability behavior of a helicopter in a quartering flight condition. The flow around the TR for the full and isolated TR configurations was simulated by CFD to develop physical insights into the underlying mechanisms causing these effects. Additional parameters, such as varying MR thrust coefficient, were investigated.

2. Experimental Setup

2.1. Model Description. Photographs of the model are shown in Figure 1. The experiments were performed on a CR MR



FIGURE 2: Illustration of the position relationship between the MR and the TR.

and with a bottom-blade forward-rotating TR model located near the vertical height of the MR hub center. The MR model was a 3 m diameter Mach-scaled Bo-105 MR, which consisted of four blades, a hub, and a swash plate. The TR consisted of two blades and a hub. The TR was not equipped with a swash plate, and its collective pitch could be varied by changing the different hubs. The properties of the two rotors are summarized in Table 1. A fuselage model similar to UH-60 was utilized to protect the MR and TR balances and streamline the test rig. The location of the TR with respect to the MR is illustrated in Figure 2.

2.2. Facility Specification. Experiments were performed at the open test section of 5.5 m × 4 m aeroacoustics' wind tunnel at the China Aerodynamics Research and Development Center, which is a low-speed, single-return flow-type wind tunnel with a maximum flow of 80 m/s and a free stream turbulence level below 0.2%. The test rig was mounted on the rear sting support system in the wind tunnel test hall. The wind azimuth of the helicopter model can be remotely controlled by the sideslip-shift mechanism of the support system. In the fuselage body, a five-component balance measured the MR hub forces in three axes and the pitching and rolling hub moments. A torque cell was attached to the rotor shaft to measure the torque. A 120 kw electric motor that drove the MR was mounted in the faring below the fuselage. The TR, together with the 20 kw electric motor and transmission that powered it, was mounted on a six-component balance attached on the skeleton inside the fuselage. The accuracy of the balance was within 0.03%, and the resolution of the balance in the TR thrust direction was 0.24 N. Two encoders were connected to the shaft of the MR and TR, each providing a 64/rev rotational azimuth signal.

2.3. Test Contents. The test was set up in two parts. The first part explored the variation of the TR thrust with wind speed at different wind azimuth angles. In this part, wind speed sweeps of 8, 11, 13, 14, 16, 19, and 22 m/s were performed in 50°, 60°, and 70° starboard wind azimuth angles. The definition of the wind direction angle is shown in Figure 3. The MR was trimmed to a specified thrust force coefficient, and the rolling and pitch moments were close to zero.



FIGURE 3: Illustration of the definition of wind azimuth in this study.

To investigate the directional stability characteristics dominated by the TR in a rapid and low-cost manner, the collective pitch of the TR was set to a fixed value of 11° throughout this study. Although the overall yaw equilibrium of the helicopter at each flight condition was not satisfied, this simplification could obtain the directional stability of the helicopter. In the case of yaw stability, the helicopter should tend to return to an equilibrium condition when subjected to some form of yawing disturbance. Given that the vertical fin has a limited lift in low flight speed conditions, the yaw stability could be mainly detected on the curve slope of the TR thrust versus the wind azimuth. The yaw stability characteristics that were detected with this scheme have been widely applied in previous wind tunnel [15] and numerical simulation [22, 24] studies.

The second part of the test focused on the contrast of the effect of the MR disc load on the performance of the TR. Data were acquired at a lower thrust force coefficient of MR at 60° wind azimuth with the same airspeed sweeps as the first part. Table 2 provides the detail of the test condition.

After the MR reached the trimmed goal at each test condition, data signals were recorded simultaneously on a digital data acquisition system. Data recorded included the forces and moments from the two balances, the instantaneous

TABLE 2: Wind tunnel test matrix.

Wind azimuth (°)	Wind speed (m/s)	MR thrust coefficient	TR collective pitch (°)
50	8, 11, 12, 13, 14, 16, 19, 22	0.01	11
60	8, 11, 12, 13, 14, 16, 19, 22	0.01	11
60	11, 12, 13, 14, 16, 19, 22	0.008	11
70	8, 11, 12, 13, 14, 16, 19, 22	0.01	11



FIGURE 4: Illustration of computational domain.



FIGURE 5: TR thrust test and numerical results versus wind speed.

rotational speeds of the two rotors, the MR torque, and the tunnel velocity. The signals from the two balances were filtered, and the data recorded were time-averaged to steady-



FIGURE 6: TR thrust coefficient results versus wind azimuth.

state values. The thrust coefficient rotor is calculated as follows:

$$C_T = \frac{T}{0.5\rho A(\omega R)^2},\tag{1}$$

where ρ is the air density, which is calculated from the temperature and atmospheric pressure recorded during the test, and *A*, ω , and *R* are the rotor disc area, rotor angular velocity, and radius, respectively.

3. Numerical Methodology

3.1. Numerical Methods. The characterization of the MR wake using overset mesh technology is a time-consuming task due to the hole cutting process and data transfer between donor and acceptor cells at each time step [25, 26]. The actuator disk approach has been used to perform successful rotor wake simulations in MR-fuselage [27, 28], MR-TR [22], MR-tail boom [29], and MR-lateral rotor and wing [30, 31] interaction calculations. Several researchers have demonstrated that one characteristic feature of the MR disc vortices wake is well-known coherent supervortices, as the blade tip vortices roll up in the downstream [32]. Previous sideward flight test investigations by Ellin [9] indicated that the unsteady loading information of the TR, measured



(c) 70° wind azimuth case

FIGURE 7: Q-criterion (250) of the rotor wake colored by velocity in the transverse direction ($V_{\infty} = 8 \text{ m/s}$).

by pressure taps along the leading edge, does not contain a significant component at the blade passage frequency of the MR. This phenomenon occurring due to the coalescence of the tip vortices into coherent supervortices smears the temporal variability in the velocity field near the TR considerably at the MR blade passage frequency. Although the actuator disk method has certain limitations in capturing the trajectory of the MR blade tip vortex, the slipstream or coherent supervortices of the MR wake can be accurately and efficiently considered by it. Therefore, the actuator disk method can be used to generate the MR wake around the TR in the present numerical simulation. To account for the relative motion of the TR blade in the nonuniform MR wake, the sliding mesh model was used in this study to resolve the time-accurate solution for TR thrust.

A three-dimensional unsteady Reynolds-averaged Navier–Stokes CFD framework was used in this simulation. A second-order spatial scheme finite volume method was used for space discretization. Compressible flow solvers and preconditioning technology were used to handle compressible and incompressible flow fields in the TR wake. An implicit unsteady flow solver with an ideal gas and an SST (Mentar) *K*-Omega turbulence model were used. The time step was set to correspond to a 1° rotational azimuthal sweep of the rotor.

3.2. Geometry and Grid. The TR and fuselage geometry utilized in the test was used to generate a series of hexahedral unstructured grids. The MR was modeled by entering the momentum equations in the form of a source term that is distributed over the virtual MR disk. The influence of the MR blade geometry on the flow field is described by the aerodynamic behavior of the blade in terms of lift and drag coefficients obtained from the corresponding twodimensional cross section of the blade. The strength distributions of the source terms were interacting determined from the MR geometry and local velocity field.

The computational domain (Figure 4) comprised a rotating region where the mesh inside the volume rotates along with the TR blade geometry, and a nonrotating volume is composed of the MR disk and fuselage geometry. The rotating region was a cylinder with a radius of 1.05. The height of the cylinder extended 2.2 tip chord lengths the front and rear of the TR plane. Each rotating volume was bounded by a sliding mesh interface that passed information into and out of the nonrotating volume. The volume meshes around the MR actuator disk, fuselage, and TR were refined to capture the detail of the MR wake and the TR blade tip vortices. The initial wall spacing of the TR has a dimensionless mesh size of y + <1 and extruded 0.3 chord length in the wall, which is normal to generate the prism boundary layer mesh. The computational domain was a cuboid extending from -2.5 to 5 times the radius of the MR in the x-direction (free stream direction), -2 to 2 times the radius of the MR in the y-direction (transverse), and -2 to 3 times the radius of the MR in the z-direction (vertical). The whole grid system contains approximately 13.5 million grid points.



FIGURE 8: Velocity vector perpendicular to the TR plane $(V_{\infty} = 8 \text{ m/s}).$



FIGURE 9: Inflow distributions on the 0.1 TR radius in front of the TR disc (V_{∞} = 8 m/s).

3.3. Calculation Contents. The primary objectives for the calculations are to acquire flow details, obtain the fundamental understanding of MR-TR interference phenomenon, and identify the mechanisms of the yaw stability characteristics in the front-right crosswind environment. Therefore, CFD analysis was performed for wind tunnel model configurations in three wind speed regions selected based on their different yaw stability features. The second objective is to quantify the change in the TR thrust resulted by aerodynamic interaction with the MR. For this purpose, the isolated TR results were assessed by CFD.

4. Results and Discussion

4.1. TR Thrust Characteristics. Figure 5 presents the results for the TR thrust coefficient versus wind speed at different values of wind azimuth angles. The solid lines with dots indicate the wind test results, the hollow dots represent the CFD results for the TR thrust under the influence of the MR, and the dotted lines with dots show the isolated TR thrust. The MR-TR configuration results were compared at the same MR thrust coefficient of 0.01. In these cases, a satisfactory agreement between simulation and experimental results was achieved, and the average percent error for the TR thrust coefficient under MR interaction present in



FIGURE 10: Q-criterion (250) of the rotor wake colored by velocity in the transverse direction ($V_{\infty} = 12 \text{ m/s}$).

Figure 5 is 5.5%. Thus, the analysis of isolated TR thrust and aerodynamic interference of the MR wake on TR based on the simulation flow field was reliable.

In the front-right crosswind condition, as the free stream wind passes through the TR, it increases the out-of-plane inflow, which is similar to the climbing flight state of the MR. Clearly, the isolated TR thrust monotonously decreases with the wind speed and wind azimuth, which is expected due to the stronger inflow.

The TR thrust at each wind azimuth angle shows remarkable recovery in the moderate velocity region under the influence of the MR. The overall trend of the TR thrust as a function of wind speed at the 60° wind azimuth generally agrees with Refs. [17–20]. In addition, the discrepancy of the variation in the TR thrust with wind azimuth is apparent between each wind speed region, leading to more complex yaw stability characteristics in crosswind flight.

To examine this yaw stability difference in the wind speed region more clearly, the thrust coefficient of the TR versus the wind azimuth angle at various wind speeds (i.e., 8, 12, and 22 m/s) is shown in Figure 6. The slopes of the TR thrust with wind azimuth have a significant difference characteristic in the lower, moderate, and higher wind speed regions. At lower wind speed (8 m/s), the maximum TR thrust occurs at 50° wind azimuth angle and the TR thrust at 70° wind azimuth angle is slightly higher than the 60° wind azimuth angle case, which is nonmonotonic in the thrust curve. Within the moderate wind speed range when the TR thrust is regained, the TR reaches its maximum thrust at 70° wind azimuth angle, and the slopes of the rotor thrust varying with the wind azimuth angle are positive, indicating that unstable yaw control will be experienced by the pilot in this region. As the wind speed further increases, after the TR thrust resumes its decreasing trends with the increasing wind speed, the TR thrust shows a monotonic



(c) 70° wind azimuth case

FIGURE 11: Velocity vector on the 0.45 TR radius in front of the TR disc ($V_{\infty} = 12 \text{ m/s}$).

decrease with the wind azimuth angle within the range examined. Consequently, the yaw stability produced by the TR is resumed.

4.2. MR Wake Interference Effect on TR. In this section, the evolution process of the MR disc vortex and its impinging effect on the TR are analyzed at wind speeds of 8, 12, and 22 m/s.

Figure 7 shows the Q-criterion colored by the Y-directional velocity magnitude under each wind azimuth angle at 8 m/s. Given the difference of pressure existing between the upper and lower surfaces of the MR disc on the forward and retreating sides, the MR wake rolls up to form a pair of concentrated vortices along the downstream, which are generated in a principle similar to that of the wing tip vortex of the fixed wing aircraft. The MR disc vortex shedding from advancing is located vertically below the TR in 8 m/s and



FIGURE 12: Inflow distributions on the 0.1 TR radius in front of the TR disc (V_{∞} = 12 m/s).

intersects the bottom of the TR. As shown in Figure 8, the disc vortex induces the inner wash across the TR. Figure 9 compares the phase-averaged inflow velocity contour on the front plane of the TR disc. The influence of the inner wash introduced by the MR disc vortex for all the three



FIGURE 13: Q-criterion (250) of rotor wake colored by velocity in the transverse direction ($V_{\infty} = 22 \text{ m/s}$).

azimuth cases is evident in the local increase in the TR inflow for the disc vortex impingement positions. With the increase in the wind azimuth angle, the disc vortex filament tends to be more tangent to the TR disc plane, which causes the component of the disc vortex-induced velocity that enter the TR plane to weaken. Therefore, at 8 m/s crosswind, the main interference effect of the MR wake on the TR is to increase the inflow of the TR, subsequently reducing the angle of attack of the TR blade element, causing reduction in thrust. This effect mitigates with the increase in the wind azimuth angle.

Given that the free stream velocity in the crosswind condition will also improve the TR inflow, this effect is more lessened at the lower wind azimuth angle. The maximum TR thrust occurs at the 50° wind azimuth within the range examined at 8 m/s because of the lowest axial free stream velocity at this wind azimuth. The TR thrust at 70° wind azimuth is slightly greater than the 60° wind azimuth case, which is caused by the inflow enhance effect that is considerably alleviated, given that the TR is located nearly at the edge of the MR disc vortex (Figure 7(c)). Moreover, the TR shaft is more parallel to the disc vortex filament.

Figure 10 shows the wake under each wind azimuth at 12 m/s wind speed. In contrast to the lower wind speed case

of 8 m/s, the structure and position of the MR disc vortex significantly change; the structure of the disc vortex becomes more concentrated; and the vortex core moves upward, vertically close to the TR center. Significantly, the disc vortex moves to the right, relative to the TR with the wind azimuth increase (as highlighted by the red circle in Figure 10). At this wind speed, the aerodynamic interference effects of the MR disc vortex flow on the TR can be divided into two aspects. First, the concentrated vortex induces a rotating component in the disc plane of the TR, Figure 11(a) shows the velocity vector distribution on the cross section at a distance of $0.45R_{TR}$ in front of the TR plane at 50° wind azimuth angle. Given that the rotation of the TR is opposite to the concentrated vortex, this effect will increase the leading edge dynamic pressure of the TR blade, this mechanism is similar to the study of Brown [20]. A comparison of that under the 60° and 70° wind azimuths is shown in Figures 11(b) and 11(c), respectively. From the figures, the TR moves toward the side of the concentrated vortex core as the wind azimuth angle increases. Specifically, the disc vortex core at the 70° wind azimuth angle is outside the radius of the TR, and the induced speed of disc vortex increases the advancing ratio of the TR and has a positive effect on the TR performance.

6 7 8 9 10 11 12 13 14 16 17 18 19 20 21 22 23 24 26 27 28 29 30 6 7 8 9 10 11 12 13 14 16 17 18 19 20 21 22 23 24 26 27 28 29 30 (a) 50° wind azimuth case (b) 60° wind azimuth case 4 6 7 8 9 10 11 12 13 14 16 17 18 19 20 21 22 23 24 26 27 28 29 30

(c) 70° wind azimuth case

FIGURE 14: Velocity vector on the 0.1 TR radius in front of the TR disc ($V_{\infty} = 22 \text{ m/s}$).

The second aspect of the main disc vortex rotor effect in this wind speed region introduces an additional inflow at the TR disc. In comparison with the results in Figures 9 and 12, the location of the inflow peak on the TR disc increases to the level with the TR center as a result of the disc vortex moving up. As the wind azimuth increases, the angle between the disc vortex filament and TR shaft decreases, and the component of the disc vortex-induced velocity that enters the TR disc then decreases. As a consequence, the negative effect on the TR thrust force is alleviated, which causes the TR thrust to increase with the wind azimuth angle in the moderate wind speed range, and a sudden loss of yaw stability can then occur.

Moreover, in this wind speed region, the aerodynamic performance characteristic of the TR is affected by the freestream. Although the increased front crosswind speed comes with a larger intensity of the inflow stream of the TR, the TR thrust characteristics are dominated by the effect of the MR disc vortex interference in this moderate wind speed range. The TR thrust still increases with the wind speed at each wind azimuth angle.

Figure 13 shows the wake under each wind azimuth at 22 m/s wind speed. The structure of the MR disc vortex and the relative position relationship with the TR are close to the 12 m/s wind speed case. The position of the disc vortex slightly moves up, and the vortex becomes more concentrated. The velocity vector distribution over the cross-sectional fronts of the TR plane is shown in Figure 14. The in-plane component of the disc vortex still increases the leading edge dynamic pressure or the advancing ratio of TR, and the out-of-plane component still increases the TR inflow. However, given that the free stream is sufficiently large to compensate for the interference of the MR disc vortex, the effect of the crosswind velocity plays a dominant role in the characteristics of the tail performance. Therefore, the thrust of the TR decreases with the wind speed, and it



FIGURE 15: Comparison of the TR thrust results under different MR disc loadings at 60° wind azimuth.



FIGURE 16: Comparisons of the rotor wake under different MR disc loadings at 12 m/s under 60° wind azimuth.

declines with the increase in wind azimuth, thereby resuming yaw stability.

4.3. Effect of MR Disc Loading. The TR thrust coefficient obtained for MR thrust coefficients of 0.008 and 0.01 in the 60° wind azimuth case is plotted as a function of the wind speed in Figure 15. The TR thrust increases at all wind speeds for lower MR disc loading case in experimental and numerical data. Figure 16 compares the wake near the TR obtained from the CFD simulation with the wind speed of 12 m/s under two MR disc loadings. It illustrates that when the MR thrust coef-

ficient decreases, the MR disc vortex strength also decreases and the disc vortex height increases. With the reduction of the wake strength from the MR, the increase effect on the TR inflow should be weakened, thereby reducing the negative effect on the TR thrust force. Moreover, as the disc vortex moves up, the relative vertical distance between the disc vortex and the TR increases, which is similar to the lowering position of the TR. The test performed by Wiesner and Kohler [15] showed that the TR installed in the lower position exhibited a higher thrust in the front-right wind measurement area than that installed in the higher position.

5. Conclusions

Through wind tunnel tests and numerical calculations, this study analyzes the aerodynamic behaviors of the bottomblade forward-rotating TR at the high position and the evolution of flow field interference of the MR-TR under different combinations of wind azimuths and speeds in the front-right crosswind environment. The yaw stability characteristics provided by the TR are obtained, and the underlying mechanism is analyzed. The effect of the disc loading of the MR on the TR performance is also investigated. The conclusions can be drawn as follows.

- (1) The disc vortex generated by the pressure difference between the upper and lower surfaces of the MR disc has a significant aerodynamic interference effect on the TR. This interference can be divided into two aspects. On the one hand, the direction of the disc vortex is opposite to the rotation direction of the TR, which increases the dynamic pressure of the leading edge of the blade and enhances the thrust of the TR. On the other hand, the induced speed of the disc vortex enters the TR disc, which increases the inflow of the TR, thereby degrading the thrust of the TR
- (2) At a lower wind speed, the disc vortex is below the TR; it induces out-of-plane inflow velocities on the TR. The maximum TR thrust occurs at the 50° wind azimuth, and this phenomenon is caused by the free stream velocity becoming the dominant at the relatively small azimuth region. The nonmonotonic property of the TR thrust in a larger azimuth region is caused by the significant decrease in the additional inflow at the 70° wind azimuth, corresponded by the farther distance to the MR disc vortex
- (3) At the moderate wind speed region, the disc vortex moves up to the TR center with more concentration structure. The TR thrust increases with the wind speed due to the fact that the direction of the disc vortex is opposite to the TR. The TR thrust increases monotonously with the wind azimuth angle due to the decrease in the out-of-plane inflow component. Consequently, instability yaw control will be experienced by the pilot in this research region
- (4) At the higher wind speed region, the free stream is sufficiently large to offset the effect of the disc vortex, although disc vortex still exists. The thrust of the TR resumes its tendency to decrease with the increase in the crosswind speed and the wind azimuth angle. The thrust generated by the TR provides yaw stability within this research region
- (5) As the MR disc loading decreases, the vertical position of the MR disc vortex slightly moves up, and the strength of the MR disc vortex is reduced. The reduction in the inner wash and the more relative vertical distance between the concentrated vortex and TR simultaneously improve the TR thrust

(6) In the crosswind environment, the aerodynamic interference effect of the MR wake on the TR is closely related to the configuration of the TR. In the analysis of flight mechanics for a specific helicopter model, the evolution characteristics of the MR wake and its aerodynamic interference effect on the TR should be considered.

Nomenclature

- T: Rotor thrust (N)
- ρ : Air density (kg/m³)
- R: Rotor radius (m)
- A: Rotor disc area (m^2)
- C_T : Rotor thrust coefficient
- μ : Advance ratio
- ω : Rotor angular velocity (rad/s)
- V_{∞} : Free stream velocity (m/s)
- CR: Counterclockwise rotating
- MR: Main rotor
- TR: Tail rotor.

Subscripts

MR: Main rotor

TR: Tail rotor.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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