Rotor Vibratory Load Reduction by Piecewise Linear Blade Twist

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Abstract: Piecewise linear blade twist is studied as a method for reducing the rotor vibratory loads. A rotor model based on an elastic beam concept is used to predict the loads. A four-bladed rotor with a shape similar to the UH-60 rotor is used as a baseline for comparisons. The blade is divided into three segments, which are inner, middle and outer segments respectively. Effect of the twist at different segments on the loads is discussed. The twists at all the segments can reduce the 4/rev (revolution) vertical hub force at low speeds. The 4/rev force can be reduced by 99.5% with a $-24°/R$ (R is the blade radius) twist at the middle segment at 80 km/h. The twist at the inner segment is not helpful for reducing the 4/rev rolling and pitching moments, while the twists at other segments can control both the moments at most speeds. A parameter sweep is conducted to minimize these loads. To reduce the 4/rev force, all the segments need to be twisted at low speeds, while untwisted blades perform better at high speeds. For controlling the 4/rev moments, the outer segment should be highly twisted at low speeds, while high twists at the middle segment are essential at medium to high speeds.

Key words: helicopter rotors; vibratory load; piecewise blade twist; vertical hub force; rolling moment; pitching moment

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0 Introduction

The high vibratory loads of helicopter lead to a range of problems such as fatigue damage to components, reduced crew comfort, and increased maintenance costs. How to reduce the loads is one of the key technologies in helicopter design[1-6]. Helicopter rotor blades suffer from asymmetrical and periodic aerodynamic environment, which is the main source of the vibratory loads. Naturally, if the loads transferred from the rotor blades to the fuselage through the hub are reduced, the vibration problem of the helicopter would be alleviated substantially. Studies and experiments showed that the blade twist could alter the airloads applied to the blades, increase the coupling between flatwise and edgewise motion, and thus significantly influence the rotor blade loads[7-8].

One of the earliest studies concerning rotor vibratory load reduction via blade twist was conducted by Landgrebe[9]. He developed simplified procedures to predict the flapwise bending moments of helicopter rotor blades using basically linear functions, and found that the flapwise airloads included components which were proportional to twist times advance ratio squared. Ref.[10] investigated the sensitivity of the vibratory hub loads of a four-bladed articulated rotor to variations in blade parameters. It indicated that high blade twist aggravated vibration, but did not have a powerful effect on vibratory root forces. Keys et al. evaluated a 10 ft (1 ft = 0.304 8 m) diameter model rotor to quantify the effect of blade twist on flight performance and vibratory loads[11]. The result showed that the increasing blade twist increased hub

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and blade 4/rev vibratory loads. Laxman and Venkatesan analyzed the effect of pretwist (as a coupling parameter) on the rotor loads[12]. They indicated that the pretwist had a significant influence on the rotor loads, and reduced the amplitude of the hub load variations. The wind tunnel tests confirmed that highly twisted blades provided better hover performance, but higher forward flight blade loads and vibratory fixed frame hub loads[13].

Linear twist has significant limitations due to spanwise differences in the airflow. With the progress in theoretical basis, optimization methods, and computational efficiency, more and more investigations focused on the advanced nonlinear twist distribution, such as piecewise linear[14-15], Bezier curve[16-17], cubic spline[18], and so on. Mccarthy and Chattopadhyay optimized the nonlinear chord and twist distribution of the blade to reduce the vibratory shear forces at the blade root[19]. They reduced the 4/rev vertical shear by 31.2% and the 3/rev inplane shear by 22.5% simultaneously at an advance ratio of 0.3.

Although advanced nonlinear blade twist can improve rotor performance and reduce vibratory loads, it is only applicable to specific flight conditions. Therefore, the concept of active twist, which enables adjustable blade twist, has been proposed[20-22]. Micro fiber composite (MFC) actuators have emerged as a promising solution for this purpose[23-24]. By embedding MFC sheets beneath the blade skin and applying voltage, precise control over blade twist can be achieved. Previous research has mainly focused on the twist actuation that varies with azimuth[25-29]. The twist distribution along the blade span has received little attention, which is the topic of this work.

In this paper, the piecewise linear blade twist control is investigated to reduce the vibratory loads of the helicopter rotors. A validated helicopter rotor loads prediction model[20-23] is used to predict the vibratory loads. Effect of the twist at different segments of the blade on the loads is discussed. The effect of twist distribution along the blade span on vibratory loads is explained from the angle of attack distribution. A parameter sweep is conducted to enhance the potential of the nonlinear blade twist in reducing the loads.

1 Methodology

1.1 Rotor load prediction model

A comprehensive helicopter rotor model is utilized to predict the vibratory loads. The model, as described in Refs.[30-33], comprises a main rotor model, a fuselage model, a tail rotor model, and a propulsive trim method. The equation of motion of the rotor blade is derived from Hamilton's principle, including blade elastic potential energy, blade kinetic energy, and work done by the aerodynamics. The blade is divided into a series of beam elements along the blade span. The beam element consists of five nodes and fifteen degrees of freedom. The shape functions are used to determine the displacements of arbitrary points in the element.

The elastic deformation of the blade is described using a moderate deflection beam model. The beam model provides a second-order nonlinear strain-displacement relationship. Using this relationship in conjunction with the generalized Hooke's law allows the strain energy, force resultants, and moment resultants to be expressed in terms of deformation quantities. The stiffness matrix resulting from elasticity can be obtained by calculating the partial derivatives of the sectional forces and moments with respect to the generalized coordinates. The kinetic energy of the system can be calculated using the velocities of the degrees of freedom and mass distribution. The generalized force induced by the kinetic energy and the corresponding mass, damping, and stiffness matrices can be obtained. The external forces acting on the blade, such as aerodynamics, are characterized by a set of generalized distributed loads. The induced velocity field of the rotor is calculated using the Pitt-Peters inflow model[34]. The airflow velocity and angle of attack of the section can be determined by analyzing the displacement and velocity of the node along with the local induced velocity. The aerodynamic forces and moments are obtained by the look-up table method. The generalized force introduced by the aerodynamics can be calculated.

The implicit Newmark method is used to solve the equation of motion of the rotor blade. The matrices should be updated with the solved displacements during the iteration, since the matrices are obtained by the generalized displacements. The blade root vibratory loads can be obtained directly from the sectional forces of the beam element node at the root of the blade. The vibratory hub forces and moments of the main rotor are obtained by performing a Fourier transform of the resultant root forces and moments of the blade along the azimuth.

Three-force and two-moment equilibrium equations are used for propulsive trim of the helicopter, while the input variables are the collective pitch, the longitudinal cyclic pitch, the lateral cyclic pitch, the longitudinal tilt of the fuselage, and the lateral tilt of the fuselage. The required tail rotor thrust to counter the main rotor torque is determined by the torque which is divided by the distance from the hub center of the tail rotor to the main rotor shaft. The tail rotor thrust and power are obtained by performing a numerical integration over the blade elements along the blade radius and azimuth with uniform induced velocity.

1.2 Blade piecewise twist distribution

When the piecewise linear blade twist is applied, the twist distribution of the blade can be expressed as

$$\theta=\begin{cases}\theta_{\text{inr}}\bar{r} & 0\leqslant\bar{r}\leqslant\bar{r}_1\\ \theta(\bar{r}_1)+\theta_{\text{mid}}(\bar{r}-\bar{r}_1) & \bar{r}_1<\bar{r}\leqslant\bar{r}_2\\ \theta(\bar{r}_2)+\theta_{\text{out}}(\bar{r}-\bar{r}_2) & \bar{r}_2<\bar{r}\leqslant 1\end{cases} \tag{1}$$

where θ is the twist angle of the section and $\bar{r}$ the dimensionless radial coordinate; $\bar{r}_1$ and $\bar{r}_2$ are the locations of the joint points, and θ_{inr}, θ_{mid}, and θ_{out} the twist rates of the inner, middle, and outer segments of the blade, respectively.

2 Effect of Twist at Different Segments on Vibratory Loads

A four-bladed rotor is used as the baseline rotor in this work, which has the same aerodynamic shape as the UH-60 helicopter rotor[35]. The baseline flight state is for sea level and a takeoff mass of 9 474.7 kg (the corresponding mass coefficient of 0.007 4).

According to the airfoil distribution of the UH-60 rotor blade, the blade is divided into three segments with $\bar{r}_1=0.48$ and $\bar{r}_2=0.84$, as shown in Table 1. In the following analysis, the helicopter is trimmed to meet the level flight conditions with a constant takeoff mass and given forward flight speed for various blade piecewise twist schemes.

Table 1 Piecewise blade scheme

Segment	Start location	End location	Dimensionless length
Inner	0.00	0.48	0.48
Middle	0.48	0.84	0.36
Outer	0.84	1.00	0.16

2.1 Twist at the inner segment

Fig.1(a) shows the 4/rev vertical hub force (F_z), the 4/rev rolling moment (M_x), and the 4/rev pitching moment (M_y) with the forward flight speed for different twists at the inner segment. Fig.1

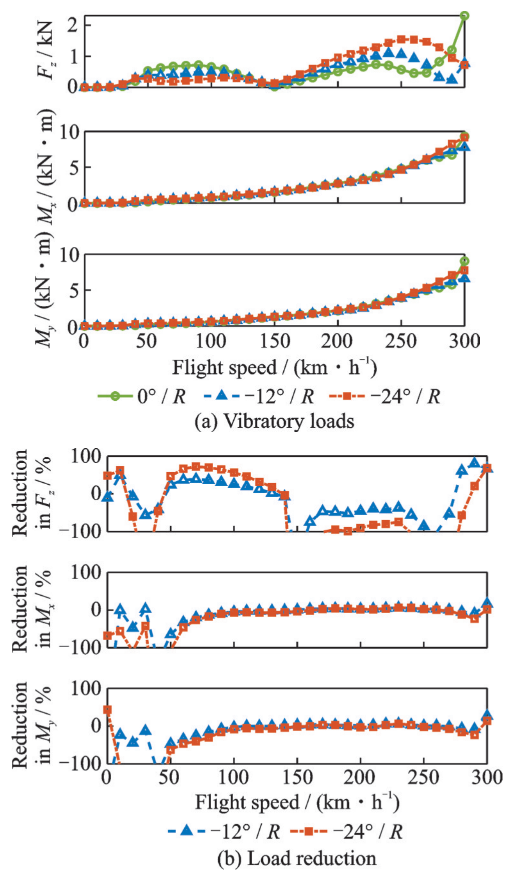
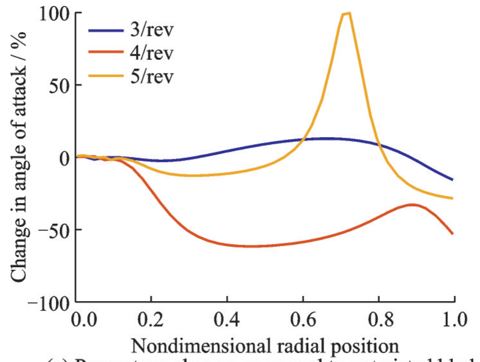


Fig.1 4/rev vibratory loads and the corresponding reduction by twist at the inner segment

(b) shows the corresponding reductions compared to the untwisted blade. At hover and low speeds, although the percentage reductions in loads vary significantly with the speed, the variations in loads have no practical significance due to the very low baseline loads. At the speeds between 50 km/h and 140 km/h, the twist reduces the 4/rev force obviously. At medium to high speeds, the twist causes an increase in the 4/rev vertical hub force. At speeds greater than 250 km/h, the baseline force increases significantly. The twist at the inner segment leads to a decrease in the 4/rev force with increasing speed, and eventually below the baseline force. At most speeds, the twist has little influence on the 4/rev rolling and pitching moments. It indicates that the twist at the inner segment is not suitable to control both vibratory moments.

Fig.2 compares the angle of attack distributions resulting from 0°/R and −24°/R twists at the inner segment of the blade at a speed of 70 km/h. At this speed, the −24°/R twist reduces the 4/rev vertical hub force by 72.51%. The angle of attack distribution of the inner blade is significantly affected by the change in twist rate of the inner segment of the blade. In the case of the untwisted blade, the angles of attack near the blade root are negative. The

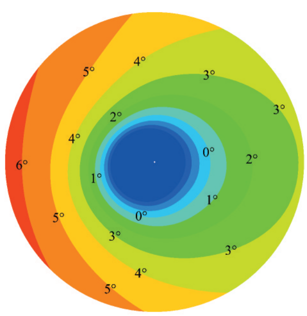


(c) Percentage change compared to untwisted blade

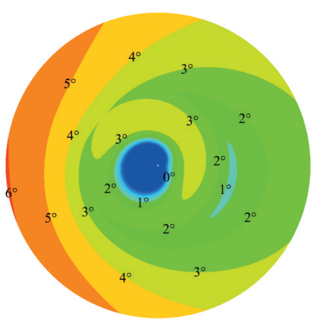
Fig.2 Angle of attack distributions at 70 km/h

−24°/R twist increases the angle of attack of the inner part of the blade. The 4/rev change in the angle of attack along the azimuth is reduced by about 50% for most blade sections. This reduction leads to a decrease in the 4/rev lift of the blade, which reduces the vibratory vertical hub force.

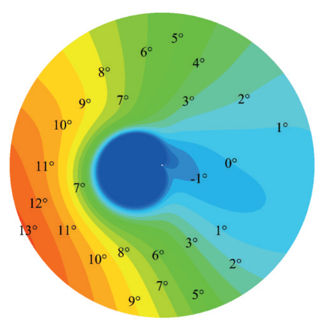
Fig.3 compares the angle of attack distributions of the two cases at a speed of 250 km/h. The −24°/R twist increases the angle of attack near the root of the advancing blade, and reduces the high order change in the angle of attack along the azimuth at those positions. While the twist causes a large increase in the 4/rev angle of attack at the radial positions between 0.6 and 0.85. This introduces higher-order aerodynamics, and results in higher vibratory loads.



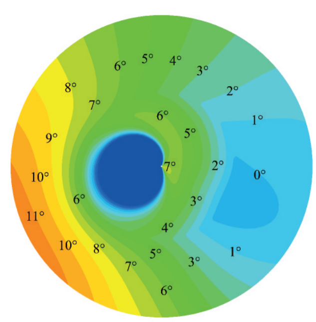
(a) Untwisted blade



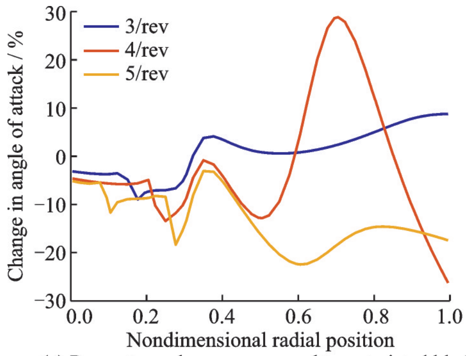
(b) −24°/R twist at the inner segment



(a) Untwisted blade



(b) −24°/R twist at inner segment

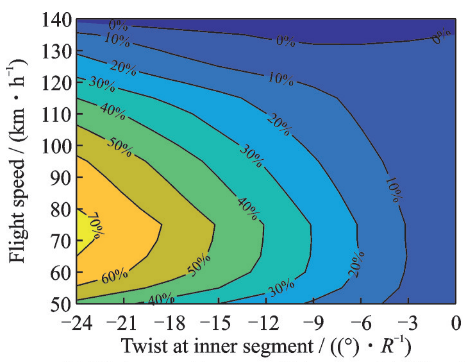


(c) Percentage change compared to untwisted blade

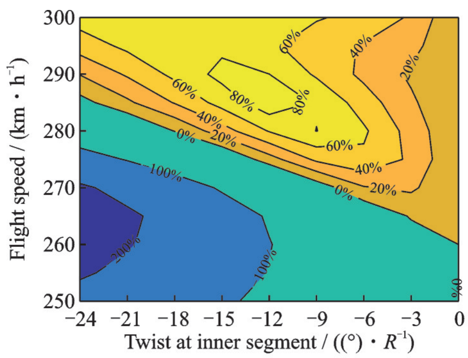
Fig.3 Angle of attack distributions at 250 km/h

Fig.4(a) shows the reduction in the 4/rev vertical hub force with the twist and the flight speed. The speed varies from 50 km/h to 140 km/h. In the twist range from 0 to $-24°/R$, higher twist leads to larger force reduction. The force reduction increases and then decreases with the speed. The maximum force reduction is obtained at 70 km/h. At the speed, a twist of $-24°/R$ at the inner segment can reduce the 4/rev force by 72.5%.

Fig.4(b) shows the reduction at the speeds between 250 km/h and 300 km/h. At the speeds, the reduction changes significantly with the twist. The twist can reduce the 4/rev force at the speeds exceeding 260 km/h. The optimal twist becomes higher with the increasing speed. The maximum reduction occurs at 290 km/h. At the speed, a twist of $-15°/R$ at the inner segment can reduce the 4/rev force by 86.4%.



(a) Flight speed between 50 km/h and 140 km/h

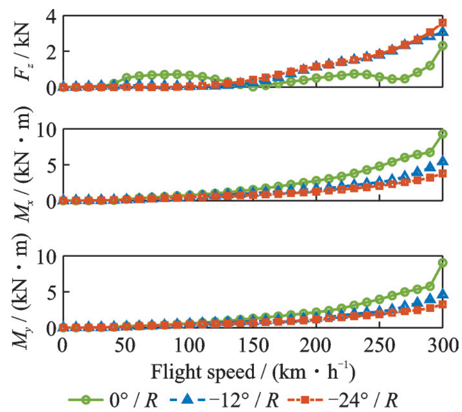


(b) Flight speed between 250 km/h and 300 km/h

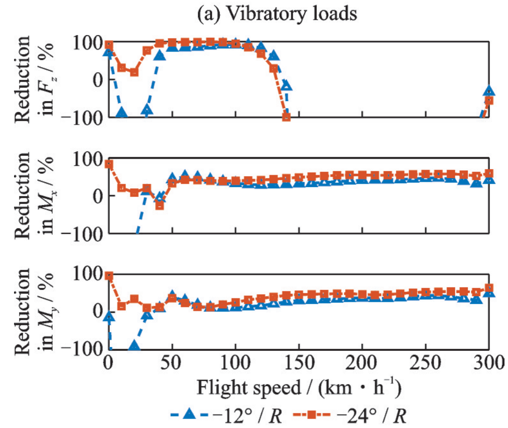
Fig.4 Reduction in the 4/rev vertical hub force by twist at the inner segment

2.2 Twist at the middle segment

Fig.5 shows the 4/rev vibratory loads with the forward flight speed for different twists at the middle segment of the blade. The twist reduces the 4/rev vertical hub force at low to medium speeds, but increases the force significantly at high speeds. The twist also decreases the 4/rev rolling and pitching moments at medium to high forward flight speeds.



(a) Vibratory loads



(b) Reduction in loads

Fig.5 4/rev vibratory loads and the corresponding reduction by twist at the middle segment

Fig.6(a) shows the angle of attack distribution resulting from the $-24°/R$ twist at the middle segment at the speed of 250 km/h, and Fig.6(b) illustrates the percentage change in the high-order angle of attack compared to the untwisted blade. The twist actuation reduces the 3/rev angle of attack for most positions of the blade and the 5/rev angle of at-

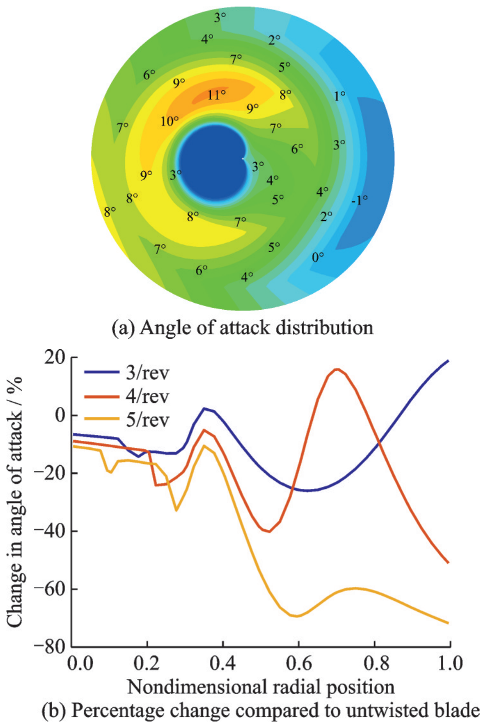


Fig.6 Angle of attack distribution at 250 km/h resulting from $-24°/R$ twist at the middle segment

tack for the entire blade, leading to a decrease in the 3/rev and 5/rev moments at the blade root and, consequently, the 4/rev hub moments. Although the 3/rev angle at the blade tip increases, the angle of attack of the retreating blade tip decreases from over 13° (shown in Fig.3(a)) to around 8°. The stall at the retreating blade tip is significantly reduced, implying a substantial decrease in higher-order aerodynamic forces and moments near the blade tip.

Fig.7 shows the 4/rev force reduction with the speed and the twist at low to medium speeds. For the negative twists less than $9°/R$, the reduction hardly changes with the speed. The negative twist over $12°/R$ can reduce the 4/rev force by more than 90% in the speed range of 50 km/h to 110 km/h. Once the speed exceeds 120 km/h, the force reduction decreases rapidly with the increasing speed. The maximum force reduction is obtained at 80 km/h. The twist of $-24°/R$ brings a 99.5% reduction at the speed.

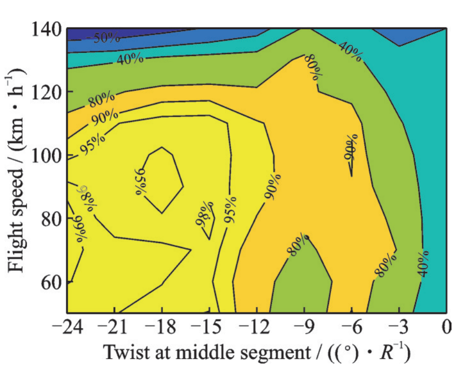


Fig.7 Reduction in the 4/rev force by twist at the middle segment

Fig.8 shows the 4/rev rolling moment reduction with the speed and the twist. It is obvious that higher twist leads to lower 4/rev rolling moment. The moment reductions of the highly twisted blades increase with the increasing speed, and reach maximum at 270 km/h. A $-21°/R$ twist at the middle segment decreases the 4/rev moment by 58.3% at the speed. The moment reductions of the lowly to moderately twisted blades are insensitive to the speed.

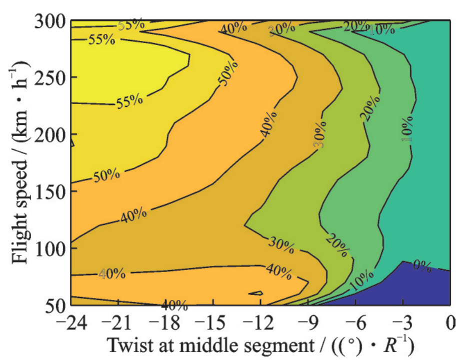


Fig.8 Reduction in the 4/rev rolling moment by twist at the middle segment

Fig.9 shows the 4/rev pitching moment reduction with the speed and the twist. Compared to the rolling moment reduction, the reduction in the 4/rev pitching moment varies more significantly with

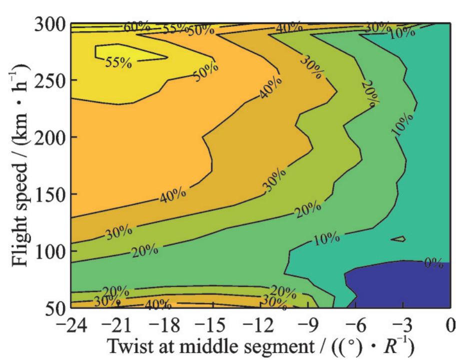


Fig.9 Reduction in the 4/rev pitching moment by twist at the middle segment

the speed at low speeds. The pitching moment reduction is also slightly lower than that of the other moment at most speeds.

2.3 Twist at the outer segment

Fig.10 shows the 4/rev vibratory loads and the corresponding reductions with the forward flight speed for different twists at the outer segment of the blade. The effect of the twist at the outer segment on the 4/rev vertical hub force is similar to that of the twist at the middle segment at low to medium speeds, while moderate twists could reduce the 4/rev force at high speeds. The percentage reductions in the vibratory moments due to the twist at the outer segment are slightly smaller than that at the middle segment, which may be related to the shorter length of the outer segment.

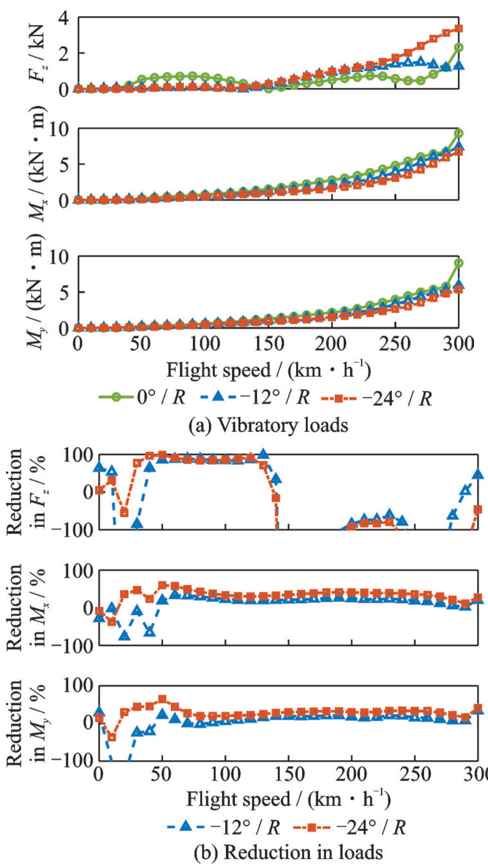


Fig.10 4/rev vibratory loads and the corresponding reduction by the twist at the outer segment

Fig.11 shows the 4/rev force reduction with the speed and the twist at high speeds. The high twist would increase the vibratory force at the speeds. The twist can reduce the 4/rev force at the speeds above 260 km/h. As the negative twist increases, the force reduction increases first and then decreases. At the speed of 290 km/h, a twist of $-6°/R$ at the outer segment makes the maximum force reduction, which reaches 88.9%. It indicates that the moderate twists at the outer segment can effectively reduce the 4/rev vertical hub force at high speeds.

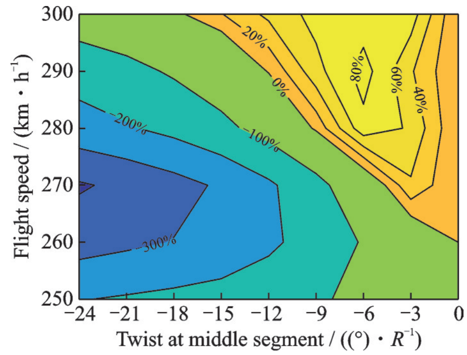


Fig.11 Reduction in the 4/rev vertical hub force by the twist at the outer segment at high speeds

Fig.12 shows the reductions in the 4/rev vibratory moments due to the twist at the outer segment. Only high twists can reduce the 4/rev moments at low speeds, while any twist will lead to the reduc-

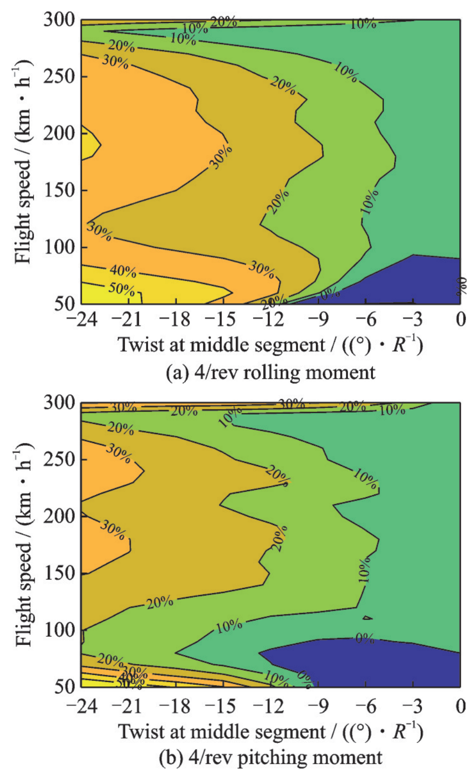


Fig.12 Reduction in the 4/rev rolling and pitching moments by the twist at the outer segment

tions at medium to high speeds. The blades with higher twist suffer from lower moment loads. The reduction in the 4/rev rolling moment due to the twist is larger than that in the 4/rev pitching moment. The pitching moment reduction varies more significantly with the speed.

3 Piecewise Linear Blade Twist

To minimize the vibratory loads, a parameter sweep method is used to find the optimal piecewise twist at each forward flight speed. The flight speed varies from hover to 300 km/h with an increment of 10 km/h. The negative twist at each segment ranges between 0 and 24°/R. An initial piecewise twist scheme is obtained by sweeping the twist at 3°/R intervals. Based on this scheme, the final twist scheme is obtained by scanning the twist at intervals of 1°/R around the values in the initial scheme, which minimizes the three vibratory loads at each speed respectively.

Fig.13 shows the optimal piecewise twist scheme for reducing the 4/rev vertical hub force at various forward flight speeds. The second subfigure compares the vibratory forces resulting from the optimal piecewise twist with those resulting from conventional linear twists, including the untwisted scheme. The third subfigure shows the corresponding reductions in the vibratory force of the optimal twist compared to the conventional linear twists. Overall, the optimal piecewise linear blade twist scheme is consistent with the expectation of the previous analysis of single-segment blade twist. All the blade segments need to be twisted at low speeds. The middle segment requires a higher twist than the other segments. The twist is no longer desired as the speed increases. At medium to high speeds, the 4/rev force of the untwisted blade is the lowest. A slight twist at the inner and outer segments can result in a significant reduction in the 4/rev force at high speeds. By the piecewise twist scheme, the 4/rev force reductions of 91.8%, 95.5%, and 95.8% are obtained compared to the untwisted, −12° linear twisted, and −18° linear twisted blades, respectively.

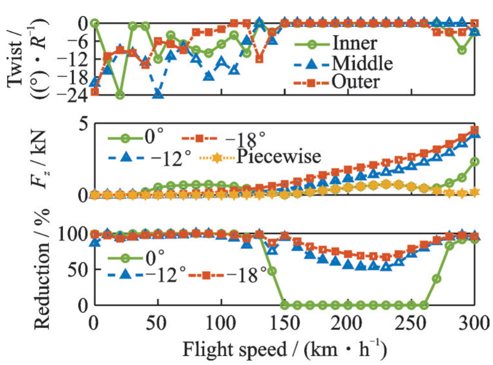


Fig.13 Piecewise twist scheme for the 4/rev vertical hub force

Fig.14 and Fig.15 show the piecewise twist schemes used to reduce the 4/rev rolling and pitching moments at different forward flight speeds. The comparisons with the conventional linear twists are shown in the second and third subfigures. To reduce the harmonic moments, the inner segment does not need to be twisted at most speeds. The middle segment does not require twist at low speeds, and requires a high twist at medium to high speeds. The outer segment should be highly twisted at low to medium speeds, and untwisted at high speeds. Com-

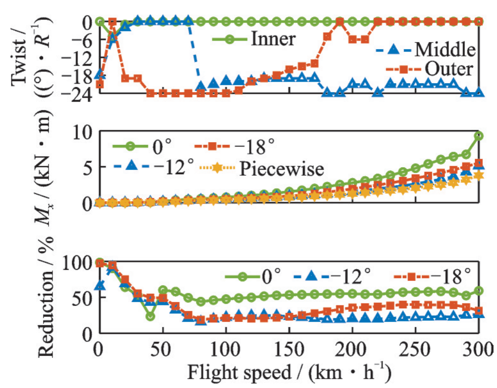


Fig.14 Piecewise twist scheme for the 4/rev rolling moment

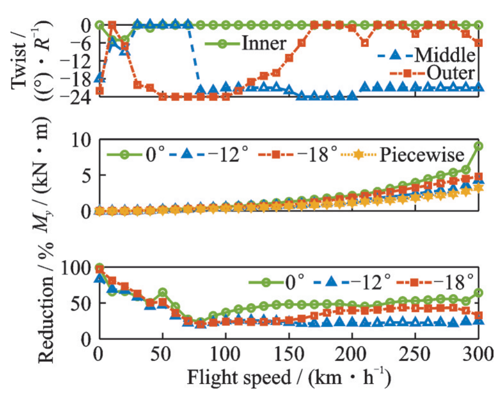


Fig.15 Piecewise twist scheme for the 4/rev pitching moment

pared to the untwist and common linear twists, the piecewise linear twist reduce the 4/rev rolling and pitching moments at hover. As the speed increases, the reductions decrease gradually and remain stable at the speeds exceeding 80 km/h.

4 Conclusions

This work focused on the investigation of the effect of the piecewise linear blade twist control on the rotor vibratory load reductions. A validated helicopter model is used to explore the blade twist in controlling the 4/rev vertical hub force, and the 4/rev rotor rolling and pitching moments for a four-bladed rotor. Effects of the twists at different segments of the blades on the loads are discussed, and explained from the angle of attack distribution. A parameter sweep is conducted to enhance the potential of the blade twist in controlling these harmonic loads. The analysis yielded the following conclusions:

(1) The twists at all the segments help reduce the 4/rev vertical hub force at low speeds. Among them, the twist at the middle segment is the most effective. At a speed of 80 km/h, the 4/rev force can be reduced by 99.5% with a $-24°/R$ twist at the middle segment.

(2) Moderate twists at the inner and outer segments can reduce the 4/rev vertical hub force at high speeds.

(3) It is not beneficial to twist the inner segment of the blade for reducing the 4/rev rolling and pitching moments.

(4) The twists at the middle and outer segments can reduce the 4/rev rolling and pitching moments at most speeds. The twist at the middle segments is more effective at high speeds, while the twist at the outer segment leads to larger reduction at low speeds.

(5) To minimize the 4/rev vertical hub force at low speeds, all the segments need to twisted. The twist at the middle segment should be higher than that at the other segments.

(6) Untwisted blades suffer from lower 4/rev force at medium to high speeds. Slight twists at the inner and outer segments are necessary at very high speeds for the 4/rev force reduction.

(7) To minimize the 4/rev rolling and pitching moments, high twists at the outer segment are helpful at low speeds, while high twists at the middle segment are essential at medium to high speeds.

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Author contributions Mr. **ZHANG Yuhang** designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Prof. **HAN Dong** provided data and model components for the rotor model, contributed to the discussion and background of the study. All authors commented on the manuscript draft and approved the submission.

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桨叶分段线性扭转对降低旋翼振动载荷的作用分析

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摘要：研究了用桨叶分段线性扭转来降低旋翼振动载荷。使用基于弹性梁的旋翼模型用于预测旋翼振动载荷。采用4片桨叶旋翼作为基准旋翼,桨叶形状与UH-60直升机桨叶相似。桨叶被划分为内、中、外3段,讨论了各段扭转对载荷的影响。低速时桨叶每一段的扭转都能减少桨毂四阶垂向力。当以80 km/h前飞时,中段$-24°/R$的扭转可使其降低99.5%。桨叶内段的扭转不利于降低桨毂四阶滚转和俯仰力矩,另外两段的扭转则可以在大多数前飞速度时控制这2个振动力矩。使用参数扫描以尽可能降低旋翼振动载荷。降低四阶垂向力方面,低速时桨叶所有段都需要扭转,而高速时未扭转的桨叶表现更好。降低四阶滚转和俯仰力矩方面,在低速时需要桨叶外段高度扭转,而在中高速时则需要桨叶中段的扭转。

关键词：直升机旋翼;振动载荷;分段桨叶扭转;桨毂垂向力;滚转力矩;俯仰力矩