Design and Realization of New Conceptual Collectible Rotor for Compound Aircraft

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A compound aircraft with a collectible rotor has the ability of vertical take-off and landing (VTOL), high-speed flight and long-range cruising. Compared to systems in other compound aircraft, the collectible rotor can work as a conventional rotor in helicopter mode and can be gathered into a disk in the center in fixed-wing mode, thereby relieving the rotor’s limitations pertaining to forward flight performance. The collectible rotor is a key component in the design and realization of a compound aircraft. Based on a 35-kg-level prototype, in this study, the principle of a folding rotor is proposed, a dynamic model of the rotor is established considering the complex nonlinear compound motion of rotation and folding, and the aerodynamic and dynamic characteristics are analyzed considering the coupling of different speeds of the rotor and folding strategies for the folding process. According to the above research, a complete rotor system, including an unconventional rotor structure, closed-loop real-time control system, and high-torque driving system, is designed. A demonstration model was constructed to verify the feasibility of the folding rotor. Finally, through an on-board test, the folding rotor system was verified in a simulated real flight state. This paper provides a theoretical basis for folding rotor design and proposes a set of design methods and research concepts.

Key Words: Compound Aircraft, Collectible Rotor, Folding Rotor Design and Realization, On-board Test

Nomenclature

\( a_h \): the absolute acceleration of any point on the hub part
\( a_m \): the absolute acceleration of any point on the middle part
\( a_o \): the absolute acceleration of any point on the blade part
\( f \): force
\( L \): the moment of momentum
\( m \): mass
\( M_{O_H} \): the moment equation for the rotor shaft
\( M_{O_I} \): the moment equation for the internal joint
\( M_{O_O} \): the moment equation for the external joint
\( t \): time
\( v \): velocity
\( v_h \): the absolute velocity of any point on the hub part
\( v_m \): the absolute velocity of any point on the middle part
\( v_o \): the absolute velocity of any point on the blade part
\( \omega_h \): angular speed of the rotor shaft
\( \omega_I \): angular speed of the internal joint
\( \omega_O \): angular speed of the external joint

Superscript

c: Coriolis
e: frame
r: relative

Subscript

h: the hub part
is: the middle part
IS: the internal joint
os: the blade part
OS: the external joint

1. Introduction

Compound aircraft generally have vertical take-off and landing (VTOL), high-speed flight and long range cruise capabilities. Such aircraft combine the advantages of helicopters and fixed-wing aircraft, enabling them to perform a wide variety of tasks in a faster and more flexible manner.

Compound aircraft primarily consist of compound helicopters and tilt-rotor aircraft. Compound helicopters possess wings and a propulsion system to provide additional lift and thrust to offload the rotor and increase the maximum achievable speed. However, the simple combination of a helicopter and a fixed wing does not eliminate the limitations of the rotor pertaining to flight performance. Some compound helicopters, such as the advancing blade concept (ABC) rotor system,1,2 use an unconventional rotor to improve the flight performance and incorporate a rigid rotor that can be stopped to enable a fixed-wing.3 These two kinds of rotors overcome the limitation of the rotor, but the ABC rotor system does not solve the problem of the shockwave drag caused by the blade tip when the flight speed is further increased. Therefore, such systems cannot satisfy the requirement for high-speed helicopters.

Another type of compound aircraft is the tilt-rotor aircraft, such as the V-22. The rotors on the wings can be used as heli-
copter rotors or fixed-wing propellers under different flight modes by tilting the rotors. With this layout, however, the wing structure is complex: to ensure sufficient strength and stiffness, the wingspan cannot be too long and the wing string length cannot be excessively small, which limits the aspect ratio. Therefore, it is difficult to fully exploit the advantages of the fixed wing. In addition, there are still a multitude of problems left unresolved in terms of complex control systems.\textsuperscript{4-6)}

To fully realize high hovering efficiency in the helicopter mode and cruise efficiency in the fixed-wing mode, the concept of a collectible rotor has emerged. The collectible rotor can work as a traditional rotor in the helicopter mode and can be gathered into a disc in the center in the fixed-wing mode, which can relieve the limitation of the rotor pertaining to flight performance. This capacity is beyond the reach of other types of existing compound aircraft. At present, there are few studies on compound aircraft with a collectible rotor; mainly including the RD-15,\textsuperscript{7)} shown in Fig. 1, proposed by the Nanjing University of Aeronautics and Astronautics and the high-speed “DiscRotor” concept aircraft jointly proposed by DARPA and Boeing, shown in Fig. 2.

The key technological aspects and difficulties associated with the collectible rotor correspond to the realization of a collectible rotor and the primary factors that restrict the collection process. However, these aspects have not been advanced in existing research. A folding rotor system for a compound aircraft was thus proposed by the “Air Team” of Beihang University to fill this gap in knowledge. The rotor can be collected into a disc in the center in the fixed-wing mode. The principle of the folding rotor is proposed herein: a dynamic model of the rotor is established considering the compound motion of rotation and folding, and the aerodynamic forces and folding strategy are analyzed. Finally, to verify the feasibility of the folding rotor scheme and the validity of the theoretical analysis, a scaled folding rotor system model is designed and evaluated using an on-board test, thereby providing a probable approach and theoretical foundation for the design of a folding rotor.

The basic parameters of the scaled folding rotor system model are based on a 35-kg-level compound aircraft with a vectored tail rotor recently developed by the “Air Team” of Beihang University, as shown in Fig. 3.

The prototype weighs 35 kg and is equipped with a vectored tail rotor, which can balance torque and provide thrust. During the folding or spreading process of the rotor system, the prototype is in the minimum level flight state, the lift and control of the prototype are almost entirely provided by the fixed wing and control surfaces. According to the design parameters, the plane’s minimum flight speed is 10 m/s.

2. Research on the Collectible Rotor Scheme

2.1. Principle of a collectible rotor

Two basic schemes involving a telescopic rotor and a folding rotor, as shown in Fig. 4, are discussed herein.

The telescopic rotor has a long straight stroke and a small extension rate (i.e., percentage of disc diameter to rotor diameter), which is only 50% in theory. By comparison, the extension rate of a folding rotor can reach nearly 60%, and the rotational motion is easier to achieve. Therefore, in this study, the collectible rotor is realized using the folding mode, which divides the rotor into three parts: the hub, blade and middle. The rotor system is a articulated rotor. The flapping hinge, drag hinge and pitch hinge are set in the hub. A joint exists between the hub and the middle, which we call the internal joint in this paper. The external joint is the joint between the middle and the blade. When the folding rotor works as a traditional rotor in helicopter mode, each part is unfolded in a straight line. There are four openings on the disc, which can meet the requirements of rotor flapping, lead-lag and pitch. When the rotor is not needed in fixed-wing flight mode, it is folded into a disc by rotating the joints.

The principles of the folding rotor and the folding process are shown in Figs. 5 and 6.
The folding rotor allows the blade to always pass through a fixed point when the disc is used as a reference system. Therefore, the disc simply needs to open four holes to allow the blades to pass through. This modification is a minor change to the disc, and thus, the aerodynamic efficiency in the fixed-wing mode is not significantly affected.

The flight process of the compound aircraft is as follows:

The aircraft takes off vertically in helicopter mode and then continuously increases forward speed using the tail propeller. When the lift and control of the aircraft are almost entirely provided by the fixed wing and control surfaces, the rotor starts folding. Finally, the aircraft switches to fixed-wing mode.

### 2.2. Dynamic model of a folding rotor

According to the principle of a folding rotor, a model and reference frames for a single rotor arm, shown in Fig. 7, were established: these included an inertial frame and three fixed-component reference frames (i.e., hub, inside and outside).

The inertial reference frame is fixed to the Earth. The origin $O_I$ is located at a point on the rotor shaft. $X_I$ points toward the initial direction of the hub, and $Z_I$ points along the direction of gravity. $Y_I$ is determined using the right-hand rule. The hub reference frame is fixed to the hub. The origin $O_H$ is located at the center of the rotor, and $X_H$ points toward the direction of the hub. The inside reference frame is fixed to the middle section. The origin $O_{IS}$ is located at the internal joint, and $X_{IS}$ points toward the direction of the middle section. The outside reference frame is fixed to the blade section. The origin $O_{OS}$ is located at the external joint, and $X_{OS}$ points toward the direction of the blade section. The $Z$ axes of all of three fixed-component reference frames are perpendicular to the plane of the rotor, and all the $Y$ axes are determined using the right-hand rule.

Consider an infinitesimal volume of each component. Their position vectors in the different reference frames are shown in Fig. 8.

According to Newton’s second law, the equation for an element $dm$ is expressed as

$$\frac{d}{dt}(\vec{v}dm) = \vec{f}$$  \hspace{1cm} (1)

By integrating the above expression over all parts, we obtain...
The absolute velocity of any point on the blade section is

$$\bar{v}_{i} = \bar{v}_{i} + \bar{v}_{h} = \bar{v}_{i} + \bar{v}_{h}$$

The absolute acceleration of any point on the blade section is

$$\bar{a}_{i} = \bar{a}_{i} + \bar{a}_{h} = \bar{a}_{i} + \bar{a}_{h}$$

By integrating, we obtain

$$\int_{\text{outside}} \bar{f} = \int_{\text{outside}} \frac{d\bar{v}_{i}}{dt} \bigg|_{i} \, dm$$

Subsequently, we deduce the expression of moment via the moment of momentum theorem for a particle system. Consider the moment of the rotor shaft as an example. The moment of momentum of the particle system at a fixed point is

$$\bar{L} = \sum_{i=1}^{n} (\bar{r}_{i} \times m_{i}\bar{v}_{i})$$
tion, the middle section and the blade section. First, an expression for the moment of momentum of the three sections with respect to the rotor shaft is obtained.

The moment of momentum of the hub section with respect to the rotor shaft is

\[
\hat{L}_{Oh} = \int_{Oh} (\vec{p}_h \times d\vec{\nu}_h)
\]

(18)

The moment of momentum of the middle section with respect to the rotor shaft is

\[
\hat{L}_{O\text{in}} = \int_{\text{in}} ((\vec{p}_{\text{HIS}} + \vec{p}_{\text{I}}) \times d\vec{\nu}_{\text{I}})
\]

(19)

The moment of momentum of the blade section with respect to the rotor shaft is

\[
\hat{L}_{O\text{out}} = \int_{\text{out}} ((\vec{p}_{\text{HIS}} + \vec{p}_{\text{ISOS}} + \vec{p}_{\text{ost}}) \times d\vec{\nu}_{\text{ost}})
\]

(20)

In summary, the moment of momentum of the rotor shaft is

\[
\hat{L}_{O} = \hat{L}_{Oh} + \hat{L}_{\text{in}} + \hat{L}_{\text{out}}
\]

(21)

\[
= \int_{\text{hub}} (\vec{p}_h \times d\vec{\nu}_h) + \int_{\text{inside}} ((\vec{p}_{\text{HIS}} + \vec{p}_{\text{I}}) \times d\vec{\nu}_{\text{I}})
\]

\[
+ \int_{\text{outside}} ((\vec{p}_{\text{HIS}} + \vec{p}_{\text{ISOS}} + \vec{p}_{\text{ost}}) \times d\vec{\nu}_{\text{ost}})
\]

According to the moment of momentum theorem, by differentiating the moment of momentum with respect to time, we obtain

\[
\hat{M}_{O} = \int_{\text{hub}} \left( \frac{d\vec{L}_{Oh}}{dt} \right) dm
\]

\[
+ \int_{\text{inside}} \left( \vec{p}_{\text{HIS}} + \vec{p}_{\text{I}} \right) \times \frac{d\vec{\nu}_{\text{I}}}{dt} dm
\]

\[
+ \int_{\text{outside}} \left( \vec{p}_{\text{HIS}} + \vec{p}_{\text{ISOS}} + \vec{p}_{\text{ost}} \right) \times \frac{d\vec{\nu}_{\text{ost}}}{dt} dm
\]

(22)

Similarly, the moment equation for the internal joint is

\[
\hat{M}_{O\text{I}} = \frac{d\hat{L}_{O\text{I}}}{dt} + \vec{p}_{\text{ISCG}} \times M_{O\text{I}} \vec{a}_{\text{ISCG}}
\]

\[
+ \frac{d\hat{L}_{\text{O\text{out}}}}{dt} + \left( \vec{p}_{\text{ISOS}} + \vec{p}_{\text{OSCG}} \right) \times M_{O\text{I}} \vec{a}_{\text{OSCG}}
\]

In this manner, the moment equations for the rotor shaft, internal joint and external joint are established.

### 2.3 Calculation of aerodynamic force

In the process of folding and spreading, because of the change in the exposed length and chord of the blade, the lift and resistance change continuously, as shown in Fig. 9. Thus, investigating the variation in lift and resistance over time is of great significance in the design of such an aircraft.

In this study, the blade element theory is used to obtain the lift and resistance of the blade element. The results are as follows:

\[
dT = \frac{1}{2} \rho C_L \cdot c \cdot (\omega r)^2 dr
\]

(25)

\[
dD = \frac{1}{2} \rho C_D \cdot c \cdot (\omega r)^2 dr
\]

(26)

The chord and exposed length vary with the angle of the joint. Using the sine and cosine theorems, we obtain

\[
c = c_0 \left\{ \sin \left( \frac{\pi}{2} - \arcsin \left[ 2 \cdot l_{\text{I}} \sin \left( \frac{\alpha}{2} \sin \left( \frac{\pi + \alpha}{2} \right) \right) \right] \right) \right. 
\]

\[
\left. \sqrt{(R - l_h - l_{\text{I}})^2 + \left( 2 \cdot l_{\text{I}} \sin \left( \frac{\alpha}{2} \right) \right)^2 - 2 \cdot (R - l_h - l_{\text{I}}) \cdot 2 \cdot l_{\text{I}} \sin \left( \frac{\alpha}{2} \right) \cos \left( \frac{\pi + \alpha}{2} \right) \right] \right\}
\]

(27)
3. Analysis of the Folding Process

In this section, the variation characteristics of the aerodynamic forces and moment of the joints are analyzed. According to the principle of a collectible rotor, as shown in Fig. 10, we obtain the relationship of the angles between the internal and external joints:

\[
\begin{align*}
L &= \left[ l_{\text{tot}} - \sqrt{(R - l_h - l_{is})^2 + \left(2 \cdot l_{is} \sin \left(\frac{\alpha}{2}\right)\right)^2 - 2 \cdot (R - l_h - l_{is}) \cdot 2 \cdot l_{is} \sin \left(\frac{\alpha}{2}\right) \cos \left(\frac{\pi + \alpha}{2}\right)}\right] \\
&\cdot \cos \left(\arcsin \left[\frac{2 \cdot l_{is} \sin \left(\frac{\alpha}{2}\right) \sin \left(\frac{\pi + \alpha}{2}\right)}{(R - l_h - l_{is})^2 + \left(2 \cdot l_{is} \sin \left(\frac{\alpha}{2}\right)\right)^2 - 2 \cdot (R - l_h - l_{is}) \cdot 2 \cdot l_{is} \sin \left(\frac{\alpha}{2}\right) \cos \left(\frac{\pi + \alpha}{2}\right)}\right]\right)
\end{align*}
\]

(28)

It can be seen that when the angle of the internal joint is known, the other angle can be determined. If we specify the change rule of the internal joint angle, we can obtain a folding rule called the folding strategy. Therefore, a variety of folding strategies can be obtained by changing the regularity of the internal joint angle. The internal joint angle generally changes as follows: The angular velocity accelerates from zero to a certain speed, then remains unchanged, and finally rapidly changes to zero. The whole process can be divided into the acceleration and uniform sections. Accordingly, the variation of aerodynamic force and the moment of the joints can be obtained for different folding strategies.

For the case in which the total time is fixed and the time of the acceleration section varies, the curves of the resulting change in lift and resistance are shown in Fig. 11.

According to the results, the lift produced by the rotor is less than 1 N, which is about 0.29% of the gravity of the prototype. This means that in the process of rotor folding or spreading, the prototype does not need the rotor to provide any aerodynamic force or control.

The folding process takes a total of 30 s, and the time of the acceleration section ranges from 1 to 25 s. The overall trend of the curve shows that the lift and resistance first decrease rapidly and later gradually decrease to zero. As the time for acceleration increases, the overall trend of the curve becomes more gradual; moreover, the impact of the acceleration time on the trend of the curve decreases.

For the case in which the total time is fixed and the time of the acceleration section varies, curves for the resulting moment of the joints are shown in Fig. 12.

The folding process takes a total of 30 s, and the time used for acceleration ranges from 1 to 25 s. The moment of the external joint is greater than that of the internal joint. With a change in folding strategy, the maximum moment remains nearly constant, and the occurrence of the maximum value point is delayed as acceleration time increases.

For the case in which the time of the acceleration section is fixed and the total time varies, curves for the resulting moment of the joints are shown in Fig. 13.

The time of the acceleration section is 10 s, and the total time ranges from 30 to 80 s. As in the previous case, the magnitude of the maximum moment remains constant, and the occurrence of the maximum value point is delayed as total time increases.

Thus, it can be seen that the folding strategy has only a slight effect on the moment value of the joints, and there is almost no constraint on the design of the drive systems.
It can be seen that the speed of the rotor shaft is also an important factor influencing the moment of the joints. Curves for the moment of the joints at different rotor shaft speeds are shown in Fig. 14.

For a given folding strategy, the speed of the rotor shaft ranges from 60 to 1200 rpm. As the speed increases, the moment of the joints increases in a pronounced manner, and the amplitude increases gradually. It can be seen from the above analysis that the speed of the rotor shaft is the primary factor influencing the moment of the joints.

The relationship between the rotor speed and maximum moment of the internal joint can be obtained, as shown in Fig. 15.

In the design of the folding rotor, the driving system can also be designed, and the motor can be selected based on the above curve.

4. Design of the Folding Rotor System

The folding rotor system primarily includes a control system, driving system, structural system and so on. The control system is vital in ensuring the process of folding. Its schematic is shown in Fig. 16.
The system controls the motor through a single-chip microcomputer (SCM) and implements closed-loop control using feedback of the actual angle from the angle sensors.

A simulation model of the control system is established, as shown in Fig. 17.

The expected angle of the internal joint is considered as the input, and the output is the actual angles of the internal and external joints. A PID controller and motor link are added to the system.

For a total folding time of 30 s, the angle of the internal joint varies from 0 to 120 deg. The results obtained from the simulation are shown in Fig. 18.

It can be seen from the above curve that the actual angles are highly consistent with the angles predicted by the PID controller, demonstrating that the control system is reasonable and feasible.

The driving system is mainly composed of the motor, positioning controller, and worm gears, shown in Fig. 19. The maximum torque that can be provided is 4 N·m, enabling the rotor system to fold at a speed of approximately 200 rpm, according to the curve shown in Fig. 15. The positioning controller receives instructions from the SCM to control the motor. Each joint is rotated by a pair of worm gear and motor.

The structural system is designed in accordance with the folding principle, including the double-deck hub, middle section, blade section, disc section and the platform for installing accessories. The system is complex and different from that of a conventional rotor, produced through multiple iterations of manufacture, assembly and testing.

The overall structure and a mockup are shown in Figs. 20 and 21. The diameter of the rotor is 1500 mm. The diameter of the disc is 700 mm.

The double-deck hub, shown in Fig. 22, is designed to prevent structural interference caused by rotor folding and to improve the extension rate.

The middle section, shown in Fig. 23, is one of the most important and complex parts of the folding rotor system. This component connects the hub and the blade sections, and is equipped with driving motors, the transmission and angle sensors.

One of the rotor arms with accessories is shown in Fig. 24. An envelope framework is used for the disc structure, as shown in Fig. 25. There are four openings in the disc, which can meet the needs of cyclic pitch control of the blade.

The platform for installing accessories, such as positioning controllers, batteries, the SCM, an instruction receiver and voltage transfer module, is shown in Fig. 26. It is installed on top of the rotor shaft.

5. Verification of the Folding Rotor Project

A ground test and on-board test were conducted to verify the folding rotor system. According to the curve in Fig. 15 and the maximum torque provided by the driving system, the maximum speed of the folding rotor system designed in this work is approximately 200 rpm.

The ground test was carried out primarily to evaluate the folding process under the rotating state of the rotor shaft.
To verify the feasibility of the rotor and accuracy of the theoretical analysis in Section 5, the complete folding operation was carried out at speeds of 50, 100, 150 and 200 rpm. Snapshots of key moments in the test are shown in Fig. 27.

The ground test shows that the proposed system can realize rotor folding independently and precisely while the rotor shaft is spinning. When the speed of the rotor is more than
200 rpm, a delay phenomenon occurs in the folding process, which is in agreement with the design expectations.

Because the folding rotor system cannot be integrated into the prototype, the on-board test shown in Fig. 28, was designed and conducted in order to simulate the working conditions of the folding rotor system in an actual flight environment. This is an effective, low-cost simulation test, as proved by this demonstration. The height between the floor of the car and the rotor model is 2000 mm. The front and floor of the vehicle have little effect on the rotor model because of the relatively small forward and rotor speeds.

The rotor folding and spreading occurs when the prototype switches between the helicopter mode and fixed-wing mode. The prototype is in the slowest level flight state and does not require high forward and rotor speeds. The minimal flight speed of the prototype is 10 m/s according to the prototype performance. Thus, the maximum speed of the carrier vehicle is set as approximately 40 km/h in this test.

Four flight states were used in this test:
1) 30 km/h forward speed, 120 rpm rotor speed;
2) 30 km/h forward speed, 200 rpm rotor speed;
3) 40 km/h forward speed, 120 rpm rotor speed; and
4) 40 km/h forward speed, 200 rpm rotor speed.

The results of the typical flight status are shown in Fig. 29.
The on-board test proves that the rotor system can fold successfully under conditions similar to those of actual flight. No seizing, structural interference or damage occurred under any of the tested flying conditions. The results show that the complete folding rotor system meets the design requirements for a compound aircraft. In addition, the aerodynamic data measured in this test is too small to be read from the measuring instrument, which shows that the aerodynamic change caused by the rotor can be ignored in the process of flight mode conversion.

6. Conclusions

The principles of a collectible rotor and a complete folding rotor system were set forth, and a dynamic model was established. The changes in aerodynamic forces and moments of the joints during the folding process were analyzed. A mock-up of the rotor system was constructed and relevant testing was performed. Through the design, analysis, manufacture and testing processes, the following conclusions were obtained:

1) The folding strategy has a negligible effect on the maximum moment of the joints. The speed of the rotor shaft strongly influences the moment of the joints, and the rotor speed during the folding process is related to flight performance when in the fixed-wing mode. Therefore, when designing the folding rotor, the three factors—fixed-wing flight performance, rotor speed and driving system—limit one another.

2) The trend of lift and resistance can be changed by altering the folding strategy. A reasonable increase in the acceleration time causes the lift and resistance to change more gradually. However, the aerodynamic force caused by the rotor is very small compared to the weight of the prototype, and it can be ignored in the process of flight mode conversion.

3) Tests proved that the proposed rotor system can realize the concept of a collectible rotor. The folding rotor system can satisfy the requirements of a collectible rotor and those of typical flight conditions for a compound aircraft.

After completing the design iteration process and producing a folding rotor system, the concept for designing a collectible rotor is provided and a set of design methods and research ideas is established.

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