EXPERIMENTAL RESEARCH ON WHIRL FLUTTER OF TILTROTOR AIRCRAFT

Dong Linghua | Zhou Jinlong | Yang Weidong

donglinghua@nuaa.edu.cn | zhoujinlong101@nuaa.edu.cn | ywdae@nuaa.edu.cn

College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics,

Yudao Street 29, Nanjing, China

Abstract

The instable phenomenon of the tiltrotor aircraft's whirl flutter is induced from the aeroelastic coupling between flapping of the rotor and bending/torsion of the flexible wing when its flight velocity exceeds the critical speed of the stability boundary. The wind tunnel test using semi-span model is an effective and convincing method to validate the accuracy of analytical methodologies and effect of active/passive control techniques to suppress whirl flutter. A semi-span model was developed and fabricated to conduct tests related to aeroelastic problems of tiltrotor aircrafts. Tests were carried out to ascertain the critical speed of this model with different configurations including rotor/wing tests and rotor/wing/fuselage tests. The stiffness of this model was adjusted to guarantee that whirl flutter would occur in wind tunnel test. Good agreement was shown in the comparison between results of the wind tunnel tests and the theoretical analysis, which indicated that the semi-span model designed in this study and the corresponding theoretical analysis method were capable for studies of whirl flutter problems.

1. INTRODUCTION

Tiltrotor aircrafts have advantages of both helicopters and fixed-wing propeller-driven aircrafts, such as high-efficiency hovering and high-speed forward flight. But stability problem is encountered due to aeroelastic coupling between rotors and elastic wings. Because of the coupling between the in-plane aerodynamics resulting from the flap motion of the rotor blades and the bend-twist distortion of the elastic wings, instable phenomenon of whirl flutter would happen, and it has negative effect on the maximum flight speed of the tiltrotor aircrafts.

Wind tunnel test is an important method to research the mechanism of whirl flutter and techniques of whirl flutter suppression, and it plays an unsubstitutabel role for the validation of theoretical models' precision, the analysis of parameters' influence on whirl flutter and the effectiveness of whirl flutter suppression techniques. For the lack of knowledges and experiment techniques of tiltrotor aircrafts in the early stage, the prototype of XV-3 tiltrotor aircraft crashed during the flight test due to instable problem of aero-elastic coupling. In order to have a deeper understand of this phenomenon, wind tunnel tests of a full-scale model of XV-3 were carried out in the 40-by 80-foot wind tunnel of Ames Aeronautical Laboratory[1]. Wind tunnel tests of a full-scale semi-span model consisting of a rotor and a wing were conducted by Bell helicopter and Boeing in the 40-by 80-foot wind tunnel of Ames Aeronautical Laboratory in 1970s[2][3]. For the reason of the maximum wind speed is lower than the critical speed of whirl flutter for this semi-span model, both the stiffness of the wing and the rotation speed of the rotor were reduced to study its stability of whirl flutter. Although these parameters are lower than the practical values, the data obtained in these tests have been used as the standard to validate the precision of theoretical analysis. A large amount of wind tunnel tests on 1/5 and 1/7.5 scaled models of the Bell Model 266 and the Model 300 tiltrotor aircrafts were conducted in NASA Langley Transonic Dynamics Tunnel (TDT), and the data obtained in these tests was of great value for the development of XV-15 tiltrotor aircraft[4].

A 1/5 scaled full-span model was tested in the Transonic Dynamics Tunnel of NASA Langley Research Center to support the development of V22 tiltrotor aircraft. The right half of this model was modified into the Wing and Rotor Aeroelastic Testing System (WRATS) in 1994, and the WRATS had been used to study whirl flutter stability[5], dynamic tests of transient tilt transition[6] and active control techniques to enhance the stability of tiltrotor aircrafts[7][8]. Aeroelastic characteristics of tiltrotor aircraft with soft-in-plane tiltrotors, and stability enhancement of tiltrotor aircrafts using rotors of advanced geometries, were also studied based on WRATS [9][10].

TDT could satisfy the requirement of wind speed for WRATS, and heavy gas (currently R-134a, and previously R-12) was used to simulate the Mach number and Reynolds number conditions. Based on these advantages of TDT, scaled model experiments equal to a full-span model could be achieved, and it provides an important experimental method for the validation

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

of the aeroelastic coupling analysis of tiltrotor aircrafts. In order to guarantee the security of the WRATS, the control requirement of the wind tunnel was relatively strict during dynamic stability tests, and the cost of these tests were extremely high. So a light-weight model, for which whirl flutter could happen in lower wind speed, is needed to conduct experiments on whirl flutter mechanism and active control techniques for suppression of this instable phenomenon with lower cost and less risk, when the requirements for similarity conditions are not very strict. A light-weight semi-span model was tested in low speed wind tunnel at the Pennsylvania State University, during which whirl flutter occurred at the wind speed of 100 ft/s, and this model was also used to carry out aeroelastic optimization study of tiltrotor aircrafts with wing extensions and winglets[11].

In this study, a light-weight semi-span model for aeroelastic coupling dynamic tests was designed based on dynamic analysis. Whirl flutter boundary test was conducted in the wind tunnel of Nanjing University of Aeronautics and Astronautics, and whirl flutter phenomenon emerged at the wind speed about 20.5 m/s. And this test is useful for the validation of theoretical analysis and for the active control tests of whirl flutter in the near future.

2. SEMI-SPAN MODEL FOR WIND TUNNEL TESTS

The semi-span model consists of several main components including rotor, elastic wing, nacelle, and fuselage with an installation platform used to support the whole model. The installation platform offered interfaces between the wall of wind tunnel and the fuselage of the semi-span model, and a rigid plate was fixed on the installation platform to assure the symmetric boundary of aerodynamics. The fuselage was mounted on the installation platform, and its pitch angle was adjustable to simulate different flight conditions of tiltrotor aircrafts. The elastic wing was constructed of carbon fiber tubes and 3D printed airfoil sections, and the stiffness of the wing was determined by the length of the carbon fiber tubes and the numbers of airfoil sections. With the help of modular design of the airfoil sections, some of them could be substituted by those with deformable trailing-edge flaps to satisfy requirements of different tests. The deflection angle of the trailing-edge flaps was controlled through Arduino board and its host computer. The motor and the gear box to drive the rotor were installed in the nacelle, and accelerometers were fixed on the nacelle to monitor its vibration responses. Since the rotor speed was important for whirl flutter analysis, it was measured by the rotary encoder installed in the nacelle. In the wind tunnel test, winglets of different geometric shapes could be installed on the nacelle and the positions of these winglets were adjustable in order to study their effects on whirl flutter phenomenon.

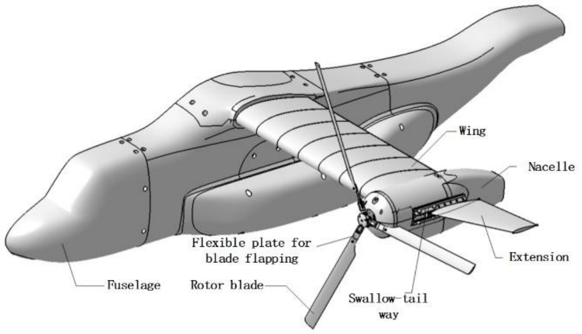


Figure 1: Semi-span model of tiltrotor aircraft

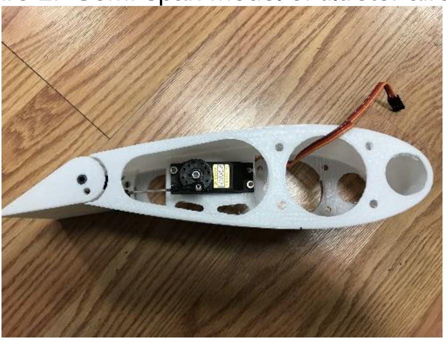


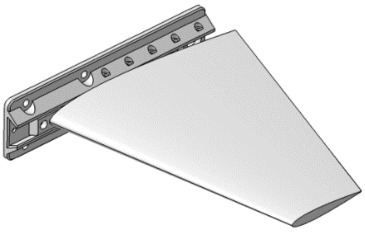
Figure 2: A wing section with deformable trailing-edge flap

Basic parameters of the semi-span model consisting rotor and wing are listed in table 1.

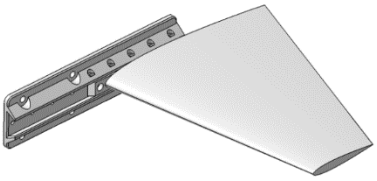
Table 1: Parameters of the semi-span model

Parameters	Value
Wing span	690 mm
Wing chord length	240 mm
Airfoil of wing	NACA0024
Numbers of wing sections	7
Wing section length	80 mm
Dihedral angle of wing	0 deg
Sweepforward angle of wing	0 deg
Preinstall angle of wing	0 deg
Chord length of rotor blade	31 mm
Rotor mast height	150 mm
Rotor clutch speed	1200 rpm

Wing extensions and winglets could be installed on the outside of the nacelle. The distance between the aerodynamic center of the extension/winglet and the elastic axis of the wing, and the installation angle of the extension/winglet, were adjustable to satisfy requirements of different tests. The chordwise position of the extensions could be adjusted through swallow-tail way on which five location holes were equidistantly distributed, and the position was locked by bolts as shown in figure 3. When the extension was installed in the first location hole, the quarter-chord position of the airfoil section at the root of the extension (Point A) would coincide with the quarter-chord line of the wing (Line B). The distance between Point A and Line B would be 100 mm when the extension was locked in the fifth location hole. 3D printing was utilized to manufacture the winglets to guarantee their mass deviation and geometric shape including sweep angle, taper ratio, dihedral angle, and plane shape. In order to compare results of different tests, clump weight would be added on the nacelle to guarantee the consistency of the dynamic characteristics when no extension was installed, and the measured dynamic characteristics are listed in table 2.



(a) Extension locked in the 1st location hole



(b) Extension locked in the 5th location hole

Figure 3: Swallow-tail way to install the extension

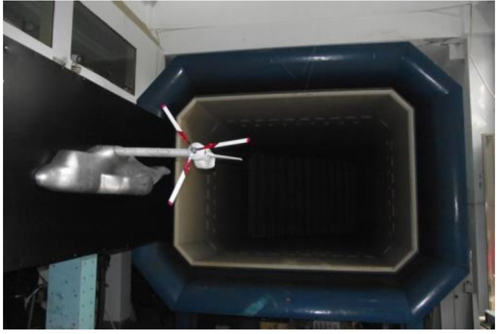
Table 2: Dynamic characteristics of the model under different extension configuration

Extension geometry parameters			Vertical bending		Torsion		Chordwise bending	
Taper ratio	Location hole	Sweep angle	f/Hz	ζ/%	f/Hz	ζ/%	f/Hz	ζ/%
200/40	2nd	none	7.49	0.82	11.12	0.82	12.45	1.88
200/40	4th	none	7.43	0.8	11.09	0.76	12.39	1.94
none	none	none	7.44	0.59	10.95	0.77	12.51	1.63
none	1st	none	7.47	0.78	11.02	1.01	12.17	2.87
none	5th	none	7.39	0.71	11.05	0.8	12.78	1.15
none	1st	40	7.44	0.72	11.06	0.85	12.40	0.56
none	5th	40	7.32	0.81	10.85	1.19	12.27	0.59

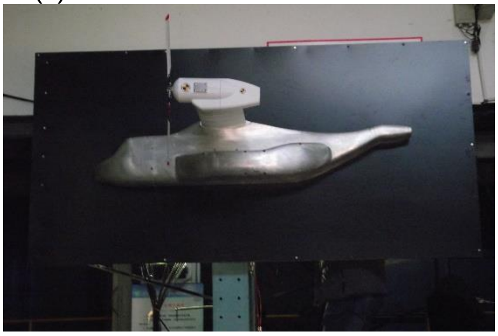
According to the results of the dynamic characteristic measurement, the chordwise position of the extension has less influence on the dynamic characteristics of the wing, and the variation range of the frequencies is less than 0.3 Hz. More specifically, extension has the least influence on the frequency of chordwise movement, while its influence on the frequency of wing twisting is relatively significant, and frequency of wing flapping is reduced slightly with an extension.

3. WIND TUNNEL TEST

Whirl flutter boundary test of the semi-span model consisting of a rotor and a wing is conducted in the 3.4- by-2.4 m low-speed open-circuit wind tunnel of Nanjing University of Aeronautics and Astronautics. The minimum and maximum steady wind speeds are 5 m/s and 50 m/s respectively, and the control precision of wind speed is about 0.5m/s. The semi-span model and the wind tunnel are shown in figure 4.



(a) front view with nacelle extension



(b) side view with clump weight

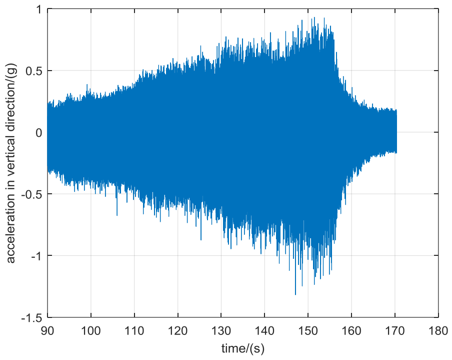
Figure 4: The semi-span model tested in wind tunnel

The semi-span model was fixed on the support of the wind tunnel open test section. Accelerometers were attached on the nacelle in vertical and horizontal direction to measure the accelerations, while the movement of the model was logged using video camera. Whirl flutter boundary test was carried out with the rotor under windmilling condition. The rotor would go into windmilling condition if the wind speed exceeded 15 m/s. A rotary encoder was connected to the rotor shaft to obtain its rotate speed, which was also recorded by the data acquisition system. The measured rotate speed of the rotor and the corresponding wind speed are listed in table 3.

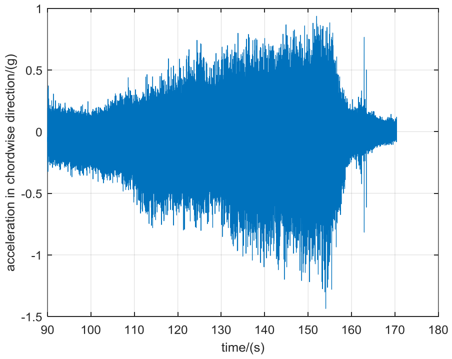
Table 3: Rotor speeds and wind speeds

Scheduled wind speed	Actual wind speed	Scheduled rotor speed	Actual rotor speed
0 m/s	0 m/s	800 rpm	800 rpm
5 m/s	5 m/s	800 rpm	800 rpm
10 m/s	10 m/s	800 rpm	800 rpm
15 m/s	15 m/s	1200 rpm	1180 rpm
20 m/s	19.5 m/s	1600 rpm	1560 rpm
22.5 m/s	22.5 m/s	1800 rpm	1800 rpm

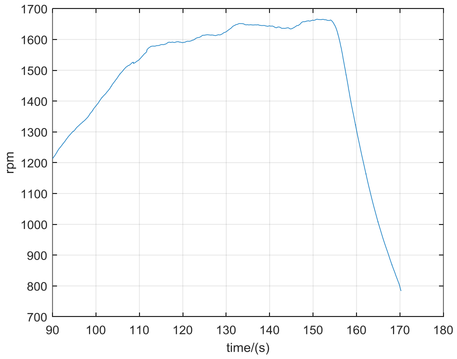
During the wind tunnel test, the rotor was driven by a motor installed in the nacelle if the wind speed was lower than 15 m/s, and the rotor speed gradually increased to its scheduled value of 1200 rpm. Once the wind speed exceeded 15 m/s, the motor would be shut down to eliminate its undesired influence on the acceleration signals. Because of the existence of the clutch installed between the rotor shaft and the motor, the rotor would rotate freely and go into windmilling condition. Wind speed was increased step by step until instable phenomenon of whirl flutter occurred, and the critical value of the wind speed was logged which was the whirl flutter boundary of the model under current configuration. The acceleration response signals as well as the rotor speed of the model under baseline configuration(with clump weight) was shown in figure 5.



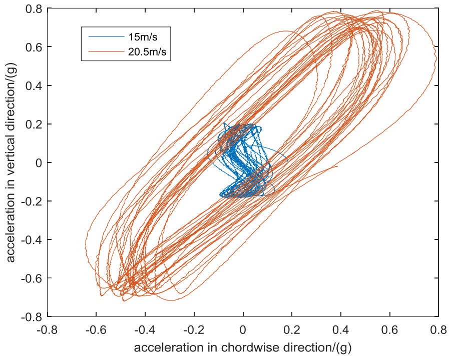
(a) vertical vibration



(b) chordwise vibration



(c) rotor speed



(d) v-c lissajous curves

Figure 5: Wind tunnel test results

4. ANALYSIS OF WIND TUNNEL TEST RESULTS

Two different methods including eigenvalue analysis and transient response calculation are employed in this study to predict the whirl flutter boundary, and the predicted wind speeds were compared with the test results. The critical wind speed predicted by eigenvalue analysis method was 18 m/s at the rotor speed of 1600 rpm, while this speed would become 21 m/s using transient response calculation method. And the actual critical wind speed measured in the wind tunnel test is about 20.5 m/s. Good agreement was shown in the comparison between the wind tunnel test and the predicted values of the theoretical analysis. The critical wind speed given by transient response calculation based on the non-linear model of unsteady aero-elastic coupling is much more close to the measured result, while the result of eigenvalue analysis is slightly lower than the actual value.

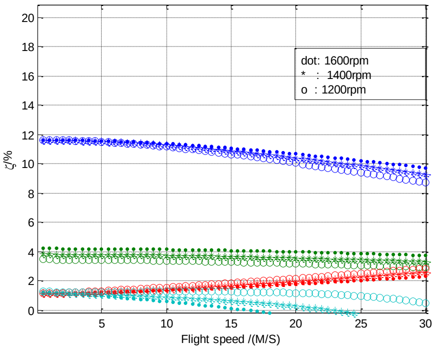
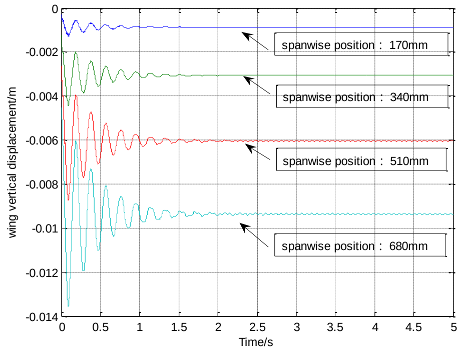
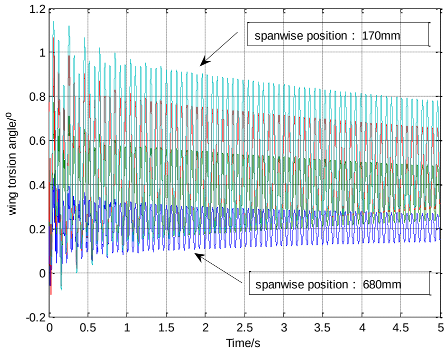


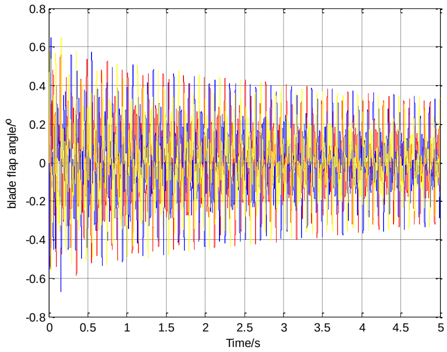
Figure 6: Whirl flutter boundary predicted by eigenvalue analysis



(a) Vertical vibration

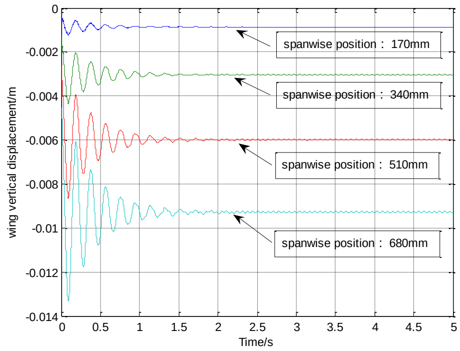


(b) Torsion

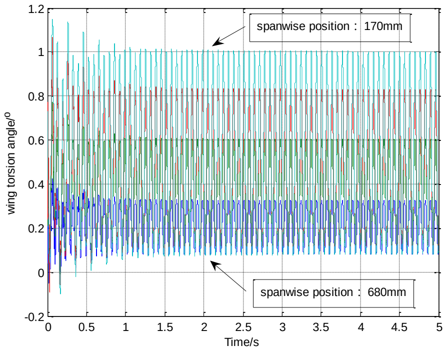


(c) Blade flap angle

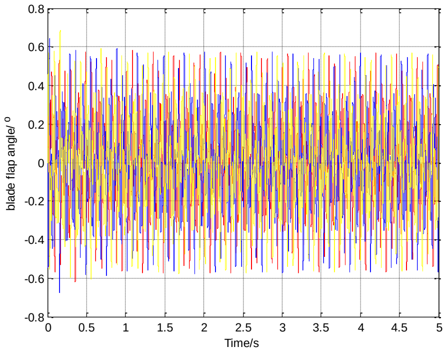
Figure 7: Responses given by transient response calculation at wind speed of 20 m/s



(a) Vertical vibration



(b) Torsion



(c) Blade flap angle

Figure 8: Responses given by transient response calculation at wind speed of 21 m/s

5. CONCLUSIONS

A semi-span model of tiltrotor aircraft, which could be used to carry out studies of aeroelastic stability in a low-speed wind tunnel, was designed and fabricated. Wind tunnel test results showed that instable phenomenon of whirl flutter occurred at the wind speed about 20.5 m/s. Extensions and winglets could be installed on the nacelle of this model in addition to the deformable flaps on the elastic wing, and this model could be used to test active control techniques aimed to enhance stability of tiltrotor aircrafts. The critical wind speed is relatively low due to the light weight of this model, which dramatically reduces the cost and risk of wind tunnel tests, and it could also be used for education purpose to provide a visualized explanation of the whirl flutter mechanism.

6. REFERENCES

[1] Martin D. Maisel, Demo J. Giulianetti, Daniel C. Dugan. The History of the XV-15 Tilt Rotor Research Aircraft: From Concept to Flight[R]. NASA SP-2000-4517. National Aeronautics and Space Administration Office of Policy and Plans,NASA History Division, Washington, D.C.2000.

[2] Magee J.P.,Alexander H.R. ,Gillmore K.B. ,etc.

Wind Tunnel Tests of a Full Scale Hingeless Prop/Rotor Design for the Boeing Model 222 Tiltrotor Aircraft[R]. Report No.D222-10059-1,Contract NAS2-6505,April 1973.

[3] Wayne Johnson, Dynamics of Tilting Proprotor Aircraft in Cruise Flight[R]. NASA-TN-D-7677. Ames Research Center and U.S. Army Air Mobility R&D Laboratory Moffett Field, Calif.

[4] William T. Yeager, Jr.,Raymond G. Kvaternik， A Historical Overview of Aeroelasticity Branch and Transonic Dynamics Tunnel Contributions to Rotorcraft Technology and Development[R]， NASA/TM-2001-211054， ARL-TR-2564，August 2001.

[5] David J. Piatak, Raymond G. Kvaternik, Mark W. Nixon, and etc., A Wind-Tunnel Parametric Investigation of Tiltrotor Whirl-Flutter Stability Boundaries[C], Presented at the American Helicopter Society 57th Annual Forum, Washington, DC, May 9-11, 2001.

[6] G.L.Ghiringhelli, P.Masarati1,P. Mantegazza， M. W. Nixon，Multi-Body Analysis of the 1/5 Scale Wind Tunnel Model of the V-22 Tiltrotor[C], Presented at the American Helicopter Society 55th Annual Forum, Montreal, Canada, May 25-27,1999.

[7] Mark W. Nixon，Raymond G. Kvaternik，T. Ben Settle，Tiltrotor Vibration Reduction Through Higher Harmonic Control[C], Presented at the American Helicopter Society 53rd Annual orum, Virginia Beach, Virginia, April 29 - May 1, 1997.

[8] Raymond G. Kvaternik, David J. Piatak, Mark W. Nixon, and etal. An Experimental Evaluation of Generalized Predictive Control for Tiltrotor Aeroelastic Stability Augmentation in Airplane Mode of Flight[C], Presented at the American Helicopter Society 57th Annual Forum, Washington, DC, May 9-11, 2001.

[9] Mark W. Nixon, Chester W. Langston, J. D. Singleton and etal. AEROELASTIC STABILITY OF A FOUR-BLADED SEMIARTICULATED SOFT-INPLANE TILTROTOR MODEL[C], Presented at the 2003 International Forum on Aeroelasticity and Structural Dynamics, June 4-6,2003, Amsterdam, The Netherlands.

[10] Mark W. Nixon, Chester W. Langston, Jeffrey D. Singleton，and etal., Aeroelastic Stability Of A Soft-Inplane Gimballed Tiltrotor Model In Hover[C],AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 16-19,2001/Seattle, WA.

[11] Sandilya Kambampati， Edward C. Smith， Aeroelastic Optimization of High-Speed Tiltrotor Wings with Wing Extensions and Winglets[J]. JOURNAL OFAIRCRAFT,Vol. 54, No. 5, September–October 2017.