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BODY FREEDOM FLUTTER OF SCALED VEHICLES: FROM BLENDED WING BODY TO CONVENTIONAL CONFIGURATION

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Abstract: In this presentation, the state of the art of the development of flight flutter test vehicles for Body-Freedom-Flutter (BFF) study in the last decade is briefly reviewed at first. Next, as an effort of the authors during recent years, the development and BFF investigation of scaled vehicles for flight flutter test is introduced. The design, build and test campaigns are detailed, first for a blended wing body (BWB) scaled vehicle, and then for a conventional configuration with very short fuselage. Theoretical and experimental correlation study is conducted for the aeroelastic stability of both vehicles. Finally, lessons learned are summarized and pertinent conclusions are drawn upon the present work.

1 INTRODUCTION

Body freedom flutter (BFF) is a serious issue in the design of tailless aircraft, which has been received continued interest, such as blended wing body (BWB) configuration with highly flexible wing. The physical mechanism beneath the BFF phenomenon has been revealed for a long time[1]-[3]: an aeroelastic instability dominated by the coupling between wing bending and the short period modes. Such kind of rigid body mode involved flutter validation is quite challenging by the wind tunnel test, which usually needs a sophisticated supporting mechanism allowing almost "free-free" flying for the flutter model[4],[5].

Due to the restrictions related to wind tunnel test, there are growing interest in sub-scale flight test model development for unconventional aircraft designs and validation[6]. The X-56A NASA Multi-Utility Technology Testbed (MUTT) was designed to investigate the active feedback control for BFF and successfully suppress the instability and restabilize the aircraft when flew into flutter[7].

As precursors to the X-56A vehicle, a series of sub-scale flight flutter test models have been designed. The Lockheed Martin's BFF vehicle flight tests were conducted at NASA Dryden Flight Research Center (DFRC). Five BFF vehicles were tested to open loop BFF flutter several times and it is shown that the tested open loop flutter speeds and the corresponding analytical predictions are in good agreement[9]. The University of Minnesota's "mini MUTT" is a laser-scanned replica of Lockheed Martin's BFF vehicle BFF06 and resembles NASA's X56 MUTT aircraft, specifically, the third mini MUTT built named "Geri."[10] Flight tests were carried out for both open-loop flutter and flutter suppression[11].

It should be noticed that the flight test of BFF could be rather costly due to its dangerous nature to damage structures and loss of vehicles, even in the active flutter suppression program. To address this issue, Northwestern Polytechnical University's low-cost and low-risk (LCLR) flying wing was developed and tested by the first author and his colleagues[12], which is a further sub-scale model of Lockheed Martin's BFF vehicle and could be served as the flight test platform for the study of BFF.

For readers' convenience, wingspan and weight data are summarized in Table 1 for several typical BFF vehicles developed in the last decade, with rough timeline indicating the successful flight flutter testing first accomplished.

Table 1 BFF vehicles developed in the last decade

	Wingspan, ft	Weight, lb	Timeline
Lockheed Martin's Body-Freedom-Flutter (BFF) vehicle[9]	10	12	2010
X-56A[7]	28	525	Stiff Wings 2013 Flex Wings 2017*
University of Minnesota, mini MUTT (Geri）[10]	9.8 (3 m)	14.8 (6.7 kg)	2015
Northwestern Polytechnical University, LCLR flying wing[12]	6.5 (2 m)	2.9 (1.3 kg)	2018

* (Loss of vehicle 2015)[13]

In recent years, with the emerging unconventional aircraft designs, there are still needs in characterizing the potential BFF phenomenon in conventional configurations but with very short fuselage like General Dynamics RB-57F [13]. Motivated by this issue, we have designed and built a scaled BFF vehicle of this kind for flight flutter testing study. Currently, the GVT and model updating have already been finished, and the taxiing and preliminary flight were conducted.

In this presentation, we first reviewed our work in the LCLR flying wing development[12] and in companion, report the BFF vehicle design and validation for a conventional configuration but with very short fuselage. Lessons learned are summarized and pertinent conclusions are drawn.

2 STUDY FOR A SUB-SCALE BWB BFF VEHICLE

In this section, the development of a low-cost low-risk (LCLR) vehicle was reviewed for the purpose of BFF phenomenon demonstration in flight test. The background vehicle of interest is Lockheed Martin's BFF vehicle [9] as depicted in Fig. 1, which has a 10 ft (roughly 3.0 m in SI units) wingspan and 12 pound weight. A flexible LCLR sub-scale BWB model was designed by the first author and his colleagues with a wing span of 2.0 m and the gross takeoff weight is 1.3 kg, as depicted in Fig. 2. FEM modeling and flutter analysis show an achievable flutter speed in flight, then a vehicle was built and the GVT and flight flutter test was conducted consequently.

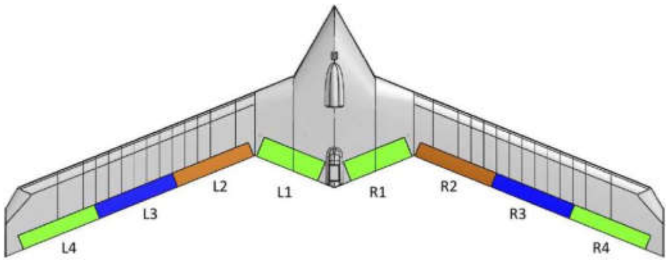


Fig. 1 Lockheed Martin's Body-Freedom-Flutter (BFF) vehicle [9]

Fig. 2 Structural layout of LCLR flying wing[12]

2.1 BWB BFF Vehicle Design and Fabrication

In this section, the CAD model is presented and the theoretical FEM model is established, based on which the normal modes and flutter characteristics are calculated.

2.1.1 CAD modeling

The CAD sketch of the vehicle is shown in Fig. 2. A 2.024 m span blended wing body design is implemented with similar configuration data as reported in [14]. The leading edge sweep angle is 22 deg. The area of the wing body surface is 0.15 m^2. The main spar is made by carbon fiber composite beam which provide the stiffness of the main structure. The wing body surface is covered by flat polypropylene (PP) foam and strengthened with balsa wood in chordwise direction.

2.1.2 FEM modeling and normal mode analysis

The FEM model of the vehicle is shown in Fig. 3. The main spar and wing body surface are discretized by CQUAD4 element. Inertial distribution is modeled as concentrated mass by CONM2 element. The linkages of actuators are modeled as CBAR element.

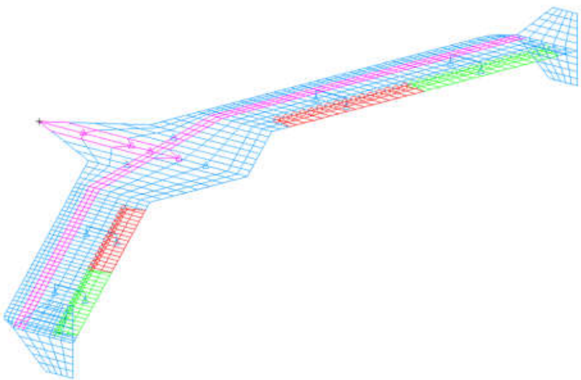
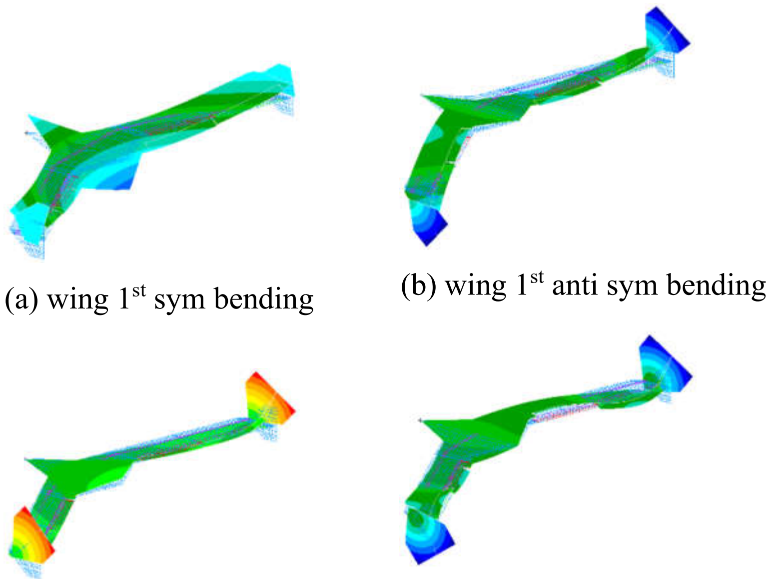


Fig. 3 FEM model

Free-free mode analysis is carried out by using Nastran. The first four elastic modes are shown in Table 2 and Fig. 4.

Table 2 Normal mode frequencies

Modes	Freq, Hz
wing 1st sym bending	5.03
wing 1st anti sym bending	7.54
wing 2nd sym bending	9.57
wing 2nd anti sym bending	11.75



(a) wing 1st sym bending

(b) wing 1st anti sym bending

(c) wing 2nd sym bending

(d) wing 2nd anti sym bending

Fig. 4 Mode shapes

2.1.3 Flutter analysis

The DLM aerodynamic model for flutter analysis is shown in Fig. 1Fig. 5. The flutter speed calculated based on the previous free-free modes is 18.1 m/s, and the corresponding flutter frequency is 5.2Hz. The V-g-f diagram is shown in Fig. 6.

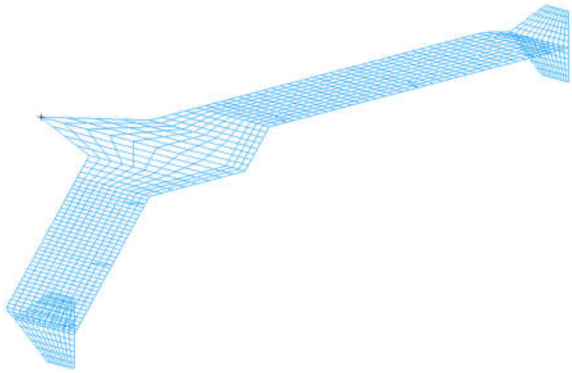


Fig. 5 DLM aerodynamic model

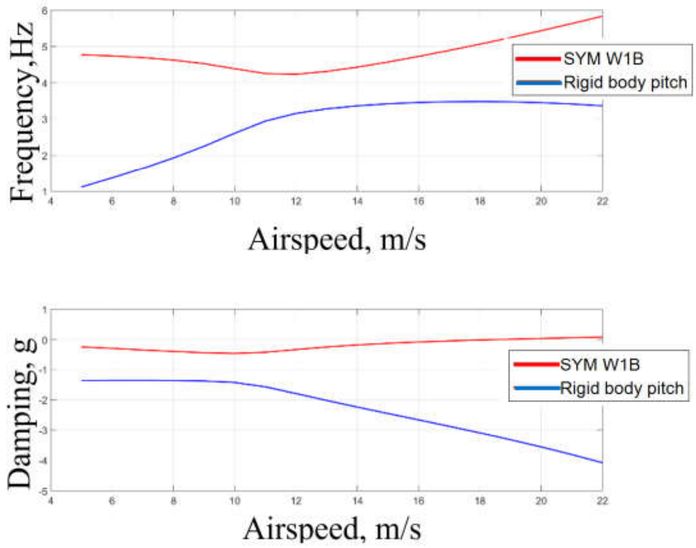


Fig. 6 V-g-f diagram

2.2 Model Fabrication and GVT

The designed flutter speed could be achieved according to a previous performance evaluation. The fabricated model with airborne instruments is shown in Fig. 7. The take-off weight is 1.3kg and the c.g. is 400 mm aft the nose.

The ground vibration test (GVT) is conducted. The FEM model is updated according to the test results and the flutter characteristics are reexamined.

The test setup is as shown in Fig. 8. The vehicle is suspended by a soft enough bungee cord and the suspension mode is well separated from the fundamental elastic mode.

The GVT test results are shown in Table 2. The first four elastic mode shapes are shown in Fig. 9.

The FEM model is updated according to the test results and also shown in Table 3. Flutter analysis is conducted based on the updated model. The flutter speed is 10.15 m/s and the flutter frequency is 2.5 Hz.

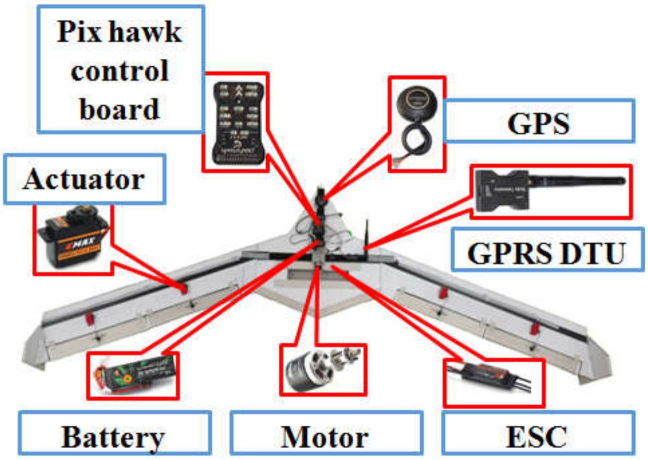


Fig. 7 BFF vehicle

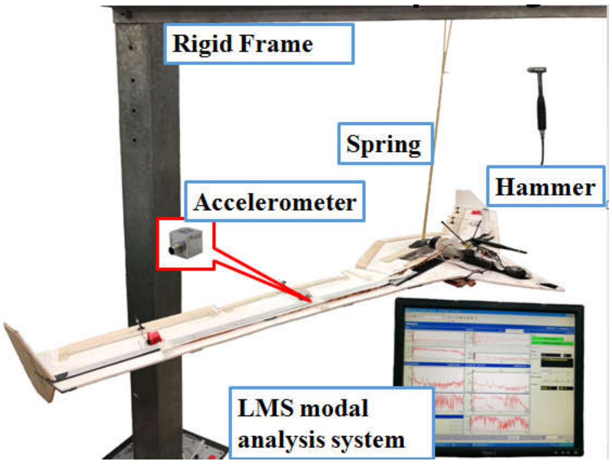
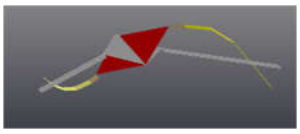


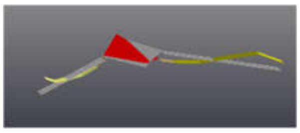
Fig. 8 GVT setup

Table 3 Modal frequency comparison

Modes	Test results Hz	Theoretical updated Hz	Relative error
1st sym wing bending	3.74	3.74	0.00%
1st anti sym wing bending	7.51	7.12	-2.34%
2nd sym wing bending	10.07	9.81	-2.42%
2nd anti sym wing bending	12.73	11.94	-1.6%



(a)1st sym wing bending (b)1st anti sym wing bending



(c)2nd sym wing bending (d)2nd anti sym wing bending

Fig. 9 Test mode shapes

2.3 Flight Flutter Test

The first flight test was made on October 21, 2018 in Northwestern Polytechnical University's ChangAn campus, and the BFF phenomenon was successfully observed. Response time histories were recorded by the onboard instrument. The vertical acceleration response history is shown in Fig. 9 in companion with the ground speed time history resulted from the GPS differentiation. The ground speed can be taken as airspeed roughly thanks to the calm weather during the test.

In the test, the pilot carefully increased the throttle and let the vehicle fly well into flutter and then decreased the throttle to exit. It could be observed the flutter motion diverged quickly once the flutter speed was exceeded. Such process was repeated several times by monitoring the response level. The flutter speed can be estimated from Fig. 10(b) as the response in Fig. 10 (a) begins to diverge. The flutter frequency could be determined by FFT analysis of chosen diverge signal segment as shown in Fig. 11.

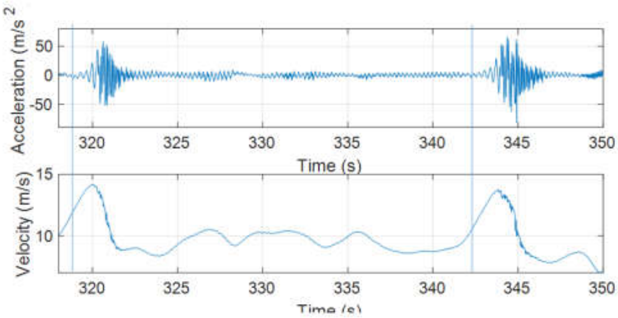


Fig. 10 Time histories of vertical acceleration (a) and ground speed (b)

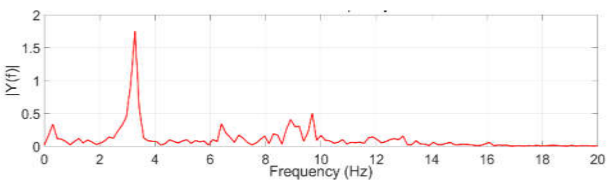


Fig. 11 Single sided spectrum for a segment of flutter response

The test flutter characteristics are shown in Table 4 in comparison with the theoretical results of the updated FEM model.

Table 4 Comparison of theoretical flutter characteristics against flight test

Item	Test results	Theoretical results	Relative Error
Flutter speed,m/s	12.0	10.15	-15.42%
Flutter frequency,Hz	3.13	2.5	-20.13%

In summary, a scaled LCLR BWB BFF demonstration vehicle was designed and tested successfully. Typical BFF phenomenon was observed during the flight test, which is dominated by the coupling of wing 1st symmetric bending mode and rigid body pitch mode.

The test flutter characteristics agree reasonably well with the analysis results. The present LCLR vehicle could be taken as a research platform in active flutter suppression test.

3 STUDY FOR A SCALED BFF VEHICLE OF CONVENTIONAL CONFIGURATION

In this section, a scaled vehicle was designed to study the BFF characteristics for aircraft of conventional configuration but with very short fuselage, which has a wing span of 2.4 m. One vehicle was built and the GVT and model updating have already been finished. The flight flutter test will be conducted in the near future.

3.1 Aerodynamic configuration and structure design

Design for the aerodynamic and structure layout is first introduced herein for a conventional configuration scaled BFF vehicle.

3.1.1 Aerodynamic design

To "produce" BFF in a conventional configuration scaled BFF vehicle, the fuselage should be as short as possible, which will result in a lowest pitch inertia. Meanwhile, a wing span of 2.4 m is selected. The aerodynamic layout is shown in Fig. 12 with puller propeller. A swept angle of 11 deg is chosen with a constant chord length of 0.15m.

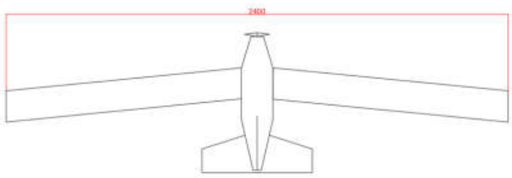


Fig. 12 Conventional aerodynamic layout with swept wing and very short fuselage

3.1.2 Structural design

Only the wing is designed with flexible structure made of aluminum spar covered by foam and fastened to the fuselage, as shown in Fig. 13. The wing tip device is implemented to compensate the directional stability for very short fuselage.

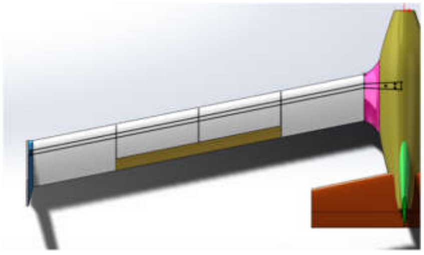


Fig. 13 Structural layout for the BFF vehicle with fuselage and empennage

3.2 Structural dynamic modeling and flutter analysis

3.2.1 Structural dynamics

The FEM model is built for the vehicle as shown in Fig. 14, in which beam elements are applied to model the elastic wing spar, and concentrated mass elements are adopted for inertial distribution modeling of the vehicle according to the CAD layout. Fuselage and empennage structures are considered as rigid beam. All the control surfaces are simplified as concentrated mass elements. The normal modes analysis results are listed in Table 4 in the "Theoretical" column.

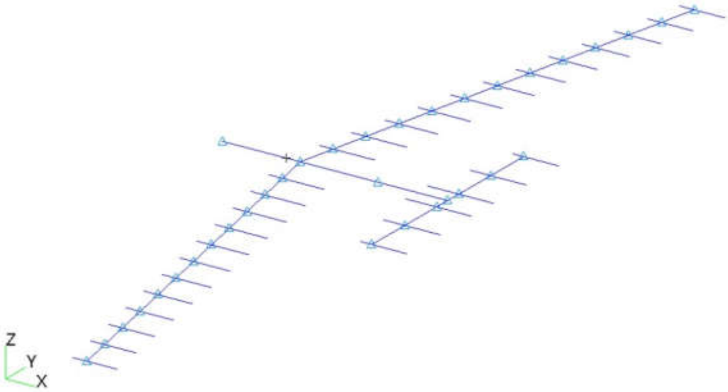


Fig. 14 FEM model for BFF vehicle

3.2.2 Flutter analysis

The DLM model is built for the lifting surfaces as shown in Fig. 15. The wing tip device and vertical tail surface are not considered here because only symmetric flutter is interested. Flutter analysis is carried out using incompressible aerodynamics by Nastran. The V-f and V-g diagrams are shown in Fig. 16. It is found that the critical flutter point is corresponding to a typical BFF dominated by the pitching mode and wing 1st symmetric bending mode, with a flutter speed of 25.2m/s and flutter frequency of 2.4Hz.

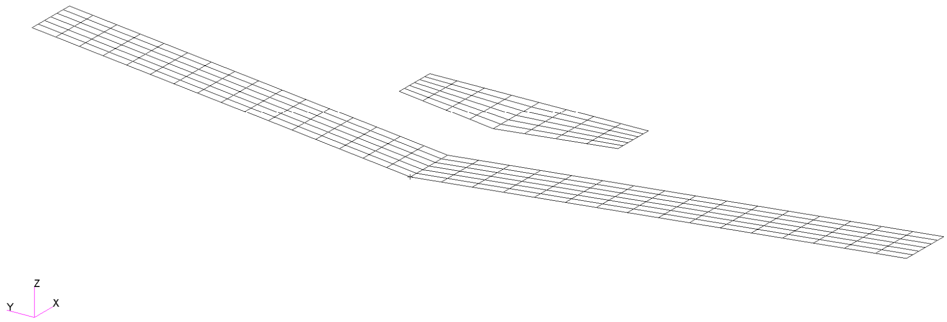
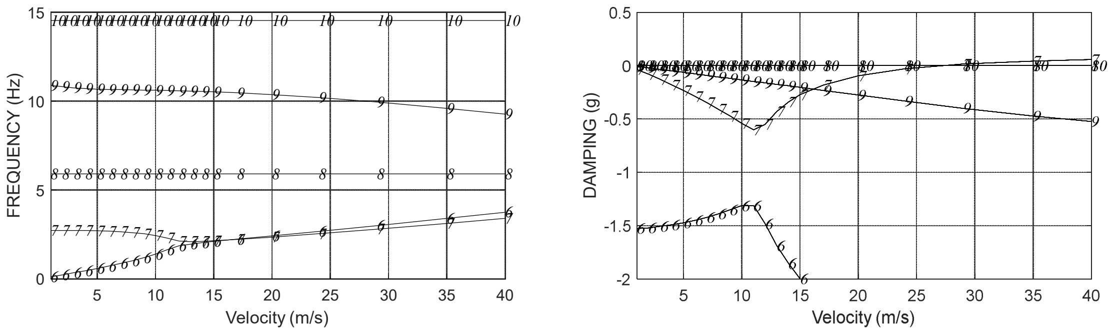


Fig. 15 DLM lifting surface model



(a) (b)

Fig. 16 V-f (a) and V-g (b) diagrams

3.3 GVT and model updating

One vehicle was built for GVT and later taxiing and test flight. The gross takeoff weight is 3.4 kg. GVT test setup is shown in Fig. 17. First several elastic modes were tested and model updating was finished. The comparisons of updated theoretical results and test data are summarized in Table 5.

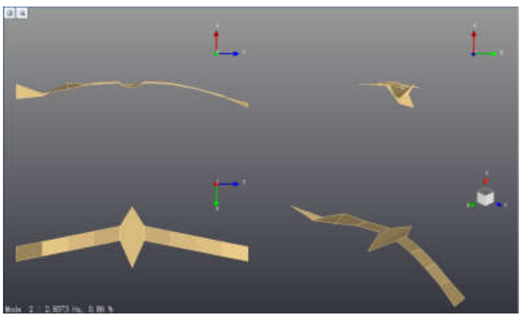
By tuning the Young's modulus alone, the natural frequency of the updated wing first symmetric bending mode correlates well with the test value. As the fuselage and the empennage are modelled as rigid element, no comparisons were available for related modes. It is also noted that the wing first antisymmetric bending mode frequency is much higher than the test result, further review should be made to clarify this issue.

According to the updated FEM, the critical flutter speed is 27.4m/s and flutter frequency is 2.6Hz, which is dominated by the coupling between the rigid body pitch and the wing 1st symmetric bending modes.

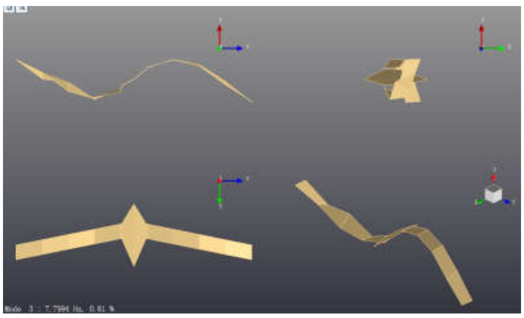
Table 5 Modal frequency comparison

Modes	Test results Hz	Theoretical Hz	Theoretical updated Hz	Relative error
1st sym wing bending	2.857	2.499	2.748	-3.82%
1st anti sym wing bending	7.799	9.227	10.061	29.00%
2nd sym wing bending	14.751	15.415	16.944	14.87%
2nd anti sym wing bending	15.868	16.573	17.238	8.63%
1st sym H-tail bending	23.699	NA	NA	NA
1st anti sym tail bending	41.014	NA	NA	NA

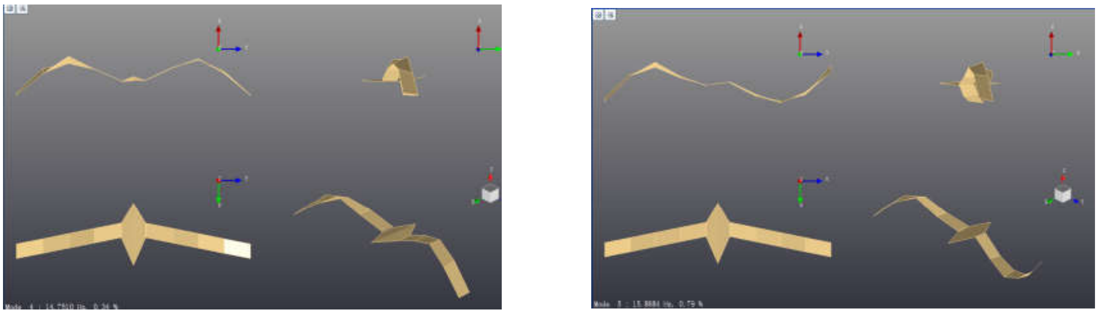
Fig. 17 GVT test setup



(a) wing 1st sym bending



(b) wing 1st anti sym bending



(c) wing 2nd sym bending

(d) wing 2nd anti sym bending

Fig. 18 Test mode shapes

3.4 Taxiing and preliminary test flight

After GVT, the vehicle (coded 01) was delivered for ground taxiing, but unfortunately it was resulted in severe damage of fore fuselage in an attempt to maiden flight due to stall. As a backup, two more vehicles (coded 02 and 03) are built for further test.

The taxiing and preliminary flight for vehicle 02 were conducted as shown in Fig 19, which show a good to go for future flight flutter test.

(a) (b)

Fig 19. Taxiing (a) and airborne (b) of vehicle 02

4 LESSONS LEARNED

Because of the practical importance of BWB configuration, the BFF study of which has received more and more attention. Researchers from industry, government organizations and universities have been well engaged in the modeling, wind tunnel test and flight test.

The flight flutter test of BFF could be rather costly and risky due to its dangerous nature to damage structures and even loss of vehicles. Specifically for the BFF vehicle with landing gears, there is even more risk in the high-speed taxiing and takeoff stage than in-flight test.

For the conventional configuration BFF vehicle developed herein, it reveals strong coupling between rigid body motion and flexible wing deformation during preliminary test flight. The test pilot should be well informed about this issue before flight.

5 CONCLUSIONS

A scaled LCLR BWB BFF flight demonstration vehicle was designed and tested successfully. The tested flutter characteristics agree reasonably well with the analysis results. The present LCLR vehicle could be taken as a potential research platform in active flutter suppression test.

Similar to the BWB configuration, it was demonstrated that there may also exist BFF instability for conventional configuration aircraft with very short fuselage. A BFF vehicle of such category is designed and still under flight testing. It is expected to get encouraging results in the near future.

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