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WIND TUNNEL EXPERIMENT FOR BODY FREEDOM FLUTTER OF FLYING WING UNMANNED AERIAL VEHICLE

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Abstract: Body Freedom Flutter (BFF) has always been known to be a potentially catastrophic event for any flying aircraft. BFF is a dynamic instability that results from the strong coupling between rigid-body and elastic modes of the aircraft. Here, we demonstrate how different parameters affect the speed and frequency at which BFF occurs using a wind tunnel with a test rig. The test rig was designed to allow the degrees of freedom needed for BFF to occur, which is then fabricated using 3D printing to optimise weight savings. Different flying wing profiles are considered and the UAV is subject to the different parameter variations. The mount allowed freedom to the wing profile in both the pitch and plunge movement. It is found that BFF characteristics are affected by the additional wing tip weights and spanwise weight location. These parameters directly affect the centre-of-gravity for the wing profile, its wing inertia, and its structural properties. The results and trends obtained can be used to further understand the BFF phenomenon.

1 INTRODUCTION

With recent rise in the development of aircrafts with high aspect-ratio wings adopting lightweight flexible structures, these aircrafts become increasingly vulnerable to aeroelastic phenomena. One such example is flutter, a self-excited instability resulting from the coupling between inertial, structural, and aerodynamic forces. Presently, investigations into flutter assumes a clamp-fixed boundary condition, resulting in a cantilever configuration. However, in flying wing configurations, strong interactions between rigid-body modes and elastic modes can be observed, leading to body-freedom flutter (BFF), where the fuselage of the aircraft undergoes significant pitching and plunging oscillations. If uncontrolled, the system can undergo diverging oscillations which can lead to catastrophic failure.

Conventionally, the investigations into flutter assume that the fuselage of the aircraft experiences negligible movement during flutter. Such flutter characteristics are often called classical flutter or bending-torsion flutter (BTF). This is true in aircrafts with the conventional wing-tail-fuselage configuration, which enables the assumption of a cantilever configuration for the wing. With this assumption, many wind tunnel experiments performed in the past to investigate flutter adopted the clamped-free boundary condition in their setup [1]–[3]. Additionally, numerical simulations were performed on cantilever wings to determine the flutter boundary for preliminary designs, as well as open-loop gust response for the development of flutter suppression systems [4].

Unlike conventional aircrafts, flying wings, sometime known as blended wing body aircrafts, are tailless aircrafts without a clear definition of a fuselage. Such configuration often results in very efficient aircrafts due to the lack of protrusions from a proper fuselage and a tail. Preliminary studies on a McDonnel Douglas blended wing concept showed a 21% increase in the aerodynamic efficiency of the aircraft [5]. This efficiency is achieved by reducing the wetted area and increasing the lifting area of the aircraft. Additional aerodynamic efficiency can be obtained by increasing the aspect ratio of the wing to reduce lift induced drag. However, in flying wing UAVs, rigid-body motions and flight dynamics are significant, and often observed to be coupled with the wing elastic modes, causing the fuselage to undergo significant plunge and pitch oscillations during flutter [6]. This phenomenon is commonly known as body-freedom flutter (BFF), and if uncontrolled, can cause diverging oscillations leading to catastrophic failure. In such cases, the cantilever assumption no longer holds, and the rigid-body dynamics of the flying wing has to be considered.

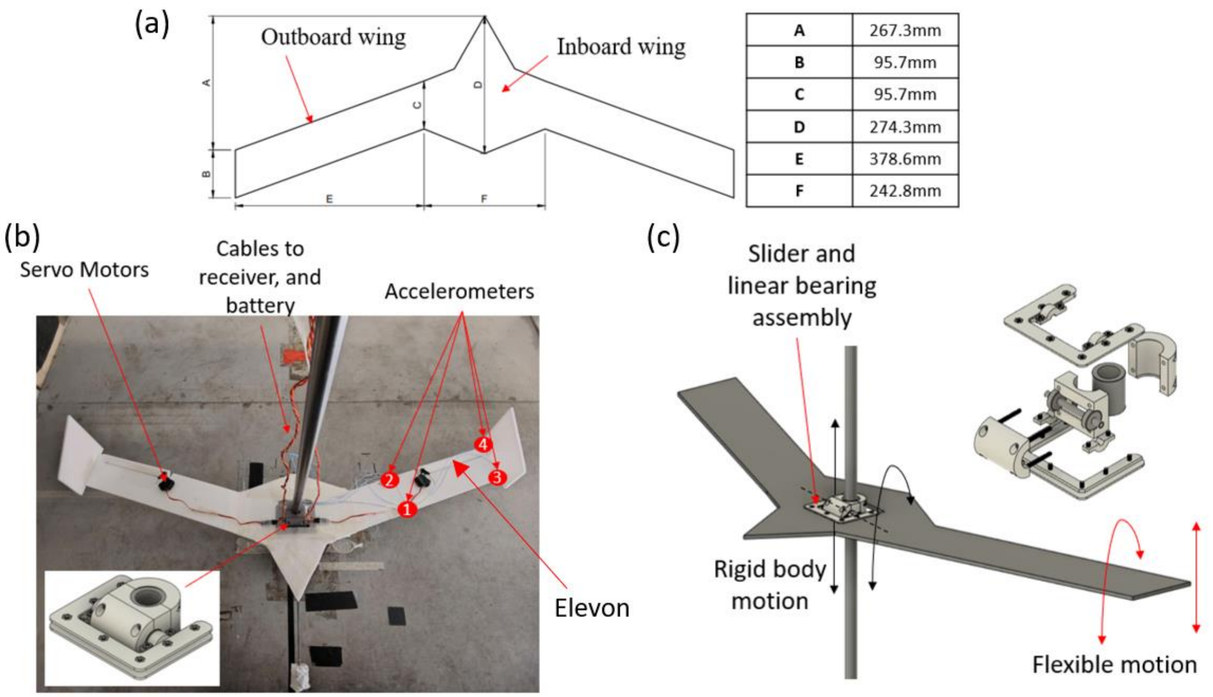
Flight tests are effective ways to study BFF as the body of the aircraft is not restricted, and they provide the most realistic environment for data collection. One notable test bed is the X-56A Multi-Utility Technology Test-bed (MUTT), designed by Lockheed Martin [7], which was developed as a research platform for BFF, active flutter suppression, gust load alleviation and other advanced aerodynamic concepts. While flight tests are highly effective, they are often difficult, expensive, and time consuming to perform. Due to the complex nature of BFF, numerical simulations are gradually being adopted. However, the methods used were often low-fidelity solutions for aerodynamics and structural dynamics, which limits the application to simplified wing models [8], [9]. On the other hand, high-fidelity solution involving computational fluid dynamics (CFD) and computational structural dynamics (CSD) in a fluid-structure interaction (FSI) problem were also used to study BFF [10]. While these methods provide accurate solutions, large computational costs are often incurred when running these simulations.

While the obvious solution to overcome the aeroelastic effects is to use stiffer materials, the accompanying increase in weight may negatively impact the overall performance of the UAV. Hence, gust load alleviation (GLA) techniques utilizing trailing edge devices have become increasingly popular as a way to push the stability margins of a flexible wing aircraft [11]. Similarly, previous efforts to incorporate control strategies for GLA only considered the wing deflection and bending moments as the aircraft experiences disturbances from gusts. Large displacements and pitch angles experienced by flying wings were rarely regulated by the controller. With the increased demand for high performance UAVs that incorporate flexible structures with aerodynamically efficient designs in the form of flying wings, the key research question is how to ensure that such UAV designs achieve the necessary aeroelastic and rigid-body stability required for their mission. Given the unique aeroelastic challenges posed by flying wings undergoing BFF, conventional flutter investigation methodologies utilised in the past may no longer be directly applicable. As such, this brings about a need for a new methodology to flutter investigations for flying wings. The key difference in methodology arises from the need to release the rigid-body modes which enables the coupling of plunge and pitch motions with wing elastic modes. Hence, this research aims to study the BFF phenomenon of a flying wing UAV by presenting experimental approaches, and its findings will provide insights to the design and GLA of flying wing UAVs for enhanced performance and increased stability margins. The objective of this paper is on the experimental investigation of BFF on flying wings. This will involve parametric studies on critical design parameters of a UAV to determine the BFF boundaries and stability margins.

2 BODY OF THE PAPER CHAPTERS

2.1 Methodology

The test model used in this investigation is modelled after the X-56A MUTT, as seen in Figure 1(a). The test models are manufactured from 5mm sheets of compressed foam, chosen for its lightweight properties and ease of fabrication. The planform shapes and dimensions of the model are designed in a computer-aided design (CAD) software for precise modelling of the geometry. To fabricate the model, a laser cutter is used to cut out individual parts from the compressed foam sheets. Due to limitations in the size of laser cutter, the wings and body of the model have to be cut separately, and subsequently attached together using adhesives. The test model includes a pair of elevons, shown in Figure 1(b), which are controlled by servo motors. The elevons are used to trim the model in the wind tunnel. To ensure directional stability, winglets are attached to each of the wing tips of the models to act as vertical stabilizers. Due to the flexibility of the compressed foam sheets, carbon fiber spars are attached to the foam to increase strength of the model and to prevent failure. This is crucial as it allows each model to be reused for the different test cases.



A	267.3mm
B	95.7mm
C	95.7mm
D	274.3mm
E	378.6mm
F	242.8mm

Figure 1: (a) Model planform and dimensions (b) BFF model assembly including electronic components (c) slider assembly to release rigid degree-of-freedom

In order to achieve BFF, it is critical that the rigid-body plunge and pitch degrees-of-freedom are released. To facilitate that, a BFF wing clamp slider assembly based on [12] is designed specifically for the BFF wind tunnel experiments. Schematics of the slider assembly is shown in Figure 1(c), which includes a linear bearing which slides along the cylindrical rail to enable uninhibited plunge motion. To allow for pitching motion, a pair of ball bearings are placed on each side of the assembly. All 3 bearings are encased in a housing that is 3D printed using PLA and lubricated with grease to minimise friction as much as possible. A wing clamp that is attached to the side pitching bearings securely holds the test model in place. The wing clamp is comprised of an upper and lower piece, held together with screws and nuts. This design allows for a quick and easy way to swap the test pieces as necessary.

The pitch axis of the slider assembly is placed at 15% mean aerodynamic chord, equivalent to 10% static margin. This placement ensures static stability of the wing and provides adequate control surface effectiveness required to trim the test models. In this study, we vary the tip weights and spanwise location of the weights to investigate the effect on flutter speeds.

2.1.1 Results

Figure 2 shows a snapshot of the UAV model undergoing pitching and heaving oscillations as flutter occurs. Additionally, there is some visible bending and torsion of the wing, which confirms the coupling of the wing elastic modes with the rigid-body modes of the model.

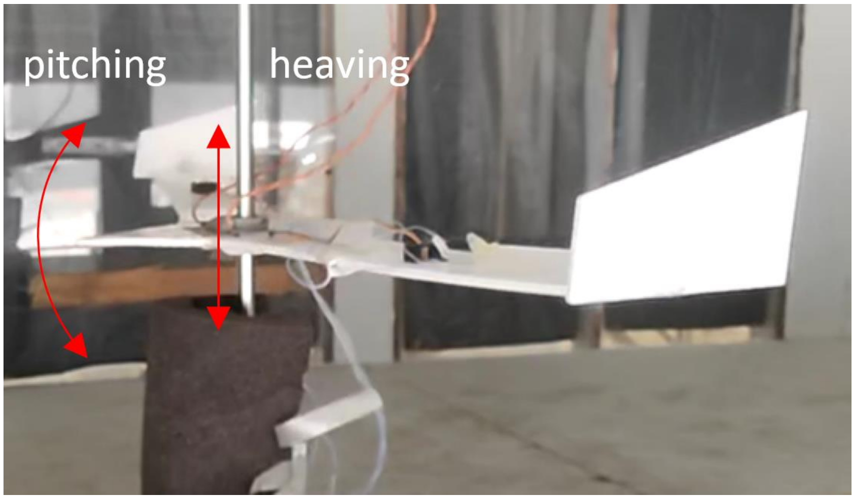


Figure 2: Snapshot of wing undergoing BFF. See https://youtu.be/IXv1083lozg for video of the experiment.

It is observed that increasing tip weights causes the BFF speed to decrease. Due to the sweep of the wing, additional tip weights cause the position of the center of gravity (C.G.) to shift backwards. This results in greater instability of the rigid-body short-period mode, causing the flutter speed to decrease with additional tip weights. For the flutter frequency, adding tip weights causes a decrease in frequency. The addition of tip weights causes the natural frequency of the bending mode to decrease, resulting in a lower BFF frequency. These findings suggest that the stability of the rigid-body modes has a significant impact on BFF velocity.

Similar to varying tip weights, shifting the weights towards the wing tip causes BFF speed to decrease. Same as before, due to the sweep of the wing, shifting the weights outboard causes the C.G. to move backwards, reducing the stability of the short-period mode. The frequency of oscillation sees a downwards trend as the weights shifts outboard. Comparing the flutter speed between the two wing sweep angles, it is observed that the 20deg swept wing has a higher BFF speed as compared to the 10 deg swept wing. Firstly, a higher wing sweep causes larger moment of inertia about the pitch axis, and secondly, the increase in wing sweep results in greater damping of the short period modes, leading to higher stability. Similarly, the 20deg swept wing has higher frequencies of oscillation than the 10deg swept wing, primarily due to the effect of sweep angle on the short-period oscillations characteristics.

To extract the influence of sweep angles on the flutter speed and frequency as the tip weights and spanwise weight location changes, flutter velocity ratios and flutter frequency ratios are plotted in Figure 3. Figure 3(a) shows the BFF speed as the number of tip weights increases, normalised to the case with no tip weights. It is observed that the BFF speed for the case with 20deg wing sweep is significantly more sensitive to the increase in tip weights as compared to the case with 10deg swept wing. The higher wing sweep angle causes a larger shift in C.G. as the number of tip weights increases, hence the stability for the 20deg swept wing decreases at a faster rate. Looking at Figure 3(b), whilst the frequency ratio for the 10deg swept wing has a slightly gentler slope than the 20deg swept wing, the two curves are very close together, showing that change in frequency for both wing sweeps are very similar.

The BFF speeds for the spanwise location case, normalised to the flutter velocity of the case where the weights are at 0% span, is shown in Figure 3(c). Same as the above, the 10deg swept wing shows significantly smaller change as the weights shifts outboard, as compared to the 20deg swept wing. Due to the higher sweep angle, the 20deg swept wing experiences a larger change in C.G. location as compared to the 10deg wing, and thus a larger change in the longitudinal stability. The BFF frequency for the 10deg swept wing also experienced smaller change when compared to the frequencies for the 20deg swept wing, as illustrated in Figure 3(d).

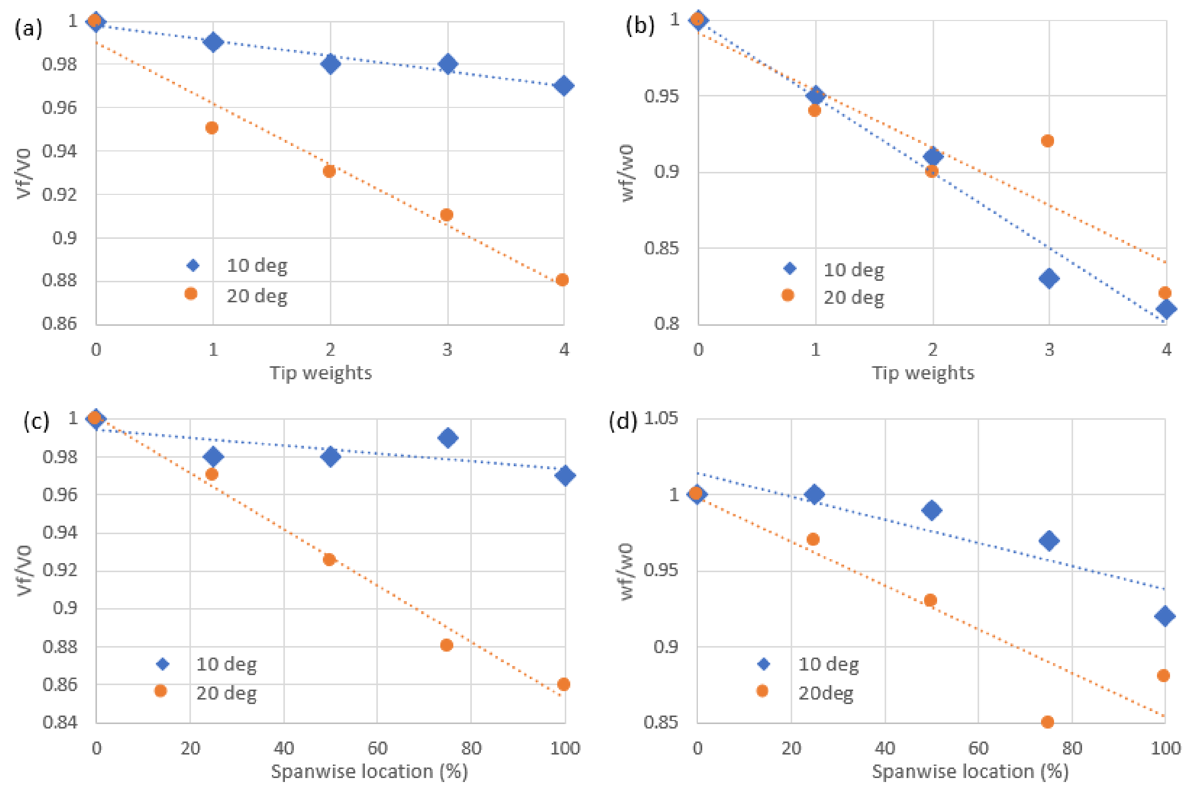


Figure 3: (a) Normalized flutter speeds for changing tip weights (b) normalized frequencies for changing tip weights (c) normalized flutter speeds for changing spanwise location of weights (d) normalized frequencies for changing spanwise location of weights.

3 CONCLUSIONS

This paper described the wind tunnel setup used for investigation of BFF. In summary, BFF experienced rigid-body and short period modes during flutter. By adding tip weights or relocating the weights towards the wing's tip, the flutter speed for BFF decreases as the location of the C.G. is shifted back with an increase of tip weights and moving spanwise weight location outboard, resulting in the increase in instability. Both of these factors contribute to decreased frequencies since the additional weights lead to a reduction in the wing's natural structural frequency due to increased inertia. Furthermore, wings with higher sweep angles demonstrate greater sensitivity to added weights, resulting in a greater reduction in the BFF speed when compared to wings with smaller sweep angles.

REFERENCES

[1] A. M. Pankonien and G. W. Reich, "Multi-material printed wind-tunnel flutter model," AIAA Journal, vol. 56, no. 2, pp. 793–807, Feb. 2018. doi:10.2514/1.J056097.

[2] O. Avin, D. E. Raveh, A. Drachinsky, Y. Ben-Shmuel, and M. Tur, "Experimental aeroelastic benchmark of a very flexible wing," AIAA Journal, vol. 60, no. 3, pp. 1745–1768, Mar. 2022. doi: 10.2514/1.J060621.

[3] B. Lv, Z. Lu, T. Guo, D. Tang, L. Yu, and H. Guo, "Investigation of winglet on the transonic flutter characteristics for a wind tunnel test model CHNT-1," Aerospace Science and Technology, vol. 86, pp. 430–437, Mar. 2019. doi: 10.1016/j.ast.2019.01.025.

[4] J. A. Luton and D. T. Mook, "Numerical simulations of flutter and its suppression by active control," AIAA Journal, vol. 31, no. 12, pp. 2312–2319, Dec. 1993. doi: 10.2514/3.11930.

[5] M. Potsdam, M. Page, R. Liebeck, M. Potsdam, M. Page, and R. Liebeck, "Blended wing body analysis and design," in 15th Applied Aerodynamics Conference, Atlanta, Georgia, Jun. 23, 1997. doi: 10.2514/6.1997-2317.

[6] L. T. Imiblett, "The fundamentals of body-freedom flutter," The Aeronautical Journal, vol. 90, no. 899, pp. 373–377, 1986.

[7] E. L. Burnett, J. A. Beranek, B. T. Holm-Hansen, C. J. Atkinson, and P. M. Flick, "Design and flight test of active flutter suppression on thex 16056a multi-utility technology test-bed aircraft," The Aeronautical Journal, vol. 120, no. 1228, pp. 893–909, Jun. 2016. doi: 10.1017/aer.2016.41.

[8] A. Iannelli, A. Marcos, and M. Lowenberg, "Study of flexible aircraft body freedom flutter with robustness tools," Journal of Guidance, Control, and Dynamics, vol. 41, no. 5, pp. 1083–1094, May 2018. doi: 10.2514/1.G003165.

[9] T. A. Weisshaar and T. A. Zeiler, "Dynamic stability of flexible forward swept wing aircraft," Journal of Aircraft, vol. 20, no. 12, pp. 1014–1020, Dec. 1983. doi: 10.2514/3.48205.

[10] P. Lei, H. Guo, B. LYu, D. Chen, and L. Yu, “Verification of a body freedom flutter numerical simulation method based on main influence parameters,” Machines, vol. 9, no. 10, p. 243, Oct. 2021. doi: 10.3390/machines9100243.

[11] Y. Zhao, C. Yue, and H. Hu, “Gust load alleviation on a large transport airplane,” Journal of Aircraft, vol. 53, no. 6, pp. 1932–1946, 2016. doi: 10.2514/1.C033713.

[12] P. Shi, J. Liu, Y. Gu, Z. Yang, and P. Marzocca, “Full-span flying wing wind tunnel test: A body freedom flutter study,” Fluids, vol. 5, no. 1, p. 34, 2020. doi: 10.3390/fluids5010034.