

# **Original Research Article**

## **Flutter modelling and computation of a flying wing aircraft**

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### **ABSTRACT**

Flying wing aircraft has many encouraging advantages, but there still were many unsteady aerodynamic uncertainty of the structures. Dynamic stability is a most significant analysis object. This paper wants to propose the flutter characteristic of a real flying wing aircraft. Firstly, an efficient finite element modelling method was taken to find basic dynamic features of the presented aircraft with effective mode analysis. Typical dynamic characteristics including bending and twisting modes of the structure were analyzed to propose possible dynamic stability of the aircraft. Secondly, a frequency domain fluid-structure interaction method was proposed to solve flutter analysis problem of the aircraft. With different heights and Ma number, flutter features of the aircraft were presented. It was seen from the computational results that dynamic stability analysis is necessary for the flying wing aircraft with proper flight velocity and height. The present dynamic modelling method and flutter computation process can give an effect reference for the design of flying wing aircraft. Also it can provide useful suggestions for existing flying wing aircraft structures.

*Keywords: flying wing aircraft, FEM, dynamic characteristics, flutter*

### **1. INTRODUCTION**

Flying wing aircraft is an aircraft without tail wings and the main part of the fuselage is hidden in the thick wings. This kind of aircraft only needs wings, so it is theoretically feasible to remove all other redundant components in the design. Therefore, the flying wing configuration was born. Of course, some flying wing aircraft still retain the fuselage. Since the 1920s, the advantages of flying wing aircraft have attracted people's attention, but due to the technical conditions at that time, it did not develop rapidly. With the improvement and development of traditional aircraft layout, its shortcomings begin to be obvious. People urgently need special aircraft structure layout to solve the problem, and flying wing has become the focus of research. In the continuous exploration, the all wing aircraft X-35 developed by the United States for the first flight after World War II has become a typical and effective attempt. Then the B-2 bomber was born and became the focus of the world. After the 21st century, UAVs began to develop vigorously, and the flying wing layout has become the focus of research because of its outstanding tactical advantages. At present, in addition to the x-45 and x-47b of the United States, there are Russian rays, French led Neurons, British Thor, Chinese sword and so on [1-3].

It was demonstrated from some works that some characteristics of static aeroelasticity of flight wing through some basic examples in the literature [4]. The most prominent one is the influence of trim control on the wing divergence. The model was established by the basic beam rod differential equation and aerodynamic strip theory. The divergence of a non-swept wing rolling freely around a fixed axis was discussed. The resulting torsional divergence velocity was almost three times than that of a half span non-rolling wing fixed at the root. If the rolling speed of the whole wing is balanced by the lifting aileron, the antisymmetric

divergence may occur at a lower speed than the classical torsional divergence speed. This paper introduces the rolling trimming of the wing with 30% Fowler flap. It also makes a similar preliminary analysis of the free rolling and trimming of the inclined or skewed wing on the axis parallel to the air flow. Considering only the bending elasticity of the wing, it was found by applying the method that the divergence caused by the application of aileron trim roll was five times of the similar symmetrical swept wing fixed at the center. Finally, a similar free-flight yaw wing adjusts pitch and roll by lifting ailerons so that the total lift was equal to the weight of the aircraft. It was found that the divergence in this case was almost 12 times than that of a fixed symmetrical swept wing.

It was mentioned in the literature that the plane shape design of the wing mainly considered the sweep angle of the leading edge, the chord length of the outer wing and the turning point of the leading edge [5]. Leading edge sweep angle is the most important aircraft parameter in wing layout, which plays a decisive role in the longitudinal static stability of aircraft and the peak distribution of radar cross section. Increasing the leading edge sweep angle is conducive to improve the high-speed aerodynamic efficiency, reduce the drag and improve the stealth performance, but it is not conducive to the low-speed lift characteristics and stall performance. Smaller sweep angle was easier to meet the lift drag performance requirements during takeoff and landing, but it would increase the longitudinal static instability and bring difficulties to the longitudinal control. Increasing the chord length of the outer wing could effectively improve the longitudinal static stability, with resulting in large pitch moment increment and increasing the difficulty of balance. Secondly, it could effectively weak the shock wave, suppress the separation, improve the characteristics of low-speed stall and high-speed flutter, and improve the lift drag ratio of cruise design. But reducing the aspect ratio would reduce the low-speed aerodynamic efficiency. In addition, the increase of outer wing chord length had an adverse impact on stealth performance and structural weight. Therefore, under the premise of low-speed stall characteristics, the chord length of the wing should be as small as possible. The improvement of wing tip shape could improve the stall shape of wing tip and prevent the control surface from losing control efficiency or even control due to the existence of air flow separation zone. According to the principle of the parallel edge design, the double swept back structure could be modified at the wing tip, while the single swept back structure could not be modified. The large swept back oblique shear wing could improve the high-speed performance of the wing, avoid the forward convergence of the wing isobaric line, delay the formation of shock wave, increase the divergent Mach number of the wing surface resistance and improve the flutter characteristics. The main function of wing tip correction device and wing tip device could reduce the induced drag of wing tip, improve the lift drag ratio and dissipate wing tip vortex.

As an aircraft layout mode superior to traditional layout, flying wing has attracted much attention due to its excellent aerodynamic performance, good stealth performance and many other advantages. However, the advantages are obvious and the disadvantages still exist. The poor operational performance and stability of the flying wing have become two major problems hindering its rapid development. Researchers are trying their best to find the best way to solve the problem while maintaining the favorable layout of the flying wing.

In order to find an effective reference of flutter analysis for flying wing aircraft, dynamic modelling and a flutter simulation method are proposed in this paper. An actual flying wing aircraft structure is employed to find effective dynamic characteristics, which is the necessary basement for flutter evaluations. Different Mach numbers and flight height will be used to find different situation related to flutter effects.

## 2. STRUCTURE INTRODUCTION

Based on the general structure of RQ180 UAV, the structure model of flying wing is established in this paper. The flying wing has no tail and fuselage, only the huge wing plus fuselage, as shown in Fig. 1. The flying wing model, which is shown in Fig. 1, consists of the fuselage, wings, fuselage frame, and beam ribs. Compared with traditional aircraft, flying wings do not have vertical tail, with better stealth performance.

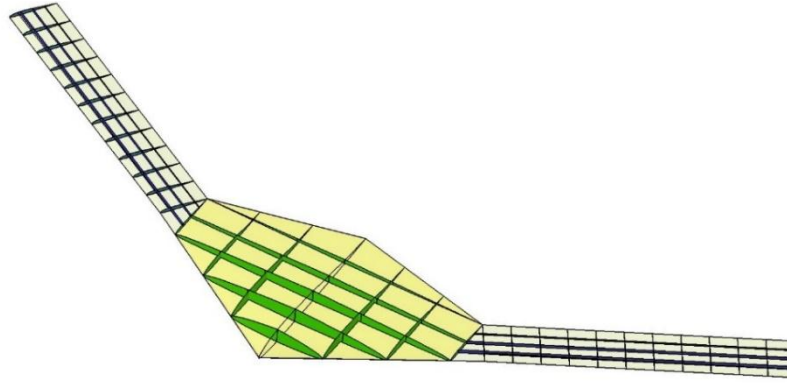


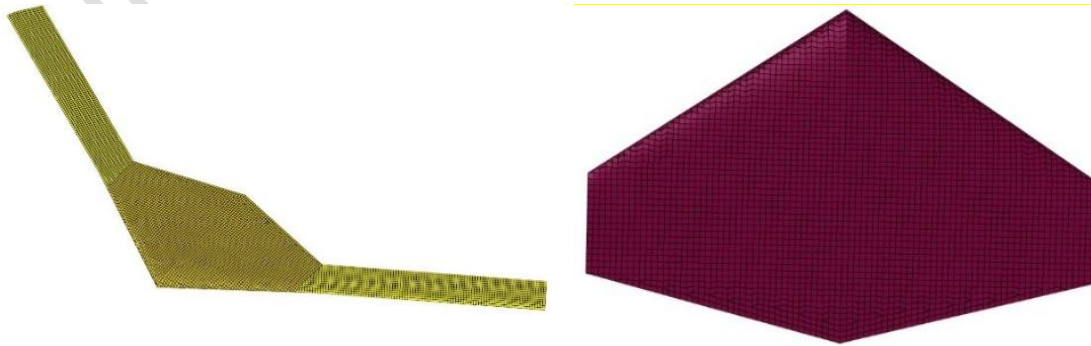
Fig. 1. Structure of flying wing model

Numerical model is presented according to the actual size of RQ180 UAV. The wing span of the model is 62,788.8mm, the fuselage length of the model is 14,325.5mm, and the total length is 22,324.0mm. The model wing has a swept-back angle of  $33^\circ$ , a taper ratio of 1, and a chord length of 4,315.0 mm. The material of the model is aluminum, with a total weight of 19,350 kg, of which the fuselage part weighs 14,280 kg and the wing part weighs 5,070 kg.

## 3. DYNAMIC CHARACTERISTIC ANALYSIS

### 3.1 FINITE ELEMENT MODELLING

A global coordinate system is used for the whole flying wing model. The detailed definition is: the origin O is at the vertex of the leading edge of the flying wing; the X-axis is parallel to the longitudinal direction and the positive direction points to the trailing edge of the wing; The Z-axis is on the longitudinal symmetry plane of the flying wing, perpendicular to the X-axis, with the positive direction pointing to the upper surface of the wing; and the Y-axis is perpendicular to the OXZ plane. For numerical modelling, 2D shell elements were used. The material chosen is aluminum, with modulus of elasticity  $E=70\text{Gpa}$ , density  $\rho=2.7\text{e}^{-12}\text{t/mm}^3$ , Poisson's ratio  $\nu=0.3$ . The established finite element modelling of the flying wing is shown in Fig. 2.



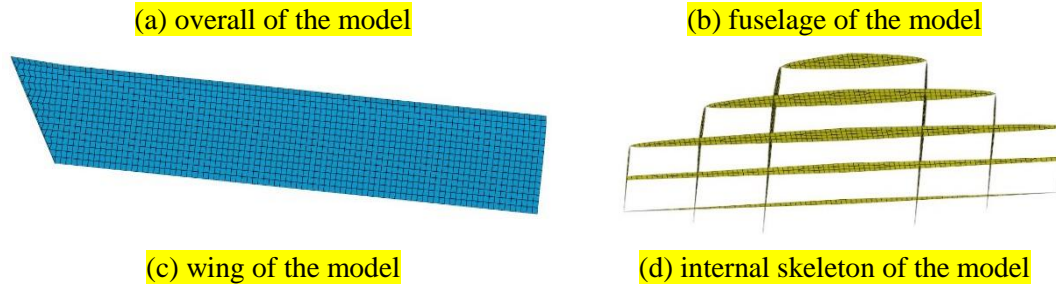


Fig. 2. Finite element model of flying wing.

### 3.2 DYNAMIC CHARACTERISTIC ANALYSIS

For dynamic analysis of undamped multi-degree-of-freedom structures, the equations of motion is written as [1-5]

$$[M]\{\ddot{y}\} + [K]\{y\} = 0 \quad (1)$$

where  $[M]$  is the structural mass matrix;  $[K]$  is the stiffness matrix; and  $\{y\}$  is the nodal displacement vector of the structure. Assuming that the free vibration of each degree of freedom is simple harmonic with the same frequency and phase at the same time, it can be expressed as

$$\{y\} = \{\phi\} \sin(\omega t + \nu) \quad (2)$$

where

$$\{\phi\} = [\phi_1 \ \phi_2 \ \dots \ \phi_n]^T \quad (3)$$

Substitute equation (2) into equation (1) and eliminate the common factor sine function.

$$([K] - \omega^2 [M])\{\phi\} = 0 \quad (4)$$

To solve equation (4), the coefficient determinant of the amplitude is required to be equal to zero, i.e.

$$|[K] - \omega^2 [M]| = 0 \quad (5)$$

Solving equation (5) yields  $n$  positive real roots of  $\omega^2$ , which leads to  $n$  frequencies  $\omega_1, \omega_2, \dots, \omega_n$ . The corresponding amplitude  $\{\phi_i\}$  can be found by substituting  $\omega_i$  into Eq. (4). Here  $\omega_i$  was called natural circular frequency and  $\{\phi_i\}$  was called natural mode.

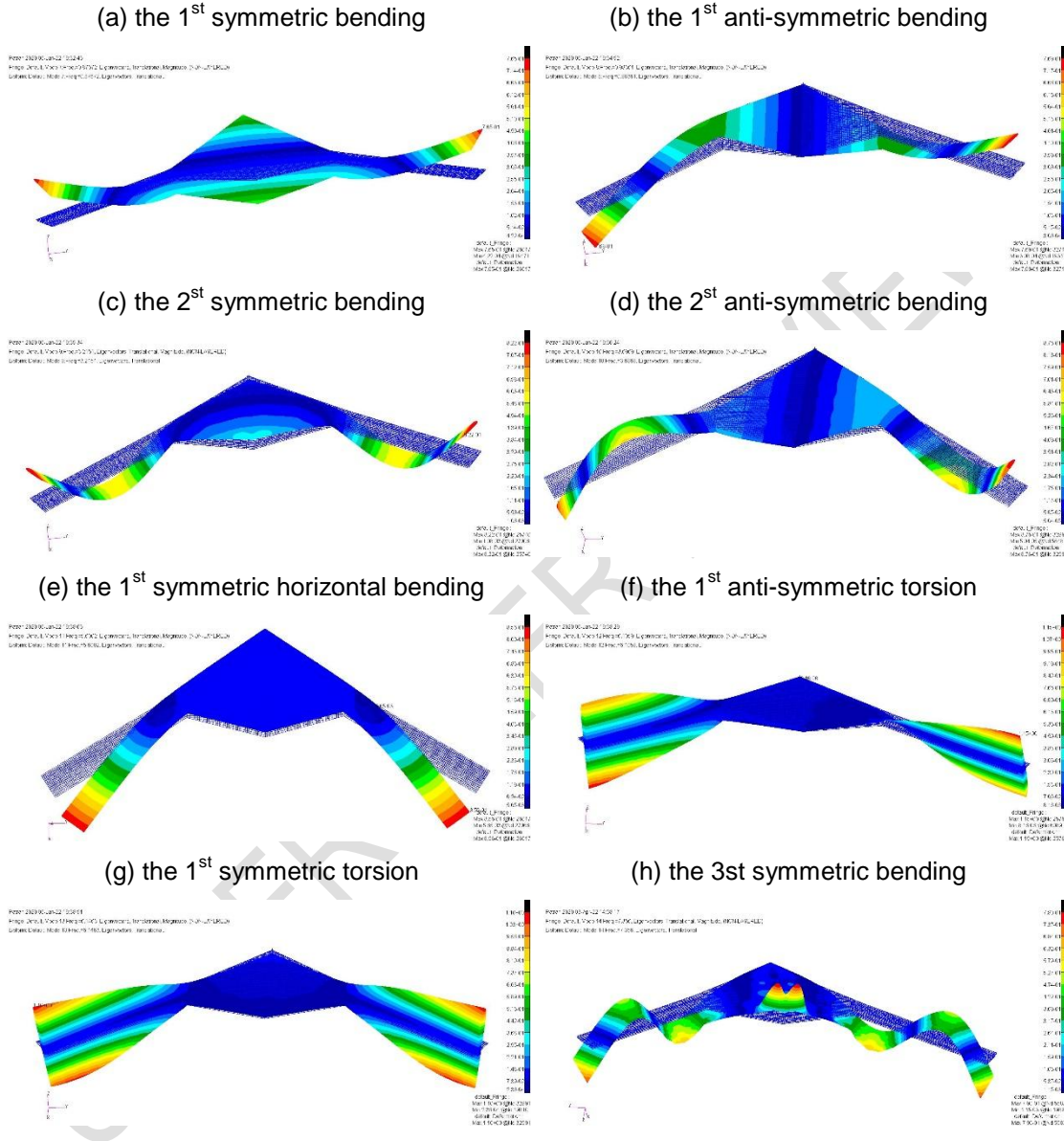
Table 1. Mode analysis

Order	Frequency (Hz)	Modes
1	0.87672	The 1st symmetric bending of the flying wing
2	0.98361	The 1st anti-symmetric bending of the flying wing
3	3.2151	The 2nd symmetric bending of the flying wing
4	3.6969	The 2nd anti-symmetric bending of the flying wing
5	5.6002	The 1st symmetric horizontal bending of the flying wing
6	6.1059	The 1st anti-symmetric torsion of the flying wing
7	6.1463	The 1st symmetric torsion of the flying wing
8	7.356	The 3rd symmetric bending of the flying wing

The modal analysis of the flying wing model is carried out by Lanczos algorithm which is included in a widely used commercial FEM analysis software, MSC Nastran. This software

was the only famous FEM code over the world which includes aeroelastic analysis module [9].

The first 6 modes are all rigid body modes. The elasticity frequencies and modes of the 7th to 14th orders are shown in Table 1 and Fig. 3.



**Fig. 3. Modes of the flying wing. ((a) and (b): the 1st symmetric and anti- symmetric bending, respectively; (c) and (d): the 2st symmetric and anti- symmetric bending, respectively; (e): the 1st symmetric horizontal bending; (f) and (g): the 1st symmetric and anti- symmetric torsion, respectively; (h): the 3st symmetric bending).**

#### 4. FLUTTER ANALYSIS

The flutter of a flying wing is a phenomenon of aeroelastic dynamic instability triggered by the coupling of elastic structural dynamics and non-constant aerodynamics. According to the

theory of vibration [10-13], the equations of motion of the aeroelastic system under the discrete system can be derived:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F} \quad (6)$$

Where  $\mathbf{M}$  and  $\mathbf{K}$  are the mass and stiffness matrices of the structure;  $\mathbf{q}$  is the generalized coordinates of the system; and  $\mathbf{F}$  denotes generalized non-constant aerodynamic forces.

A linear flutter computational method was adopted to calculate the flutter characteristics with Equation (7) [14-16]:

$$[-\omega^2 \mathbf{M} + (1 + ig)\mathbf{K} - q_\infty \mathbf{Q}(ik)]\mathbf{q} = 0 \quad (7)$$

$$k = \frac{\omega L}{V} \quad (8)$$

where  $k$  is the reduced frequency and the dynamic pressure of the flow  $q_\infty$  can be written as:

$$q_\infty = \frac{1}{2} \rho V^2 = \frac{1}{2} \rho \left( \frac{\omega L}{k} \right)^2 \quad (9)$$

where  $L$ ,  $V$  and  $\rho$  are the reference length (generally defined as half of reference chord), the velocity of undisturbed flow and the air density, respectively.

Substitute Equation (9) into Equation (7):

$$\left[ \mathbf{M} + \frac{\rho}{2} \left( \frac{L}{k} \right)^2 \mathbf{Q}(ik) - \lambda \mathbf{K} \right] \mathbf{q} = 0 \quad (10)$$

where:

$$\lambda = \frac{1 + ig}{\omega^2}$$

Flutter frequency  $\omega_f$ , velocity  $V_f$  and the added artificial structural damping  $g$  are given by [17]:

$$\begin{aligned} \omega_f &= \frac{1}{\sqrt{\text{Re}(\lambda)}} \\ V_f &= \frac{\omega_f L}{k} \\ g &= \frac{\text{Im}(\lambda)}{\text{Re}(\lambda)} \end{aligned}$$

A P-K method based on the above equations is a commonly used method to solve the flutter problem [16], and this paper used this method to analyze flutter of the present model. The fundamental equation for modal flutter analysis by the PK-method is

$$\left[ \mathbf{M}p^2 + \left( \mathbf{B} - \frac{1}{4} \rho \bar{c} V \mathbf{Q}^l / k \right) p + \left( \mathbf{K} - \frac{1}{2} \rho V^2 \mathbf{Q}^R \right) \right] \{u\} = 0 \quad (11)$$

where  $\mathbf{B}$  is the modal damping matrix, and this term is not considered in this paper;  $\mathbf{Q}^l$  and  $\mathbf{Q}^R$  are the modal aerodynamic damping matrix and the modal aerodynamic stiffness matrix, respectively, both as a function of Mach number  $Ma$  and the reduced frequency  $k$ . The damping term is not considered in this paper;  $p$  denotes the eigenvalue;  $\bar{c}$ ,  $\rho$  and  $V$  are the reference length, fluid density and velocity, respectively;  $\{u\}$  is the modal amplitude vector.

The main advantage of the PK method is that it can produce results directly for a given value of flow velocity.

The aeroelastic analysis module for flutter computation was used to build a flying wing aero-lift surface model, as shown in Fig. 4. According to the selected aerodynamic shape of the flying wing layout, the flying wing model is divided into four aerodynamic partitions according to the structures. The numbers of aero-lift surface meshes for the left and right wings (i.e. wing structures can be found in Fig.2(c)) are 20 and 5 in spanwise and chord direction, respectively. The meshes for the left and right fuselage (i.e. the fuselage structure can be found in Fig.2(b)) are 10 and 5 in spanwise and chord direction, respectively.

Flutter results were also computed with MSC NASTRAN software. The reference chord length of the present model was chosen as three times of the total length. The reduced frequency was chosen based on the demand of the numerical method and the software.

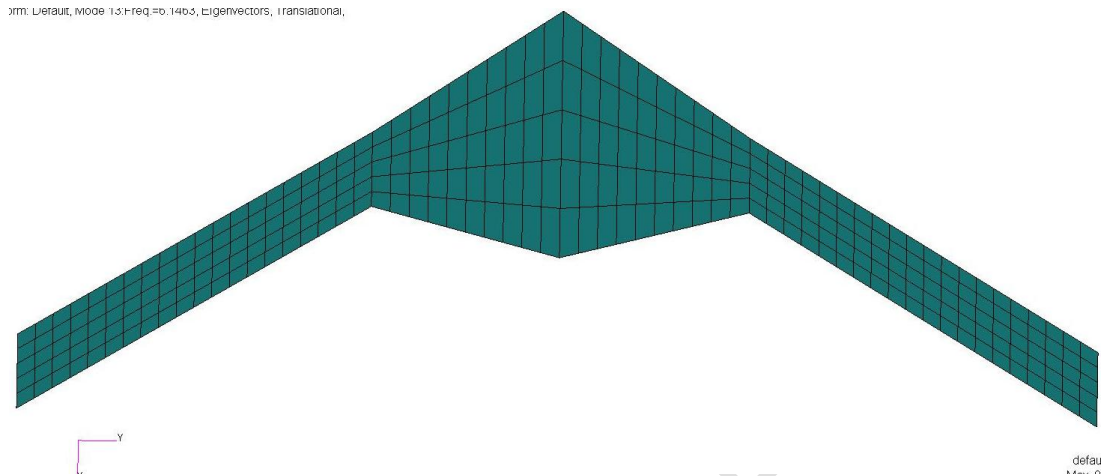


Fig. 4. Flying wing aerodynamic lift surface model

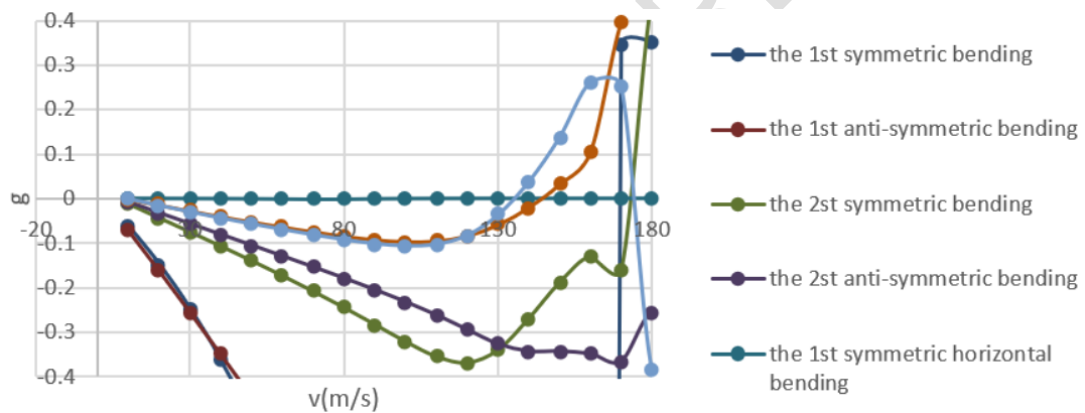


Fig. 5. V-g diagram of the flying wing flutter model.

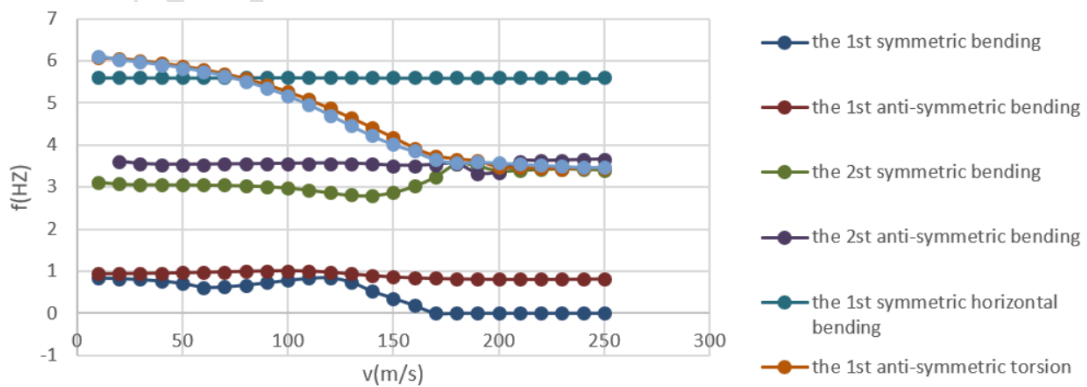


Fig. 6. V-f diagram of the flying wing flutter model.

Figs. 5 and 6 present flutter computational results as a basement via  $Ma=0.5$  and the flying height is the sea level. There is a flutter divergency based on V-g relationship in Fig. 5 and it can be found the flutter frequency 4.338Hz and the related flutter velocity is 134.928m/s.

In order to discuss Mach number effect and the influence due to flying height, three different Mach numbers and flying heights are employed to compute flutter characteristics of the present flying wing aircraft. The results are shown in Tables 2 and 3. As shown in Table 2, the flutter velocity increased with Mach number was found which is a normal feature for aircraft. This feature is induced due to aerodynamic damping at different flying velocity. It is consistent to basic flutter changing laws of most aircraft which can prove that the present flutter computational modelling is effective [14]. It can be seen that Mach number influenced the flutter significantly, if the flying height is in the sea level, the aircraft is dangerous due to flutter critical limitation. Some other method can be applied to increase the flutter critical velocity, such as adding some weight part. Flutter stability should be concerned based on the flight demands.

**Table 2. Mach number effects.**

Mach number	Flutter velocity	Flutter frequency
0.5	134.928m/s	4.338Hz
0.3	84.351m/s	4.221Hz
1.3	397.439m/s	4.409hZ

**Table 3. Flying height influence.**

Mach number	Flying height (km)	Flutter velocity	Flutter frequency
0.5	0	134.928m/s	4.338Hz
	5	193.625m/s	4.339Hz
	10	283.637m/s	4.431Hz

## 5. CONCLUSION

A flying wing aircraft structure which is the simple model of the real flying wing aircraft was modelled and analyzed in this paper. Basic dynamic characteristics and flutter critical features were analyzed.

It can be concluded:

- for flutter analysis of the flying wing aircraft, basic dynamic characteristic of the structure is necessary, effective mode identification can be used for the further flutter computation;
- engineering numerical method such as PK algorithm can be employed to find flutter boundary of the flying wing aircraft, effective aero modelling based on simple aero-panel is useful;
- the present aircraft is dangerous when subsonic flight velocity is adopted, some flutter decreased method should be found to solve this limitation.

The numerical simulations in this paper can be applied to the designs of flying wing aircraft related to aeroelasticity. It can provide significant application value in finding effective dynamic modeling and numerical analysis for such aircraft.

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