

Experimental Study on Determining the Critical Speed of Bending-Torsion Flutter Phenomenon in a Thin Wing Model

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Abstract: Aircraft structures are not perfectly rigid. Under external forces, aircraft components deform, leading to redistribution of aerodynamic loads. This, coupled with the emergence of inertial forces, causes aeroelastic phenomena. Among these, wing bending-torsion flutter is a dangerous self-excited oscillation that can induce damage leading to structural failure. Determining the speed at which wing bending-torsion flutter initiates, also known as the critical speed (V_{KF}), is crucial for the calculation, design, and operation of flying vehicles.

Keywords: Flutter phenomenon; Critical speed; Aeroelasticity; Thin wing model.

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I. INTRODUCTION

Solving aeroelastic problems in general, and flutter in particular, can be approached using analytical methods, experimental methods, or some newer methods that allow the synthesis of relevant scientific data - mathematical modeling and computational testing. Researching the flutter phenomenon, this study uses an approximate theoretical formula to determine V_{KF} for a thin wing model under the assumptions: the wing material is homogeneous and isotropic, temperature effects are neglected, the wing structure operates within the elastic limit, the wing is rigidly fixed to the aerodynamic balance strut in the experiment (considered as cantilevered to a rigid fuselage), aerodynamic drag is neglected, and shear-induced transverse section deformations are not considered. The theoretical calculation results are verified with experimental research conducted in the OKD-0,2M wind tunnel at the Air Defense - Air Force Academy.

During the experiment, the thin wing model was clamped onto a 6-component aerodynamic balance strut. The balance strut has high stiffness; its deformation is much smaller than the wing's deformation and can be considered absolutely rigid.

II. THEORETICAL CALCULATION

The thin wing model used in the experiment is a straight wing. According to reference [3], when investigating the bending-torsion flutter phenomenon of a thin wing, considering additional aerodynamic forces and moments $\Delta Y = q_{kd} dz$ and $\Delta M = m_{kd} dz$, we have the system of differential equations:

$$\begin{cases} \frac{\partial^2}{\partial z^2} \left(EJ \frac{\partial^2 y}{\partial z^2} \right) + m \frac{\partial^2 y}{\partial t^2} - \sigma m \frac{\partial^2 \varphi}{\partial t^2} - q_{kd} = 0 \\ \frac{\partial^2}{\partial z^2} \left(GJ_k \frac{\partial \varphi}{\partial z} \right) - I_m \frac{\partial^2 \varphi}{\partial t^2} + \sigma m \frac{\partial^2 y}{\partial t^2} + m_{kd} = 0 \end{cases}$$

Here, the first equation of the system represents pure bending oscillation, and the second represents pure torsional oscillation of the wing. Solving the system will yield the critical speed for wing bending-torsion flutter V_{KF} :

$$V_{KF} = \pi \sqrt{\frac{2GJ_k}{C_y^\alpha \cdot I_k \cdot \rho_H \cdot (x_{TO} - x_{AO}) \cdot S}}$$

The thin wing model for the experiment was made of wood. Its mechanical properties and model parameters are shown in Table 1.

Table 1. Some mechanical properties of the material and parameters of the wing model

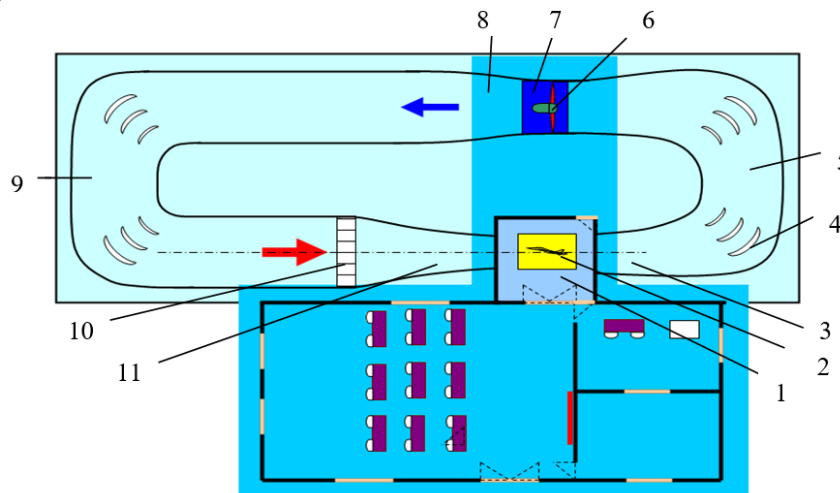
No.	Parameter Name	Symbol	Value	Unit
1	Length of cantilever beam wing	l_k	0,5	m
2	Chord length	b	0,1	m
3	Wing area	S	0,05	m ²
4	Derivative of lift coefficient wrt angle of attack	C_y^α	2π	
5	Shear modulus	G	$3,582 \cdot 10^5$	kN/m ²
6	Aerodynamic center coordinate	x_{AO}	0,025	m
7	Center of gravity coordinate	x_{TO}	0,042	m
8	Distance between center of gravity and elastic center	σ	0,008	m
9	Polar moment of inertia	J_k	$955,67 \cdot 10^{-9}$	m ⁴
10	Air density	ρ_H	1,225	kg/m ³

Using the theoretical formula for the critical speed of wing bending-torsion flutter with the mechanical properties and geometric parameters of the thin wing model from Table 1, $V_{KF} \approx 45.4$ m/s was determined.

III. EXPERIMENTAL DETERMINATION OF THE CRITICAL SPEED FOR THE BENDING-TORSION FLUTTER PHENOMENON IN A THIN WING MODEL

3.1. Airflow Generation System

To simulate real-world operating conditions for aircraft propellers, the experimental setup employs a closed-loop subsonics wind tunnel (OKD-0.2M). This wind tunnel generates a stable airflow within the test section, with adjustable airflow velocities ranging from 0 to 0.2 Mach. The schematic of the wind tunnel is illustrated in Figure 4.



1-Test section; 2-Ropeller model; 3-Small Diffuser Tube; 4-Main Flow Plates; 5-Air Recirculation Duct to the Engine; 6-ThreePhase Electric Fan Motor; 7-Engine Compartment; 8-Large Diffuser Tube; 9-Air Guide Tube; 10-Flow Stabilization Device; 11-Acceleration Tube

Figure 4. Schematic Diagram of the OKD-0.2M Wind Tunnel

3.2. Experimental Model

The model used for the experiment to determine the critical speed of bending-torsion flutter in the OKD-0.2M wind tunnel is a rectangular thin wing (Figure 1).

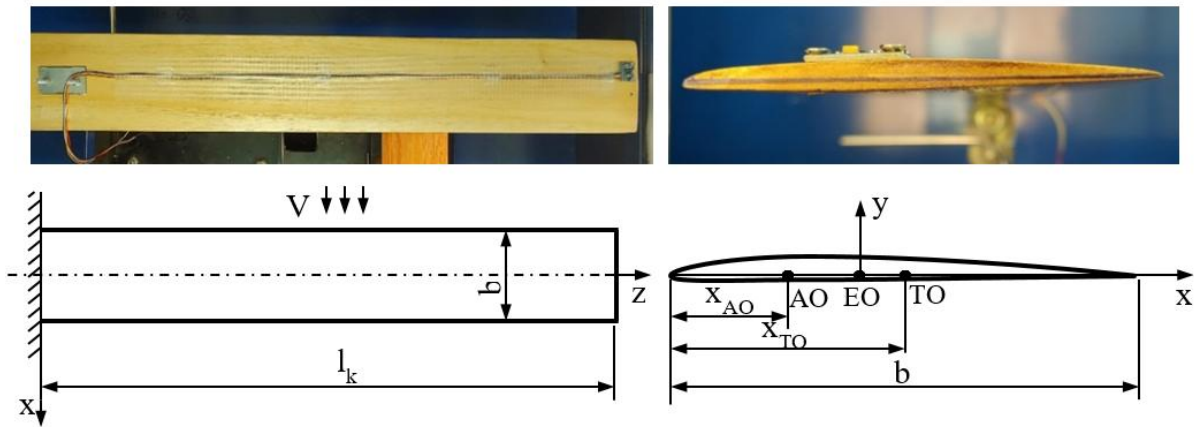
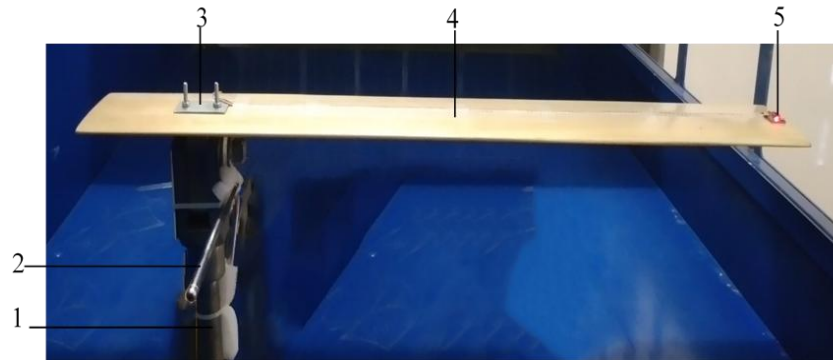


Figure 1. Thin wing model used in the experiment

The wing was installed in the test section of the wind tunnel as shown in Figure 2.



1 - Aerodynamic balance strut; 2 - Speed measurement device;
3 - Wing mounting clamp to the balance strut; 4 - Wing model; 5 - Sensors

Figure 2. Thin wing model in the test section

3.3. Experimental Procedure

Experimental conditions: Air temperature: $T_H = 24^{\circ}\text{C}$; Atmospheric pressure: $P_H \approx 760\text{mmHg}$; Air humidity: 70%; Air density: $\rho_H \approx 1,225\text{kg/m}^3$. Determining the critical speed for bending-torsion flutter of the thin wing model was conducted in the wind tunnel within an airflow velocity range: $V = 0\div 68$ m/s. The parameters of the thin wing during the experiment were the input parameters for the theoretical calculation. Thus, the similarity factors during testing were basically satisfied.

During the experiment, the airflow velocity was gradually increased by adjusting the electric motor power; the airflow velocity was monitored on the measuring device; phenomena in the test section and parameter changes on the displacement/rotation angle measurement software were observed. When signs of bending-torsion flutter appeared, adjusting the airflow velocity was stopped, results were saved, and the experiment concluded.

IV. EXPERIMENTAL RESULTS

Experimental results at some airflow velocities are as follows:

$V_1 = 10\text{m/s}$ và $V_2 = 30\text{m/s}$. Graphs showing the variation of displacement and twist angle of the thin wing model over time at velocities $V_1 = 10\text{m/s}$ and $V_2 = 30\text{m/s}$ (Figure 3).

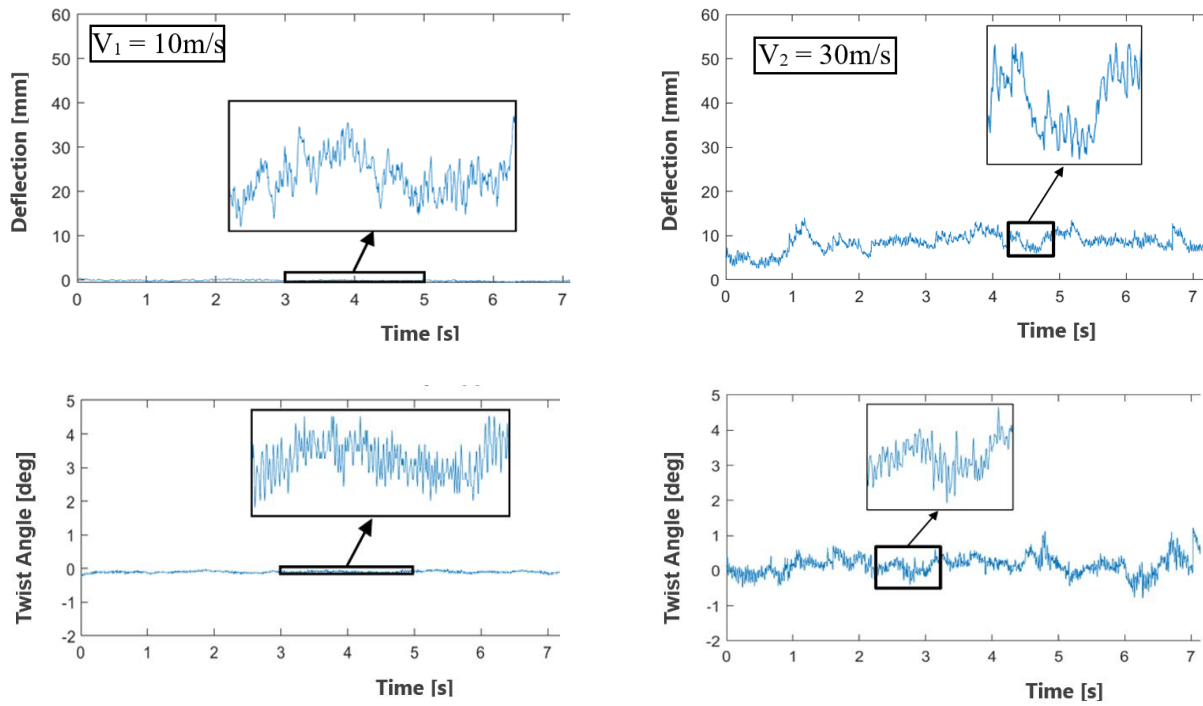


Figure 3. Measured displacement and twist angle results at $V_1 = 10\text{m/s}$ and $V_2 = 30\text{m/s}$

The graphs in Figure 3 show that at velocities $V_1 = 10\text{m/s}$ and $V_2 = 30\text{m/s}$, the wing displacement is a function varying with time, synthesized from two components (displacement along the y-direction and torsion about the z-axis). The displacement values describe the wing's motion around an axis offset from the initial position by $y_1 = -0,1\text{mm}$ (for $V_1 = 10\text{m/s}$) and $y_2 = 8 \text{ mm}$ (for $V_2 = 30\text{m/s}$). At velocity $V_2 = 30\text{m/s}$, the equilibrium position is higher, and the oscillation amplitude around this position is greater than at $V_1 = 10 \text{ m/s}$. The reason is that at $V_2 = 30 \text{ m/s}$, the lift force on the wing increases, causing more wing bending upward, thus a higher equilibrium position. The values y_1 and y_2 correspond to the static displacement of the wing structure under its weight and the lift generated at speeds V_1 and V_2 . The oscillation amplitude is stable over time, indicating that bending-torsion flutter has not occurred at these speeds.

$V_3 = 39\text{m/s}$ and $V_4 = 40\text{m/s}$. Continuing at speeds $V_3 = 39\text{m/s}$ and $V_4 = 40\text{m/s}$, the resulting graphs showing wing displacement over time are obtained (Figure 4).

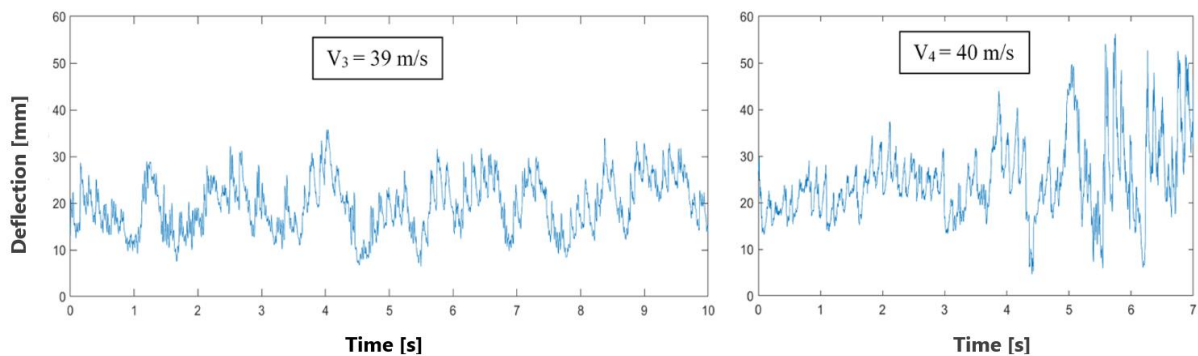


Figure 4. Graph of wing displacement at velocities $V_3 = 39\text{m/s}$ and $V_4 = 40\text{m/s}$

The graph in Figure 4 shows that at velocity $V_3 = 39\text{m/s}$, the displacement oscillation pattern is stable, the displacement amplitude is almost unchanged and larger than at V_2 . However, when the airflow speed increases to $V_4 = 40\text{m/s}$, the amplitude tends to increase over time (the thin wing model exhibits divergent oscillation), indicating that velocity $V_4 > V_{KF}$. Thus, bending-torsion flutter has occurred on the studied thin wing model within the velocity range of $39 \div 40 \text{ m/s}$.

The measured component forces acting on the wing via the 6-component balance, displayed on the balance software at velocities $V_3 = 39\text{m/s}$ and $V_4 = 40\text{m/s}$, are shown in Figure 5.

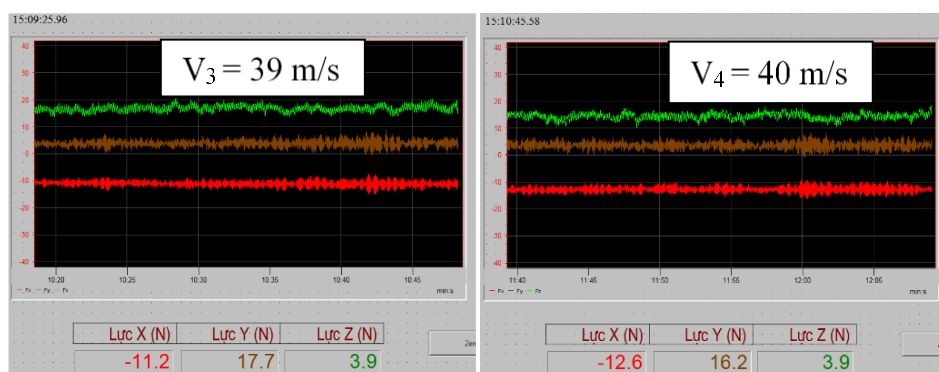


Figure 5. Aerodynamic forces acting on the wing at velocities $V_3 = 39\text{m/s}$ and $V_4 = 40\text{m/s}$

The results in Figure 5 show that when the velocity reaches $V_4 = 40\text{m/s}$, the drag force X on the wing increases, and the lift force Y tends to decrease; the forces acting on the wing change continuously with large amplitude. The cause is that when bending-torsion flutter occurs, the wing oscillates with a large and increasing amplitude, the angle of attack changes accordingly, and the pressure distribution on the wing surface is redistributed, leading to changes in the component forces acting on the wing.

IV. CONCLUSION

From the experiment, the critical speed for bending-torsion flutter of the thin wing model in the OKD-0.2M wind tunnel was determined to be in the range of $39 \div 40\text{m/s}$. The theoretical and experimental values of V_{KF} differ by approximately $13 \pm 1\%$. The causes of error between experimental results and theoretical calculations include multiple factors: some input data for theoretical calculations are approximate; measurement errors of equipment during the experiment; influence of wing fixation on the balance strut and vibration of the balance strut on the wing; manufacturing accuracy of the model. During operation, flying vehicles are not allowed to fly at speeds $V > V_{KF}$ to avoid divergent oscillation leading to structural destruction. The research results form a basis for calculating, designing, testing, and certifying flying vehicle structures; this is highly significant in the design, manufacture, and operation of flying vehicles, ensuring flight safety.

Conflict of interest

There is no conflict to disclose.

FUTURE DEVELOPMENT

The content of the thesis presents research results for thin wings in low-speed regimes. Based on these findings, the study can be further extended to other configurations using experimental models such as wings equipped with control mechanisms (ailerons, flaps), as well as complete models integrated with fuselages, at higher speed ranges.

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