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Experimental investigation of the effect of flapping on the lift and thrust forces of 3D-wing

M. Ramezani Voloojerdi, M. Mani*

Aerospace Engineering Department, Amirkabir University of Technology, Tehran, Iran

ABSTRACT: Effects of flapping on lift and thrust forces in a 3D flapping wing have been investigated at low Reynolds numbers and several reduced frequencies, using experimental tests in a subsonic wind tunnel. Tests have been performed at Reynolds numbers 42000 to 170000 and reduced frequencies 0 to 0.45 that most birds flight at this ranges. Also, the ranges of the angle of attacks are between 0°-24°. Results have shown that an increase of reduced frequency can enhance the lift force by up to 100 percent and in some cases reduce drag force to zero. Furthermore, increment of reduced frequency has caused a delay in stall of the wing. Also by increasing the Reynolds number from 42000 to 86000, the major region of the boundary layer of the wing surface becomes turbulent, so maximum lift force increases by 40 percent. Wind tunnel test results show that the effect of reduced frequency on the lift force was dependent on the angle of attack, so at the lower attack angles, the increase of reduced frequency did not affect the lift coefficient, but, with increment in the angle of attack, the positive effect of the reduced frequency on the coefficient of the lift force increased.

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1. Introduction

Shortened takeoff and landing distances and lowered stall speeds, a characteristic of birds' flights, would be achievable with improved aerodynamic performance including higher lift coefficient at lower incidence angles and delayed stallSelig and Guglielmo designed and analyzed a new high-lift S1223 airfoil [1]. This airfoil which has $CL_{max} = 2.2$ at $Re = 2\times10^5$ is one of the most known bird-like airfoils.

On the other hand flapping of the wing change the aerodynamic properties of the wing by providing thrust force and increasing lift force. Some research about flapping flight focused on the aerodynamic properties of membrane wings [2-7]. Thrust force in membrane wings is more than thick wings but the lift force of thick wings is more than membrane wings, so thick flapping wings can provide a large capacity of payload in flight. Therefore, the aerodynamic properties of the thick airfoil in flapping flight have been the subject of several studies [8-13].

According to previous studies, testing and analyzing a thick airfoil flapping wing that is very similar to a cross-section of bird's wing are mainly considered. Bird-like S1223 airfoil is chosen for flapping wing in order to be similar to bird wings cross-section. All experiments are conducted at different angles of attack for finding the aerodynamic characteristics of flapping wings along with the analysis of thrust and lift coefficients.

2. Experimental Methods and Facilities

2.1 Test Models

The test model consists of two parts. The first is a straight wing that is inspired by nature, the S1223 airfoil has been selected as the cross-section of this. The aspect ratio of wing is 4.1. The second is flapping mechanism that includes an electric motor, gearbox, shaft, and rods. The characteristic of the flapping model in comparison to a typical pigeon [8] is illustrated in Table 1.

2.2 Experimental Setup

Experiments were conducted in a subsonic, open-loop wind tunnel in the aerodynamic research laboratory at the Amirkabir University of Technology with a rectangular 1m ×1m cross-section and having a 1.8m length test section. For boundary layer growth along the tunnel walls, the test section is diverged by 1 degree. The minimum and maximum velocity of the tunnel is 2.5 m/s and 60 m/s respectively that can be achieved via a 100kW alternating current electric motor. To ensure good flow quality in the test section, the tunnel settling chamber contains a 4mm thick honeycomb and three-layer anti-turbulence screens. The maximum turbulence intensity is less than 0.2% measured by hot-wire anemometry.

A view of the test bed and the model can be seen in Fig. 1. The external force balance was used to detect the aerodynamic lift and drag forces of the wings. The load

*Corresponding author's email: mani@aut.ac.ir

Table 1. Geometric and kinematic characteristics of the Test model and pigeon

Parameter	Test model	pigeon
Wing chord	0.15 m	0.11 m
Wing span	0.8 m	0.66 m
Wing area	0.1 m	0.062 m
Aspect ratio	4.1	7.2
Flapping frequency	0-5 Hz	8 Hz
Reduce frequency	0-0.45	0.25
Flapping amplitude	30°	0° -90°
Air speed	5-20 m/s	11 m/s

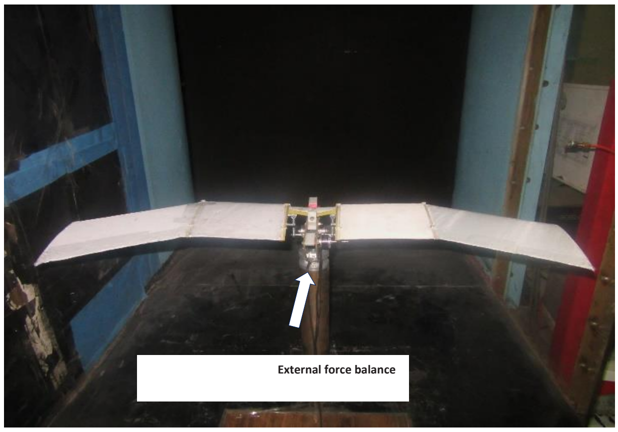

Fig. 1. Model in the test section

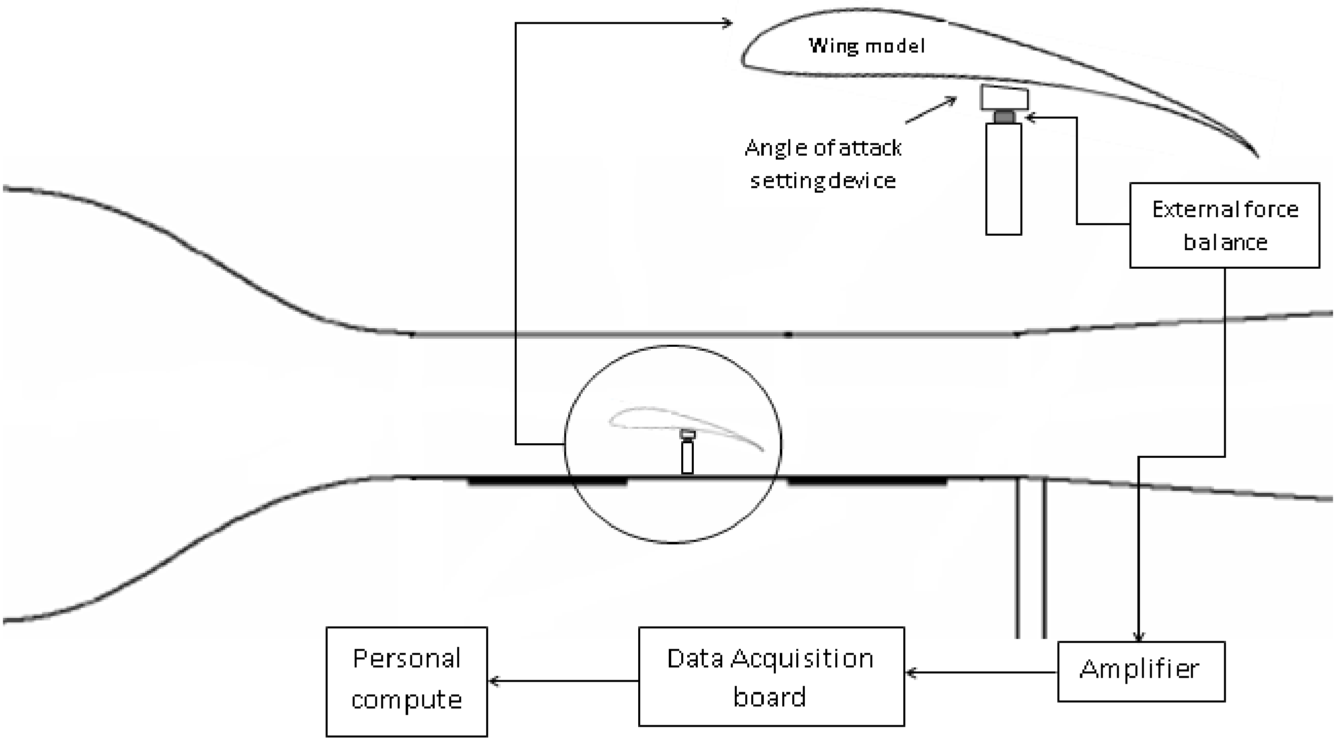

Fig. 2. Schematic of the experimental setup

limits are 240N along the normal axis (lift) and 80N on the horizontal axis (drag). In addition, the minimum resolution along the horizontal axis is 0.001N, and along the normal axis, it is 0.003N. Also, the hysteresis of lift and drag forces are less than 0.1 and 0.15 percent respectively. The model is mounted on the angle of attack setting device and this device is placed on the external force balance as shown in Fig. 2. As illustrated in Fig.1c the analog voltage signals of force balance are transmitted to a personal computer by an amplifier and a data acquisition board. The data was collected at a sample rate of 10 kHz for 7 seconds.

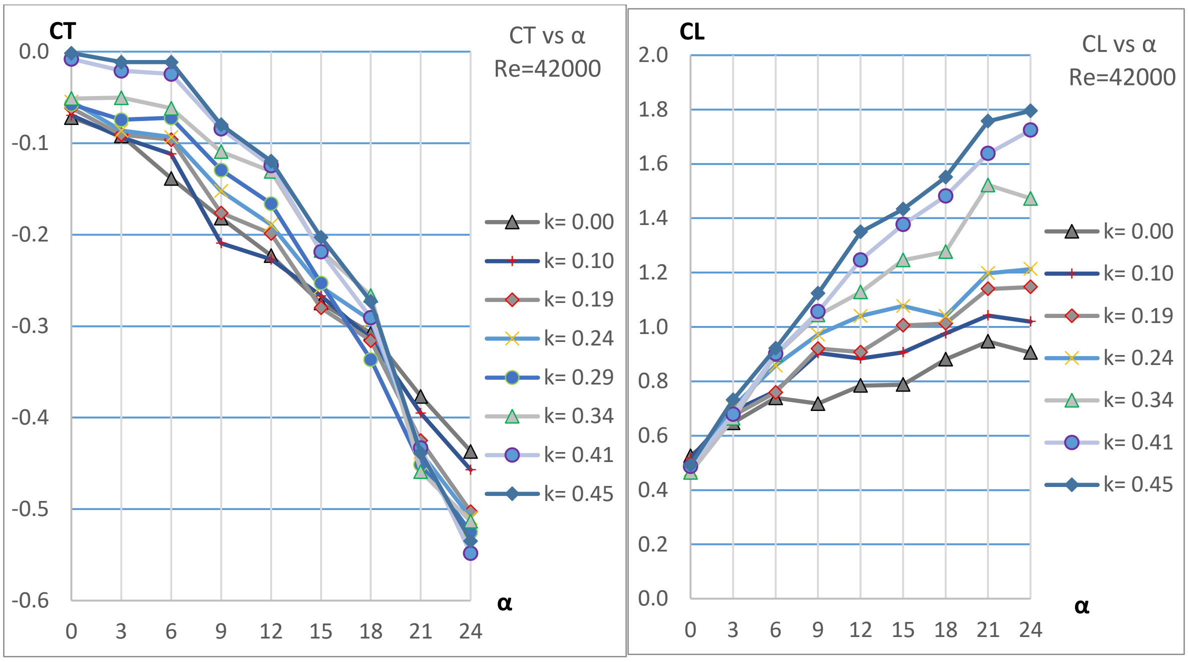

Fig. 3. Effects of reduce frequency on force coefficients

3. Results and Discussion

The results of the wind tunnel test are presented in this section. Aerodynamic forces on the flapping wing are measured in 0°-24° angles of attack and Reynolds numbers 4.3×10^4, 8.6×10^4, 1.3×10^5, and 1.7×10^5. The results are investigated in two subsections. In the first subsection, the effects of reducing frequency on lift coefficient (*CL*) and thrust coefficient (*CT*), are discussed. In the second subsection, the effects of increasing Reynolds number on *CL*, *CT* are analyzed. The blockage of flow by walls would not occur as the span of the wing is less than 80 cm, and the test section width of the wind tunnel is 1m.

The Reynolds number and reduce frequency are given by Eqs. (1) and (2):

$$K = \frac{\pi f C}{V} \quad (1)$$

$$\mathrm{Re} = \frac{\rho V C}{\mu} \quad (2)$$

where ρ is the density of air, V is the airspeed, C is the cord of wing, μ is the coefficient of air viscosity, and f is the flapping wing frequency.

3.1. Effects Of Reduced Frequency

The effect of reduced frequency on lift and thrust coefficients shown in Fig. 3 for *Re*=42000. Based on Fig. 3 increment of reduced frequency, increases the lift force up to 100% and increases the stall angle, also reduce the thrust force.

The effect of angle of attacks on lift and thrust force coefficients shown in Fig. 4. At low angle of attacks, reduced frequency is not affected by lift force but at high angle of attacks lift force increases by increment of reduced frequency due to reattachment of separated flow on the wing.

3.2. Effects Of Reynolds Number

The effects of Reynolds number on lift and thrust force for k = 0.1 are shown in Fig. 5. As shown in this figure the increment of Reynolds number from 42000 to 86000 increases the lift force and the stall angle due to the enlargement of the turbulent boundary layer on the wing.Conclusions

A flapping bird-inspired wing platform is proposed and investigated experimentally. The main results of this investigation are mentioned below.

- Increment of reduced frequency increases stall angle and lift force up to 100% for *Re*=42000.

At low angle of attack, increment of reduced frequency increases thrust force but not affected on lift force while in high angle of attacks not affected on thrust force and increases the lift force.

- The increment of Reynolds number from 42000 to 86000 increases the lift force the stall angle due to the enlargement of the turbulent boundary layer on the wing.

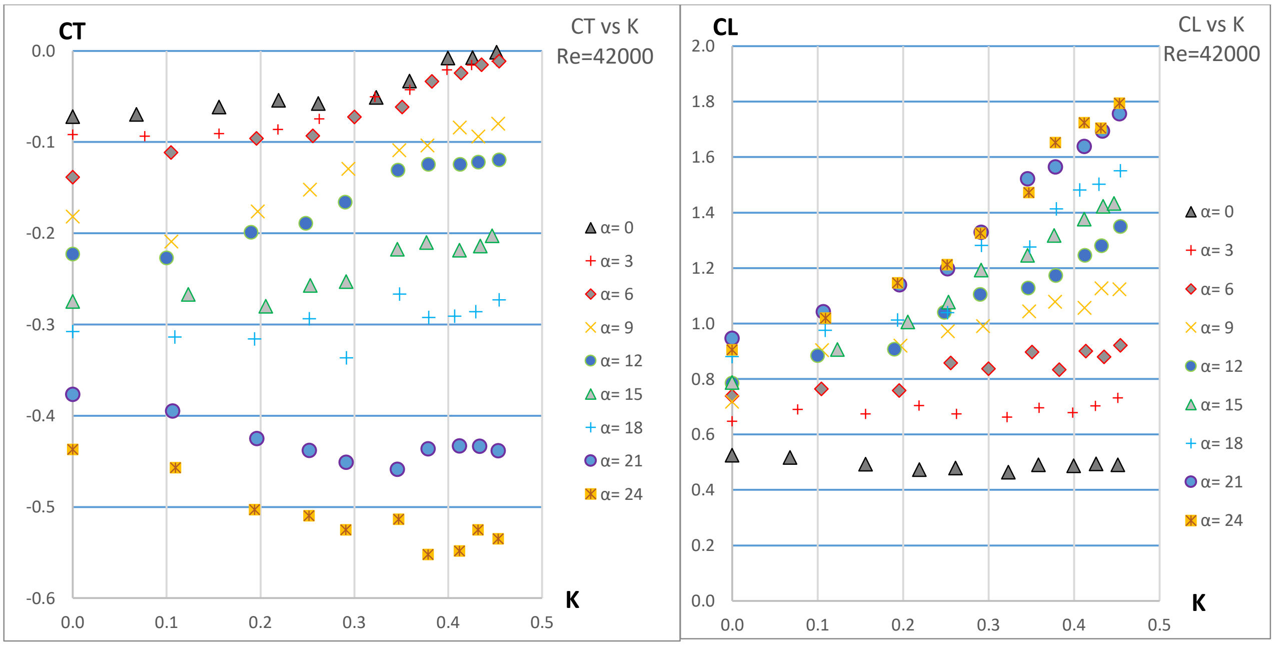

Fig. 4. Effects of angle of attacks on force coefficients

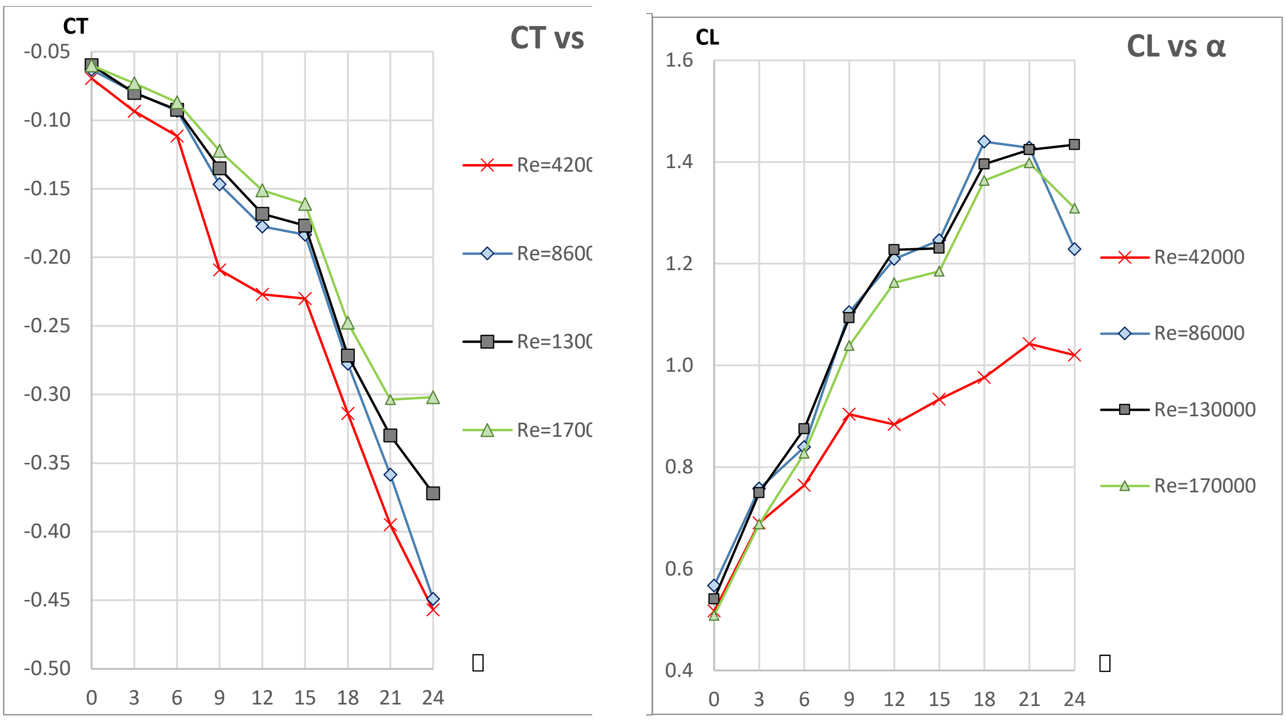

Fig. 5. Effects of Reynolds No. on force coefficients

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