

Original Article

An Experimental Analysis on the Effects of Stagger on the Aerodynamic Forces of Tandem Wings

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Abstract: This study is inspired by the flapping motion of natural flyers: insects. Many insects have two pairs of wings referred as tandem wings. Literature review indicates that the effects of tandem wing are influenced by parameters such as stagger (the stream-wise distance between the aerodynamic center of the front and the rear airfoil), angle-of-attack and flow velocity. As a first stage, this study focuses on the effects of stagger (St) on the aerodynamic performance of tandem wings. A recent numerical study of stagger on tandem airfoils in turbulent flow ($Re = 6000000$) concluded that a larger stagger resulted in a decrease in lift force, and an increase in drag force. However, for laminar flow ($Re = 2000$), increasing the stagger was not found to be detrimental for aerodynamic performance. Another work also revealed that the maximum lift coefficient for a tandem configuration decreased with increasing stagger. The focus of this study is to perform an experimental analysis of tandem two-dimensional (2D) NACA 0012 airfoils. The two airfoils are set at the same angle-of-attack of 0° to 15° with 5° interval and three variations of stagger: 1c, 1.5c and 2c. The experiments are conducted using an open-loop-subsonic wind tunnel at a Reynolds number of 170000. The effects of St on the aerodynamic forces (lift and drag) are analyzed.

Keywords: drag lift, low Reynolds number, tandem airfoil, stagger

1. Introduction

MAVs operate in a low Reynolds number regime of 103-105 [1,2]. MAVs can be divided into fixed, rotary, and flapping wings. Examples of a fixed-, rotary- and flapping-wing MAV is Black Widow, Skybotix Coax, and DelFly Micro TU Delft respectively (Figure 1) [3].

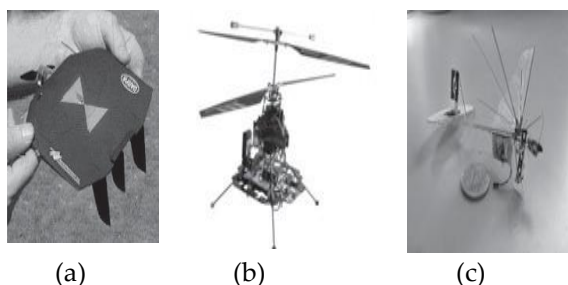


Figure 1. (a) Black Widow, (b) Skybotix Coax, and (c) DelFly Micro TU Delft

Flapping wing MAVs are inspired by the configuration of insect wings that usually have one or two pairs of wings with the later referred as tandem wing. A tandem wing can generate a greater lift force than a single wing because of the wing interaction between wings. A numerical analysis on the effects of stagger at $Re = 6000000$ concluded that a larger stagger resulted in a decrease in lift and an

increase in drag force [1]. However, for laminar flow ($Re = 2000$) the effects of stagger were found to be more complicated and no clear relation with aerodynamic forces was found [1,2]. This research focuses on tandem configuration of fixed-wing MAVs due to its potentially better performance compared to one with single wing.

2. Experimental Method

Series of experiments are conducted on a subsonic wind tunnel in the Laboratory of Mechanical Experiments at the Atma Jaya Catholic University of Indonesia.

2.1. Validation

Validation is done in three steps. The first step is the validation of wind-tunnel force sensors. This validation process is performed by putting weighing mass on the load stem. It has been found that the average error rate of the force sensor is 1.37% (Table 1).

Table 1. Force sensor validation

Load (Kg)	Theoretical Force (N)	Experimental Force (N)	Error
0.025	0.245	0.25	-2.10
0.045	0.441	0.45	-1.94
0.065	0.638	0.65	-1.81
0.085	0.834	0.85	-1.94
0.105	1.028	1.04	-1.12

The second step is the validation of the digital airspeed indicator. The validation is conducted by placing an anemometer in the wind-tunnel test section. The reading of the anemometer is compared to that of the digital speed indicator which is connected to a pitot tube inside the test section, as shown on Figure 2.



Figure 2. Anemometer inside the test section

The speed of the digital speed indicator is 14% below that of the anemometer inside the test section. This error will affect the force measurement of the tandem-wing model by an average of 46.79% as shown in Table 2. The error is represented by the error bars on the force plots.

Table 2. Effect of speed error for C_L and C_D measurement

α	C_L			C_D		
	Speed Indicator	Test-section Anemometer	Error	Speed Indicator	Test-section Anemometer	Error
0	0.043	0.015	185.71		0.006	66.67
2	0.111	0.082	35.33	0.018	0.015	21.43
4	0.215	0.239	-9.91	0.014	0.011	30.00
6	0.325	0.196	65.93	0.020	0.013	58.33
8	0.460	0.395	16.35	0.031	0.022	45.00
10	0.504	0.433	16.42	0.054	0.043	24.12
12	0.609	0.479	26.97	0.045	0.030	50.83
14	0.705	0.556	26.74	0.062	0.037	68.89
		Average	47.92		Average	45.66

The third step is the setup validation using a single NACA 0012 airfoil. The current results are compared to other experiment [4]. The force variations with angle-of-attack (α) is presented on Figure 3 below.

The drag (C_D) predictions are in a good agreement with the literature with an average error of 6.89%, but lift (C_L) predictions have a larger difference with an average of -54.13%. However, by taking into account the error bar from the speed reading, then difference between the two data is below 10% on all angles-of-attack tested.

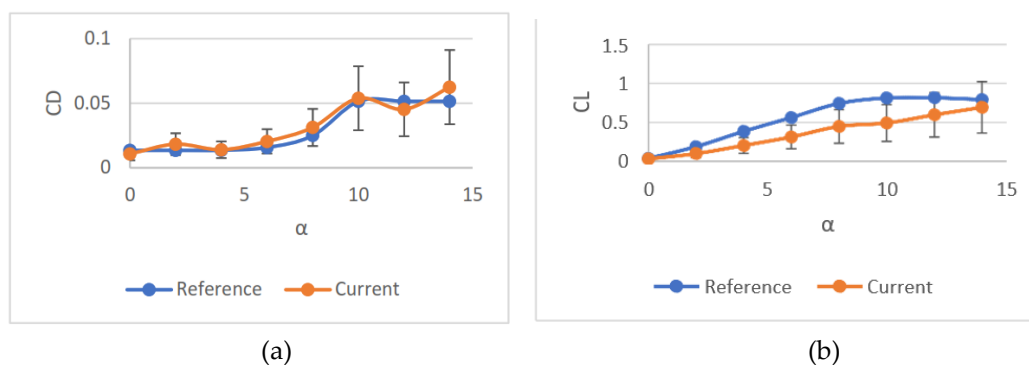


Figure 3. Validation results of single NACA 0012: (a) C_D vs. α and (b) C_L vs. α

2.2. Parametric Study

After the validation process, the next step is testing tandem configuration with NACA0012 profile at a Reynolds number of 170000 (Figure 4). This is a two-dimensional (2D) study with the two wings stretch across the width of the test section. The two airfoils are set at the same angle-of-attack ranging from 0° to 15° with an interval of 5° and three staggers are tested: 1c, 1.5c and 2c



Figure 4. Tandem wing with NACA 0012 profile

3. Results and Discussion

The tandem results for each stagger are compared with the sum of two single airfoils to assess the effects of wing interaction on lift and drag.

3.1. The Effects of Stagger to Lift Force

The wind-tunnel tests show that tandem airfoils with stagger 1.5c and 2c generate comparable lift to the single ones at 0° and 5° (Figure 5). The tandem airfoils with a stagger of 1c produces approximately 37.16% less lift at 5°. At 10°, all tandem airfoils produce higher lift than the single ones, with the highest increment of 37.22% observed on 1c. In comparison to single airfoils, these results indicate that tandem airfoils are able to generate higher lift to carry heavy load in the operational regime of fixed-wing MAVs, which is between 0° and 10°. This is a positive outcome because heavy-lifting capability is a desirable trait for MAVs. At 15°, all tandem airfoils except for the 2c stagger produce comparable lift to the single ones.

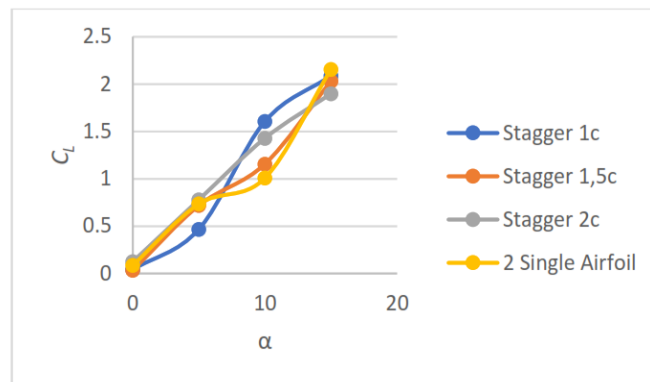


Figure 5. Stagger effects on C_L vs. α

3.2. The Effects of Stagger to Drag Force

For all angles-of-attack, tandem airfoils generate higher C_D than the sum of two single airfoils (Figure 6). The curve for single airfoils is visibly more linear than the tandem wings. Therefore, it can be concluded that setting airfoils in tandem configuration where there is wing interaction introduces non-linearity into drag force particularly in the range of 10°-15°.

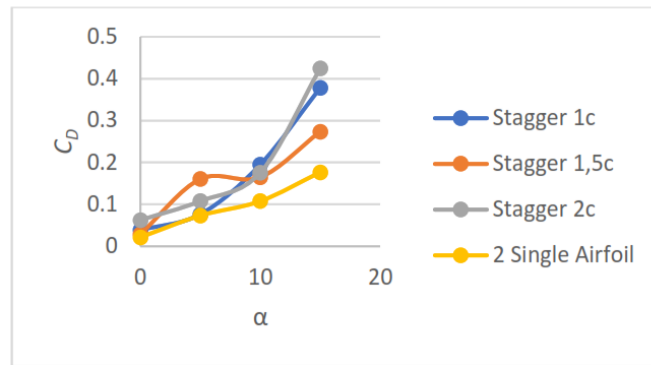


Figure 6. Stagger effects on C_D vs. α

3.3. The Effects of Stagger to Lift-to-Drag Ratio

The lift-to-drag ratios of tandem airfoils are lower than the single ones for all angles-of-attack (Figure 7). This is because for tandem airfoils the increase in C_L is less than C_D . The non-linear increase in C_D as seen in Figure 6 causes the drop in lift-to-drag ratio at higher angles-of-attack ($>10^\circ$).

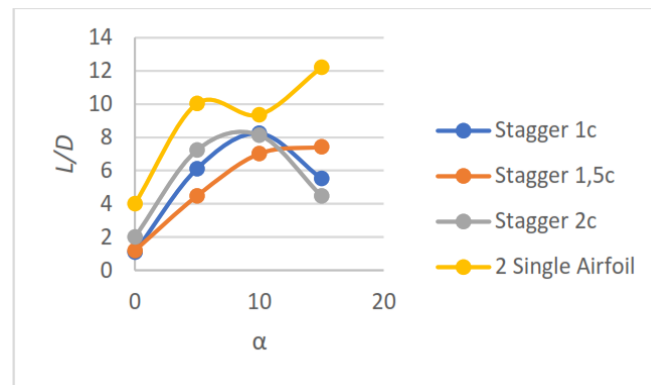


Figure 7. Stagger effects on C_L/C_D vs. α

4. Conclusions

Experimental analysis on two-dimensional tandem NACA 0012 airfoils is conducted in a low-speed wind tunnel at Re of 170000. The airfoils are tested with three variations of stagger 1c, 1.5c and 2c, and angles-of-attack from 0° to 15° with 5° increment. The force measurements of tandem airfoils are compared with the sum of two single airfoils to assess the effects of stagger on lift and drag production. It can be concluded that tandem airfoils produce comparable lift to two single ones at 0° , 5° and 15° . The tandem airfoils generate a significantly higher lift than single airfoils at 10° . Tandem configuration introduces non-linearity into drag production. This non-linearity can be observed in the parabolic shape of the C_D vs. α curve of tandem airfoils. The lift-to-drag ratios of tandem airfoils are lower than the single ones for all angles-of-attack tested due to the higher increment of drag than lift. These results imply that setting airfoils in tandem configuration do not improve the lift-to-drag ratio. However, the tandem configuration can be used to improve the heavy-lifting capability of MAVs throughout operational angles-of-attack. The ability to carry heavy load is crucial as engineers are looking into deploying MAVs to deliver goods.

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