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The Effect of Elevons Deflection to Aerodynamic Coefficients of A Tail-less Blended Wing-Body Planform

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ABSTRACT

Control surfaces play a big role in stabilizing and maneuvering an aircraft. This paper investigates the effect of control surface allocations, specifically deflection of four elevons on a BWB planform, on aerodynamic coefficients. Elevon allocations can be in a form of single-elevon deflection, two-elevon deflection in unison or in opposite deflection angles and four-elevon deflections in unison or in opposite deflection angles. Six aerodynamic coefficients which represent three forces and three moments in three axes are measured via wind tunnel experiment at 25 m/s. The wind tunnel model is of a flat, thin plate with planform similar to a typical stealth, flying-wing aircraft. Thirty-one (31) cases of different elevon deflections are tested at a fixed pitch angle of attack and zero angle of sideslip. The results shows that significant changes in drag, sideforce and lift forces are observed at almost all elevon deflection cases. The roll moment and pitch moment change with respect to elevon angle depends on the number of elevons utilized while yaw moment is not much affected by elevon deflections except for some cases.

Keywords: Aerodynamics, Blended Wing-Body, Control Surface

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Introduction

The Blended Wing-Body (BWB) aircraft, by its unique configuration and potential benefits, is well suited for the role of environmentally friendly, long range, high capacity airliner [1]. However issues of flight stability and control need to be addressed and solved. The BWB tends to have poor departure characteristics due to its lower maximum lift coefficient resulting from the absence of, or limited number of, high lift devices and tails with long moment arm [2]. The tailless nature of BWB aircraft with multiple elevons as control surfaces requires understanding of the impact of these elevons to stability thus usually a BWB aircraft requires an active flight control system [3]. In addition, strong coupling of inertial forces and aerodynamic forces affect the stability of the BWB airplane [4]. Large lift force, short moment length between elevons and centre of gravity, multi-purpose nature of elevons (They are both elevators and ailerons at the same time) requires large area or deflection angle of elevons that increases trim drag and increases engine thrust demand [5].

The BWB has low pitch and yaw control authority due to its short moment arm [6]. Hence, multiple control surfaces are required to provide sufficient control force for longitudinal and lateral control. Furthermore, excessive power is required to actuate large multi-functional control surfaces with high hinge moments. This feature of the BWB increases the challenge of improving lateral and longitudinal stability [7]. The BWB is also subject to high yaw rates and auto-rotation tumble. The longitudinal and lateral forces and moments of the BWB are coupled creating a tendency for the airplane to get stuck in dutch roll. This degrades handling quality [8].

Alternatively, a novel approach to stabilizing and controlling pitch and yaw motion via a set of horizontal tail that can act as elevator and rudder is highlighted in [9]. The tail is incorporated into a new design of blended wing body (BWB) aircraft, known as Baseline-V, located just aft of the trailing edge of its inboard wing[10].

It seems that multiple elevons are still the best configuration in achieving high aerodynamic efficiency while providing adequate flight stability and controllability [11]. The problem is which elevons are more suited to become elevator or aileron? To simplify analysis, the study proposed here focuses on a BWB planform similar to many stealth flying-wing airplane with two inboard and two out board elevons, all of which have the same longitudinal distance from the centre of gravity. Any combination of these elevons can function as elevator for pitch control, aileron for roll control, drag rudder for yaw control and even as an airbrake. The objective of this paper is to investigate the effect of deflection of four elevons on a BWB planform, on aerodynamic coefficients. In this case, the focus is on studying the changes in coefficients for elevon deflections of -30°, 0° and +30° on the BWB planform that is modeled as flat plate only. The reason for using flat plate only is because to eliminate the effect of airfoil thus only focus at the impact of elevons deflection to the planform's aerodynamic coefficients.

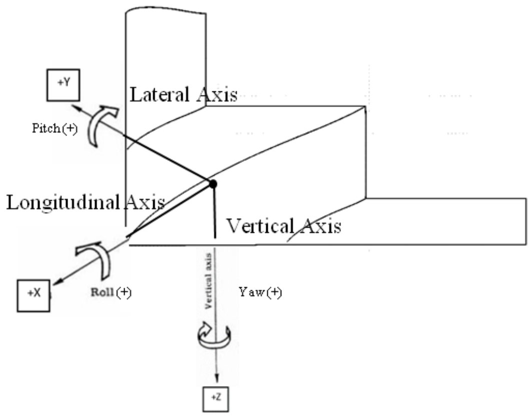

Fig.1 The body axes of the aircraft.

Theory

The BWB planform design is shown in Fig. 2. It is a 45-degree leading-edge swept wing with cranked trailing edge similar to B-2 stealth bomber, X-48 UCAV and NeURON UAS. The dimensions shown here is for the wind tunnel model. The actual aircraft is a 1.4-metre wingspan fixed-wing drone carrying camera for surveillance mission. It has four elevons each has the same size and located at the same longitudinal distance from its centre of gravity. The differences between these elevons are only their spanwise locations and lateral orientation where outboard elevons are facing outward while inboard elevons are facing inward when deflected. Theoretically, all elevons will give the same effect to pitch moment due to the same longitudinal locations. Inboard elevons will have less effect to roll moment than the outboard elevons due to their closer proximity to the longitudinal centerline of the aircraft. Meanwhile, elevons 1 and 3 (outboard starboard and inboard port) may produce side force to the left (port) causing the aircraft to yaw to the right while the opposite effect is shall be observed for the remaining two elevons due to their lateral orientation. Combination of any two or four of these elevons will have impact to the trim angles (incidence and sideslip) and turning rate depending on magnitude and direction of each elevon deflection. Therefore, combination of these elevons enable, at least theoretically, the BWB aircraft to control its pitch, roll and yaw at the same time similar to having elevator on horizontal tail, aileron on wings and rudder on vertical tail. Additionally, these elevons can also be made to function as flaps or airbrake.

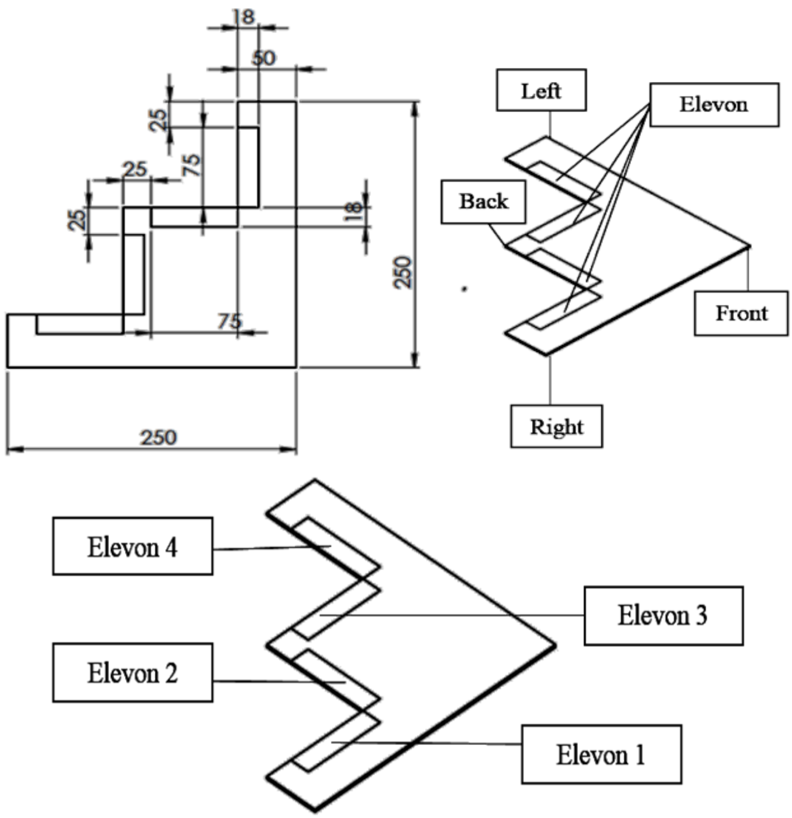

Fig. 2: Dimension of BWB flat model in mm unit and numbering of elevons

Methodology of Investigation

The dimension of the model has been downscaled to four times smaller than the actual aircraft size. This is due to the limitation of size of the wind tunnel which has 0.5 x 0.5 m test section dimension. The model has a wingspan of b = 0.3536 m and mean chord of c = 0.212 m. The model, which is a flat plate, has a thickness of t = 6 mm and A = 0.0325 m^2 wing-body plan form area. The model was made of flat acrylic glass cut into the designed planform by using CNC water jet to ensure precise and accurate dimension. Eight thin aluminium plates are used in which four are straight (0°) and another four aluminium plates are bent to 30° angle and connect the main body to each elevon via screws and will act as wedges to hold these elevons at either 0° or ±30° angle of deflection.

Fig 3: BWB model mounted inside the wind tunnel chamber (left) and Low Speed Wind Tunnel (LST-1) at FTTC, UiTM (right)

The wind tunnel experiment was conducted using a low speed wind tunnel LST-1 as shown in Fig. 3 located at the Flight Technology and Test Centre (FTTC), Universiti Teknologi MARA (UiTM). The experiment are conducted at U = 25 m/s airspeed with average air density of $\rho = 1.17$ kg/m^3 and average temperature of T = 23°C. The experiments measures aerodynamic coefficients (C_D, C_S, C_L, C_{ROLL}, C_{PITCH}, C_{YAW}) of the model for 31 cases where each case consists of combination of four elevons with different allocation of upward, downward and zero deflections. The upward and downward angle of deflection is fixed to be -30° and +30° respectively. All cases are run at zero degree angle of attack (hence zero pitch angle), zero sideslip (zero yaw angle) and level wing (zero roll angle). The model is mounted at locations where its centre of gravity is at the centre of turntable which is located at 30% mean chord behind the leading edge of the aircraft "nose". The orientation of elevon for each case are shown in Table 1 with numbering of elevon can referred back to Fig. 2.

Result and Discussion

The measured forces and moments are computed into force and moment coefficients as mentioned before. The coefficients calculation also take into account corrections due to tare effect and solid blockage in which the latter is insignificant due to thin plate nature of the wind tunnel model. The experiment cases and their aerodynamic coefficients are tabulated in Table 1.

Figures 4-9 show plots of C_D, C_S, C_L, C_{ROLL}, C_{PITCH}, and C_{YAW} with respect to elevon deflection angle. Case 1 is for condition when all elevators are not deployed (zero deflection).

Table 1: Wind Tunnel Experiment Result

Case	Right (Starboard)		Left (Port)							
	Out board	Inboard		Out board						
	Elev. 1	Elev. 2	Elev. 3	Elev. 4	C_D	C_S	C_L	C_{ROLL}	C_{PITCH}	C_{YAW}
1	0	0	0	0	0.047	0.000	0.048	0.000	0.006	0.000
2	-30	0	0	0	0.053	-0.006	-0.025	0.022	0.038	0.000
3	-30	30	0	0	0.065	0.003	0.143	0.011	-0.014	-0.002
4	-30	-30	0	0	0.058	-0.003	-0.105	0.026	0.055	0.004
5	30	-30	0	0	0.063	-0.004	0.079	-0.014	0.001	-0.001
6	30	0	0	0	0.054	-0.009	0.186	-0.020	-0.029	-0.001
7	30	30	0	0	0.062	-0.004	0.303	-0.028	-0.049	-0.002
8	0	30	0	0	0.049	0.002	0.193	-0.008	-0.016	0.008
9	0	30	-30	0	0.067	-0.005	0.088	-0.016	0.003	0.002
10	0	0	-30	0	0.061	-0.010	-0.055	-0.008	0.042	0.003
11	0	0	-30	-30	0.074	-0.009	-0.149	-0.024	0.066	0.010
12	0	0	-30	30	0.066	-0.004	0.047	0.015	0.017	0.009
13	0	0	30	30	0.057	0.001	0.277	0.031	-0.040	0.008
14	0	0	30	0	0.052	-0.006	0.197	0.010	-0.021	0.001
15	0	0	30	-30	0.061	-0.003	0.111	-0.007	0.002	0.007
16	0	0	0	-30	0.051	0.001	-0.016	-0.007	0.035	0.016
17	30	0	0	-30	0.065	-0.006	0.103	-0.041	-0.001	-0.001
18	30	30	-30	-30	0.087	-0.007	0.097	-0.060	0.006	0.001
19	-30	30	30	-30	0.083	-0.010	0.141	0.007	0.001	0.003
20	30	30	30	30	0.071	-0.003	0.482	0.003	-0.101	0.006
21	30	-30	-30	30	0.088	-0.005	0.054	-0.003	0.011	0.003
22	-30	-30	-30	-30	0.088	-0.007	-0.293	0.010	0.107	0.006
23	-30	-30	30	30	0.081	-0.002	0.112	0.057	-0.002	0.003
24	0	-30	30	0	0.065	0.000	0.118	0.015	-0.005	0.002
25	0	-30	0	0	0.055	0.004	-0.015	0.010	0.032	0.004
26	0	0	0	30	0.051	0.006	0.200	0.019	-0.027	0.007
27	-30	0	0	30	0.064	0.000	0.096	0.044	0.004	0.002
28	-30	0	0	-30	0.066	-0.008	-0.094	0.012	0.057	0.009
29	30	0	0	30	0.096	-0.005	0.323	-0.001	-0.068	0.002
30	0	-30	-30	0	0.069	-0.008	-0.143	0.003	0.067	0.003
31	0	30	30	0	0.062	-0.002	0.357	-0.004	-0.061	-0.003

Each line of plot represents three cases combined and these can be divided into three major groups;

- Single elevon – four plots (Elev. 1, Elev. 2, Elev. 3, Elev. 4). Since only one elevon operates here, it functions mainly as aileron
- Two elevons in unison – four plots
  - Elev. 1 & 2 [starboard] – aileron
  - Elev. 3 & 4 [port] – aileron
  - Elev. 1 & 4 [outboard] – elevator
  - Elev. 2 & 3 [inboard] – elevator
- Two elevons in opposite deflection – four plots
  - Elev. 1(+) & Elev. 2(-) [starboard] – rudder
  - Elev. 3(+) & Elev. 4 (-) [port] – rudder
  - Elev. 1(+) & Elev. 4 (-) [outboard] – aileron
  - Elev. 2 (+) & Elev. 3 (-) [inboard] – aileron
- Four elevons – three plots
  - Elev. 1 & 2 [starboard] (+), Elev. 3 & 4 [port] (-) – aileron
  - Elev. 2 & 3 [inboard] (+), Elev. 1 & 4 [outboard] (-) – airbrake/flaps
  - All elevons in unison (Elev. 1 – 4) – elevator

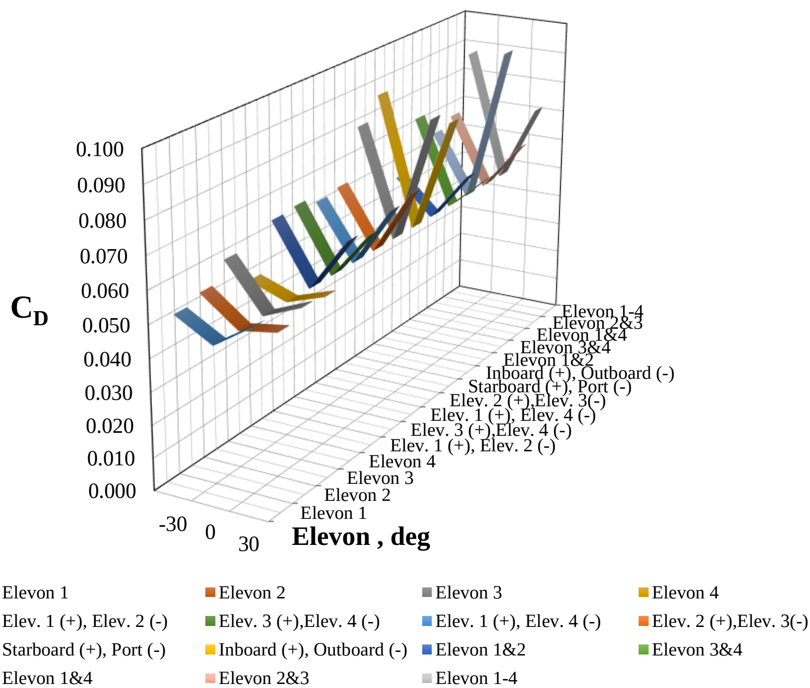

Fig. 4: Drag coefficient versus deflection angle

Fig. 4 shows plots of drag coefficients, C_D, against elevon deflection angle. Ideally, all plots must be symmetrical about C_D axis but this is not the case here possibly due to slight asymmetrical shape of the model and its assembly plus slight yawing angle of the model. As expected, the lowest drag are found in single elevon group while two-elevon groups, both in unison and in opposite deflection cases, have higher drag than the single-elevon group. However, the range of drag increase spreads from as low as 0.0555 to 0.097 at elevon +30°. Four-elevon group generally has larger drag than two-elevon group. This is logical since the more area of elevon is deployed or deflected the more drag is expected. The overall plots seem to agree with logical sense although not all cases bear proper magnitude of drag. Most importantly, there are no negative magnitude of drag. Zero-elevon deflection drag is around 0.047 and this is the lowest drag coefficient magnitude in this experiment.

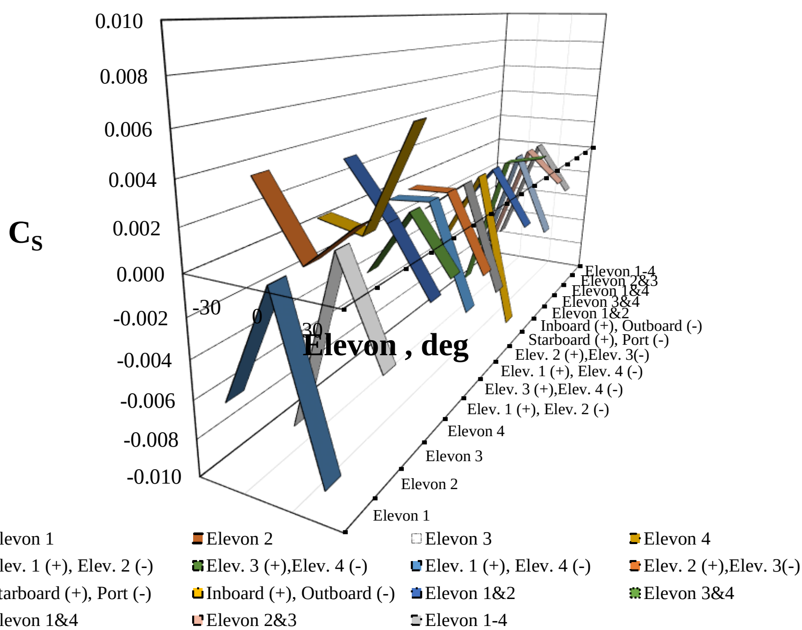

Fig. 5: Side force coefficient versus deflection angle

Fig. 5 shows sideforce coefficients C_S plots. The C_S axis is scaled like the C_D axis in Fig. 4 to highlight the size of sideforce magnitude with respect to drag magnitude. No matter what is the direction of the elevon deflection, either up or down, it is the lateral orientation of the elevon surface that determines the direction of sideforce. Elevon 1 case and Elevon 3 case which face 45° starboard side when deflected shall produce negative C_S

(force to the left) and this is shown in the plots but the magnitude of sideforce is larger for the outboard elevon (Elev. 1) than the latter. Similarly, both Elevon 2 case and Elevon 4 case which are facing 45° port side when deflected have positive sideforce magnitudes with outboard (Elev. 4) has the larger magnitude than the inboard (Elev. 3) ones. The existence of sideforce indicates that yaw moment is expected where sideforce to the left (negative C_S) causes the aircraft to yaw to the right. Therefore, while single elevon cases are expected to function as aileron, they also cause the aircraft to yaw slightly.

Combination of two starboard elevons (Elev. 1 & 2), two port elevons (Elev. 3 & 4), two inboard elevons (Elev. 2 & 3), two outboard elevons (Elev. 1 & 4) and all elevons either in unison or in opposite elevator deflection angle shall cause small increase in sideforce magnitude and less significant than the single elevon cases assuming that inboard and outboard elevons produce the same drag increase. However, this is not always be true in this study where the largest sideforce magnitude comes from Elev. 1 & 2 (starboard) in unison case where C_S = - 0.010. Generally, all cases has C_S magnitude between zero to 1/5th of the smallest drag C_D = 0.047. Sideforce is less significant than drag force due to the fact that a BWB aircraft usually has wider wingspan than body longitudinal length hence creating asymmetrical drag between port and starboard side has more profound impact to generating yawing moment.

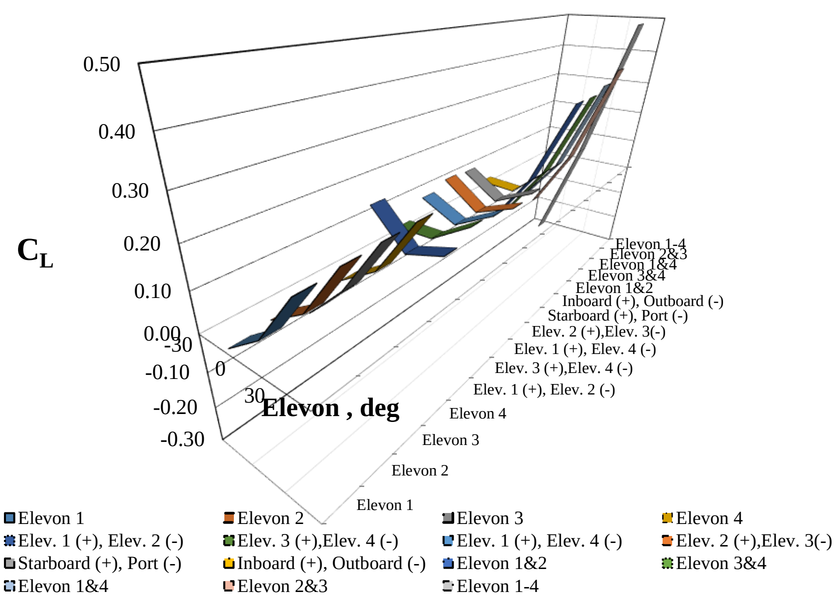

Fig. 6: Lift coefficient versus deflection angle

Fig. 6 shows the effect of elevons to lift coefficients. For all-elevon in unison case (Elev. 1 – 4), the lift increase tremendously from 0.048 to nearly 0.5 at elevon angle +30° and drops to nearly -0.30 at elevon angle -30°. The rate of change of C_L with respect to elevon angle is 0.013 per degree of elevon or 0.76 per radian. This shows that if strong pitching moment is needed then all elevons shall work together in unison. All other two-elevon-in unison cases have less change of lift with respect to elevator angle (-0.15 to 0.36) at around 0.0085 per degree of elevon angle (0.49 per radian). Two-elevator-in-opposite cases and four elevator-in-opposite cases do not have near linear plots but rather near parabolic or simply the change of lift is insignificant because additional lift is cancelled out by additional downforce of the same magnitude. For all single-elevon case, the plot trend is linear but with shallower slope at average of 0.004 per degree than the two-elevon-in-unison cases. In short, two-elevon-in-unison cases can possibly generate enough lift to control pitch motion provided that the centre of gravity of is located near but slightly in front of the aircraft's neutral point. If the centre of gravity is located too far in front of the neutral point then all elevons must be worked in unison to counter the nose-down moment and there shall be no provisions of control surface left for other functions such as roll and yaw control. However, the large increase in lift for all-elevon-in-unison case also indicate its feasibility of becoming flaps (high-lift devices) to lower the landing speed provided other means of stabilizing pitch motion (making pitch moment zero) is utilized i.e. weight shifting control that shifts centre of gravity back and forth actively.

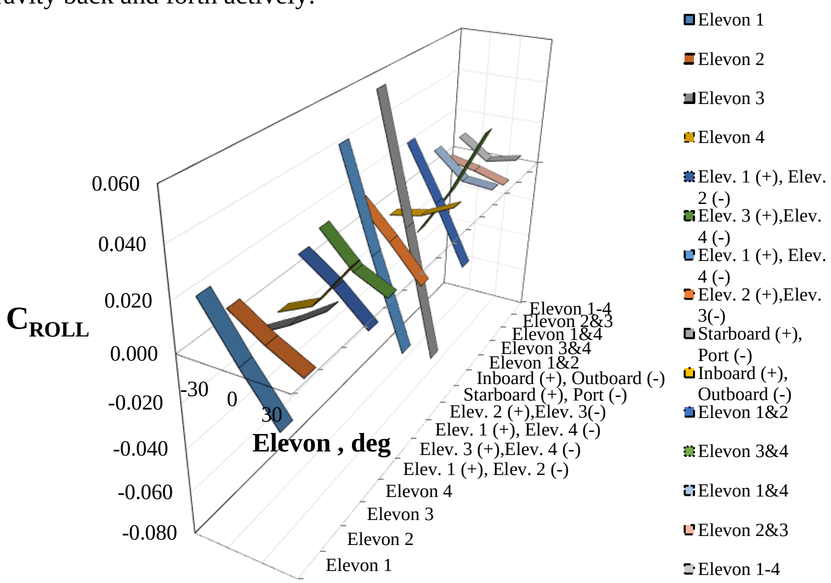

Fig. 7: Roll moment coefficient versus deflection angle

Normal convention would suggest that if any of the starboard elevons deflected downwards (positive elevon angle) or port elevons is deflected upwards (negative elevon angle), it shall produce lift or downforce that causes the roll moment to be negative (banking to the left). The opposite effect is to be expected if any of the starboard elevons deflected upward or port elevons deflected downwards. In short, the plot is expected to have negative change of roll moment with respect to elevator deflection angles or simply negative slope for starboard-elevon cases and positive slope for port-elevon cases. Roll moment slope is an indicator of how fast the aircraft will roll or, in technical terms, it will determine the roll rate. Fig. 7 shows these trends. The largest slope magnitude is recorded for four-elevon-in-opposite case with both starboard elevons working in unison and port elevons working in unison but opposite to starboard (Starboard (+), Outboard (-)). This is the case where all elevons are used purely as ailerons. The second largest slope magnitude is when both outboard elevons are deflected in opposite direction (Elev. 1 (+), Elev. 4 (-). The third steepest slope belongs to two contender – both are two-elevons on the same side working in unison - Elevons 1 & 2 [starboard] and Elevons 3 & 4 [port] where the latter has positive slope because they are located on the port side. For single-elevon cases, the slope is even lesser but Elevon 1 and Elevon 4 case have steeper slope than the other two because they are located outboard of the wing. The rests of elevon-in-opposite-deflection cases have insignificant or almost flat slopes because these are cases where inboard elevons produce lift and outboard elevons produce downforce or vice-versa that these forces of the same magnitude cancel out each other.

Fig. 8 shows pitch moment plots and these may be the most critical plots of all because BWB aircraft is generally unstable in pitch motion. In this case, at zero elevon deflection angle, the pitch moment is positive or nose up at C_{PITCH} = 0.006 indicating that the planform is slightly unstable. Just like roll moment plots, pitch moment slope with respect to elevon angle can be used later to determine pitch rate. The slope shall be negative irrespective of spanwise location of the elevon. Positive elevon deflection (deflects down) increases lift of the elevon thus causing the aircraft to have negative pitch (nose down) and opposite effect shall be expected for negative elevon deflection angle. The trend of C_{PITCH} plots follows the trend of C_L plots but with negative slopes because lift is almost the sole contributor to pitch moment. From the figure, the steepest slope is for all four elevons deflected in unison, or in other words, as pure elevators which is recorded at -0.0037 per degree of elevon or -0.21 per radian. It is followed by two-elevon-in-unison cases at around -0.0020 per degree (-0.11 per radian) and then single-elevon cases at around -0.0010 per degree (-0.05 per radian). All elevon-in-opposite cases for both two-elevon and four-elevon setup have either insignificant changes in pitch moment (zero slope, horizontal plot) or slightly positive slope with magnitude change of not more than 0.0005 per degree of elevon angle (-0.025 per radian).

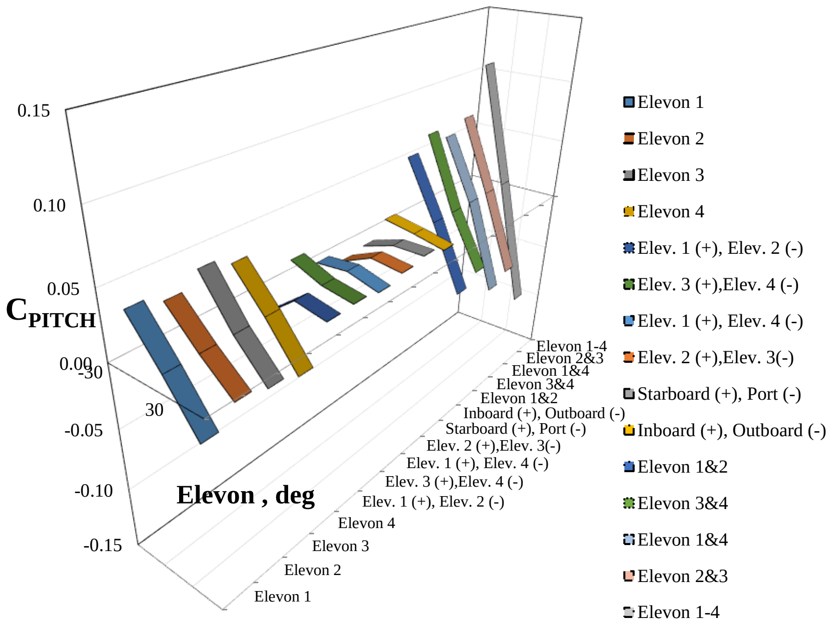

Fig. 8: Pitch coefficient versus deflection angle

Yaw moment C_{YAW} plots are shown in Fig. 9. In general, these plots seem to have similar trends with C_D plots. Since rudder function for many BWB or flying wing aircraft is executed by inducing more drag on one side of the wing (hence it is called drag rudder) the focus is mainly for cases where asymmetrical drag is expected such as two-elevon-in-unison cases (Elev. 1 & 2 [starboard], Elev. 3 & 4 [port]) and two-elevon-in-opposite cases (Elev. 1(+) & Elev. 2(-) [starboard], Elev. 3(+) & Elev. 4 (-) [port]). These four cases are cases where only elevons of one side of the wing are used. The trend of plot must be parabolic curve following the drag curve because no matter which direction the elevon is deflected (either up or down) the additional drag is almost the same provided the magnitude of elevon is the same. The plots of C_{YAW} show these four cases have significant effect to the magnitudes of yawing moment, however, the effect of these elevons to yaw moment is small that the largest change is only about $1/4^{th}$ of the changes in roll moment. Cases other than the four just mentioned have insignificant effect to yawing moment thus shall not be executed if rudder function is needed. The BWB aircraft discussed here, just like the B-2, X-48 and

NeURON, does not have vertical tail hence it is susceptible to directional instability. The lack of yawing moment magnitude even for the four significant cases means two things – firstly, the aircraft is unable to yaw at fast rate thus maneuverability in directional motion is low, and secondly, it has less tendency to fall into flat spin. In other words, there is an unfavorable effect that turns out to be a blessing in disguise.

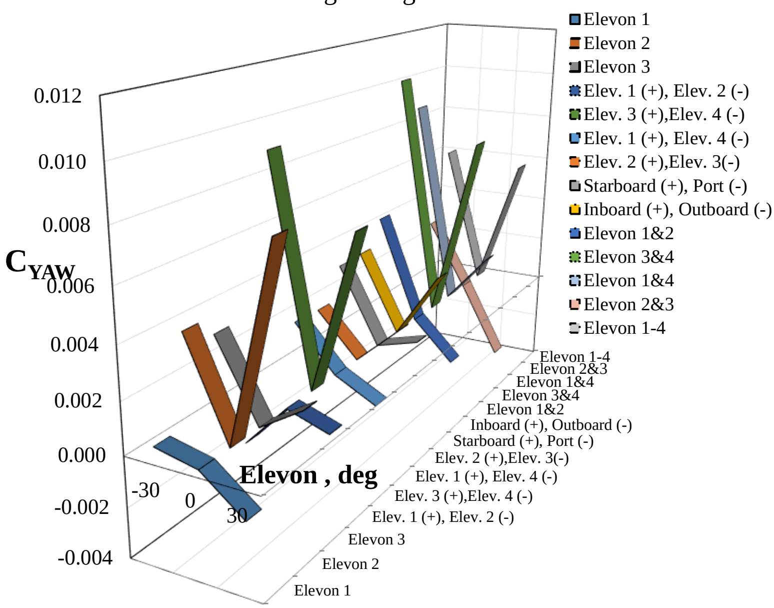

Fig. 9: Yaw coefficient versus deflection angle

Concluding Remarks

This experiment is meant to become a baseline study of a tail-less BWB aircraft with cranked trailing edge. Based on the 31 cases of any four elevon combination mentioned before, it can be concluded that drag coefficient increases as the magnitude of elevon deflection is increased no matter where is the direction of deflection (either up [-] or down [+]). Drag coefficient also increases as the number of deflected elevons increases possibly due to increase in frontal area of the BWB planform model. This increase is also irrespective of the direction of deflection. The largest sideforce coefficient magnitude is only 20% of the smallest drag coefficient magnitude. Although all elevons are at 45° lateral angle the effect of elevon deflection(s) to generating sideforce is small although, for some cases, significant enough to produce mild yawing moment. All cases with single, two or four elevons deflected in unison have obvious, linear and postive-slope plots of lift coefficient versus elevon deflection angle. The slope of lift versus elevon angle more or less doubles as the number of elevons is doubled. In this case, the slopes of single elevon cases averages at around 0.004 per degree, two-elevon-in-unison cases at 0.0085 per degree and all-elevon-in-unison (four elevons) case at 0.13 per degree. Lift coefficient is the most affected parameter when elevon is deflected. It has magnitude change five times larger than drag coefficients per degree of elevon angle. If other means can be used to control pitch, then all elevons can be recommended to function as flaps to increase lift while slowing down the aircraft with their high drag during landing approach.

The roll moment is the largest when all elevons are used where starboard side elevons are deflected in opposite direction (but with the same magnitude) to the port elevons. The roll moment is also large for outboard elevons to deflect at opposite direction. The other cases also produce significant roll moment as long as asymmetrical lift is produced between port and starboard sides of the wing-body. For low roll rate turn, it is recommended to utilize inboard elevons in opposite deflection angle while for normal/medium roll rate turn the outboard elevons in opposite deflection angle is more suitable. If high roll rate is needed then all elevons shall be used in opposite deflection between port and starboard side. Just like lift coefficient, pitch moment magnitude more or less doubles if the number of elevons used is doubled. Pitch moment magnitude change per elevon angle is around twice larger than roll magnitude change. For purely pitch control, it is not recommended to use single-elevon setup nor two-elevon-in-unison setup where only one side of elevons is utilized because this will create asymmetrical lifting force that causes roll moment to increase. Instead any of onboard elevons-in-unison or inboard elevons-in-unison setups can be used for normal pitch rate control. However, if high pitch rate is desired then all-elevon-in-unison setup can be used provided there is no need for roll control. Only cases where asymmetrical drag is expected can be utilized if yaw control or rudder function is needed but the most effective, although it is still fairly mild, setup would be two-elevator-in-opposite deflection with both elevons at the same spanwise sides of the wing i.e. any of starboard elevons deflected downward with another deflected upward in the same magnitude while the port elevons are kept at zero deflection. This shall make the aircraft yaw to the right. In simple sentence, deploy starboard elevons only to turn right and deploy port elevons only to turn left.

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