AERODYNAMIC PERFORMANCE OF A BLENDED-WING-BODY CONFIGURATION AIRCRAFT

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Abstract

In recent years new configurations for large commercial transport aircraft have been investigated to meet an increasing demand in international travel, particularly between major capital cities (hubs). A configuration that shows promise in terms of improved efficiency over conventional configurations is the Blended-Wing-Body (BWB) concept.

Fig.1 Image of BWB Concept Aircraft

The BWB concept design was analysed an aerodynamic feature using Computational Fluid Dynamics (CFD) based on the structural weight prediction with NASA handbook methods.

1 Information

Aircraft technologies that could give greater performance include a large improvement in Lift-to-Drag ratio of a wing coupled to evolutionary improvement in composite structure and engines, such as Blended Wing Body aircraft configuration. This next generation airlifter has been researched with a high L/D ratio wing configuration design, engineered materials, composite fabrication and fastening, and next generation material for airframe and skin. A BWB design approach is to maximise overall efficiency by increasing the propulsion systems, wings, and the body into a single lifting surface. This BWB configuration is a new concept in aircraft design which expects to offer great potential to substantially reduce operating costs while improving an aerodynamic performance and flexibility for both passenger and cargo mission.

1.1 Definition of A BWB Configuration Aircraft

A BWB aircraft is a configuration where the wing and fuselage are integrated which essentially results in a large flying wing. The BWB configuration has shown promise in terms of aerodynamic efficiency, in particular for very large transport aircraft, because the configuration has a single lifting surface that means aerodynamically clean around the configuration. In addition, BWB aircraft were previously called 'tailless airplanes' and 'Flying-Wing aircraft'.
BWB aircraft have been on the drawing board for more than a half century by aircraft researcher such as such the Northrop Corporation (Fig.2) in the UAS and the Horten Brothers (Fig.3) in Germany.

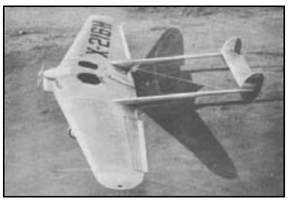

Fig.2 Semi-Flying-Wing

Fig.3 Ho I

2 Methodologies

A BWB concept was designed considering aerodynamics and structural capabilities based on the CFD results and several existing structural methodologies.

2.1 Design Approaches

A BWB configuration is a novel aircraft proposed as a commercial airliner, and the concept design is under development and investigation of flight capabilities. The BWB aircraft for next generation of airliner was considered with the conceptual design process, in particular aerodynamic performance of BWB configuration to investigate and optimise using the CFD solver based on the Raymer's design process. The several softwares were critical tools to design and visualise the features such as CATIA V5 and FLUENT 6.2.

Several key mathematical parameters were utilised to design and optimise the configuration as follows;

・**L/D Estimation** - The L/D ratio is a significant parameter to analyse an aerodynamic performance based on the Bernoulli's equation [4];

$$\frac{L}{D}=\frac{Lift}{Drag}=\frac{\frac{1}{2}\rho V^2 SC_L}{\frac{1}{2}\rho V^2 SC_D}=\frac{C_L}{C_D}. \qquad (1)$$

Moreover, the equation (1) will be simplified as;

$$\frac{L}{D}=\frac{\sqrt{\pi}}{2}\frac{b\sqrt{e}}{\sqrt{C_{D_P}S}}, \qquad (2)$$

where, $(L/D)_{max}$, the C_L equals to $(C_{Dp}e\pi AR)^{1/2}$. In addition, AR is the aspect ration between wingspan, b, and reference area, S, defined as (b^2/S).

Another measurement to estimate the L/D is to analyse the relationship between the wetted area of the configuration and wingspan, because the L/D is highly dependant on the configuration arrangement and directly affects the wingspan and wetted area, in particular at subsonic flight. In level flight at subsonic cruise, parasite drag is related to skin friction drag, and as such is directly corresponding to the total surface area of the configuration exposed to the air. The comparison between wetted area and wingspan can be restated as a wetted aspect ratio, which is defined as the square of the wing span divided by the wetted area of configuration, as being similar to the normal AR. For initial design purposes, wetted aspect ratio is utilised to assume L/D based on the initial sketch. Since the relationship between L/D and wetted aspect ratio considered existing aircrafts, Fig. 4 shows L/D estimation chart as;

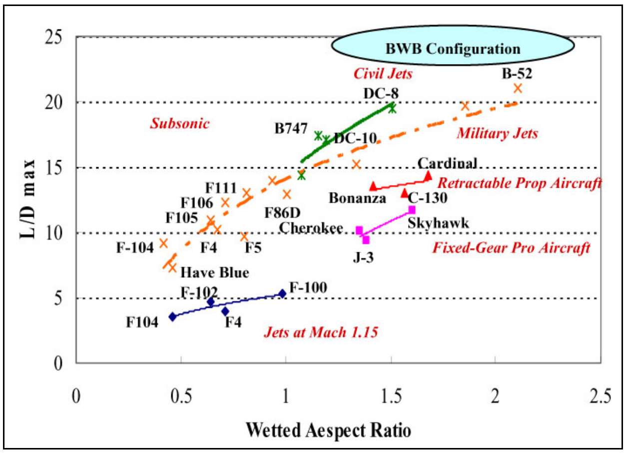

Fig. 4 L/D Estimation Chart with Wetted Aspect Ratio

・**The Breguet Range equation** - is related to the aerodynamic (L/D) and propulsion capacity efficiencies (V/c). The cruise range is calculated by integrating the specific range as [15];

$$\frac{W_i}{W_{i-1}}=\exp\frac{-Rc}{V\left(\frac{L}{D}\right)}, \qquad (3)$$

where, i is the mission segment, (W_i/W_{i-1}) is the mission segment weight fraction, R is the range, c is the specific fuel consumption (SFC) and (L/D) is the lift-to-drag ratio [15].

Table 1 Weight Function of Transport aircraft

	(W_i/W_{i-1})
Take-Off	0.970
Climb	0.985
Landing	0.995

・**Component Weights Estimation** - The estimation of aircraft weight is a significant part in the conceptual design process, especially the BWB configuration as a new concept design, because the aircraft weight directly relates to the flight performance. Conventional aircraft are approximately composed from 20 component sections including avionic systems and amenity equipments. For BWB weight estimation, methodologies of the traditional weight estimation for commercial aircraft design, NASA's Laboratory results [6] and data of existing components have been utilised.

・ **Monotonous Parameters of BWB Configuration Design** - The priority considerations of a BWB configuration design were that 555 passengers can accommodated on while achieving flight comfort and meeting safety standards with a 66.4 tonnes payload, 8,000 nautical miles (approximately 15,000 km) range and the cruising speed of Mach 0.85, as conventional aircraft.

2.2 NASA's Structural Handbook

NASA's methodology was presented to develop the capability of BWB concept design using Finite Element Analysis (FEA) in 2004. In regards to the fuselage structure of BWB transport at NASA, the pressurised cabin was designed considering with bending, share and torsion from aerodynamics loads. In the comparison between conventional circular fuselage and non-conventional fuselage, it was predicted that the non-conventional fuselage shape requires higher structural strength because of large bending stresses on the skin [6].

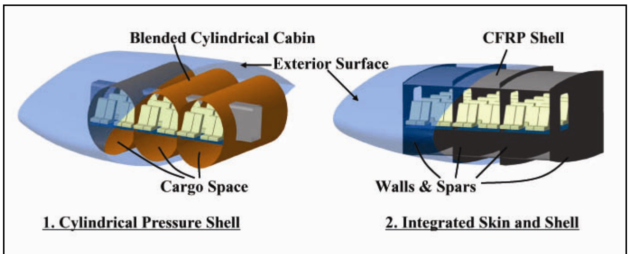

Fig. 5 Structural Cabin Design Concept

The first BWB design consisted of inner cylindrical shells for the internal pressure and the outer skin for bending, and utilised approximately 12.7 cm (5 inches) thickness sandwich structural shell with a deep skin/stringer concept (Fig. 5 No.1). After optimising the NASA design based on cost and weight, the skin/stringer concept with 12.7-15.24 cm (5-6 inches) deep stringers was redesigned to take the inner pressure concept without the bending shells (Fig. 5 No.2). According to the skin design, the internal ribs had Y-braces to reduce the bending force from internal pressure.

Since the internal pressure was on all sections, NASA presupposed that the depth of the stringers would be a function of the cabin size and the maximum aerodynamic loads of TOGW. Thus, a weight estimation of the entire pressurised cabin may be defined in the following equation;

$$W_{cabin} = a \times (W_{takeoff})^b (S_{cabin})^c, \qquad (4)$$

where, a, b and c are constants, and W_{cabin} is the weight of cabin compartment, S_{cabin} is the area of cabin [6].

With the cabin design using FEA, the weight of the pressurised cabin section of BWB concept was explained with various values of TOGW. This TOGW involves the thickness of ribs and spars of the centre body, aerodynamic load, and the element of thickness of cabin skin. The materials used in the wing and centre body were composed of carbon fibre reinforced plastic (CFRP) laminates with a Young's modules of $E=1\times10^7$ pis, Poisson's ratio $\nu = 0.4$, 0.056 lbin.^{-3} density and allowable tensile stress of approximately 50,000 pis [6].

Thus, equation (4) is redescribed from regression analysis as;

$$W_{cabin} = 0.31642 \times W_{takeoff}^{\ 0.16655} S_{cabin}^{\ 1.06116} \qquad (5)$$

Moreover, the weight of centre body was scaled to match data supplied by the Boeing Company to estimate the credible actual weight of BWB pressurised cabin. The final equation of cabin weight is defined with a scale factor, K_s, [6].

$$W_{cabin} = K_s \times \left(0.31642 \times W_{takeoff}{}^{0.16655} S_{cabin}{}^{1.06116}\right) \quad (6)$$

3 Results and Discussions

A BWB configuration has been researched using CAE softwares based on typical aircraft design methodologies in this design project. With the BWB design processes several advantages of BWB concept design have been encountered.

All of the BWB design requirements have been considered and achieved, meeting the safety requirements of ICAO (International Civil Aviation Organisation) and FAA (Federal Aviation Administration) regulations. In particular, the BWB configuration has been carefully designed to ensure a less than 80 m wingspan to meet the current airport compatibility issues, and to also accommodate 555 passengers with a three class layout (First, Business and Economy Classes). Other monotonous parameters of BWB design meets safety standards with a 66.4 tonnes payload, 8,000 nautical miles (approximately 15,000 km) range and the cruising speed of Mach 0.85 as the current high density hub-to-hub aircraft.

3.1 Aerodynamic Performance of BWB

First of all, the NACA series was utilised to analyse the aerodynamic features for the baseline airfoil selection of the BWB design, as well as H_Quabeck and Eppler airfoil series have analysed for the wing section.

In regards to an airfoil selection for the central section of the BWB, the initial airfoil design was referred to as NACA0015 (Upper Surface) and NACA0009 (Lower Surface). The thickness of the initial airfoil was enough for the cabin compartment at the location of maximum thickness. However, for the whole cabin compartment, the initial airfoil was not feasible to achieve passengers' comfort. The initial airfoil was redesigned with consideration of cabin space, as well as improving aerodynamic performance. Also, the location of the maximum thickness was moved to the airfoil chord, approximately 15 percent backward. The results of the modified NACA airfoil series, and H_Quabeck and Eppler airfoil series were shown in Fig. 6 to compare looking at aerodynamic features for a body/wing design of BWB configuration.

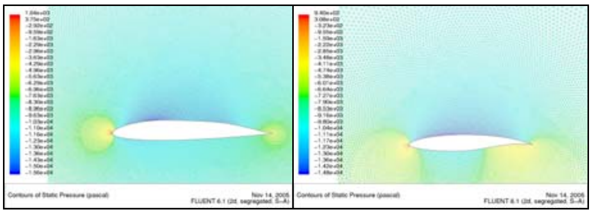

Fig. 6 CFD Results of Body/Wing Airfoil Sections

Table 2 CFD Results of the Selected Airfoils

Airfoil	C_M	C_L	C_D	L/D
Initial	0.721	0.0479	0.002118	22.62
Optimised	2.380	0.223	0.006767	34.43
Eppler417	2.627	0.569	0.009702	58.65

*C_M:Momentum Coefficient, C_L:Lift Coefficient, C_D:Drag Coefficient

3.2 Component Weights Estimation of BWB

After deciding on a BWB configuration profile with assumption made of the aerodynamic features, the next phase was to analyse and estimate component weights of the BWB configuration. With the typical transport trends [15], a T/W of the BWB design was estimated to be 0.23, which is lower than the typical aircraft trend (Current Aircraft Trend: T/W = 0.25-0.4).

In regards to the weight estimation of the wing and cabin designs of the BWB, the NASA estimation methodology, the existing equation and the wing weight trend of the existing aircraft were utilised to assume these component weights. The detailed descriptions of the main components' weight estimations are shown as below (Wing, Engines and Cabin).

・Wing Component Weight Estimation

For weight estimations of wing, tails and propulsion, weight trends of aircraft components were analysed and obtained from relationships based on existing aircraft. The BWB configuration design also includes the current aircraft technology assembly in each part, such as rib, stringer and spar cap with skin for wing structure.

$$W_{wing} = 3.8297 \times S_{wing}^{\ 1.0156} \qquad (7)$$

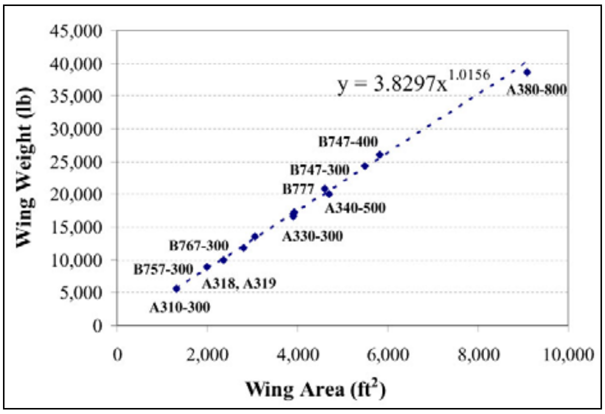

Fig. 7 Comparative Wing Weight Trends

·Propulsion System Weight

The weight of propulsion systems was estimated including the nacelle and pylon as 1.6 times heavier than the dry engine weight. With the existing engines, the weight of propulsion system was assumed as,

$$W_{deng} = 0.3114 \times T^{0.9433} \qquad (8)$$

$$W_{pro} = 1.6 \times W_{deng} = 0.4982 \times T^{0.9433} \qquad (9)$$

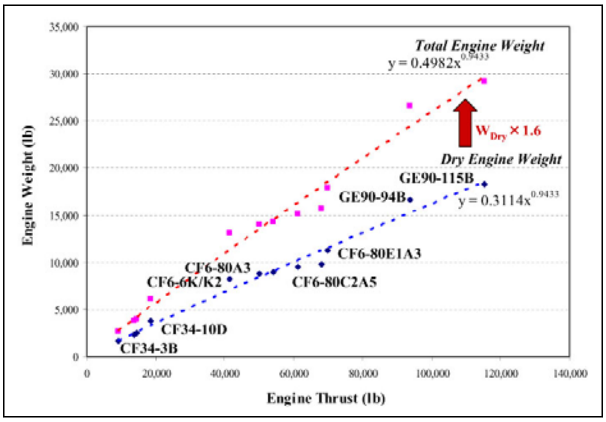

Fig. 8 Comparative Propulsion Weight Trends

·Cabin Weight Estimation

To estimate the cabin weight of the BWB, the equation (6) was utilised and redefined based on the 450 passengers' BWB pressurised cabin [6],

$$W_{cabin} = 5.698865 \times \left(0.31642 \times W_{takeoff}^{\ 0.16655} S_{cabin}^{\ 1.06116}\right) \qquad (10)$$

where K_s is 5.698865 [6]. For the 555 passengers' BWB pressurised cabin, Equation (10) was redefined with the scale factor, K_s, which was calculated to be 7.0267 for 555 passengers and 24 m width cabin design as,

$$\begin{aligned} W_{cabin} &= 7.0267 \times \left(0.31642 \times W_{takeoff}^{\ 0.16655} S_{cabin}^{\ 1.06116}\right) \\ &= 2.223388 \times W_{takeoff}^{\ 0.16655} S_{cabin}^{\ 1.06116} \end{aligned} \qquad (11)$$

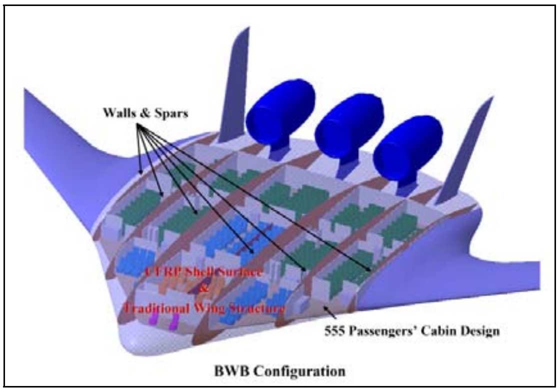

Fig. 10 Structural BWB Conceptual Design

Fig. 10 shows the image of structural BWB design concept based on the NASA's handbook. This structural design was chosen to utilise the CFRP shell pressured surface and the traditional wing structure methodology integrated to surround the cabin area (Fig. 10: Area of Transparent Blue Colour).

·Fuel Weight Estimation

Ratio 0.23 of the T/W with TOGW of aircraft in cruise was referred to estimate a fuel consumption of the BWB. With the cross point of the T/W and the optimised estimation in Fig. 11, the minimum configuration weight of the BWB design was estimated to be 236,193 kg (520,806 lbs) excluding the fuel weight and the weight of the propulsion system. With the traditional equations, the equation of the optimised trend based on engine thrust requirement and TOGW is described as,

$$W_{takeoff} = 520{,}805.58 + 1.04 \times W_{pro} + 1.1 \times W_{fuel} \qquad (12)$$

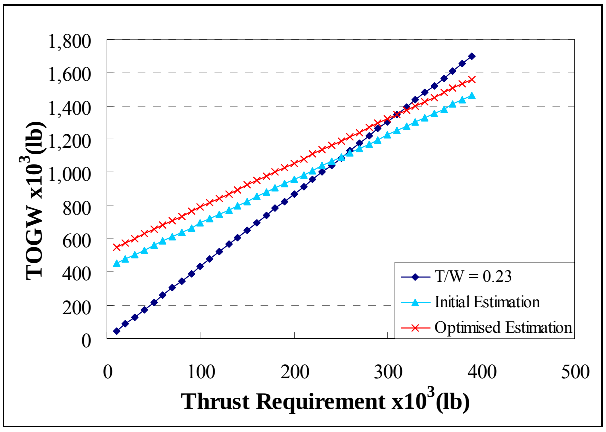

Fig. 11 Thrust Requirement vs. TOGW Diagram

This integrated matching chart was designed to estimate a fuel weight and the propulsion weight of the BWB.

The weight of the propulsion system and the fuel weight estimation with SFC, *c*, the endurance, *d*, and the thrust, *T*, for jet engine [15], was described as,

$$W_{pro} = 0.4982 \times T^{0.9433} \tag{13}$$

$$W_{fuel} = cdT \tag{14}$$

The *c* of SFC of the BWB design was calculated as the average rate of overall operation of Trent 900, because the BWB configuration requires the flight mission such as 8,000 nautical miles (15,000 km) range at Mach 0.85. With Equation (14), the average SFC of Trent 900 referring the A380 flight profile was calculated as,

$$c = \frac{W_{fuel}}{dT \times time} = \frac{64{,}937.25}{284{,}004 \times 60{,}300} = 3.7956 \times 10^{-5} \quad 1/lb \tag{15}$$

With the BWB flight segment profile like conventional aircraft mission, the fuel weight, W_{fuel}, was recalculated with the each flight mission segment as,

$$W_{fuel} = W_{f-takeoff} + W_{f-climb} + W_{f-cruise} + W_{f-descent} \tag{16}$$

where *c* is the SFC, $W_{f\text{-}takeoff}$ is the fuel weight of takeoff segment, $W_{f\text{-}climb}$ is the fuel weight of climb segment, $W_{f\text{-}cruise}$ is the weight of cruise segment and $W_{f\text{-}descent}$ is the fuel weight of the descent segment.

With the Breguet Range equation (3), the fuel weight estimation was redesigned based on equation (16) as,

$$W_{fuel} = c \times \left(AW_{takeoff} + BW_{climb} + CW_{cruise} + DW_{descent}\right) \tag{12}$$

To conclude, the TOGW of the designed BWB was estimated as 430 tonnes, showing in Fig. 12 with several data of BWB configuration.

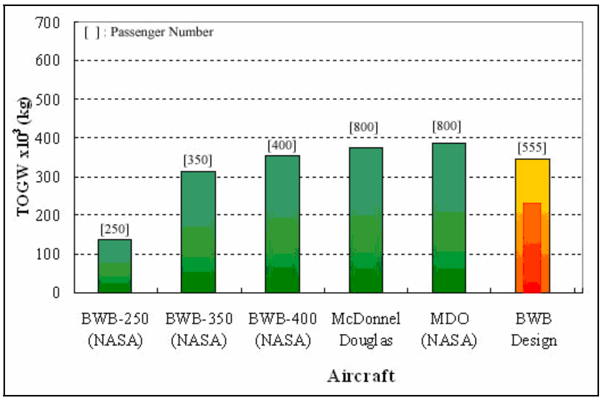

Fig. 12 BWB Design Project TOGW Data

3.3 BWB Configuration Design

The BWB design was considered with several structural parameters and the safety issues. Based on the considerations such as L/D ratio, capability of cabin layout and wetted aspect ratio of BWB, the BWB was designed as Fig. 13.

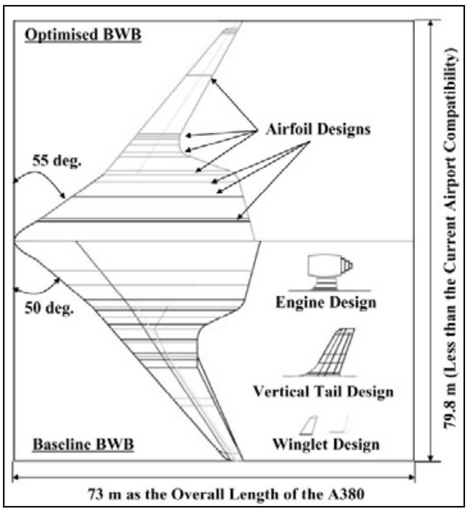

Fig. 13 2D BWB Design Layout

The 3D design was created using CATIA V5, as showing in Fig. 14.

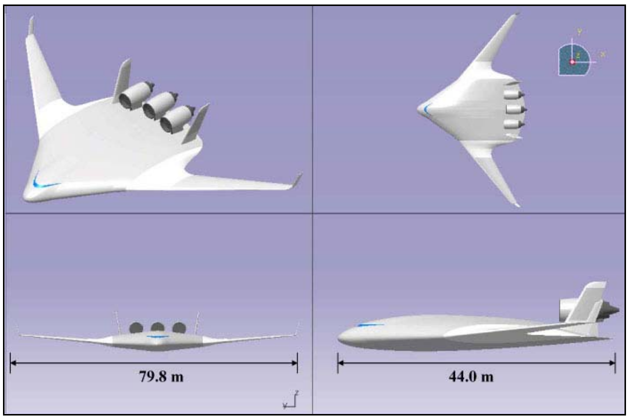

Fig. 14 BWB Configuration Design

To improve the aerodynamic performance of the BWB (e.g. higher L/D ratio), the BWB shape was optimised the wetted aspect ratio. This improvement of the BWB flight performance is showing in next section.

3.4 CFD Results of BWB Configuration

The BWB configuration was calculated an aerodynamic performance in FLUENT6.2. The parameters for setting boundary conditions were shown in Table 3.

Table 3 Flight Conditions of the BWB

Mach Number	0.85
Reynolds Number	5.12×10^{8}
Altitude	11,000 m

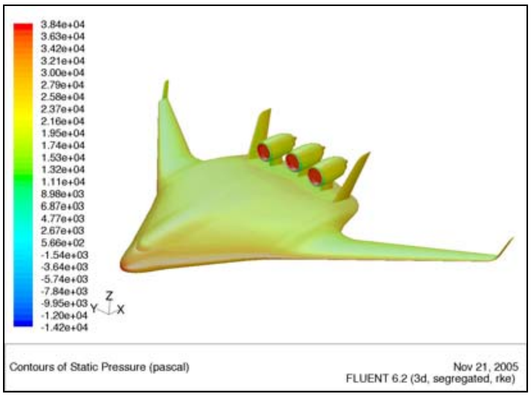

Fig. 15 CFD Result of BWB (Pressure Contours)

The detailed description of the optimised BWB model was analysed according to airflow impact on the surfaces showed with contour lines of static pressure and turbulent kinetic energy (k) in Fig. 16. The pressure distribution and the flow separating locations were identified with these contour lines. On the upper surface of the 16 m spanwise extension a large increase in drag and separations were identified by the contour lines of turbulent kinetic energy. This difference in the kinetic energy can show that flows create turbulent eddies (cascade processes) and it dissipates energy (i.e. heat which supplies from mean motion to turbulent and molecular motions on the area). Because of the modification of the 16 m spanwise area, the wing design had a problem because the two different airfoils were joined in this area. In addition to this, the engines and tails have energy dissipations. To solve these negative issues several techniques are possible, such as removing the tails and modifying the vertical control system on the winglets, and for the engines' propulsion system to be integrated within the aft body. However, these advanced ideas have not been included in this BWB configuration, because weight estimations of the BWB components could not be assumed and the structural analysis has not been completed.

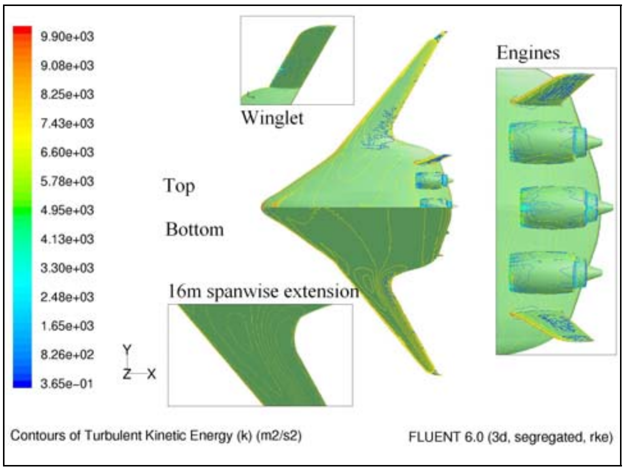

Fig. 16 CFD Results of BWB
(Pressure Contour and Turbulent Kinetic Energy)

Fig. 17 is present the relationship between wetted aspect ratio and the improvement of aerodynamic performance of BWB design. With this preliminary BWB arrangement, the baseline BWB model has been adjusted and optimised to improve aerodynamic performance in flight. Therefore, for an evaluation of its aerodynamic performance, a technique of controlling wetted aspect ratio was utilised. The wetted aspect ratio of the baseline BWB design was 1.81 (Wetted Area = 3,524.85 m^2, Wingspan = 79.8 m).

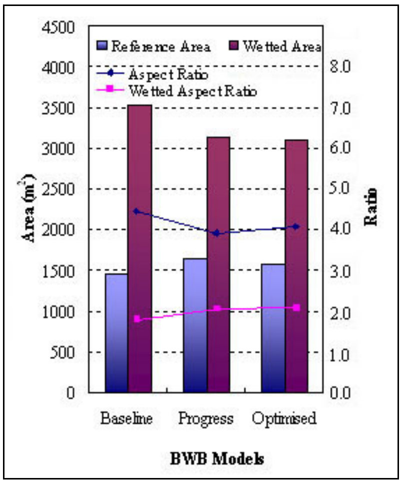

Fig. 17 Relationship between Aspect Ratio and Lift/Drag

According to the variations of the BWB modifications from the baseline to the optimised BWB design;

1. the reference area of the optimised model was increased by 8.45 %,
2. the wetted area of the optimised model was successfully reduced by 11.85 %,
3. the aspect ratio of the optimised model became 7.76 % lower,
4. the wetted aspect ratio of the optimised model was improved by a factor of 1.13.

Additionally, in regards to the turbulent kinetic energy, Fig. 18 shows the results of the comparison of the A380 and the optimised BWB design based on the horizontal axis. In the comparison of both configurations, the plots of kinetic energy of the BWB model gather around the aft body from approximately 35 m (the location of the engines) to 45 m (the end of the body). With this CFD results, the BWB design has potential to be more aerodynamically efficient, because the BWB configuration performs with less energy dissipations.

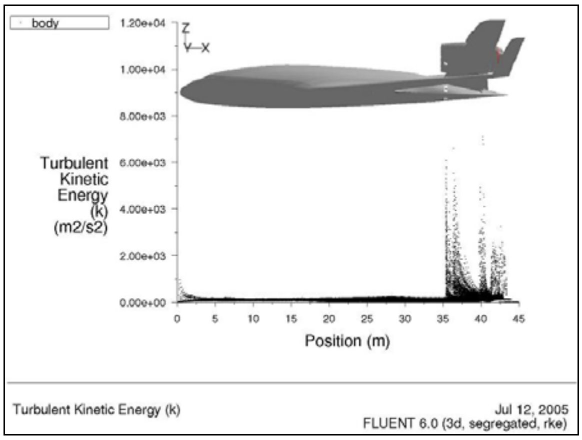

Fig. 18 Plots of Turbulent Kinetic Energy (k)

4 Conclusions

In recent years, international air tourism has increased significantly, especially in travel to East Asia, the Pacific, and the Middle East regions. According to the WTO (World Tourism Organisation) Tourism 2020 Vision, international travel numbers expected to increase to over 1.6 billion people by 2020, which means that the number is twice the current number. With this massive increase in air travel demand, the BWB aircraft configuration as a very large airfreight transport vehicle may be looked at favourably as a potential mainstream airliner for the high-density hub to hub routes in the near future.

The differences in design procedures of the BWB configuration are the cabin and fuselage sections compared to the cylindrical style of conventional aircraft. However, the cabin-fuselage compartment was assembled with typical wing structural instruments but the CFRP pressurised shell design provides for 555 passengers with its wider accommodation. The TOGW of the BWB was estimated as 430 tonnes for high density hub-to-hub rout. With the improvements in BWB aircraft performances, the more effective fuel consumption was obtained through superior flight performance of the BWB capabilities. From the CFD results of aerodynamic parameters, the BWB configuration proved to have the aerodynamic features superior to conventional aircraft, because the BWB design

(21.43 of the L/D) achieved approximately1.4 times higher L/D ratio than conventional aircraft (e.g. the conventional aircraft normally achieve approximately 15 of L/D ratio). This remarkable aerodynamic performance of the BWB configuration is that approximately 21 of L/D ratio was achieved in flight. Moreover, the flight features of small drag value and less engine thrust requirement predict to perform with less noise emission, and make it a more environmentally-friendly vehicle. Overall the CFD results and the component weight estimations, the BWB configuration demonstrates many advantages, such as in structural and aerodynamic characteristics, better than conventional aircraft with the same flight mission profile.

In conclusion, from the conceptual point of view, the BWB design has been demonstrated to be more attractive than the conventional aircraft. From these results of BWB conceptual design, a preliminary design phase (i.e. more detailed designs as structure and systems) will be required in further research. Moreover, the other significant area will be FEA equals to CFD analysis of the BWB configuration that will illuminate structural design difficulties and make the weight estimation more practical and more credible.

With these numerous advantages, combined with forecast dramatic rise in demand for passenger aircraft, the BWB concept aircraft offers the potential to become the standard commercial aircraft in the next generation - while being more fuel effective and environmentally-friendly at the same time.

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