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ON THE OPTIMIZATION OF BLENDED WING BODY AIRCRAFT CONFIGURATION VIA THE SURROGATE MODELING METHOD

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Abstract

Blended Wing Body aircrafts (BWB) remain to be one of the most promising future flight vehicle concepts. Here the surrogate Kriging model is chosen in order to find the BWB optimum angle of attack (AOA) and its engine heights. The model is verified by first predicting the best AOA for BWB without engines, and a normalized optimization parameter is created. After the predicting value is achieved, new engine position geometry will be generated according to the surrogate model prediction. The close agreement between our Kriging model prediction and CFD computation represent a first triumph in the surrogate model implementation, and this could imply tremendous saving in future aerodynamic simulation in the design phase.

1 Introduction

In pace with the airplane invented so far, lots of different aircraft configurations are created to enhance their performance. Unlike traditional aircraft, Blended-Wing-Body Aircraft (BWB), which body and wings are blended, and has aerodynamic advantage similar to joined wing. Joined wing is a vehicle which wing tips combine with horizontal tail tip, and have its own advantages and disadvantages in aerodynamic, structural, and performance aspects. Fig. 1 is a BWB aircraft of NASA creation, and Fig. 2 shown below is a typical joined wing aircraft with two alternate tails [1]. Although BWB are seldom could be seen, but its conception was proposed as early as in 1912. BWB's body profile is similar to a wing; it can create lift force when airflow flows through it. BWB not only can increase the fuel efficiency, but also improve the structure integrity and has less weight. Our group has done research on the aerodynamic performance of Blended-Wing-Body aircraft under various situations [2], thus this work use earlier configuration but add engines and pylons on.

Fig. 1 BWB aircraft of NASA

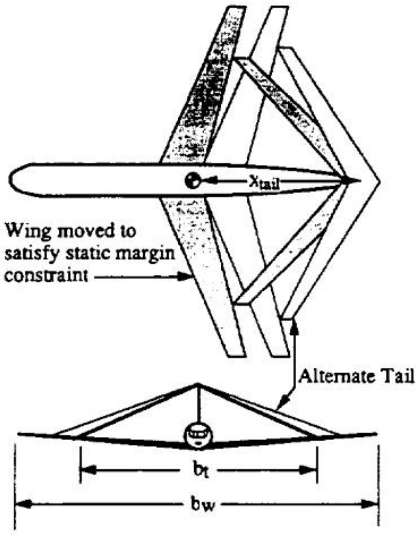


Fig. 2 Typical joined wing aircraft with two alternate tails [1]

Many different aircraft are created nowadays, and they must consider eight different parts: namely purpose, payload, velocity, range, airworthiness, distance for take-off and landing, cost, and functionality [3]. So design an aircraft is not an easy task, all of the eight different aspects has to be considered at the same time, and iteration is the name of game. For traditional aircraft its fuselage is literally a cylinder; the lift force created mostly by wings, but BWB can solve this problem. In another word, BWB does not have conventional fuselage, it combines fuselage with the main wings, so the passengers in BWB are actually sit inside the center part of a wing.

As for engines optimal location and size, a tool called surrogate model is implemented in current work. Surrogate model is a relatively new method for optimum design, and gaining popularity in recent decades. Among all the subsets of surrogate model, it is the Kriging model chosen to predict the best condition that we want to achieve. The Kriging model is a model which constructs the surrogate, and has the origin of predicting the next possible mining site via the existing mines' locations. In our research, we can not only intend to locate the best engines' vertical height, but also find the optimal angle of attack (AOA) simultaneously. Before predicting the engines' height and its AOA, it is felt that first to predict the best AOA for the BWB without engines on (bare BWB) is necessary. From earlier experience, it was concluded that our bare BWB have the best AOA in between 1.5 degree to 2.0 degree [4], thus the Kriging model will be tested on this BWB configuration first. Then we can further investigate our BWB with engines' best parameters and analyze its optimal aerodynamic performance accordingly.

2 Literature Review

In our previous research, works on BWB has focus on aircraft configuration performance under severe weather situation, or aerodynamic optimization analysis on BWB winglets, all of our prior BWB do not have engines. It is the attempt of current work that with the addition of a pair of engines on BWB, this new BWB configuration aerodynamic optimization situation can be developed by surrogate model.

BWB aircrafts have their origins in the flying wing concept. The first flying wing concept was the Stout Batwing, which was designed by William Bushnell Stout. The main aerodynamic advantages of BWB aircraft are that it has lower wetted area to volume ratio and lower interference drag than conventional aircrafts [5]. The Reynolds number of BWB is also higher than conventional aircrafts, since flying wings have longer mean aerodynamic chord length. Also there will be no skin friction and induced drag due to the horizontal tail wing, BWB aircraft does not have that. Although flying wings or BWBs can also reduce static margin in the longitudinal channel and even induce small instability at cruise, but become a less nuisance in the modern digital control era. The most advantage of BWB aircraft is in the aerodynamic efficiency aspect, it is estimated that if its load ratio is similar to a conventional layout, then BWB's lift-to drag ratio can increase as much as 20% than current generation transport aircraft [6].

Emergency evacuation in BWB aircraft is an important issue. Because the flying wing or BWB aircraft have wider body than conventional transport plane, this may increase the distance to the escape outlet [6]. According to current ICAO regulation, every transport aircraft must have passenger evacuation time in less than 90 seconds [7].

E. R. Galea [8] also studied on how to evacuate BWB with more than 1000 passengers. Because the BWB's special shape, the exit located not only on the side of fuselage but also under or behind of the aircraft's body. Since engine locations represent obstacles for passenger escape route, thus further aerodynamic investigation for BWB with engine/pylon on is needed, and is one of the main reasons for current study.

BWB's problem lays not only in the emergency evacuation but also the passengers and packages are far away from the center line, so the rolling control will be more difficult. There are some methods to solve and countermeasure for this problem, it includes strict use of seat belts on the roll maneuvers or turbulence encounter phases, limit BWB roll rates during flight maneuvers to less than 0.5 $^{\circ}$/s, and it should be optimized to minimum roll rates and accelerations [9].

Yet there is another conceptual aircraft, joined wing, which tail wings join with main wings. According to its lay-out, at least one surface of the joined wing must be swept, whereas the cantilever wing and tail can both be unswept. The advantages that joined wing aircraft has are: light weight, high stiffness, low induced drag, good transonic cross section area distribution, high trimmed C_{Lmax}, direct lift control capability, direct side force control capability, and good stability and control [10]. But the joined wing configuration has a disadvantage in terms of parasite drag when compared to conventional design. Joined wings are not just having one single profile; Fig. 3 is sketches of joined wing configuration ranging through each design variable [11].

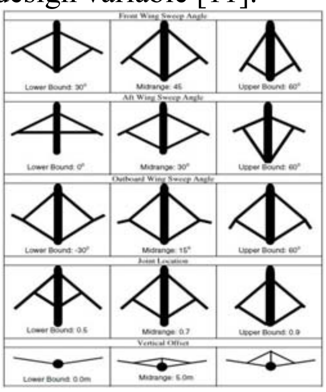


Fig. 3 Sketches of joined wing configuration ranging through each design variable [11]

If there are a "winglet" between main wing and tail wing, then joined wing will become box wing, which is confirmed can save more fuel consumption than conventional aircrafts [12]. The standard box wing is shown as Fig. 4 [13]. Although jointed wing or box wing aircraft has similar aerodynamic enhancement effect like BWB, but a full 3-D detailed CFD simulation for these configurations require tremendous computer resource, and also a deviation from our BWB research works, thus is not included in the current study.

The engine considered in this work will be the most common turbofan engine, which is especially suited for transport aircraft cruise at high subsonic speed. But for the purpose of external aerodynamic computational simulation, it is quite impossible for us to include all the detailed components within the engine, thus our engine will be treated as cylindrical tubes with realistic boundary conditions at inlet and nozzle stations.

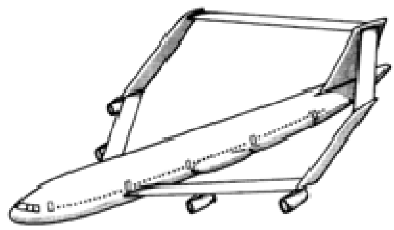


Fig. 4 Standard box wing aircraft [13]

Concerning optimum engineering design, there are many subjects can be applied: aircraft design for minimum weight, optimal trajectories finding for spacecraft, et al. Optimization can be defined to find a point x* that lead to the maximum or minimum objective function value [14]. One of most recent advance in engineering optimization is called surrogate model. It is a model that compact and affordable to evaluate, especially for optimization, design space exploration, and sensitivity analysis. The surrogate model is a tool for increasing the speed of optimization; it is not in itself an optimizer [15]. The surrogate models based on Covariance Matrix Adaptation Evolution Strategy (CMA-ES), preserving invariance with respect to both monotonous transformations of the fitness function and orthogonal transformations of the search space [16]. Although the polynomial models gradually been replaced by basis function models, it is still used most widely in practical engineering design. The radial basis function model uses a simple function by its weighted sum to emulate complicated design landscapes. On the other hand, the Kriging model is first developed by South African engineer Danie Krige, and this model is gaining more popular nowadays. Within this method the support vector regression model's theory is come from support vector machines; the model is that it allows us to calculate a margin within which we can accept errors in the sample data to affect the prediction [17].

In this study the Kriging model is used to solve our problems. The Kriging model like other optimum engineering design, its target is finding x that can let y(x) has maximum or minimum value. There are several steps for using Kriging model [18]:

1. Define the optimization problem. Determine the design variables and objective function.
2. Using Design of Experiment (DOE) technique to generate the initial sample points.
3. Calculate responses at initial sample points.
4. Use Kriging surrogate model on the sample data and corresponding responses.
5. Acquire an additional sample point by maximize the expected improvement function, and calculate its response.
6. Check convergence. If the result suit for us, then stop. If it doesn't, then add more sample data into the sample points set, and go to step 4.

Accuracy of the Kriging model is depending on the numbers of the sample data. So we can obtain the information: if the sample points are enough, then we can find more accurate Kriging model [19]. As in the same single objective case, multi-objective must find the sample points first, and then use Kriging model to find the maximum or minimum values. If the result suits us, then stop; if not then we can add more sample points [20].

3 Numerical Modeling

Creating geometry is the first step for numerical simulation. For BWB's shape, our geometry is created by Wan and Yang [22]. That BWB is a three-dimensional profile, the geometry model and the BWB's sizing parameters are shown in Fig. 5.

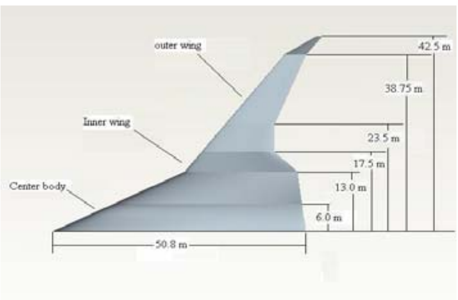


Fig. 5 Blended-Wing-Body geometry model [22]

There are two engines in current BWB, and the engine locations are between "inner wing" and "center body". Fig. 6 is showing the relationship between BWB and engines, with pylons hidden in the picture.

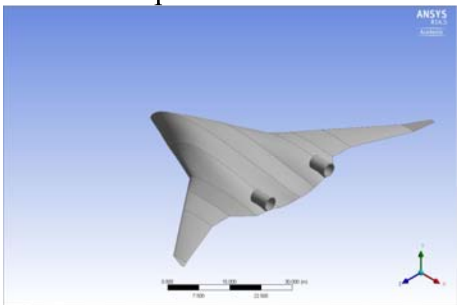


Fig. 6 BWB configuration and engines location

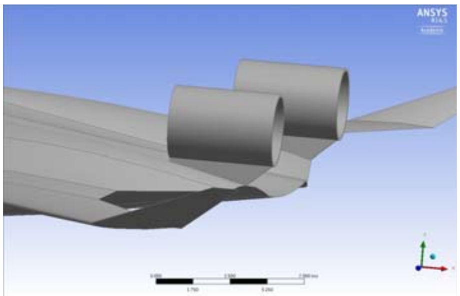


Fig. 7 Enlargements of the engine and pylon location

Our engines consists of two parts, engines itself and pylon. The main engines' shapes are cylinders, the outer circle's radius is 3.5 m, and the inner circle's radius is 3.25 m. That means the engine outer structure skin has a thickness of 0.125 m. The cylinders' length is 5 m. Finding the best possible pylon's vertical height will be our objective. The contour for both engines and pylons are shown in Fig. 7, and its pylon has 3 m in height between center of cylinder and BWB's trailing edge.

The next step for numerical simulation is generation of grids. Workbench is included in ANSYS, which nowadays is updating to version 14.5. Mesh can be classified three categories; which are structure, unstructured, and hybrid. The structure mesh can achieve more accurate results, but 3-D complicated configuration structure grid generation could be a tedious and rather time-consuming process. BWB with engines is a complicated shape. The hybrid mesh is made of both the structure and unstructured grids, and we have done two cases: hybrid mesh and structure mesh. Grid number is able to affect the accuracy of results too, computed results will be better with increasing grid number. In our cases, bare BWB hybrid mesh has 2,818,855 elements, structure mesh has 4,364,911 elements, and BWB with engines configurations also have four million to five million elements. Fig. 8 and Fig. 9 are showing hybrid mesh and structure mesh done by ANSYS workbench.

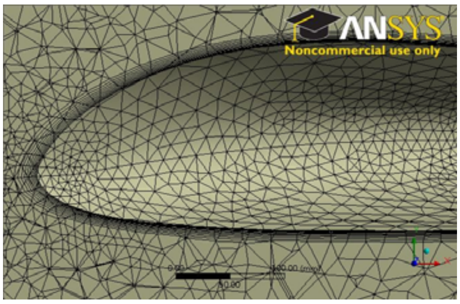


Fig. 8 BWB's hybrid mesh

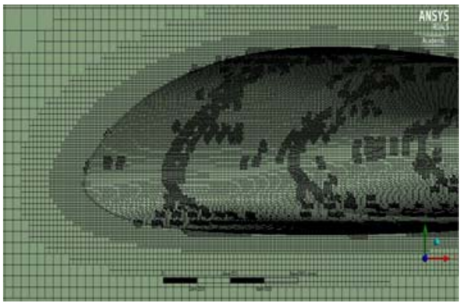


Fig. 9 BWB's structure mesh

Most traditional CFD algorithms use Navier-Stokes equations to solve the solution. There are two important issues that arise in the solution process. The details of the solution process depend upon the details of the flow to be solved. The main role of pressure is to satisfy the zero divergence condition of the velocity field. Note that pressure is only determined up to a constant. There are solver set in our CFD: Steady, Explicit Density Based Solver, Turbulence Model: κ-epsilon, Gauge Pressure: 19400 Pascal, Mach Number: 0.85, Temperature: 216.6K, Solutions Methods: Second Order Upwind, convergence criteria is 10E-6. The bare BWB configuration is put to test the validity of above two sets of software. The structure meshes with FLUENT has the best L/D: 18.73943. Because CFX can't use structure mesh, we also do the hybrid mesh test for bare BWB. The L/D is 16.34313, and the CFX's L/D is a mere 13.28502. By comparison, we find FLUENT resulting in better quality of grid points and much larger lift-to-drag ratio than CFX, so FLUENT is still chosen as our primary solver tool.

Another setting on FLUENT, boundary condition is a program which can input velocity, pressure, temperature, and other parameters at inlet and outlet surfaces. For the solution's part, we choose second order for pressure, second order upwind for momentum, turbulent kinetic energy, and turbulent dissipation rate. The residuals can decide the convergence condition. As for lift and drag coefficients, we need to create drag monitor and lift monitor first.

FLUENT also component with many different equations, and we will choose turbulence modeling first. Since the κ-epsilon model has three sub-sets, we have chosen the standard for our BWB's calculation. The realizable of κ-epsilon model has a new dissipation rate (ε), and it has a new formulation for the turbulent viscosity. The term "realizable" means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows [23]. We have done different turbulence model test on the same mesh, the case that is chosen is bare BWB with structure mesh. With Spalart-Allmaras model, we have the L/D value of 17.57474, but with κ-epsilon model, we can achieve a better L/D of 18.73943. According to these test results, a decision is made to implement the κ-epsilon turbulence model.

There is a standard verification of ONERA M6 wing. The ONERA M6 wing is the swept wing and symmetrical airfoil that has no twist. The span length is 1.1963 meters with 0.64607 meters of mean aerodynamic chord line. The aspect and taper ratios of the airfoil are 3.8, 0.562, and the leading-edge and trailing-edge sweep angles are 30.0, 15.8 degrees respectively. Fig. 10 is showing M6 wing's geometry and mesh. We not only use FLUENT to verify the M6 wing but also compare with the other Wind code results. Fig. 11 shows the pressure coefficients along the lower and upper surfaces of the wing at 0.839 Mach and two of the seven sections [2]. The rather close match between current simulation tool and the experimental data is obviously observed.

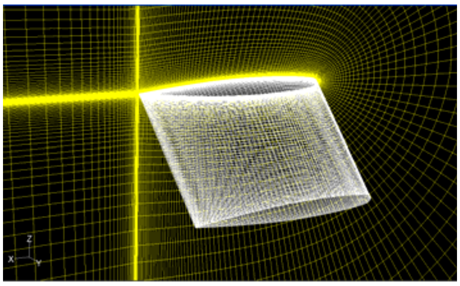
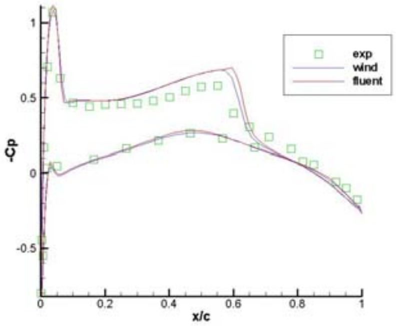
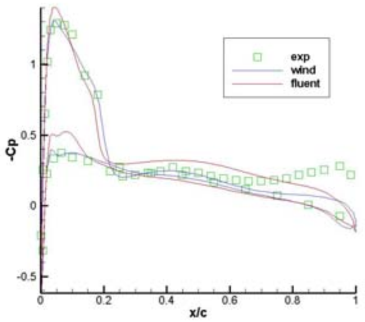


Fig. 10 Near structure mesh of the M6 wing



(a)



(b)

Fig. 11 Pressure coefficients at section y/b= (a) 0.2 (b) 0.99

Our objective is to use optimum engineering design to find the best engines' vertical position/pylon's height and the angle of attack (AOA) for BWB in cruising condition, and the tool implemented in this work is surrogate model. As mentioned before, surrogate model can be constructed by several methods; among them is Kriging model. In general all of the optimum engineering design are to find a point x* that can let the function to have extreme value, and surrogate model is no exception.

The first thing to use this tool is to build the Kriging model: independent variables x which called sample data, and dependent variable y which is the observed responses. In our cases, we must select some numeric to represent engines' vertical position. The sample data in our case are engines' vertical positions and angles of attack. The dependent variable y we can just use L/D values, but the drag will affect our answer too. So our observed responses include both the L/D values and drag. The Kriging has a basis function which form is

$$\psi^{(i)} = \exp\left(-\sum_{j=1}^{k}\theta_j \left|x_j^{(i)} - x_j\right|^{p_j}\right) \qquad (1)$$

In equation (1), θj and pj are parameters categorized by different j, j and k are number of our targets. For example, we want to find not only engines' vertical position, but also the best AOA for BWB, so the k is 2 and set $\theta_1=\theta_2=0.5$, p=2. After these parameters are decided, we can proceed to use Matlab function to calculate Cholesky factorization of psi (ψ), and come out with the matrix U. Ψ-1 is thus calculated by this matrix. Then the Kriging prediction is:

$$\hat{y}(x) = \hat{\mu} + \psi^T \Psi^{-1}(y - 1\hat{\mu}) \qquad (2)$$

That

$$\hat{\mu} = \frac{1^T \Psi^{-1} y}{1^T \Psi^{-1} 1}$$

If we can find the right x value, then the maxima y(x) value can be found [16].

4 Results and Discussion

The Kriging surrogate model can find the best AOA and engine vertical position in this section. As a practice of optimization procedure and to simplify the problem, we will engage the case that finds the best AOA with BWB with no engines on first.

4.1 BWB without the engine

We have done eight different AOA conditions for BWB devoid of the engines. The degree include 0°, 1°, 1.5°, 1.7°, 2°, 3°, 4°, and 5°. All of the eight data are BWB cruise at 0.85 Mach. This section will find the optimum AOA attitude with BWB by the Kriging model. Assuming we have six data which are 0°, 1°, 2°, 3°, 4°, 5°, and their related L/D values. The goal of the problem is to find the x which has the maxima y. The x in this case is AOA, and the y is L/D. Then, matrix X and matrix Y can be created:

$$X = \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix}, Y = \begin{bmatrix} 6.24144 \\ 16.17884 \\ 18.97323 \\ 15.53211 \\ 12.45907 \\ 10.15640 \end{bmatrix}$$

Matrix X is sample data. This case is to find AOA, so the matrix X is reference AOA. Matrix Y is L/D which correspondence with matrix X. Then, using the Matlab code, Cholesky factorization matrix U is shown:

$$U = \begin{bmatrix} 1.0000 & 0.3679 & 0.0183 & 0.0001 & 0.0000 & 0.0000 \\ 0.0000 & 0.9299 & 0.3884 & 0.0196 & 0.0001 & 0.0000 \\ 0.0000 & 0.0000 & 0.9213 & 0.3910 & 0.0198 & 0.0001 \\ 0.0000 & 0.0000 & 0.0000 & 0.9202 & 0.3914 & 0.0198 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.9200 & 0.3914 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.9200 \end{bmatrix}$$

Then, the prediction values are found when using another Matlab code. The model can predict all of different AOA L/D value. Table 1 and Fig. 12 are showing the results done by Kriging model. The maxima x in Fig. 12 is the answer in this case, and the result shows that the best AOA is 1.690016°, and its L/D can achieve as high as 19.11173. Because the result must in between 1.5° to 2.0°, so 1.690016° condition may be accepted. Then, proceed to use FLUENT to run on the case, and the L/D for 1.690016° AOA now is 18.95199. This is a small deviation from Kriging prediction, and the results by CFD show 1.7° can have slightly better L/D values than 1.690016°.

In order to find the effect to the optimal answers by different sample data set, then several cases with different AOA are tested. The results are shown in Table 2 to Table 4. The degrees in table and figure titles mean the case which we apply the data set to build the Kriging model. We can espy the cases that if the basis data contain 1.5° condition, the cases predict 1.7° are more accurate than others by Table 2, 3, and 4. Thus we can conclude that besides more data sampling is needed, data that close to the predicted optimal values are playing an even more influential role in the final solution. So the proper selection of test conditions is rather vital to the success of our method.

Table 1 L/D comparison between Kriging prediction of AOA=0°, 1°, 2°, 3°, 4°, 5° and FLUENT solver for BWB with no engine at AOA=1.7°

	FLUENT	Prediction	
AOA	1.7°	Best (1.690016°)	1.7°
L/D	18.97323	19.11172	19.11127

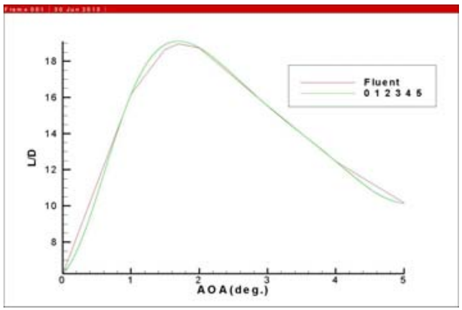


Fig. 12 L/D comparison between Kriging prediction of AOA=0°, 1°, 2°, 3°, 4°, 5° and FLUENT solver for BWB with no engine

Table 2 L/D comparison between Kriging prediction of AOA=0°, 1°, 1.5°, 2°, 3°, 4°, 5° and FLUENT solver for BWB with no engine at AOA=1.7°

	FLUENT	Prediction	
AOA	1.7°	Best (1.76358°)	1.7°
L/D	18.97323	18.90891	18.89545

Table 3 L/D comparison between Kriging prediction of AOA=1°, 1.5°, 2°, 3°, 4° and FLUENT solver for BWB with no engine at AOA=1.7°

	FLUENT	Prediction	
AOA	1.7°	Best (1.755°)	1.7°
L/D	18.97323	19.04246	19.02496

Table 4 L/D comparison between Kriging prediction of AOA=1°, 1.5°, 2°, 3°, 4°, 5° and FLUENT solver for BWB with no engine at AOA=1.7°

	FLUENT	Prediction	
AOA	1.7°	Best (1.75677°)	1.7°
L/D	18.97323	19.04789	19.02906

4.2 The Optimal Engine Position and AOA Prediction in Two Steps

After the bare BWB simulation, then we can proceed to predict the optimum AOA and its engines position for BWB with engine on. We first establish four different CFD data before predict the optimal value by Kriging model. This section will predict the best pylon height and AOA in two steps. Predict the best position of engines at first, and then the optimum AOA of BWB. Table 5 is showing BWB's C_D and

L/D when the engine vertical position at 3m, 3.5m, 4m, and 4.5m. The vertical positions mean the distance between the center of engines and BWB's trailing edge.

Table 5 BWB's C_D and L/D for engine at different vertical positions

Vertical positions (m)	C_D	L/D
3	0.013110	13.76659
3.5	0.013342	13.42153
4	0.013299	12.69344
4.5	0.013927	12.68471

All of four cases are for BWB cruise at 2 degree AOA with 0.85 Mach, and the function's form is

$$f\left(\frac{L}{D}, C_D\right) = \frac{1}{\left(\frac{L}{D}-\frac{L}{D}^0\right)^2 + (C_D^2 \times C)}$$

This function includes both L/D and C_D. Earlier the BWB without engines have value of L/D=18.73943 at 2 degree AOA in cruise condition, so we assign 18.73943 to be our reference value. It means $\frac{L}{D}^0$ is 18.73943 in our simulation. And then to calculate C_D^2, $\left(\frac{L}{D}-\frac{L}{D}^0\right)^2$, thus Table 6 will be created as follows.

Table 6 BWB's C_D^2 and $(L/D- L/D^0)^2$ for engine at different vertical positions

Vertical positions (m)	C_D^2	$(L/D- L/D^0)^2$
3	0.0001719	24.72909
3.5	0.0001780	28.28005
4	0.0001769	36.55399
4.5	0.0001940	36.65954
average	0.0001802	31.55567

The averages have a great difference between C_D^2 and $\left(\frac{L}{D}-\frac{L}{D}^0\right)^2$. So C_D^2 must multiply a constant c in order to normalize the two parameters. The constant C is 31.5556÷ 0.0001802= 175138.0254 in this case, it can convert C_D^2 to become the same magnitude as $\left(\frac{L}{D}-\frac{L}{D}^0\right)^2$, thus these two have the same weighting factor. So Table 7 can be achieved.

Table 7 BWB's f for engine at different vertical positions

vertical position (m)	$(L/D-L/D^0)^2$	$C_D^2 \times C$	f
3	24.72909	30.10134	0.018238
3.5	28.28005	31.17614	0.016819
4	36.55399	30.97551	0.014808
4.5	36.65954	33.97000	0.014158

Then use Kriging model to predict the best possible engine position. First create the matrix X and matrix Y. Unlike the last section, matrix X is position of engine in this problem. Matrix Y is f which corresponds with matrix X. The model shows the answer is 2.84752m, which f is 0.0183206. Using Pro/E to create new geometry and apply CFD to solve it can achieve an f value of 0.0178647 for 2.84752m engine position. If having more data points to predict then we may improve the answer. So two data points are added in this case, and the resulting parameter is shown in Table 8.

Table 8 BWB's C_D, L/D, and f for engine at different vertical positions for 7 data

Vertical positions (m)	C_D	L/D	C_D^2
2.84752	0.012591	13.42308	0.0001585
3	0.01311	13.76659	0.0001719
3.25	0.012711	13.10597	0.0001616
3.5	0.013342	13.42153	0.0001780
3.75	0.013617	13.43541	0.0001854
4	0.013299	12.69344	0.0001769
4.5	0.013927	12.68471	0.0001752

Table 8 (continued)

Vertical positions (m)	$(L/D-L/D^0)^2$	$C_D^2 \times C$	f
2.84752	28.26353	27.71281	0.017865
3	24.72909	30.04454	0.018257
3.25	31.73581	28.24357	0.016672
3.5	28.28005	31.11731	0.016836
3.75	28.13256	32.41328	0.016516
4	36.55399	30.91705	0.014821
4.5	36.65954	33.90590	0.014171

Once the f function of all data points is achieved, and next we can employ Kriging model to predict value again. Now the best position is 2.937746m, and its f is 0.018440, thus verify the answer of 2.937746m position by CFD again, and now come up the answer is f = 0.018226. Since the engine radius is 1.75m so pylon height is 1.18746m in this case. The f is worse than case with 3m, thus we think the optimum value must around this region. There is a slight chance that the best position of engines is exact 3m, but the Kriging model can't find the answer for which is one of the original data points. After finding the optimum engine position, next step is to predict BWB AOA, the C_D, L/D and f values at different AOA attitude are shown in Table 9. Using the Kriging model again, and the prediction obtain the optimum AOA α is 2.13217400°, f is 0.02027, and the f value is 0.020203 by CFD simulation. There is some disagreement between CFD and prediction values, but the error is within tolerance, the f also better than all of data points. So indeed to predict the optimal engine position and AOA in two different steps is complete.

Table 9 BWB's CD, L/D, and f for engine at different AOA

AOA	C_D	L/D	f
1	0.010099	7.94663	0.007409
2	0.012893	13.65935	0.019977
3	0.02045	13.68411	0.012067
4	0.032781	11.66773	0.005143

The L/D values with BWB are different between no engines and with engine added. The L/D is 18.73943 when the bare BWB is at 2 degree. But the L/D ratio greatly reduce to about 13 when the BWB with engines at the same degree. As shown in Table 7, different engine position can lead to different L/D. The largest L/D value just has 13.76659 at AOA=2 degree and the engine position is 3m, before employ Kriging model to predict the best possible answers. Two different cases' L/D is shown in Table 10. It is clearly shown that the influence of the two engines is quite obvious, and the effects to lift and drag are almost the same. Partial explanation is that our engine shape is somewhat un-streamlined, thus prove the importance of streamline shaped body in the aerodynamic design. Also, a better way to predict the optimal engine position and AOA need to be found.

Table 10 BWB's L/D at 2 degree AOA

	BWB without engines	BWB with 3m height engines
C_L	0.22373	0.18048
C_D	0.011939	0.01311
L/D	18.73943	13.76659

4.3 The Optimal Engine Position and AOA Prediction in One Step

This section is to predict the best AOA and position with BWB installed engines too, but it will predict them in a single step. The Kriging model can predict two or more unknown parameters at once. The predictions are influenced by C_D and L/D values. There are already 14 data of BWB with engines, and all of them are the BWB cruise at 12 kilometer altitude and 0.85 Mach number.

Table 11 BWB's C_D and L/D in different AOA and engine at vertical positions

AOA	Vertical positions (m)	C_D	L/D
1	3	0.010201	8.26292
1	3.5	0.010478	7.89454
1	4.5	0.011209	7.21822
2	3	0.013110	13.76659
2	3.5	0.013342	13.42153
2	4	0.013299	12.69344
2	4.5	0.013927	12.68471
3	3	0.020858	13.65136
3	3.5	0.020989	13.49040
3	4	0.020642	13.21287
3	4.5	0.021434	13.10348
4	3	0.033318	11.62915
4	3.5	0.033375	11.56345
4	4.5	0.033682	11.71229

As in the last section, the predictor considers both L/D and C_D, so there is the same function f which includes L/D and C_D. $\frac{L}{D}^{0}$ is a reference value that we want to have, and the value is 18.97323 to be our goal this time. 18.97323 is the best L/D in our simulation, and that is BWB without engines cruise at 1.7 degree data. After select $\frac{L}{D}^{0}$, calculate $\left(\frac{L}{D}-\frac{L}{D}^{0}\right)^2$ and C_D^2, and Table 12 will be achieved.

The average of L/D is larger than C_D. So C_D must multiplies a constant C like last section, the constant is the quotient too. The quotient is 57.50474÷0.0004414 = 130274.8248, the results of $C_D^2 \times C$ are also shown in Table 12.

After obtain two sets data of them, put them to the function to compute consequences, the results of these consequences are shown in Table 13. And then, Kriging model can predict the best AOA of BWB and position of the engine.

Table 12 BWB's $(L/D\text{-}L/D^0)^2$, C_D^2 and $C_D^2 \times C$ in different AOA and engine at vertical positions

α	Vertical positions (m)	$(L/D\text{-}L/D^0)^2$	C_D^2	$C_D^2 \times C$
1	3	114.71078	0.0001041	13.5564
1	3.5	122.73729	0.0001098	14.30261
1	4.5	138.18026	0.0001256	16.36799
2	3	27.10907	0.0001719	22.39059
2	3.5	30.82139	0.0001780	23.19009
2	4	39.43579	0.0001769	23.0408
2	4.5	39.54541	0.0001940	25.26824
3	3	28.32231	0.0004251	55.3741
3	3.5	30.06140	0.0004405	57.39101
3	4	33.18175	0.0004261	55.50906
3	4.5	34.45393	0.0004594	59.85034
4	3	53.93548	0.0011101	144.6166
4	3.5	54.90487	0.0011139	145.112
4	4.5	57.66664	0.0011345	147.7938
average		57.50474	0.0004414	57.50474

Table 13 BWB's f in different AOA and engine at vertical positions

α	Vertical positions (m)	f
1	3	0.007796
1	3.5	0.007297
1	4.5	0.006470
2	3	0.020202
2	3.5	0.018515
2	4	0.016006
2	4.5	0.015429
3	3	0.011765
3	3.5	0.011435
3	4	0.011275
3	4.5	0.010604
4	3	0.005036
4	3.5	0.005000
4	4.5	0.004867

The method of use Kriging model is the same of predicts one parameter: create the X matrix and Y matrix at first. The matrix X is a 14×2 matrix by AOA and position, and the matrix Y is a 14 points data by f. Achieving Cholesky factorization 14×14 matrix U next step. Finally, the prediction values are found by Matlab code, the code shows the greatest f is when AOA is 2.09 degree and engine position is 2.97m. In that situation, f can reach 0.020332. We also do the case at that degree and height by CFD. The C_L is 0.19105, C_D is 0.013602, and the L/D is 14.04573 by FLUENT. Then calculate $C_D^2=1.85014\times10^{-4}$, $C_D^2\times C= 24.10272$, $(L/D\text{-}L/D^0)^2=24.28024$. So our f is 0.020668 by CFD computation.

The result of engines height, AOA and f in two different methods are shown in Table 14. The answer in predict in one step has better f than another case. So the case of predict in two steps not only has more procedure, but also have worse answer in the case of predict in one step.

Table 14 Comparison engine's position, AOA and f in two different methods

	Predict in Two Steps	Predict in One Step
Engine's position (m)	2.93775	2.97
AOA(°)	2.13217	2.09
f	0.020278	0.020668

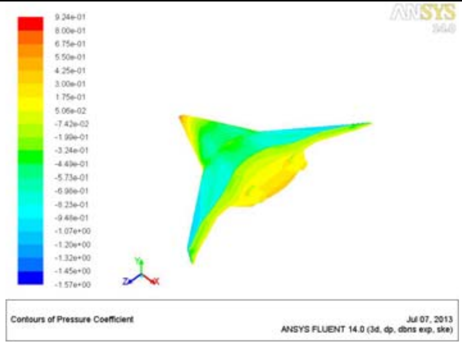


Fig. 13 Pressure contour for BWB at 0.85 Mach and 2.09 degree with engine position of 2.97m.

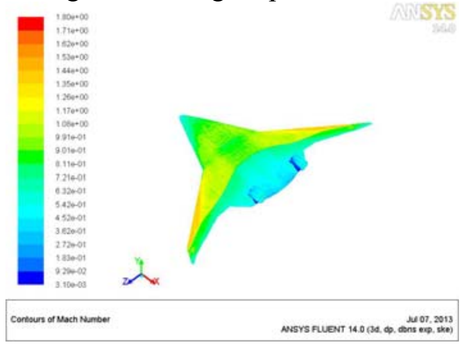


Fig. 14 Mach contour for BWB at 0.85 Mach and 2.09 degree with engine position of 2.97m.

There is error between predictive value and value by CFD. And the relative error is 1.625% in this case. We think the data points are too few at beginning. But there are already 14 data points. The values of C_D and L/D are not the real number in fact, it is approximation. And the problem occurs in C_D, C_D^2, $C_D^2\times C$, $(L/D\text{-}L/D^0)^2$, etc. Limit by computer decimal digits, the whole number in matrix U can't be reached. The error is appeared when we round up 1 for numbers higher more than 4 again and again. Figs. 13 and 14 are shown pressure coefficient contour and Mach contour when BWB cruise at 0.85 Mach at 2.09 degree and has engines at 2.97m.

The engine is deemed a tube. There is an idea that is change engine's boundary condition. Engine inlet can be set outflow, and engine nozzle is inflow. We select inlet part become "pressure outlet", the nozzle part become "velocity inlet". Velocity inlet must enter the velocity and temperature to the solver. The turbojet velocity has about 310 m/s and temperature has 800 K at the nozzle. About pressure outlet part, it must enter pressure and temperature to the solver. The pressure is 19400 Pa, the temperature is 216.6 K in pressure far field. If the pressure is 19400 Pa and the temperature is 216.6 K to pressure outlet, C_L and C_D can be found is 0.18312 and 0.012820. The L/D is 14.28393. The pressure and temperature maybe is other value. For found the correct value, we check the pressure and temperature at two cases: the case which treat engine as a tube and the case pressure outlet is 19400 Pa and 216.6 K. The average pressure is 22700 Pa and temperature is 226.75 K. And the L/D is 14.04866 in the case. Table 15 is this three cases C_L, C_D and L/D value.

Table 15 The C_L, C_D and L/D value in different boundary condition

Boundary Condition	treat engine as a tube	P=19400 Pa T=216.6 K	P=22700 Pa T=226.75 K
C_L	0.19105	0.18312	0.17610
C_D	0.013602	0.012820	0.012535
L/D	14.04573	14.28393	14.04866

5 Conclusions

In this study, the BWB cruises at about 12 kilometer altitude and 0.85 Mach number. Both the take-off/landing and cruise cases are simulated via CFD tool, but the cruise conditions are focus and solved in current work. As for engine, which is an indispensable part of aircraft, it can bring thrust force, and the engines are considered as tubes in our cases. Engine internal components are ignored which include compressor, burner, and turbine, etc. A more realistic engine should have smaller diameter at engines inlet and nozzle stations, and the pylon considered as a flat plate in our cases. Engines will increase drag force, and reduced lift force, thus their location are rather important. Recently there is a new concept plane proposed by Airbus, and the idea is its engines are almost half hide into the wings. According to report, this design can have less fuel burn and emissions. Although this new approach does not have pylon, but finding the optimum pylon's height is one of the goal of this research, so that geometry does not considered in current work, however it definitely worth urther investigation.

The main theme of this research is to employ the Kriging surrogate model in order to predict our BWB aircraft's best engine positions and AOA attitude, and also predict BWB's AOA when it does not have any engine. These two cases have the same concept by using Kriging model, and their objective function can be computed by our program. In first step finding the best AOA of BWB without engines will be our verification case. That case has just one variable, so the process is easier than the other. The resulting optimal answer lay between 1.5° to 2.0°, and the predictions are in the same region, no matter how many data points we utilize. And then, predict two variables with the same code. That mean now we can consider both the best AOA and the optimal position of engines at the same time. The predictor shows the BWB have the optimum aerodynamic performance with 2.09 degree AOA and the vertical engine position of 2.97m when in cruising condition. And the reference function value f is 0.020332, then CFD computation gives us the value of 0.020668, with the relative error of 1.626% and it is quite acceptable. Indeed this approach represents a triumph in our BWB aerodynamic optimization work, with no major effort required.

Having gained experience to predict two variables optimization (engine position and AOA) by using Kriging surrogate model, thus add more design variables will not be much more difficult. All it required is just adds another parameter in the code. But the data points must be more than two variables, thus represent a somewhat tedious work, and we are confident that we can apply the same model to other problems in the related fields. Thus it is believed that current work lays foundation for the multi-disciplinary design optimization (MDO) in our aerodynamic simulation.

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