# FLYING WING CONCEPT FOR MEDIUM SIZE AIRPLANE

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## Abstract

*This paper describes a study on an alternate configuration for medium size airplane. Blended-Wing-Body concept, which basically is a flying wing configuration, is applied to airplane for up to 224 passengers.*

*An aerodynamic design tools system is proposed to realize such configuration. The design tools comprise of Takanashi's inverse method, constrained target pressure specification method and RAPID method. The study shows that the combination of those three design methods works well.*

## 1 Introduction

The trend of airplane concept changes from time to time. Speed, size and range are among of the design parameters. Some is intended to have more speed; others have larger size or the combination of it. To have more efficient airplanes and to meet the changing of the airplane mission, the aeronautical engineers have designed many airplanes configurations. Many of their designs have flown successfully and others are still in the drawing tables. Some of their design concepts are different from the conventional airplane. One of the design concepts is the *flying wing* configuration. The flying wing and the tailless airplane are different. Although they both do not have horizontal tail, the tailless airplane still has the typical cylindrical fuselage, which carries a large part of the load.

The flying wing is regarded as an alternate configuration to reduce drag and structural weight. Since flying wing possesses no fuselage it may have smaller wetted area than the conventional airplane. In the conventional airplane the primary function of the wing is to produce the lift force. In the flying wing configuration the wing has to carry the payload and provides the necessary stability and control as well as produce the lift. The fuselage has to create lift without much penalty on the drag. At the same time the fuselage has to keep the cabin size comfortable for passengers.

In the past years several flying wings have been designed and flown successfully. The Horten, Northrop bombers and AVRO are among of those examples. However the application of the flying wing concepts were so far only for sport and military airplanes. A review on the flying wing histories is given in reference [1]. The flying wing concept for the civil transport airplane has not been build or still only in the drawing table such as a short-haul airplane proposed by Lee around 1965 [2].

Nowadays the flying concept comes again into attention, especially for very large transport airplane configuration as shown in references [3,4,5]. Reference [6] describes a concept of flying wing for 300 passengers. The constraints implied by the required cabin height for the human payloads imply an interesting application for high capacity airplane. However the advantages of the flying wing concept may be also useful for regional transports such as for 200 passengers. The flying wing usually has larger reference area that reduces the wing loading. With its lower loading the required takeoff fields length can be shorten without

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complicated high-lift devices. This aspect is attractive and important for the regional airplanes.

A Blended-Wing-Body (BWB) airplane is a conceptual transport airplane, which in essence is a flying wing airplane. The inboard wing of the BWB airplane is usually very thick because it is used to carry the payload. The outboard wing is similar to the one of the conventional airplane. It is a challenging task to design the inboard wing under severe constraints. The inboard wing should have enough space for the passengers and should have also a good aerodynamic performance.

To design medium or small size BWB airplane is very difficult because the geometrical requirements are stricter. The space requirements to give the passengers enough comfort may also contradict with the constraint on the wetted area, so that some trade-off may be required. Other potential problem is the blending from the thick inboard wing into the thin outboard wing. The blending should be done as smooth as possible.

In this paper the design process of BWB airplane for up to 224 passengers and its present results will be described. The design tools used in the design process also will be discussed. The emphasis is on the aerodynamic design process where the authors have been researching to overcome the difficulties. The main design tool will be Takanashi's inverse method. To increase its practical usefulness, constrained target pressure specification technique and surface modeling technique are incorporated.

## 2 Conceptual Design

The ground performance of an airplane including takeoff and landing distance is affected by the wing loading. The lower wing loading will give shorter takeoff field length. The other factor is the engine power and lift coefficient at lift off speed. To achieve lower wing loading the weight should be as small as possible and the wing area is increased. The lower wing loading is one of the advantages of the flying wing. For this reason this study chooses the flying wing concept to be applied for the medium size transport airplane.

In the present study Blended-Wing-Body concept is applied to a regional transport airplane for maximum of 224. The cruise speed is at Mach number of 0.8 and range up to 2500 nm.

The design of the configuration starts with specifying the required space to carry the payload. Human measurement is the primary consideration for determination of the required cabin space, since it will affect their comfort during the flight. The maximum cabin height depends on the airfoil contour. The airfoils are design in such way that at the corners of the passenger's cabin the height is 1.9 m. The location of the cabin corners should be less than 70% root chord to avoid excessively airfoil thickness. With this requirement the maximum thickness is located at the wing section that connects the passenger's cabin and cargo space. In this section the chord length is shorter than the center chord length while the required cabin height is the same, which results in thick airfoil. The cabin floor area is determined with the assumption that each passenger will require 0.929 $m^2$ area includes volume required for each passenger's share of galley, lavatories. The passenger seats are arranged in 3 cabin compartments separated by wing ribs as the partitions. The passenger's seat pitch is 90 cm, which is comparable to the business class or even first class in many aircraft configurations. At seat pitch of 80 cm the total passenger becomes 224. Two galleys and four lavatories are located at the most aft position, which give clear forward view for the passengers. Reference 2 describes the necessary methods to compute the required spaces. The outer wing is designed to have enough space to carry the fuel. On each side they are three entrances available, two for the passengers and one for the cargo hold. It is very difficult to place exit doors at the aft part of the cabin. However because the cabin length is shorter than the one of the conventional airplane, the loading and unloading process will faster. Figure 1 shows the design result. Some of its properties are given in table 1.

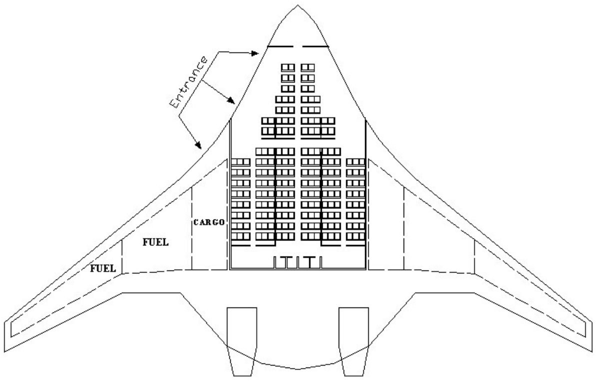


**Figure 1.** Design configuration

Figure 2 shows 3D views of the design airplane. The designed BWB airplane will have two engines at the aft center part of the wing. The configuration will also utilize the winglet, which also serves as the vertical tails.

| | |
|---|---|
| Wing span | 50 m |
| Total Length | 31 m |
| Wing Area (trap) | 325 m |
| Wetted Area | 1164 m |
| Aspect Ratio | 7.7 |

**Table 1.** Configuration's properties

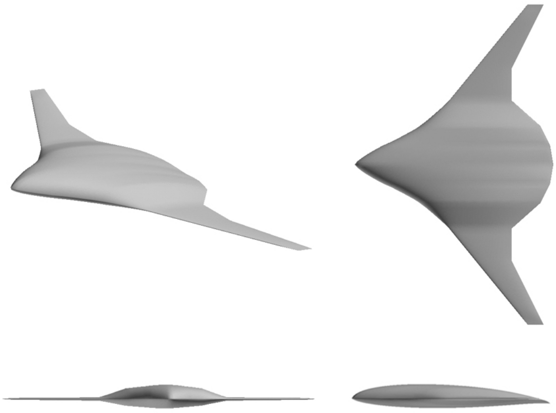


**Figure 2.** 3D-Views of design configuration

## 3 Design Tools

The wing of the BWB airplane should be designed not only to produce the lift but it should also have enough space to carry the payload. To satisfy both requirements a method for wing design is required. One way to solve this problem is by utilizing the inverse design method. One of the most useful inverse design method is the Takanashi's[7] inverse method, which uses the inversely formulated transonic small perturbation equation. This algorithm finds geometrical correction value to reduce the difference between the target pressure distribution and the computed pressure distribution of a given airfoil. The geometry corrections are obtained by solving integral equations. These integral equations are the mathematical model of the relation between the aerodynamic geometry and pressure distribution. To add the practical usefulness of Takanashi's inverse method, constrained target pressure specification technique and surface modeling technique are incorporated.

### 3.1 Inverse Design

In essence, the inverse design process consists of two primary processes, which are independent of each other. One is the analysis process, which consists of grid generation and flow simulation, and the other is the design process itself. The flow simulation solves differential equations, which describes physical phenomena. Any flow simulation can be utilized. With this arrangement the existing flow analysis still can be utilized, and when a new and more powerful flow analysis becomes available then only the flow analysis part need to be upgraded. The design part consists of the solutions of inverse problem and the smoothing algorithms as required.

The inverse design process starts with the specification of the target pressure distribution based on the required aerodynamic performance. The pressure difference between the initial and the target forms an input of the inversely formulated transonic small perturbation equations. The solutions of the equations provide the geometry's correction $\Delta f$, which are used to modify the initial geometry to form a new geometry. The flow solutions of this new shape may be obtained by applying the

Navier-Stokes equations. If, after having checked the convergence, the design requirements are not satisfied, the design cycle is repeated with the new geometry as the replaced initial geometry. The process is repeated until the pressure different is minimized.

## 3.2 Target Pressure Specification

The inverse process requires target pressure distribution. The generation of the target pressure distribution is based on the required aerodynamic performance. However other discipline in aircraft design may pose additional requirements that are usually translated into geometry constraints such as the maximum thickness, local thickness and leading edge radius. An example is a thickness requirement for structural strength or a space requirement to carry enough fuel. Thus, the choice of the pressure distribution is the most important thing in the inverse design process. The pressure distribution should meet both the aerodynamic and geometry constrains.

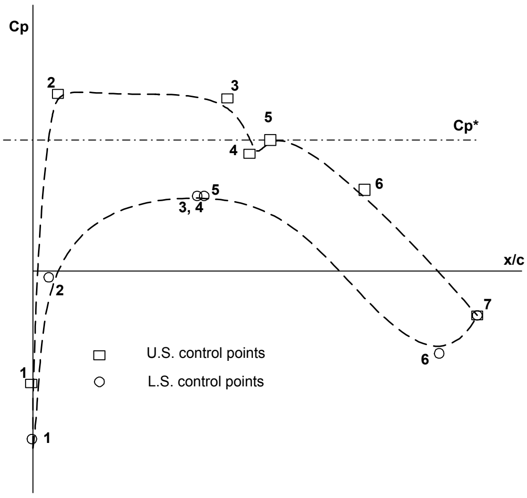


**Figure 3.** Control points to be used to generate target pressure

The most common problem of utilizing the inverse design method as a design tool is the specification of the target pressure. To realize the flow constraints and the space requirement, it requires a method to specify the target pressure distribution, which satisfies both requirements. To solve this problem a constrained target pressure specification technique as proposed by Campbell[8] is utilized. To manipulate the pressure distribution during the design process, the pressure distribution is divided into several regions bounded by several control points as shown in figure 3. The location of the control points and their pressure levels are obtained by using two approaches, *empirical estimation approach* and *control point fitting approach*.

In empirical estimation approach the controls points are developed by using empirically derived equations. Control point fitting approach is very useful to design target pressure distribution based on the existing airfoil, so the aim of this approach is to modify the existing pressure distribution.

In the control point fitting approach, the control points are initially fitted into the existing pressure distribution. Then the pressure level at every control point is modified using the equations from empirical estimation approach.

## 3.3 Surface Modeling

The BWB configuration is characterized by thick wing section in the inboard section, while the outer wing is similar to the one of the conventional airplane. To have lower drag it is required that the blending from the thick wing section into the thin wing section should be done as smooth as possible.

The wing surface between two known wing sections can be created by linear lofting method. This is especially true in the case of straight taper wing as commonly used in the conventional airplanes. However this method will be more difficult to be implemented in the BWB configuration design, especially for the inboard wing design.

Because the BWB configuration has thick inboard wing and thin outboard wing, the blending of thick inboard wing into the thin outboard wing will be quite difficult to be realized by the linear lofting method. Therefore another method of surface modeling is required to create smooth curved surface. The curved-surface modeling becomes more important for the medium-size BWB airplane because of the abrupt change from the inboard to outboard wings.

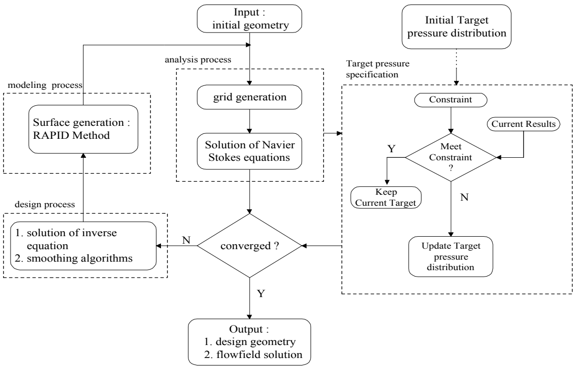


**Figure 4**. Design process

To achieve the smooth wing surface, in this study RAPID(Rapid Airplane Parametric Input Design)[9] method is employed. RAPID method generates the smooth surfaces by solving the fourth order differential equation

In this study to design the BWB airplane, the combination of all mentioned methods above are utilized. The integration of constrained target specification and RAPID method into Takanashi's inverse design is shown in figure 4.

## 4 Design Results

### 4.1 Mass Properties

The maximum takeoff weight is estimated using a method described in reference [10]. The results are used to estimate the required lift coefficient and the center of gravity location. A simple method as described in reference [2] is utilized to estimate the location of center of gravity. The travel range of the center of gravity is 8% of the root cord depends on the load configuration.

### 4.2 Inverse Design Results

Reference [11] describes the results of the initial study, let denotes this as configuration 1. The initial study result does not have the elliptical span loading distribution. The present study will try to obtain elliptical distribution of the span loading, which can reduce the drag coefficient.

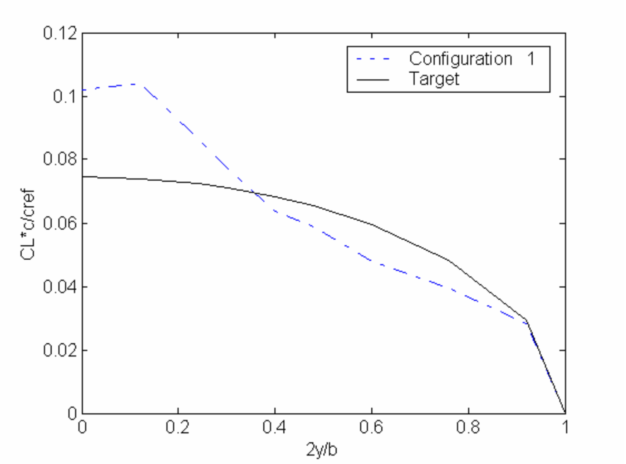


**Figure 5.** Target Span loading

The target pressure distribution is defined based on the design requirement. The aim here is to obtain the thickness distribution which lead to the geometry requirement of the inboard wing, which can carry the payload. The others aims are to have elliptical span loading and to have pitching moment coefficient as small as possible. To achieve the elliptical span loading distribution requires higher lift at the outboard wing. This high lift increases the pitching moment. To compensate the increase of the pitching moment the airfoil aft loading is reduced. Figure 5 shows the span loading of configuration 1 and the target span loading.

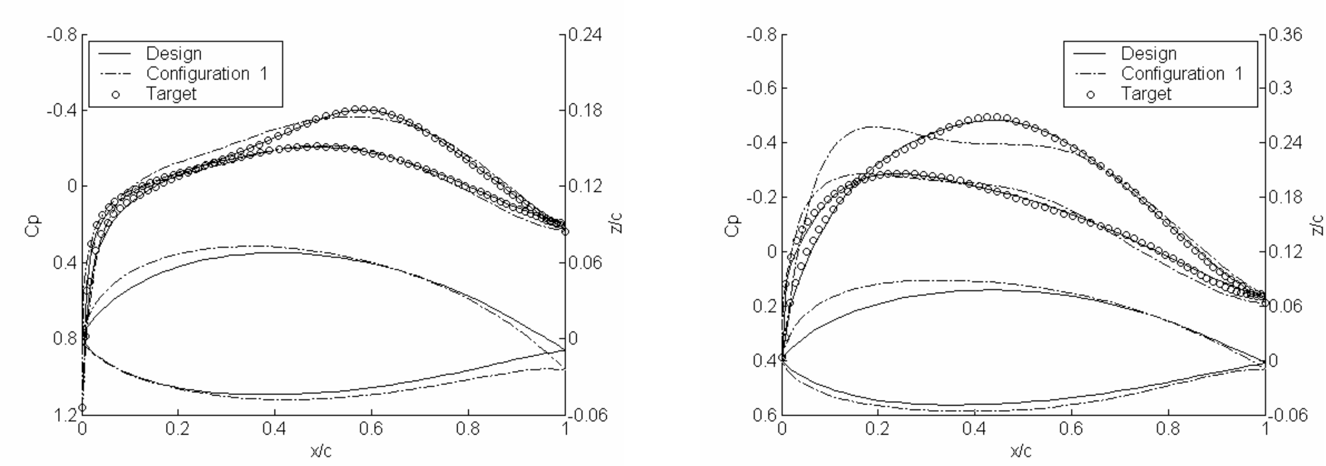
Control point fitting approach is utilized to specify the target pressure distribution and during the design process the target pressure distribution is modified iteratively. To create the wing in total 10 design locations are used. Four Design locations are used for the inboard wing design and the rest for the outboard wing. At those locations the wing sections are obtained by using Takanashi's inverse method, then the RAPID generates the wing surfaces.

To evaluate the aerodynamic performance of the wing, the Navier-Stokes equations were solved using C-H type mesh contains 191x50x49 grid points. The flow conditions is set at free stream Mach number of 0.8 and the angle of attack of 0 deg. The Reynolds Number is $10^7$.

Figure 6 shows the results of the inverse design process at several design locations. It shows that the design processes converge to the specified target pressure distribution, although there are still small discrepancy near the leading edge and trailing edge. Shockwave does not presence both on the upper and lower wing surfaces. Compare to the configuration 1, the design results have lower loading at the trailing edge.

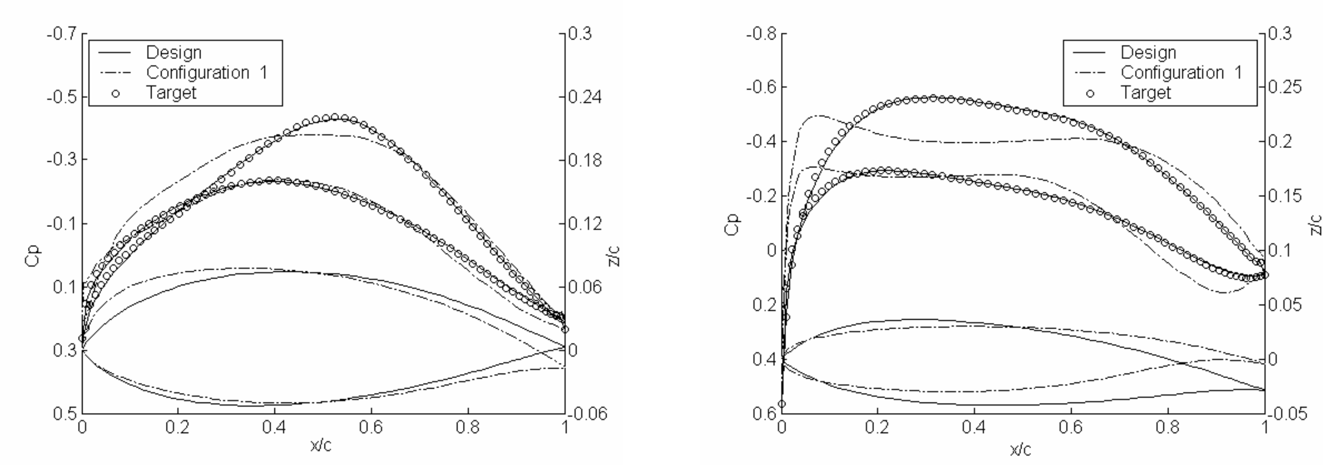
The span loading is depicted in figure 6. This figure shows that the span loading of the present result approaches the elliptical distribution.

Table 2 shows the aerodynamic performance of the design compare to the configuration 1.The drag coefficient is lower than the configuration 1; this might come from a result that the thinner airfoil in the inboard section has been designed and the elliptical distribution of the span loading is achieved.



0% semispan

24% semispan



b. 12% semispan

d. 40% semispan

**Figure 6.** Inverse design results

However the pitching moment (reference point is the leading edge of the center airfoil) is slightly higher than the one of the configuration 1 because the outboard section has higher lift coefficient than the configuration 1.

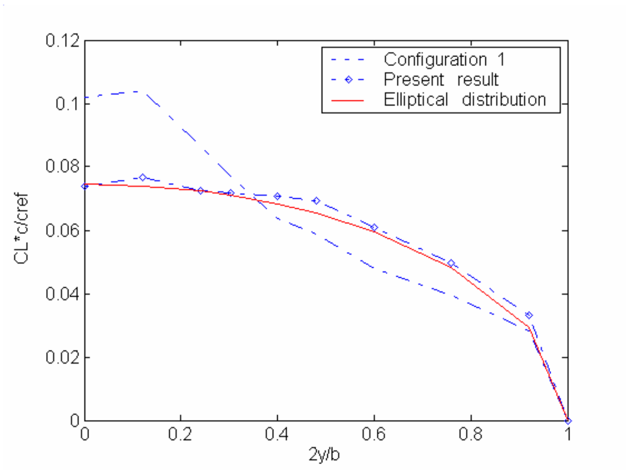


**Figure 7.** Span loading

| | Design | Config. 1 |
|---|---|---|
| Lift coefficient, *CL* | .30371 | .30441 |
| Drag coefficient, *CD* | .01574 | .01616 |
| Pitching moment coefficient, *Cm* | -.21777 | -.21167 |
| Lift to Drag ratio, *L/D* | 19.295 | 18.838 |

**Table 2.** Aerodynamic performance

Figure 8 shows the airfoils at the three design locations in the inboard wing section. The passenger's cabin is placed inside those three airfoils. In this figure the passenger's cabin is also represented as the rectangle. The figure shows that the present method can achieve the aerodynamic target with satisfying the geometry constrains to obtain wide space for the passenger's cabin.

**Figure 8.** Passenger's cabin

## 4.3 Engines and Vertical Tails Integration

The integration of the engines and vertical tails also requires special attention. They are several possibilities of the engines placement. However it is preferable to place the engines buried on top of the wing surface. First, it reduces the contribution of engines wetted area. Second, the thrust line can be aligned with the center gravity location to reduce the pitching moment caused by the engine thrust. Other potential benefits if the engines are located above the wing are the noise reduction and preventing debris from entering the engines.

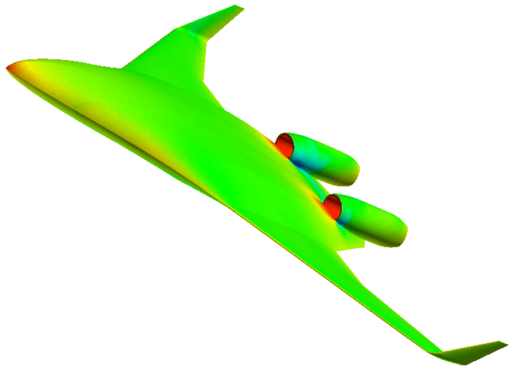


**Figure 9**. Surface pressure distribution on a medium size BWB airplane

The vertical tails are placed in the wing tip, which also has a function as winglets. Figure 9 shows the flow for the complete configurations, which is analyzed using Euler solver on unstructured grid.

## 4.4 Takeoff Field Length

Initial analysis of the required takeoff field length is performed using a method described in reference [2]. Results of the computation are shown in figure 10, which show the required maximum lift coefficient versus the desired takeoff length for different values of takeoff weight. In the calculation it is assumed that the value of thrust to weight ratio is 0.3.

The maximum takeoff weight is estimated using a method described in reference [11]. The estimation is based on the payload and flight range. For comparison, the takeoff filed length of an Airbus A321-200 with maximum T/O weight of 89000 kg is 2300 m. Thus for the designed BWB configuration, if the desired takeoff distance for example 1800 m then the required maximum lift coefficient is about 1.3. This amount of lift coefficient might be achieved by simple high lift device because of its larger wing area.

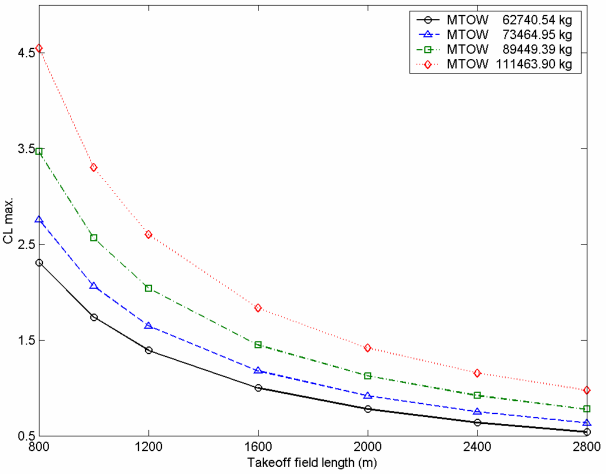


**Figure 10.** The required $C_{L_{\max}}$ vs. takeoff field length

## 5 Concluding Remarks

Aerodynamic design of a BWB airplane for up to 224 passengers has been performed using inverse design method. The present results do not represent the absolute performance of the designed airplane, however the results are encouraging. The combination of Takanashi's inverse design method, constrained target pressure specification technique and RAPID method provide a useful design system for BWB configuration airplane. The RAPID method forms a good tool for generating wing surface. It has more flexibility to create transition from one boundary to the other boundary. Constrained target pressure specification technique as proposed by Campbell is very useful to be used in the inverse design process, which works well together with Takanashi's inverse method.

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