**TECHFEST XX** **Paper 21**

# Incorporating Biplane Wing Theory into a Large, Subsonic, All-Cargo Transport

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A report prepared for the University Space Research Association, in Cooperation with the NASA Langley Research Center

July 1993

## 1.0 Abstract

If the air-cargo market increases at the pace predicted, a new conceptual aircraft will be demanded to meet the needs of the air-cargo industry. Furthermore, it has been found that not only should this aircraft be optimized to carry the inter-modal containers used by the current shipping industry, but also able to operate at existing airports. The best solution to these problems was found to be a configuration incorporating a bi-wing planform, which has resulted in significant improvements over the monoplane in Lift/Drag, weight reduction, and span reduction. The future of the air-cargo market, biplane theory, biplane wind tunnel tests, and a comparison of the aerodynamic characteristics of the biplane and monoplane are all discussed. The factors pertaining to a biplane cargo transport are then examined, with the biplane geometric parameters then resulting.

Nomenclature

$C_D$ = Coefficient of Drag

$C_L$ = Coefficient of Lift

$C_M$ = Pitching Moment Coefficient

C.P. = Center of Pressure

D = Drag

$D_i$ = Induced Drag

L = Lift

q = Dynamic Pressure

O = Origin

W = Downwash

V = Free-stream Velocity

$\alpha$ = Angle of Attack

$\rho$ = Fluid Density

## 2.0 Introduction and Objectives

### 2.1 The Air-Cargo Industry

Over the past forty years, the demand to ship goods by air has increased steadily, creating a period of uninterrupted growth in the air cargo market. There have been numerous studies on the history of this growth, as well as predictions of how this industry will behave in the future. They all agree, however, on one point: The air cargo industry will continue to increase at a significant rate well into the next century.

### 2.1.1 Past, Present, and Future

Air cargo is measured mainly in two ways: Ton Kilometers Transported (TKT's), or Revenue Ton Kilometers (RTK's). From 1955 to 1985, the TKT's carried by cargo aircraft increased from a mere 1,320 to almost 40,000 [1]. Furthermore, air cargo increased from 3.7 billion RTK's in 1960 to over 50 billion in 1985 [2]. This reference also indicates a prediction of over 120 billion RTK's by the year 2000, determined by a predicted average annual growth percentage of 5.7%. Similar studies done during this period also show the increasing trend of the air cargo industry. Reference 4 indicates a similar trend by a more recent forecast, showing a 6.3% average annual growth to the year 2000. Reference 6 gives the most current data on the trend of the air cargo market, showing a 5.5% increase between March of 1992 and 1993 alone.

The 1986 and 1991 forecasts break down the trend into regions of the world, indicating that the Asian/Pacific region will increase the greatest by the year 2000. This correlates with the earlier predictions given above, showing a greater increase in the future foreign air freight market as well. Furthermore, international air cargo growth is expected to increase at a greater rate than domestic shipments throughout this forecast period [5].

The resulting average annual growth rates to the turn of the century are 8.6% for the U.S. and 12% for the foreign air cargo market. As a whole, these studies show a past increase of between 41% and 150% per each five year period to 1988 [1], and by the turn of the century, the global air cargo industry will have more than doubled, with a fourfold increase in the air express sector alone [5].

So what are the reasons behind this expanded growth of an industry that began with delivery of mail over 75 years ago? There are as many different suggestions as to the answer of this question as there are studies that have been conducted on the future of air cargo. Perhaps Stuart Iddles of Airbus Industries came up with the best answer:

> "Packages may not be as glamorous as people, but they take up less room, need no feeding and little heating, and don't kick up a fuss if things don't go exactly as scheduled"[3]

It may not be as simple as this, but nonetheless, the air cargo industry does indeed seem to hold a bright and promising future.

### 2.1.2 The Problem

Currently, it is not uncommon for international carriers to have 20% to 30% share of their total revenue due to air cargo [2,7]; however, most of these carriers are not dedicated all cargo aircraft companies. Either the combi-type aircraft is being used, combining a passenger and cargo area, or the holding bay space underneath the all-passenger aircraft is being used. Keeping this in mind, along with outcome of the studies indicated above, we come to the most significant fact of the air cargo industry today: *Air cargo makes up less than one percent of the world's total transported cargo [4].* Considering that air cargo already accounts for one-fourth of the total revenues of international carriers who, for the most part, are not even using all-cargo aircraft, an enormous potential market growth can be seen by the air cargo industry.

If, however, the air cargo industry is to flourish as predicted, there are several factors that must be taken into consideration. The most important of these are:[9]

- Terminal Congestion
- Noise Constraints
- Lack of Appropriate Aircraft
- Regulatory Impediments

Only the first three will be considered in this study, in which possible solutions will be discussed to curtail these problems. The last factor is controlled by the government of the country that the aircraft is arriving or departing from, and pertains mostly to the custom laws enforced by that country.

### 2.1.3 The Solution

Although the global cargo market is dominated by shipping, rail, and trucking industries, the air cargo industry must break into this market if it is to see such a large total increase in its market share as predicted. Currently, most of the cargo carried by ships, trains, and trucks is transported in universal "inter-modal" containers. However, very few of the existing aircraft used in the air cargo industry can accommodate these containers. Instead, these aircraft use containers developed exclusively to fit the cargo bay of the aircraft. It has been found that, if an aircraft is developed which could transport the common inter-modal containers efficiently, the air cargo industry could capture a significant share of the global cargo market and economically justify the production of a new all cargo aircraft[4].

The inter-modal containers are not the only factor affecting the need for a new all-cargo aircraft. The combi-type aircraft, for instance, is very profitable and seems to handle the current market demand for freight quite well. If the forecasts mentioned before are accurate, however, the freight traffic will grow at a faster rate than passenger traffic, upsetting the balance between passengers and cargo which makes the combi-type aircraft profitable [8]. This imbalance will also create the need for an all-cargo aircraft.

The next factor that justifies the need for a new all-cargo design is that of derivative aircraft. Currently, the Boeing 747-400 can be converted into an all-cargo format, capable of carrying up to 13 inter-modal containers plus 30 lower lobe containers on the lower deck [4]. However, this airplane does not optimize its cargo capacity, and can operate at few existing airports. Therefore, without optimizing cargo space, and considering the great increase in the volume of shipments in the future, one study found that:

> "....the need for a new and replacement aircraft will impose a demand on the airplane manufacturers for new, modern, efficient cargo airplanes."[2]

Conceptual designs of aircraft capable of carrying these containers have been developed, such as the spanloader, the flatbed, the twin fuselage, and the Wing In Ground effect (WIG) aircraft. Developing an aircraft to carry these containers, however, will not in itself justify the time, effort, or cost incurred in the R & D process. These conceptual aircraft are very large, very heavy, and are designed to carry a very large and heavy payload (up to 1,000,000 pounds). Realizing that one of the most important aspects affecting the air cargo industry is the integration of the aircraft and airport operations, these advanced conceptual designs will incur numerous problems trying to meet the size and weight constraints imposed by these existing airports. The two most obvious solutions to this problem are to increase the size of the airport or decrease the size of the aircraft.

In a study done by the International Industry Working Group (IIWG), including responses from airports as well as industry, the conclusion was that:

> "Since adding or replacing aircraft is technically as well as politically much easier than building new airports or runways, the aviation industry will sooner or later react accordingly..."[10]

It is therefore evident that, for the air cargo industry to succeed, a new conceptual design of aircraft must be pursued. Furthermore, it has been found that for a new all-cargo aircraft to be economically feasible to a manufacturer, the aircraft must not only be designed to carry the inter-modal containers currently used by the vessels that dominate the global cargo market, but also must be able to accommodate the requirements of the airport. With the advent of a new, dedicated all-cargo aircraft, not only would the lack of appropriate aircraft problem be solved, but the noise constraints and terminal congestion factors could also be resolved, creating the perfect "All-Cargo Aircraft." With the increasing air cargo market and careful consideration of the problems outlined above, the concept of a large, subsonic, cargo transport aircraft incorporating a bi-plane wing configuration seems to offer the best advantages and alternatives to today's all-cargo conceptual designs.

## 2.2 The Biplane

### 2.2.1 History

With the beginning of powered flight, so came the concept of the biplane configuration. In 1903, the Wright brothers found the high lift and structural rigidity of the biplane to be the answer to putting man in the air. The development and improvement of the biplane continued from that moment on. The designers of early aviation used this configuration mainly because of the large engine weight, which required a large wing area that could be accounted for without increasing the wing span. Furthermore, the structural integrity of the biplane was much higher than the monoplane due to the wing trusses, giving rise to fewer structural failures. Finally, at the low speeds being flown, a high degree of maneuverability was realized with this configuration due to an increased roll response.

### 2.2.2 Discontinuation of Study

As structural materials and technology improved, support in the aviation community for the biplane began to taper off. Engine weight reduction, higher flight speeds, and an abundance of ground area for span were all significant factors that contributed to the decision of aircraft designers to switch from a biplane to monoplane planform. Furthermore, because fuel was in abundance during this time, achieving maximum fuel efficiency was not given a high priority. For these reasons, the biplane had a short-lived existence in the time of early aviation.

### 2.2.3 Why the Biplane?

If the market forecasts are accurate, a new, large cargo transport will be in demand by the cargo industry. Furthermore, rising airport congestion is leading to the need for an aircraft with a shorter wing span and smaller landing gear loads due to runway weight problems. This investigation is to determine if a biplane wing configuration is a beneficial solution to the needs of the future cargo industry.

One of the factors that must be considered when determining the advantages of the biplane is the aircraft speed. Because of the high interference and parasite drag on a biplane, high subsonic or supersonic speeds will cause the drag to increase dramatically, canceling any benefit the configuration might have gained.[1]

Taking into consideration that the biplane is being incorporated into an all-cargo transport, it has been found that *91% of all elapsed time in air cargo transportation is spent on the ground*[12]. To put it another way, if every air cargo plane currently in domestic operation could go supersonic at 1200 mph, the net improvement would amount to only 4.5%[12]. This small increase in air cargo efficiency does not seem to justify the problems encountered with the aerodynamics of supersonic flow. Therefore, only subsonic flight characteristics of about 400 knots are examined in this study.

### 2.2.4 Advanced Biplane Concepts and Their Problems

As the desire for large aircraft developed, the biplane found its way back onto the designer's drawing board. During the 1930's, a very large transport biplane was developed by Handley Page. This aircraft, the HP 42, became one of the most luxurious and safe passenger aircraft in history: not one death in ten years of operation over 2.3 million fleet miles[13]. Other aircraft companies during this period time followed similar trends using the biplane configuration for large aircraft, such as the Short Singapore and Sarafand.

Nearly three decades after the advent of these large aircraft, studies on the standard biplane configuration ceased. The monoplane became the standard at the outbreak of WWII as man pursued the interests of supersonic flight. Over the past twenty years, however, renewed interest in the biplane has stimulated two new conceptual designs incorporating the biplane configuration.

In 1974 a study was done by Lockheed on a transonic biplane concept using an aft-mounted forward-swept wing. Unfortunately, this concept encountered numerous problems with its aeroelastic stability. Flutter speeds as low as 240 knots were encountered, which are much lower than the required 524 knots considered to be within safety margins. Although research has been done on flutter analysis, it is still a misleading and frustrating problem, and more than likely was the critical factor in the decision to halt further research on this design[14].

About ten years later, Julian Wolkovitch began research on a concept called the joined wing. Similar to a biplane, the

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[1] There have been studies on a supersonic biplane configuration, namely the "Buseman" biplane, but results showed that, for supersonic flow from M=1.2 to M=4.0, the monoplane would always be more aerodynamically efficient [11].

swept forward aft wings are at a large negative dihedral angle, joining the aft wing to the wing tips of the aft-swept forward wing. Although this concept seems to show some advantages, it is still an unproven and untested design. There have been problems with landing gear placement, and no extensive aeroelastic analysis has been performed, which would seem to be a very probable area of trouble[15].

Even though the joined wing concept continues to be studied, there has been no research on the "standard" biplane since the beginning of WWII. Therefore, most of the theory and studies that are given in this paper are from the early aviation pioneers. These early studies, however, are no more or less accurate than the studies of today, and contribute prudent information to the theory of biplanes.

## 2.3 Emphasis of Consideration

There are three basic factors considered in this study that would seem to make a biplane configuration feasible:

- Lift/Drag Ratio
- Gross Take-off Weight
- Wingspan

If any of these factors can be improved, it would seem beneficial to investigate this concept further.

### 2.3.1 Lift/Drag

With a biplane, the zero lift drag will increase due to the friction drag on the struts and an overall increase in wetted area. There will, however, be a decrease in the total induced drag of the biplane, due to the interference effects in the circulatory flow around the wings, possibly creating an overall increase in the Lift/Drag ratio. The focus of this report will fall mainly in this area, for an increase in L/D could result in greater efficiency, longer range, and the possibility of a greater total payload.

### 2.3.2 Gross Take-off Weight

As the weight of an aircraft increases, so does its fuel requirement, runway take-off length, and point loads on the aircraft's landing gear. AS conceptual aircraft become larger and larger runway weight restrictions become an important factor to the designer. With a biplane, wing thickness and/or wing chord reduction could reduce the overall weight of the wing system by as much as 60%, yet still retain the lift characteristics of the heavier winged monoplane[18]. Although the weight is being analyzed separately, the GTOW has an indirect effect on the L/D and should thus be considered in the analysis of the L/D of a biplane.

### 2.3.3 Span

The final advantage of the biplane configuration is the reduction in wingspan. As the congestion at airports increases due to the large span of new aircraft, a reduction in wingspan could produce more benefits than just an increase in L/D. A brief comparison of the biplane and monoplane at the end of this report will make evident the advantages of the biplane, and will further be incorporated into an analysis of the biplane and airport operations.

## 3.0 Biplane Theory

In July and August of 1920, L. Prandtl published his famous papers on the theory of lift[16]. Two years later, Max Munk published General Biplane Theory[17], incorporating Prandtl's ideas and his own on the interaction of two lifting surfaces. Many of these early concepts are still used today in the teachings of aeronautics.

Munk identified five main geometrical variables in the analysis of the biplane. These are:

- Decalage
- Stagger
- Gap
- Aspect Ratio
- Chord

Since then, studies have been done on the effect of sweep, dihedral, overhang, and winglets on the aerodynamic efficiency of the biplane.

In this section, research will be done on theories relating these nine different geometrical constraints to their effect on lift, drag and pitching moment of the biplane. They will later be compared to the aerodynamic characteristics of the monoplane.

The terms will be defined as[20]:

Aspect Ratio (A) - The ratio of the square of the maximum span (b) to the total area (S) of a particular wing planform. On a biplane, there may be a different aspect ratio for each respective wing[19].

Chord (c) - Datum line joining the leading and trailing edges of the airfoil, and taken to be the mean geometric chord if taper is employed[19].

Gap (G) - The distance between the planes of the chords of any to adjacent wings, measured along a line perpendicular to the chord of the upper wing at any designated point of its leading edge (Figure 1),[20].

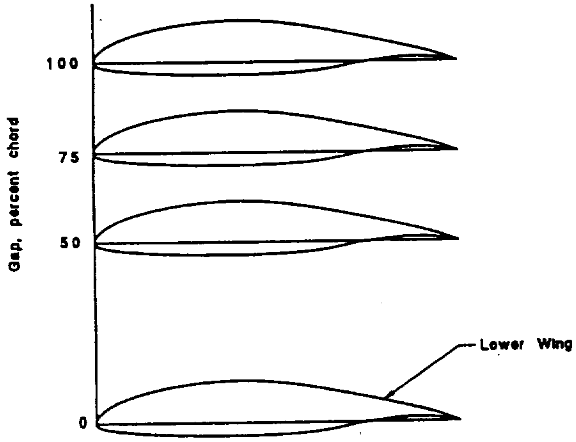

Figure 1. The Gap of a Biplane

Stagger (St) - The amount of advance of the leading edge of the upper wing of a biplane, triplane, or multiplane over that of the lower, expressed either as a percentage of gap or in degrees of the angle whose tangent is the percentage just referred to. It is considered positive when the upper wing is forward and is measured from the leading edge of the upper wing along its chord to the point of intersection of this chord with a line drawn upward and perpendicular to the chord of the wing upper wing at the leading edge of the lower wing, all lines being drawn in a plane parallel to the plane of symmetry (Figure 2),[20].

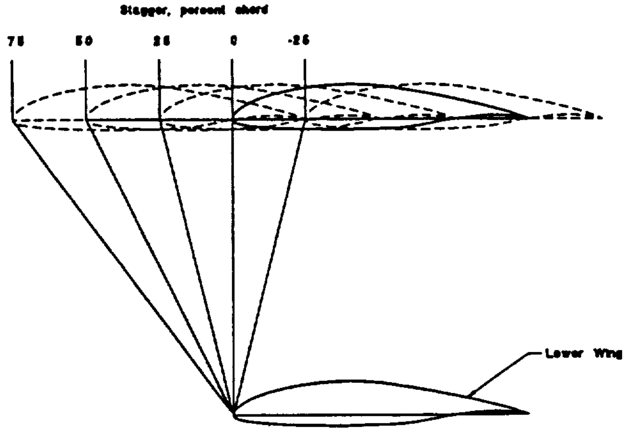

Figure 2. The Stagger of a Biplane

Decalage - The acute angle between the wing chords of a biplane or multiplane[20]. Usually considered positive when the lower wing is at a lower incidence angle than the upper wing (Figure 3).

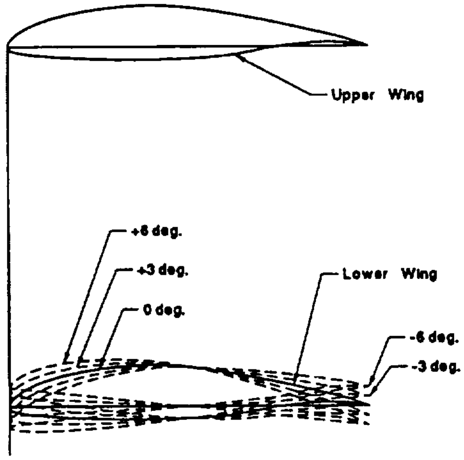

Figure 3. The Decalage of a Biplane

Sweepback - A wing design in which the leading edge (and sometimes the trailing edge) slope in planform is such that the wing tips are further aft than the wing root [19].

Dihedral Angle - The acute angle between the horizontal plane and the plane of the chords of the wing.

Overhang - The ratio of the difference in span of the lower wing to the upper wing of a biplane [20].

## 3.1 Early Research

### 3.1.1 Early Theory

The drag of an aircraft can be broken down into two main parts: Parasite drag (or zero lift drag), and induced drag (or drag due to lift). Because of the biplane lift interference effects, Munk studied the induced drag of a biplane due to the interference of one wing on the other. These studies led to three main conclusive theories[21]:

1. The total induced drag of any multiplane lifting system is unaltered if any of the lifting elements are moved in the direction of the motion provided that the attitude of the elements is adjusted to maintain the same lift distribution of lift among them [18].
2. In calculating the total induced drag of a lifting system, once all the forces have been concentrated into the O,Y,Z plane, one may, instead of using the actual values of the velocity normal to the lifting elements [$V_n(x,y,z)$] at the original points of application of the forces, use one-half of the limiting value of the normal velocity [$V_n(\infty,y,z)$] for the corresponding values at points P(O,Y,Z), (Figure 4), [18].
3. When all the elements of a lifting system have been translated longitudinally to a single plane, the induced drag will be a minimum when the component of the induced velocity normal to the lifting element at each point is proportional to the cosine of the angle of inclination of the lifting element at that point [18].

The first theorem is known as "Munk's Stagger Theorem", and basically states three important results[18]:

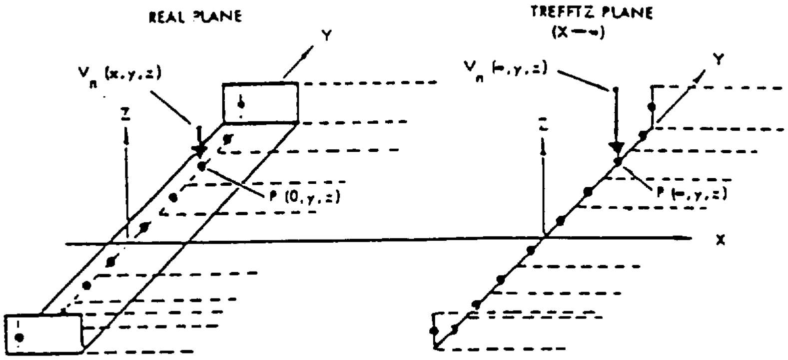

Figure 4. Munk's Second Theorem
(Copied from Reference 18)

- If constant section lift is maintained, the chordwise pressure distribution does not affect the induced drag.
- If the spanwise lift distribution is constant, there will be no effect on the induced drag from a change in biplane stagger or wing sweep.
- The sum of all the lifting surfaces, if projected in the Y-Z plane, can be made equivalent to a single lifting element, enabling easier calculation of the induced drag.

The second theorem allows calculations to be done in a plane infinitely far downstream, greatly simplifying the calculations necessary to determine the induced drag in the real plane[18].

The third theorem states that, for a minimum induced drag, the downwash across the span must be constant, and the sidewash must be zero[18].

Furthermore, Munk stated that if the two wings of the biplane are parallel and unstaggered, the downwash of each wing induced by the other wing is equal.

Prandtl, then collaborating with Munk on biplane theory, reaffirmed Munk's stagger theorem by stating that the sum of the induced downwash between the two wings will remain constant, given any longitudinal change in geometry, and at angles of attack such that the lift is constant.

Munk then concludes with a formula for determining the induced drag coefficient of a biplane compared to that of a monoplane, where $C_{d1}$ and $C_l$ are the induced drag and lift coefficients of the monoplane, respectively. The subscripts denote terms relating to the monoplane and biplane, and k denotes the "equivalent monoplane span" factor[21]:

$$C_{d2} = C_{d1} - C_l^2/\pi \, [\, (S_1/b_1^2 k_1^2) - (S_2/b_2^2 k_2^2)]$$

This equation basically states that, at the same lift coefficient, *the induced drag of a biplane will be smaller than that of a monoplane with the same span.*

Munk then found that, due to induction and interference between the upper and lower wing sections, a biplane will experience an induced angle of attack, causing a greater angle of attack than that of a monoplane with the same lift coefficient.

For the same reasons of induction and interference, Munk concluded that the shift in the center of pressure due to a change in the lift coefficient for the monoplane and the biplane were about the same, and when the shift is due to a change in the angle of attack, the CP travels an even smaller distance. Even though the difference in travel of the center of pressure between the two configurations is small, the biplane chord is only about half the length of a monoplane chord having the same airfoil section and lift, thus experiencing only about half the overall CP travel compared to the monoplane. This fact proves very advantageous in determining the stability characteristics of the biplane[21].

Although these early theories are very important, they lacked experimental confirmation of their accuracy and did not take into account the effect of streamline curvature, non-elliptical lift distribution, or any geometrical variables save stagger. For these reasons, some discrepancy between the theories and actual biplane performance were encountered. This led to experimental tests of biplane aerodynamic characteristics to be conducted at a more rapid pace.

### 3.1.2 Early Experiments

Soon after Munk's biplane theories were published, J.C. Hunsaker performed an experimental analysis on the inherent longitudinal stability of a "typical" biplane. The aircraft he tested did not vary any geometric parameters, only the aircraft angle of attack was varied to determine the lift, drag, and pitching moment characteristics and their effect on the stability of the aircraft. Using Routh's discriminant to determine the dynamic longitudinal stability, his results showed that the biplane was an inherently unstable aircraft configuration at low speeds and high angles of attack.[23].

In 1918, F.H. Norton conducted an investigation similar to Hunsaker's work utilizing a three-dimensional, non-symmetric biplane model to determine the effects of staggering the wings. All other variables held constant, Norton found that the maximum efficiency and lift are achieved at the highest degree of stagger possible. Furthermore, the travel of the CP was greatly reduced with large positive stagger, which could ease in solving the dynamic stability problem[24].

H. Glauert of the Royal Aircraft Establishment then incorporated a new variable into the Munk's angle of incidence formula to include an improved method of determining the effect of streamline curvature[25]. His results showed accurate correlation with experiment for positive stagger but did not give good results at negative stagger.

## 3.2 Continued Investigations

### 3.2.1 Wind Tunnel Testing

As flight research and the biplane became more popular, studies became more prominent throughout the United States and Europe. New concepts had been formulated, old ones improved, and many experimental tests had begun.

In 1927, R.M. Mock conducted wind tunnel tests to determine the effect of decalage angle on the distribution of loads between the wings of a biplane[26]. The results obtained using the vortex "lifting line" theory did not correlate at all with the experimental results he obtained. His conclusion was that due to the Venturi effect created by the wings at a positive decalage angle, the flow circulation around the upper wing is reduced while being increased around the lower wing. As the decalage angel increases, so does the Venturi effect, thus reducing the interference of the upper wing on the lower. This explains the reversed order of magnitudes between Mock's theories and experimental results.

In 1929, a series of papers were written by Montogomery Knight and Richard Noyes [27.28,29]. They conducted wind tunnel tests on three dimensional non-symmetrical biplane airfoils while varying the gap, stagger, decalage, dihedral, sweepback, overhang, and combinations thereof. Many useful results were obtained, some of which are as follows:

1. Increasing the gap or stagger in the positive direction tends to equalize the loads on the two wings, and also increases the maximum total lift coefficient of the biplane cellule.
2. An increasing gap or lower sweep tends to decrease the travel of the center of pressure.
3. The deviation of decalage angle from zero tends to decrease the maximum lift coefficient when there is zero stagger (due mainly to the earlier explained Venturi effect studied by Mock).
4. With positive stagger, increasing the decalage angle tends to increase the maximum lift coefficient.

The last of these results may cause some confusion, but the reasoning is relatively straight-forward. To reach the maximum lift possible, the two wings of the biplane must stall at the same time. For this to occur, the wings must also be at the same effective angle of attack. When the wings are at positive stagger, there is an increased amount of downwash imposed by the upper wing onto the lower wing, causing a reduced effective angle of attack on the lower wing. Therefore, for the effective angles of attack to be equal, and hence stall at the same time, the lower wing's angle of incidence must be increased, creating a negative angle of decalage in the biplane wing configuration.

These tests were all conducted at a low Reynold's number of 150,000, so the validity of these results are not absolute. Even so, the relative changes produced by altering these variables will more than likely show the same trends at higher Reynold's numbers.

Max Munk, still very interested in biplane theory, was influenced by the Bureau of Aeronautics of the Navy to conduct a series of tests on biplane and triplane models[30]. These tests were to determine the lift, drag, and pitching moment for different airfoils, systematically varying the gap and stagger, and then to compare the results with the Army standards. The results of these tests were very interesting:

1. There was a general tendency of the upper wing to contribute more of the lift than the lower at positive stagger and less at negative stagger.
2. The gap/chord ratio had little affect in the relative lifts on the wings at thigh lift coefficients, but significant affects at low lift coefficients.
3. An increase in gap tends to equalize the lift of the wings over a wide range of angles of attack.
4. The gap/chord ratio had little affect on the positions of the centers of pressures of the individual wings.
5. With an increase in positive stagger, the centers of pressure moved forward on the upper wing and aft on the lower wing, lying nearly together at zero stagger.

These results are very similar to the previous studies by Knight and Noyes, and would seem to verify the accuracy of both tests. Furthermore, Munk used two different airfoils, the RAF-15 and the USATS-5, to ensure that his own tests would give accurate results.

Following Munk in 1936, M. Nenadovitch used two-dimensional symmetrical biplane airfoils to conduct experimental research on the aerodynamic characteristics of the biplane, while altering an array of geometric parameters. His results showed that at a gap of one chord length, a stagger of one chord length, and a decalage angle of negative six degrees, the induced drag of a biplane is minimized[32].

### 3.2.2 New Theories

While these extensive experimental tests were being performed, a few new theories on the biplane and its interference characteristics had been developed.

In 1930, Clark B. Millikan adopted a theory from Dr. Theodore Von Karmen known as "Thin Airfoil Theory." In his paper, Millikan presented and used Von Karmen's theory to develop a procedure for determining the characteristics of the individual wings of an arbitrary biplane configuration without sweepback or dihedral[33]. Although this process showed great success over current theories when compared with experimental data (at gap/chord ratios greater than 3/4), the procedure was very tedious and cumbersome, and was therefore rarely incorporated into use by the designers of that day.

In 1933 and 1934, Walter S. Diehl published two reports on biplane theory. His first paper combined experimental and theoretical data by Fuchs and Hopf[36] to obtain a series of curves from which the lift curves of the individual wings could be found[37]. Diehl's second paper extended his own theory to include the effect of having a difference in chord length between the two wings of the biplane[17]. His results showed promise, but even Diehl agreed that:

> "Millikan's treatment of the biplane theory....appear to give somewhat better agreement with test data....but it is very difficult for an engineer to follow the steps required in a typical calculation."[31]

Although Millikan's method is cumbersome if done by hand, this author decided it worth while to write a FORTRAN computer program using Millikan's formulations and procedures. Because of time constraints, the validity of this program was only proven when testing it with Millikan's own input data. In this case, however, the program gave the same results as Millikan's hand calculations, and proved to be a valid way of determining the aerodynamic characteristics of the biplane fairly easily. This program is available to anyone interested by contacting me directly.

### 3.2.3 The Resulting Theories

(Due to lack of space, this section has been omitted. Extensive presentation of the current equations for the induced drag, the induced angle of attack, and the pitching moment coefficient are all presented. The effect of streamline curvature of a biplane is examined, with the resulting conclusion that *the best possible biplane of limited span has an induced drag smaller than that of a monoplane of the same span.*)

## 4.0 Comparison of Monoplane and Biplane Results

In all of the studies aforementioned, the only comparison of biplane and monoplane performance characteristics was theoretical. Actual experimental testing of the biplane compared to the monoplane had not been done, but in July of 1974, E. Carl Olson wrote his M.S. on the improved aerodynamic characteristics of a biplane over that of a monoplane by comparing experimental data[39].

Olson's experiments consisted of a three-dimensional non-symmetrical airfoil biplane configuration, and incorporated the results of the earlier mentioned Nenadovitch by varying the geometry about his optimum point: a gap of one chord length, a stagger of one chord length, and a decalage angle of negative six degrees. Furthermore, Olson also tested a monoplane system using the same area and similar aspect ratios of the biplane configuration. His tests were also conducted with and without a fuselage. The results obtained are probably the most significant to date.

In the first phase of testing, Mr. Olson concluded that the best range of decalage angles to continue testing at were between -5 and -7 degrees, due to the high L/D and low $C_D$ at these angles. Therefore, the remainder of his testing occurred between these angles.

In the second phase of his testing, a fuselage was incorporated onto the configuration. In these tests, gap, stagger, and decalage angle were all varied, and then the results of the biplane and monoplane configurations were compared and plotted against each other. There were many important conclusions obtained:

1. A substantial $C_D$ reduction with respect to the monoplane over a wide range of angles of attack was obtained for most biplane configurations, the most efficient showing a 25% decrease in the $C_D$ over the monoplane in a typical cruise condition.
2. A significant L/D ratio increase for the biplane configuration was obtained over a wide range of lift conditions with respect to the monoplane. The largest increase was 31.2% at the maximum L/D, with the $C_D$ being 21.4% lower than the monoplane at a $C_L$ of 0.175.
3. The endurance of the biplane would be increased over a wide range of $C_L$ over that of the monoplane due to the $L_{3/2}$/D curve.
4. While creating higher interference drag, the biplane realized a substantial increase in efficiency over the monoplane due to a decreased induced drag and/or altered pressure distribution over the wings, creating an overall reduction in the total drag.
5. The most efficient overall biplane configuration increased L/D by 16.3%, reduced the $C_D$ by 14.3% (at a $C_L$ of 0.175), but had a 10.6% decrease in $C_{Lmax}$ compared to the monoplane.
6. Decreasing decalage towards -5 degrees decreased $C_D$ and increased L/D.
7. Increasing stagger tended to decrease the overall $C_D$.
8. Pitching moment characteristics of the biplane system were markedly improved over the monoplane system, (a more negative moment curve slope).

Throughout all of the experimental testing and theoretical evaluations in the past, along with the recent studies done by Gall and Olson, it is evident that a biplane wing configuration can hold many aerodynamic advantages over that of the monoplane. It has also been shown that the rising demand for air cargo warrants the need for a new conceptual all-cargo aircraft. Combining these two factors, a large, subsonic, all-cargo transport incorporating a biplane wing configuration seems to offer the best advantages and a most promising future compared with current conceptual designs.

# 5.0 Application of the Biplane onto a Cargo Transport

## 5.1 Existing Airports

As new aircraft conceptual designs get larger, airport restrictions become one of the most important factors in the preliminary design stage. Recently, the FAA initiated a National Plan of Integrated Airport Systems (NPIAS) to determine the needs of the airports with the expected arrival of New Large Aircraft (NLA)[40]. This study determined the type and area of the airport where the development costs will be needed most. However, even if the funds can be appropriated, it can be shown that an aircraft designed to operate within existing airport requirements would hold a significant advantage over any that can operate at only a few modified airports. For these reasons, the all-cargo biplane configuration should take into consideration the following criteria.

### 5.1.1 Weight Constraints

The International Industry Working Group's New Large Aircraft Study Group had identified three main factors limiting the weight of new large aircraft over 0.9 million pounds. These are runway capacity, bearing strength, and pavement loading[10].

The runway capacity is indirectly related to the weight of an aircraft through wake vortices. As weight increases, so does the wake vortex behind it, hence increasing the longitudinal separation required between the aircraft on final approach and departure routes. At major hub airports, the loss of each slot in a peak hour of operation would offset any advantage that a new cargo transport might contribute.

The bearing strength (or "airplane bridge strength"), becomes a severe problem only at a few airports where limits are set at 400 tons. Alternate runways at these airports are also available to which heavy aircraft could be re-routed, thus making this factor seemingly insignificant.

The pavement loading factor is probably the most important. As aircraft weight increases, the number of main gear wheels must be increased to distribute the point loads on each landing gear bogey. Not only does this increase the weight of the airplane, but the placement of additional landing gear can also prove to be a very frustrating problem.

However, the current method of determining pavement loads and runway lifetime is outdated, and to some experts considered inaccurate. For this reason, a new "slope method" is being considered, which is based on pavement subgrade deflection slope rather than vertical deflection. Studies show that the current large aircraft conceptual designs, even using the new "slope" method, would not meet the load criteria to satisfy safety requirements.

Because of added lifting surface on a biplane, the wing thickness and chord can be reduced to give an overall reduction of up to 60% in the wing weight[18]. This fact would help to bring the total gross weight of the aircraft down, possibly below the 0.9 million pounds used in this study, therefore avoiding these limiting factors.

One other factor indirectly affected by aircraft weight is aircraft noise constraints. The FAR noise regulation PART 36 state 3 shows that constant independent levels of MTOW for large aircraft over a certain weight (four or more engines)[41]:

**Table 1.** FAR PART 36

| Condition | MTOW | EPNdB |
|---|---|---|
| Take-off | >385 tons | = 106 |
| Approach | >280 tons | = 105 |
| Sideline | >400 tons | = 103 |

There has also been discussion of a further noise reduction of 3 EPNdB starting in 1995. Airlines and airport operators are also sure that there will not be any exemption from the limits at most of the airports around the world[10]. It is then recommended to take into consideration these aspects when considering the future noise level certification requirements of a large biplane.

### 5.1.2 Length Constraints

The IIWG identified two main problems with aircraft length. The first is the ICAO requirements for fire fighting equipment and extinguishing agents. This requires that for an aircraft to meet its category ten requirements, its length must be between 76 to 90 m (250 to 300 ft) and have an overall diameter no greater than 8 m (26 ft). If the 8' x 8' x 20' containers are to be used, this factor would restrict the placement of the containers, if put into the aircraft in a side-by-side manner, to no more than 14 to remain less than 300 feet long.

The second factor affected by aircraft length is that of taxiing the aircraft. With the cockpit-over-centerline steering method, it has been found that fillets will have to be installed on the taxiways for these large aircraft to have turning capabilities, unless airlines could train oversteer methods as a company standard, or differential GPS could be implemented to give precision ground navigation.

### 5.1.3 Wingspan Constraints

Probably the most significant advantage that the biplane has over the existing conceptual designs is that of a reduced wingspan with no loss in L/D or increase in induced drag. Currently, there are two main restrictions on the span of an aircraft: runway span limit and taxiway clearance limits.

Apart from carrying the wheels, runway pavement width is provided to protect the engine from Foreign Object Ingestion (FOI). Only hard surfaces such as a runway can be kept clean of the debris that might cause engine wear and damage. The current span limit for large aircraft (ICAO CODE E) is 65 m [10]. By the formulations given earlier, it can be found that if a biplane's wingspan was at the 65 m limit (equal chords and a gap/span ratio @ 0.3), the resulting equivalent span of a monoplane having the same induced drag would be over 92 m! To emphasize this point, the current studies on airport integration are trying to accommodate wingspans up to only 85 m by the new large conceptual designs. Not only would this require the shut-down of the airport runway for a lengthy duration, but the cost of replacing all of the airport runways is almost $100 billion. These facts would seem to indicate that it would be much more beneficial to design a biplane with a 65 m wingspan able to operate at existing airports.

There are no requirements stated by the ICAO for the taxiway clearance of aircraft with wing spans exceeding 65 m. However, the FAA did develop airport design guidelines for aircraft with wingspans of 65 m to 80 m, but due to extremely high investment and shortage of land, it is unlikely that any existing airport could adopt these criteria[10].

There has been discussion of preferential routing, but preliminary studies show that there are neither sufficient areas for preferential routing procedures, nor ground movement capacity reserves available on busy airports for this option to be viable[10]. Folding wingtips have also been given some consideration, but structural and mechanical problems may prove to cancel any benefit as well.

### 5.1.4 Gear Width Constraints

Under the international rule of providing 4.5 m clearance between outer main gear wheels and the pavement edge, a 23 m wide taxiway will limit the gear design to a 12 m track. This can be a foreseen problem for very large wingspan airplanes which might require a 16 m track, but for the current 65 m limit, a 12 m wide track seems to be adequate. It is possible that this international rule might be reduced if differential GPS or landing gear-mounted T.V. cameras are implemented to provide more precise ground navigation, but such technology has yet to be made available to the air-cargo industry.

If the conceptual designs currently being investigated are to meet these requirements, the taxiways would have to be increased to 30 m[10]. Udo Wolffram gave the IIWG NLA Group's response to this:

> "Widening more than a thousand miles of taxiway on some hundred airports, however, is a most costly option, applicable to new or extended airports only."[10]

Therefore, it can be seen that if any new large aircraft is developed outside of these airport constraints, only new or modified airports would be able to sustain their operation.

## 5.2 Cargo

Each of the inter-modal containers to be used can each weigh up to 13 tons, depending on the cargo being shipped[4]. Provisions must be made for the structural support for the overall payload capacity of these containers. Lower-lobe containers or a new design of a container to optimize the remaining space in the fuselage of the aircraft could also be implemented, which would increase the aircraft's efficiency and load factor.

Having been shown that the time spent on ground operation is of critical importance, the loading capabilities of this aircraft must also be taken into consideration.

Currently, most cargo loading facilities load cargo in the front of the aircraft through a hinged nose and cockpit. This would seem the most advantageous location for loading, for the inter-modal containers could not be loaded inside doors, and a hinged empennage creates numerous problems with structural stability. Furthermore, wheeled tracks could be fastened to the floor of the loading bay of the aircraft for ease in the loading process.

## 5.3 Vehicle Structure

### 5.3.1 Engine Integration

One of the biggest problems with the design of the biplane has been the placement of the engines. The Handley Page Heracles of the 1930's placed the engines close to the fuselage and into the wing structure. This helped reduce One Engine Inoperable (OEI) problems and structural fatigue. However, a pitching moment was produced if the thrust of the upper engines became more than the lower engines. Because of the low power of these engines, this problem was not as significant at it could have been with the larger engines used today.

The Short Singapore of the same time period incorporated the engines into the wing struts. This would seemingly be the most optimum place for the engine, except for the problem of structural integrity. The study done on the supersonic "Buseman" biplane suggested that placing the engines within the gap would be the most optimum location[11]. Foreign object ingestion could also be minimized with placement of the engines above the lower wing, in effect shielding the engine inlet. The OEI condition must also be taken into account, for placing the engines close to the wingtips could result in the need for an absurdly large vertical tail.

The type and number of engines is another problem that needs to be considered. The GE 90 high-bypass ratio engine is currently being made ready to start flight testing. With a fan diameter of about ten feet and eventual certification of 87,000 pounds of static thrust, this engine could be incorporated into a gap of about 11 feet. At this gap, an approximate chord of the wings would be around twelve feet, which is much less than the 54 foot root chord of the Boeing 747.

### 5.3.2 Landing Gear

As mentioned earlier, the placement of the landing gear on a biplane configuration can present some problems. First of all, the reduction in wing thickness of a biplane not only limits the available fuel volume, but also restricts the available landing gear stowage volume. Because of this, streamlined pods have been considered on some aircraft, such as Lockheed's transonic biplane concept mentioned earlier. Most of the early biplanes used a fixed landing gear, so only these recent studies address the problem of landing gear placement.

### 5.3.3 Hybrid Laminar Flow Technology

Hybrid laminar-flow (HLFC) control consists of a combination of active laminar-flow control (LFC) devices from the leading edge to near the front spar, such as a mesh suction assembly, and passive laminar flow from that point aft[42].

The active control devices use suction to remove the layer of viscous particles that cause the boundary layer to separate. The passive LFC consists of an airfoil shape specifically designed with a farther aft maximum thickness point, decreasing the downstream pressure to maintain the laminar boundary layer.

Because of the improved roll response of a biplane, less wing area can be allotted to the control surfaces, allowing for application of either high lift devices or increased suction area over the chord of the airfoil. With the implementation of such devises, the induced drag could be reduced even further, hence only improving the biplane's advantages over the monoplane.

## 6.0 Conclusions

1. As the air-cargo industry market makes up less than one percent of the total global cargo market, forecasts have shown that the air-cargo industry will continue to increase at a significant rate well into the next century.
2. If the air-cargo industry is to realize such a large growth, a new aircraft must be developed capable of transporting efficiently the inter-modal containers currently used by the shipping, rail, and trucking industries that dominate global cargo transportation, and must also be able to operate within the required constraints of existing airports.
3. A subsonic biplane could be a feasible option due to the fact that 91% of all elapsed time in air cargo transportation is being spent in ground operations. This offsets the advantage a supersonic configuration might contribute and allows for a subsonic configuration to be an option.
4. Theoretical and experimental results agree that the induced drag of a biplane will be smaller than that of a monoplane with the same span.
5. Due to induction and interference between the upper and lower wing sections, the biplane will experience an induced angle of attack and a smaller overall shift in the center of pressure when compared to a monoplane.
6. The use of winglets on an already efficient biplane could further decrease its induced drag
7. The L/D ratio of an efficient biplane will be greater than that of a monoplane with the same wingspan.
8. A 60% wing weight reduction can be realized when compared to the wing weight of the monoplane.
9. The structural integrity of strut-mounted engines needs to be examined in detail, for placement of the engines elsewhere could decrease the biplane's aerodynamic advantages.
10. Due to the improved roll response of the biplane, less wing area is required for control surfaces, hence enabling the use of hybrid laminar flow technology to further decrease the induced drag of the aircraft.

With these conclusions, it is evident that the need of a new all-cargo aircraft capable of carrying inter-modal containers and able to operate at existing airports will be demanded by the air-cargo industry. Furthermore, a biplane wing configuration has been shown to be aerodynamically, as well as structurally, superior to the monoplane at subsonic flight speeds at its most efficient geometric configuration. Therefore, the investigation of a subsonic all-cargo transport biplane should be studied in greater detail.

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End Date
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June 9, 1995