Experimental Determination of Improved Aerodynamic Characteristics Utilizing Biplane Wing Configurations

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Improving the aerodynamic characteristics of an aircraft with respect to a higher lift coefficient C_L, a lower drag coefficient C_D, and a higher lift over drag L/D, as a function of angle of attack will make it more efficient, thus conserving energy and/or improving performance. Investigations were carried out to determine if the aerodynamic characteristics of biplane wing systems could be made more efficient for low subsonic speeds than those of a monoplane of comparable area and similar aspect ratio. A variable position three-dimensional biplane wing system and a fuselage that could be fitted with a monoplane wing or the variable position biplane wing system were tested in the University of Missouri-Rolla subsonic wind tunnel at a Reynolds number of 8.7×10^5/ft. Lift, drag, and pitching moment characteristics of each configuration were investigated to determine the effect of changing the position of the biplane wings relative to each other and how the characteristics compared with those of the monoplane. All the biplane wings tested were shown to have a significant decrease in C_D over a wide range of angles of attack, a significant increase in L/D for a large range of lift conditions, and significant increase in $L^{3/2}/D$ for a large range of lift conditions, all with respect to the monoplane. General trends of C_D and L/D_{max}, and how they vary with the relative position of the biplane wings to one another are presented and compared with the characteristics of the monoplane.

Introduction

WITH the advent of jumbo jets, stretched standard body jets, and general aviation aircraft, the airplane has proved to be a very efficient mover of people from a passenger-seat-miles-per-gallon and travel-time standpoint. For aircraft to continue to hold their position at the forefront of the transportation spectrum, continued improvements in efficiency must be made. This can be done by either reducing the fuel consumption for the same performance and payload capacity, increasing the airplane efficiency and therefore the speed at the same fuel consumption, or by increasing the payload capacity for the same fuel consumption.

These factors can be achieved by improving engine efficiency, reducing structural weight, reducing drag, and increasing lift. Earlier research on a limited basis indicates that proper placement of biplane wings with respect to each other can result in improved aerodynamic characteristics over those of a monoplane of similar lift capability.

Unfortunately, this research was done at a time when the biplane was receiving less support from aircraft designers because of improved structural design techniques. Originally, biplanes and triplanes were built rather than monoplanes because large engine weight necessitated a large wing area that could be accomplished without increasing wing span, increased structural rigidity due to the wing trusses, and a high degree of maneuverability that was desirable at the slower flight speeds. However, as structural materials and methods improved, engine weights were reduced and flight speeds increased and the monoplane was able to meet the aircraft designers requirements. Also, since fuel was inexpensive, little attention was given to achieving maximum efficiency, especially if two wings were involved.

Expensive energy has required the aircraft designer to look at the various factors that will improve aircraft efficiency. Some of these factors are increasing engine efficiency, reducing structural weight, and reducing aerodynamic drag. It is the purpose of this research to study the aerodynamic characteristics of biplane wings in greater detail.

Literature Review

In 1936 Nenadovitch[1] reported on aerodynamic characteristics of two-dimensional biplane configurations. Nenadovitch varied the gap (Ga), the distance one wing is above the other gap distance/chord length, the distance the upper wing is ahead (positive) or behind, (negative) the lower wing measured in distance/chord length, called stagger (St), and decalage angle (De), the angle between the chord lines of the upper and lower wings, where decalage angle is negative when the upper wing is at a lower angle of attack than the lower wing. At a gap of one chord length, a stagger of one chord length, and a decalage angle of −6 deg, Nenadovitch found a substantial reuction in drag due to the biplane configuration. His results were for identical symmetrical airfoils with infinite aspect ratios. His decalage angle variations were ±1, ±3, and 0 deg; his gap variations were ⅓, ½, ⅔, 1, and 3/2 the chord length; and his stagger variations were ±1, ±½, and 0 the chord length, except at a decalage angle of 0 deg, where he also ran staggers of ±¾ and ±¼ the chord length.

Norton,[2] in 1918, conducted some three-dimensional nonsymmetrical biplane airfoil tests. He concluded that maximum aerodynamic efficiency is achieved at the highest possible degree of stagger. His airfoil sections were USA 15 for the upper and RAF 15 for the lower, which are airfoils of similar properties. Norton reported that previous tests had shown that the individual properties of the wings have little influence on biplane characteristics. He also concluded that a positive stagger greatly restricts the center of pressure travel, thus simplifying the problem of stability. He varied only the stagger from ± 100% to 0% of the chord length in 25% increments while holding the gap constant at one chord length and decalage constant at 0 deg.

Knight and Noyes[3-5] in 1929, in three-dimensional nonsymmetrical airfoil tests, concluded that increasing the stagger in a positive direction or increasing the gap tends to equalize the loads on the two wings and also increases the normal force coefficient of the biplane cell. Their data indicate that changes in the decalage angle (positive or negative) from

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0 deg generally reduce the maximum lift coefficient when the gap is one chord length and stagger is zero. They tested various combinations of gap, stagger, and decalage angle enough and in the proper combinations to establish a general trend toward the low drag point that Nenadovitch found two-dimensionally.

None of the previous investigators made any direct comparison of biplane characteristics with those of a comparable monoplane. More work needs to be done by establishing general trends of three-dimensional biplane configurations at various positions of gap, stagger, and decalage angle, plane configurations at various positions of gap, stagger, and decalage angle, and the quantitative effectiveness of the configurations over the monoplane.

Description of Research

It is the purpose of this investigation to study the effect of improving the aerodynamic characteristics of an airplane by proper orientation of a biplane wing system. Specifically, the study: 1) investigates the aerodynamic characteristics of a three-dimensional biplane cell, using nonsymmetrical airfoils, by varying the gap, stagger, and decalage angle around Nenadovitch's best point. The application of these finding will establish quantitative aerodynamic characteristic trends for three-dimensional biplane cell wings, as was done earlier for two-dimensional ones; 2) establishes maximum lift coefficient, maximum lift over drag, and drag coefficient at a cruise angle of attack, as a function of gap, stagger, and decalage angle; 3) determines wing efficiencies, and effects of the biplane on range and endurance over the monoplane.

Model Description, Instrumentation, and Test Procedure

Models used in the tests were constructed of steel, brass, aluminum, cast epoxy, basswood, balsawood, and fiber tubing. The basswood wing contours conformed to the NACA 2412 template[6] within 0.010 in. Biplane and monoplane configurations could be compared using the same wing spans, or the same wing efficiency and hence aspect ratio, or the same lifting capability and hence area, or with each configuration optimized with respect to aerodynamic, structural, and other considerations.

Since this study is concerned with aerodynamic characteristics of biplane configurations, the models were fabricated to have the same lift capacity and hence wing areas, and as similar induced drag characteristics as possible. Making the monoplane wing with a 6½-in. chord and a 30-in. span (total area of 195 sq in) and the biplane wings with a 4-in. chord and a 24 ½-in. span (total area of 196 sq. in.) would yield an aspect ratio of 4.62 and an equivalent monoplane aspect ratio of 3.96, respectively. The equivalent monoplane aspect ratio (EMAR) is calculated from the following expression,[7] which assumes both wing efficiency factors equal to one

$$\mathrm{EMAR} = (b_1^2 / S)\ \mu^2 (1+r)^2 / \mu^2 + 2\sigma\mu r + r^2)$$

where

S = wing area

b_1 = span of upper wing

σ = Prandtl interference factor from fig. 10.10 function of gap and span[7]

μ = lower wing span/upper wing span

r = lower wing area/upper wing area

For the first phase of the tests the biplane wings were attached by adjustable N struts made of streamline aluminum tubing, steel, and epoxy (see Fig. 1), which allowed the position of the wings relative of each other to be changed. The lower wing was attached to the balance, which was made aerodynamically clean by a fairing. Plasticine was used to fillet all joints.

The fuselage (as shown in Figs. 2 and 3) was constructed with a steel framework, to which the wings and balance were attached. This framework was covered with balsa wood and resin-impregnated fiber tubing, then carved and sanded to the final shape, and painted.

Pitot pressure measurements in the vicinity of the model indicated that the velocity did not vary by more than ±1.5%. The balance system was found to be accurate to ±0.035 lb for axial force, ±0.79 lb for normal force, and ±2.15 in-lb for pitching moment.

Experimentation consisted of testing a set of biplane wings (shown in Fig. 1) at various combinations of gap, stagger, and decalage angle. The fuselage was then tested, first, with a monoplane wing and, finally, with the biplane wings attached. All tests were conducted, due the nature of the model support system, starting at an angle of attack of 20 deg and working toward −6 deg in 2-deg increments. For each angle of attack, normal, axial, pitching force, and temperature measurements of the air in the test section were recorded concurrently. Data obtained were then reduced in three computer programs,[8] which took into account the contribution of the

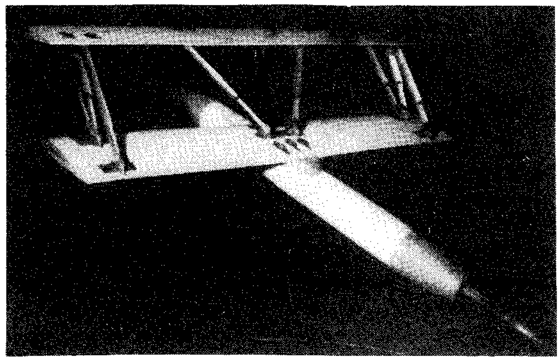

Fig. 1 Biplane wing system mounted on force balance.

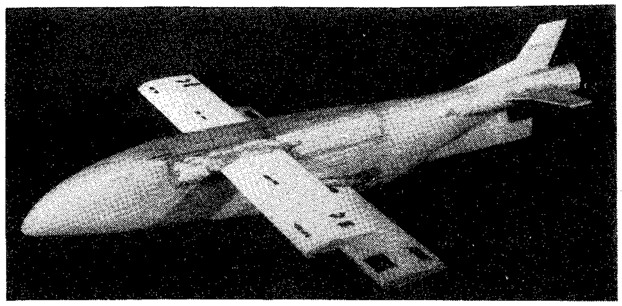

Fig. 2 Fuselage with biplane wing system.

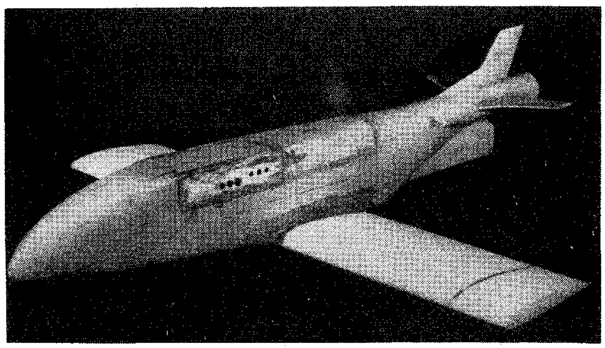

Fig. 3 Fuselage with monoplane.

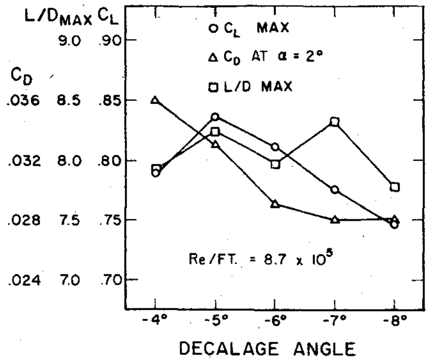

Fig. 4 Aerodynamic characteristics of three-dimensional biplane systems with gap = 1.125, stagger = 1.0, and various decalage angles.

balance and mount fairing for the tests of the wings by themselves and the effects of the test section boundaries on the results for both phases of testing.[8-10] These corrections were always less than 3%.

With this experimental facility and procedure, lift, drag, and moment data were obtained that were repeatable and could be fitted with standard curves. The deviation between the actual data points and the fitted curve was small.

Results and Discussion

The results for the first phase of testing of the wings without the fuselage were better for decalage angles between the extremes of -4 deg and -8 deg. Figure 4 summarizes the typical results as a function of decalage angle. Typically, $C_{L_{max}}$ was not as high, C_D at a cruise angle of attack of 2 deg was usually higher, and the L/D was generally lower than at the angles of -5, -6, and -7 deg. Therefore, all experiments for the second phase of testing occurred at decalage angles of -5. -6, and -7 deg. Within the physical constraints of the model, variations in staggers of 0.875, 1.0, and 1.125 of the chord length and gaps of 0.777, 0.875, and 1.0 of the chord length were made.

The results of the second phase of the tests with the fuselage showed that there was a reduction of the drag coefficient compared to that of the monoplane wing for all positions of gap, stagger, and decalage angles tested. Figures 5 and 6 are a summary of C_D at a C_L of 0.175 for the biplane configuration at various gaps, staggers, and angles of decalage. Generally, as decalage angle decreases to -5 deg, C_D decreases. This change is more apparent for a gap of 1.0 than for 0.875. With the exception of isolated cases, increasing stagger generally tends to decrease C_D, supporting Norton's[2] observation in 1918. As a whole, configurations with a gap of 1.0 have a lower C_D than ones with a gap of 0.875. An increased value of L/D also occurred for the biplane wings over the monoplane results for all the configurations tested. Figures 7 and 8 are a compilation of L/D, with the largest improvements occurring for the configurations with a gap of 1.0. L/D usually decreased when stagger was increased, with configurations with a gap of 1.0 having the largest decrease. Generally, decreasing decalage angle toward -5 deg improves both C_D and L/D. For all cases of the biplane configuration tested, the $C_{L_{max}}$, for the biplane was lower than for the monoplane.[8] The results of C_D, C_L, and L/D for all the biplane configurations tested have the same general behavior and follow the same general pattern of established airfoil section data. This similarity is in the curve shapes and general magnitudes of the coefficients.

Table 1 is a summary of the data for three aerodynamically efficient biplane wing systems. Case I has the lowest C_D characteristics for the biplane cells tested. Case II has the highest L/D drag characteristics, with relatively low C_D, of the biplane cells tested. Case III has aerodynamic characteristics which are a compromise of high $C_{L_{max}}$, high L/D, and low C_D. The biplane configuration of case I illustrates

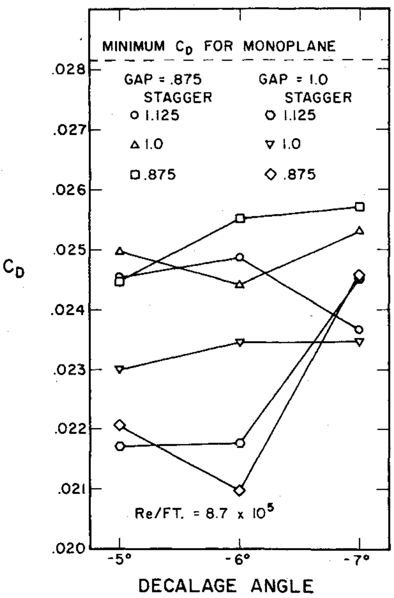

Fig. 5 Maximum efficiency trend of C_D at $C_L = 0.175$ with respect to decalage angle for biplane configurations tested.

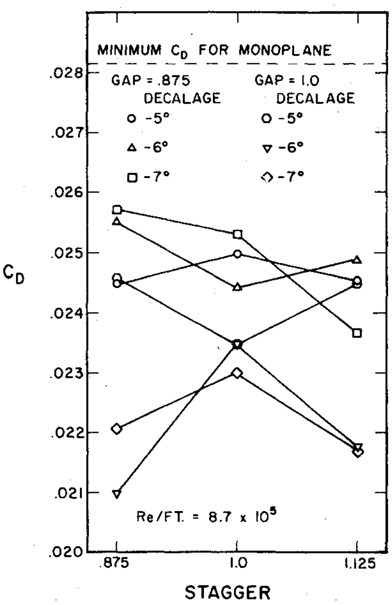

Fig. 6 Maximum efficiency trend of C_D at $C_L = 0.175$ with respect to stagger for biplane configurations tested.

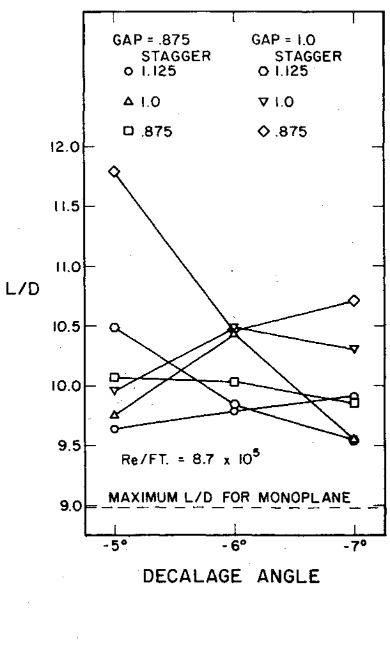

Fig. 7 Maximum efficiency trend of L/D_{max} with respect to decalage angle for biplane configurations tested.

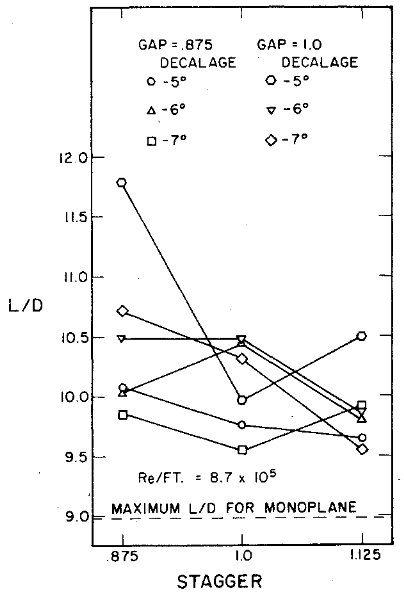

Fig. 8 Maximum efficiency trend of L/D_{max} with respect to stagger for biplane configurations tested.

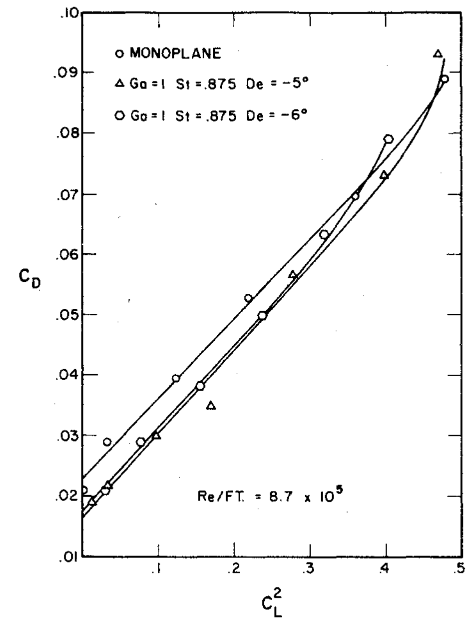

Fig. 9 Efficiency of monoplane compared with biplane configuration of cases I and II.

that a 25% reduction in C_D and a 16.7% increase in L/D are realized over the monoplane. For case II a 21.4% reduction in C_D and a 31.2% increase in L/D were obtained over the monoplane. A 14.3% reduction in C_D and a 16.3% increase in L/D for case III were realized over the monoplane.

Figure 9 illustrates the biplane wing efficiency and zero lift drag in comparison to the monoplane. For both cases shown (cases I and II) the zero lift C_D of the biplane is lower than that of the monoplane. Although the reverse would be expected, based on wetted area considerations or interference drag of the wing and the fuselage, it is postulated that the change in the invisid flow and, hence, pressure distributions about the biplane wings is causing the decreased C_D at the zero lift condition. Wing efficiencies were calculated using the expression: $m = 1/\pi eAR$, where m = slope of C_D vs C_L^2 curve, AR = aspect ratio, e = wing efficiency, $e_{monoplane} = 0.517$; $e_{biplane} = 0.604$. This increase in biplane efficiency is postulated to be due again to the changed inviscid flow distribution and, hence, induced drag from the biplane wings.

Figure 10 illustrates the improvement the biplane has over the monoplane with respect to $L^{3/2}/D$ over a wide range of cruise and climb lift conditons. This improvement will give the biplane configuration increased endurance capability over the monoplane. Figure 11 illustrates a comparison of L/D of the biplane and the monoplane. Again, for the biplane conditions considered (cases I and II) there is significant increase in L/D for the biplane over a wide range of C_L, which will

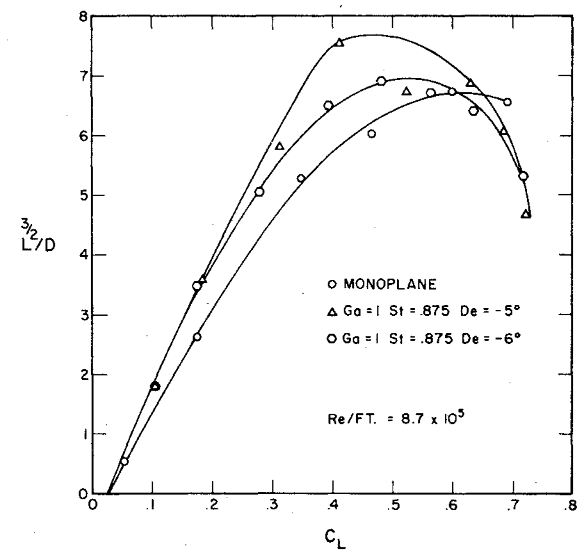

Fig. 10 Classical endurance parameter compared for propeller-driven aircraft.

Table 1 Summary of aerodynamic characteristics for three biplane wing systems and their comparison with monoplane

Configuration	L/D_{max}	$\Delta(L/D_{max})$ (%)	C_D ($C_L = 0.175$)	ΔC_D (%)	$C_{L max}$	$\Delta C_{L max}$ (%)
Monoplane	8.988	0	0.028	0	0.943	0
Biplane Case I GA = 1.0 ST = 0.875 De = −6 deg	10.49	+16.7	0.021	−25	0.722	−23.4
Biplane Case II Ga = 1.0 St = 0.875 De = −5 deg	11.788	+31.2	0.022	−21.4	0.734	−22.2
Biplane Case III Ga = 0.875 St = 1.0 De = −6 deg	10.449	+16.3	0.024	−14.3	0.840	−10.6

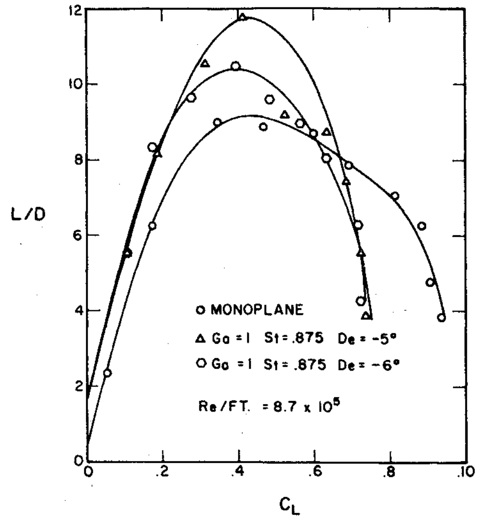

Fig. 11 Classical range parameter compared for monoplane and biplane (cases I and II).

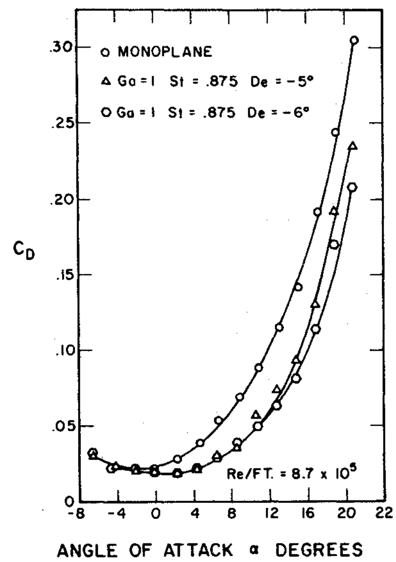

Fig. 12 Drag coefficients compared for monoplane and biplane (cases I and II).

cause the biplane to have a significant increase in range capabilities over the monoplane.

Figure 12 compares the drag coefficient variation of two biplane configurations (cases I and II) with the monoplane. For all positive angles of attack the biplane configurations have significantly lower C_D than the monoplane, which has a direct effect of reducing the power requirements of the biplane over the monoplane configuration.

Figure 13 shows the moment coefficient data for the monoplane and fuselage with the moment resolved to the wing quarter chord (16.44 in. from the fuselage nose) and for one of the biplane configurations and fuselage with the moment resolved to the quarter chord of the lower wing (16.50 in. from the fuselage nose). A large increase in slope, negatively, of the curve was realized for the biplane configuration over the monoplane with both having used the same tail surfaces. This is opposite what is classically expected with the lower wing quarter chord as the reference point. The increase, negatively, in slope is highly desirable from a stability standpoint. Possible improvement of tail surface effectiveness, due to a marked decrease in tail surface buffet with the biplane wings as opposed to the monoplane wing, may also have tended to improve the moment characteristics. The proximity of the two wings has most likely changed the flowfield about the wings and, hence, the pressure distribution. This would also account for the changed wake characteristics and the improvement in moment characteristics with the biplane configuration.

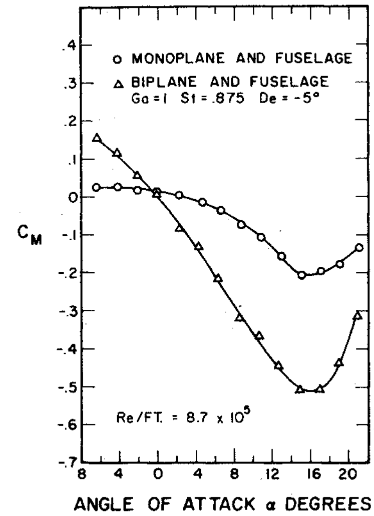

Fig. 13 Moment coefficient (about quarter chord of lower wing) comparison between monoplane and biplane with Ga = 1.0, St = 0.875, and DE = −5°.

Although these results follow the general patterns of established airfoil sections, the magnitudes cannot be taken to be representative of a biplane cell made with the new class of high-lift low-drag airfoils. Further research also needs to be done to determine the effect of flaps, slots, and other high-lift devices on the biplane characteristics for landing and takeoff purposes.

The increased biplane drag efficiency could be utilized to increase the biplane wing area and, hence the payload capacity, until the same total drag level as the monoplane is reached, thus making a more energy efficient system. This configuration might be particularly appropriate for a new class of strictly cargo transport aircraft, which would be designed from an energy efficient viewpoint. Increased lift over drag ratios of the biplane system, coupled with the low drag, could result in more efficient climb characteristics and efficient cruise characteristics, resulting in a more overall energy efficient aircraft with a high frequency of landings and takeoffs. For applications where higher maximum lift coefficient than the previous configurations is important, the third configuration would still result in a substantial improvement in both drag and lift over drag characteristics. Improved moment characteristics of the biplane system would allow the use of smaller tail surfaces, thus decreasing the parasite drag of the system.

The aerodynamic improvements found in this investigation would be most applicable to low speed, i.e., general aviation types of aircraft, where compressibility effects would be minimal.

Conclusions

Three-dimensional biplane wing tests at systematic wing orientations with respect to one another were conducted at a Reynolds number of 8.7×10^5/ft; and resulted in the following conclusions:

1) A substantial C_D reduction with respect to the monoplane over a wide range of angles of attack was obtained for most of the biplane configurations tested, with the most efficient biplane configuration showing a 25% decrease at 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 at a $C_L = 0.175$ being 21.4% lower. This implied a significantly increased range for the biplane.

3) Due to the $L^{3/2}/D$ improvement of the biplane, endurance would be markedly increased over a wide range of C_L over that of the monoplane.

4) A substantial increase in efficiency e was obtained for the biplane over the monoplane. This increase was realized with the biplane at a lower aspect ratio than the monoplane, indicating that either the induced drag was decreased and/or the altered pressure distribution reduced the drag while paying the penalty of higher interference drag.

5) The most efficient overall biplane configuration increased L/D by 16.3%, reduced C_D at a C_L of 0.175 by 14.3%, and was 10.6% lower in $C_{L_{max}}$ than the monoplane system.

6) For the configurations tested, decreasing decalage angle toward -5 deg decreased C_D and increased L/D, and increasing stagger tended to decrease C_D.

7) Pitching moment characteristics of the biplane system were markedly improved over the monplane system, i.e., the slope of the moment curve was more negative.

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