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# THE LIGHT AIRPLANE.

By Ivan H. Driggs.

BRIEF REVIEW OF THE RESULTS OBTAINED IN THE DEVELOPMENT OF LIGHT AIRPLANES - I.

MODERN THEORETICAL AERODYNAMICS AS APPLIED TO LIGHT AIRPLANE DESIGN - II.

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# THE LIGHT AIRPLANE.

## BRIEF REVIEW OF THE RESULTS OBTAINED IN THE DEVELOPMENT OF LIGHT AIRPLANES.

## PART I.

In every country interested in aeronautical development there is no question that is attracting more attention today than that of the small light airplane. It seems to be of great interest to nearly everyone, whether connected directly with aviation or not. Some writers have very great hopes. Others reserve their opinions, while some view the light airplane as an interesting but impractical toy. Whether or not the enthusiasts are correct it is the belief of a great many that these little airplanes, if properly developed, can do nothing but good in furthering the use and science of aviation.

Such men as Mr. Orville Wright, Brig. General Wm. Mitchell, and Mr. C. F. Kettering have publicly stated that in their opinion the light airplanes were the most interesting and important aeronautical development shown during the recent Air Races held at Dayton.

The little airplanes also seem to have captivated the mind of the general public. The press has broadcasted articles describing the "Aerial Flivers," and suggesting the wonderful experience in store for all in the development of a cheap little

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airplane using but a gallon of fuel to fly forty miles. However these popular conceptions may work out, the feeling seems to pervade the aeronautical profession that the light airplane may be the entering wedge, as it were, to commercial aviation.

Due to their small size and relatively low horsepower light airplanes can be produced, even in small quantities, at a cost comparable to that of some of the smaller motor cars. The uses to which these airplanes can be put are naturally somewhat limited. Those limits, however, are only those imposed by the small size and lack of overloading capacity. As far as general control ability, and performance under design load is concerned a light single seater can be constructed with a 22 horsepower engine that will equal if not surpass the performance of several airplanes used commercially today. The same degree of comfort and safety in bad air may also be accomplished. The records of British and American races seem to show that forced landings with this type are much less dangerous either to man or machine than with the larger and heavier airplanes. Very great maneuverability and sturdiness of construction may somewhat explain this interesting fact. In "The Aeroplane" of November 19, 1924, the views of an experienced pilot are given, in which he states that he would rather fly cross country in a light airplane than in a faster, high-powered airplane, because he has no fear of flying low. Traveling by airplane becomes very monotonous if done at 4000 to 6000 feet. Low flying on the other hand is very interesting when the traveler may watch everything going on around him. This man feels that low flying with a light airplane is perfectly safe due to its extreme maneuverability and ability to be "put down" in small areas of nearly any kind of ground. This thought is extremely interesting and is probably true except over mountainous country. However the above idea may work out, undoubtedly the light airplane will find great usefulness for sport and for cheap rapid transportation over sections otherwise poorly accommodated. There is also the possibility of their use for training. A great amount of money might be diverted to the construction of combat airplanes if such were found feasible by the Government. The British are already trying out this idea. It would seem that the United States should also experiment with light airplanes in some part of our training program. Possibly the Air Service Reserve officers might find them very satisfactory for practice during their yearly return for service. We, in the United States, may also follow the lead of the British in the establishment of Light Airplane clubs among the ex-service pilots and red-blooded young men of the country. Light airplanes are so recent a development in this country, however, that it is very difficult to predict just what the year 1925 may have in store. The experience gained during 1924 may be the foundation for the development during 1925 of types that will meet the needs for training and practice flying as well as for sport.

Before proceeding with a technical discussion of the principles of light airplane design, it will be well to review and to analyze the work that has been done in developing this type both abroad and in this country. It is unquestionably true that the light airplane idea is an outgrowth of gliding or soaring experiments in Germany during the last few years. After the war German aircraft activities were greatly curtailed by the conditions of the Peace Treaty. Desiring to keep up interest in aviation and to provide practice for their trained pilots the Germans offered substantial prizes for soaring flights under various specifications. After a period spent in gaining the experience necessary for the flying of these crafts, flights were made that astonished the world as a whole. It is a very significant fact that in nearly every case the most successful gliders were designed by men of some technical experience and who were thoroughly familiar with the modern theories of hydrodynamics as applied to aeronautics by Doctors Prandtl, Betz, Munk and others of Göttingen University. Although the majority of these machines were built by trade school students under the supervision of their professors, the clear understanding of the above aerodynamical principles was plainly in evidence. The application of Dr. Prandtl's theorems enabled the glider constructor to design directly for the required performance. In other words, they had been supplied with a formula by which they might solve directly for the size and shape of their machines knowing the results to be attained. Mr. Geo. H. Madelung has given an illustration of such procedure by describing the design of the Hannover Sailplane in the S. A. E. Journal of January, 1923. It is therefore very logical that Dr. Prandtl's theories shall be elaborated upon to a considerable extent further along in these articles.

Naturally after the publication of German records the French and English were desirous of trying their hands. Consequently, the year 1922 saw some very fine flights in those countries. A group of students from the Massachusetts Institute of Technology constructed a glider for entry in one of the French competitions. This was probably the first serious American attempt at soaring since the Wright's experiments at Kitty Hawk. The greatest result of these trials was not that fine records were obtained but that they gave birth to the light airplane idea.

The Europeans thought that if they could make such wonderful flights relying solely upon the wind for the power of sustentation, by installing a small auxiliary engine they might solve the problem of cheap and practical aviation. Consequently, at the Lympne competition in England during the fall of 1923, and at various French trials somewhat earlier we have the advent of the so-called light airplane. Viewed in the light of our knowledge a few years ago the 1923 single seater light airplane was a revelation. Although nearly every meet was marred by incessant engine trouble the results obtained exceeded the wildest expectations. The French very quickly developed small engines for their craft but the English were forced to rely upon standard motorcycle engines, which proved hardly suitable for full power airplane service. The displacement of the engines in the Lympne competition was limited to 750 cm³ (45.8 cu.in.). Possibly the trouble experienced by the British may have been due to the fact that they were trying to take too much power out of the displacement allowed. It does not appear that the size of an engine is a particularly good indication of its suitability for an airplane. If the power output of the engine could have been limited in some way, to say 16 HP., the designers might have had considerable more latitude in their choice of power plant. A slower, larger displacement engine would have worked a natural handicap by increasing the weight but would probably have kept the airplanes in the air for longer periods. Whatever the outcome of the engine problem may be the use by the English of the small displacement engine has proved one worth while fact regarding the light airplane. Forced landings may be made much more safely with these airplanes than with the heavier, more sluggish and faster types.

The next step was naturally to the two-seater which made its debut at Lympne in the fall of 1924. Again engine trouble was much in evidence although motorcycle engines had been replaced by engines designed especially for the service. The general performances were on the whole very satisfactory, when the airplanes were permitted to fly by their balky engines. The results were such that the conclusion may be drawn that from 30 to 35 HP. is sufficient to make a two-seater light airplane equal the performance of some of the standard training airplanes using from two to three times that power. These 1924 competitions further demonstrated the safety of these airplanes in forced landings. Out of numerous cases of engine failure away from the airdrome by nearly every airplane, but one suffered any structural damage. The two-seater competitions also further substantiate the thought that a larger displacement engine of the same power would have kept the airplanes in the air for much longer periods and have produced a more practical airplane.

During 1922 and 1923 the United States remained inactive in the development of gliders and light airplanes, except for the one case already noted. However, the N.A.A. came to life in 1924 with light airplane races to be held in conjunction with the International Air Races at Dayton. We as Americans cannot point with a great deal of pride to the results obtained. Although the conditions under which these races were run were in no way comparable to the Lympne competitions, the number of the airplanes was very disappointing as well as the general quality. Of nine airplanes entered, but six were on the line for the start. Only one of these six finished the three races on the program, one other finished two races, and one finished but one race. The remaining three either never left the ground or were forced out shortly after the start. The direct drive Henderson four-cylinder motorcycle engine gave very satisfactory service in Dormoy's "Flying Bath Tub" and Johnson's DJ-1 airplanes. Although Dormoy was forced down on his second race by very bumpy air his engine was running perfectly. Johnson made three forced landings in pastures, plowed fields, etc., due to imperfect full flow, but his

Henderson functioned smoothly in every race. It is a significant fact in comparison with the English single-seater trials that neither of these two engines had any adjustment whatever during the period of the races. Those designers employing the geared twin cylinder Vee engines, however, were not so fortunate. The vibration in some cases was so excessive that the very light structures were repeatedly broken. Chain drives also contributed their share of trouble.

Certain conclusions may be drawn from the results of the European and American races.

First. For a single-seater, from 18 to 25 horsepower, and for a two-seater, 35 to 40 should be sufficient for practical purposes.

Second. The displacement rating of the automobile races should not apply to aircraft. Power alone should determine the classifications.

Third. Gearing in any form unless highly developed is a definite source of trouble.

Fourth. The smoothness of four-cylinder engines is highly desirable.

Fifth. Light airplanes as a class possess qualities that make them very safe in forced landings, and their sturdiness on poor ground is superior to the larger airplanes.

Sixth. Performance characteristics and maneuverability equal to if not better than some standard training types have already been obtained.

A great deal of general discussion has been offered on the subject but as yet no attempt has been made to define the term "Light Airplane." That is a question that is receiving a great deal of attention both abroad and in this country today. Is a light airplane an engined glider? Is it an under-powered airplane? In the light of what has been accomplished it is neither. Of course, as pointed out previously the original idea was the outgrowth of glider or soaring machine development. In fact, one of the British single-seaters, the "Wren", could very truly be called an "engine-glider," as in 1922 the same airplane without engine had been used in the soaring competitions. However, the problems of gliding and flying from place to place are widely separated. A glider receives its sustentation from a wind which has a strong upward component. Such a machine is designed so that its sinking speed will be a minimum and equal to or less than the rising speed of the wind in which it is flying. This necessitates a very high ratio of lift to drag at a very low speed. The aim in soaring is to stay off the ground as long as possible. Powered flight, on the other hand, has for its purpose the accomplishment of useful work, namely, the transportation of a required pay load through the maximum distance, in the shortest possible time and at the least cost. This is a problem of range of flight rather than of duration, as in the case of the glider. Winds cannot be depended upon for assistance as it may be necessary to fly in a direction from which no help but rather hindrance can be expected from the air currents. An airplane will be the most efficient in meeting the demands of commercial work when it is least affected by the wind. This means that the cruising speed should be high in order that the percentage reduction in velocity over the ground experienced in average air conditions may be low. The practical airplane should have a margin over its most efficient cruising speed at least equal to the average velocity of the winds liable to be encountered. The light airplane, therefore, must have a very high ratio of lift to drag at high speed in order that flight may be accomplished with low power.

Thus the requirements of a glider and of a light airplane are similar in one respect only, the necessity for a very high ratio of lift to drag. The engined glider will have a phenomenal duration but will not be a practical airplane.

Light airplanes are not underpowered in the true sense of that term. The number of pounds carried per horsepower is much greater than designers have previously deemed advisable in the construction of military types. This high power loading is the _raison d'etre_ of the light airplane. For commercial work the greatest possible load must be carried by the minimum power. Everything else being equal, that airplane which has the highest power loading will be the cheapest both in first cost and in operation. An airplane is underpowered only when it is unable to properly function in the service for which it was intended.

If that service be to transport a pilot and baggage 200 miles at a speed of 75 miles per hour and passing over a mountain range 12,000 feet high on the way, that airplane which fails in the accomplishment of the above is underpowered whether it carries 15 or 30 pounds per horsepower.

The advocates of the light airplane believe that there are two ways of increasing airplane performance, namely, by either increasing the engine power available or by decreasing the power required for flight; and that the latter method is by far the most logical and scientific.

An increase of power necessitates an increased fuel load, and therefore a greater total weight. Consequently, the cost of the airplane both as to original outlay and as to maintenance increases. Everyone has heard the statement "Give us power enough and we can fly the kitchen table." The light airplane is diametrically opposite to a powered "kitchen table." It may be defined as a scientific attempt to obtain the greatest possible useful work from the least power. Incidentally this results in an airplane extremely cheap in all respects.

Brief mention has been made of the different stages of light airplane development, and attention has been directed to the dependence of the designers to a great extent upon the work of Dr. Prandtl. The engine glider idea as well as the criticism of light airplanes being underpowered have been discussed and shown to be the wrong conception.

Table I.

| Airplane | Type | Engine | Weight light | Weight loaded | Wing loading | Power loading |
|---|---|---|---|---|---|---|
| Avro 558 | B-S | 500 cm³ | 294 | 480 | 2.89 | 26.7 |
| Avro 560 | M-S | 698 " | 285 | 471 | 3.41 | 23.5 |
| A.N.E.C. | M-S | 698 " | 289 | 465 | 3.21 | 23.2 |
| Wren | M-S | 398 " | 232 | 408 | | |
| Gull | M-S | 698 " | 402 | 500 | 3.52 | |
| Gannet | B-S | 750 " | 283 | 460 | 4.47 | |
| D.H.53 | M-S | 750 " | 310 | 490 | 4.08 | |
| Viget | B-S | 750 " | 395 | 575 | 2.88 | 26 |
| Poncelet | M-S | 750 " | | | | |
| Peyret | M-S | 750 " | | | | |
| Raynham | M-S | 750 " | | | | |
| Pixie | M-S | 500 " | | | | |
| Hurricane | M-S | 600 " | | 520 | 6.4 | |
| H.P.23 | M-S | 500 " | | 480 | 2.85 | |
| H.P.25 | M-S | | | 430 | 2.75 | |
| H.P.26 | M-S | 698 " | | 500 | 8.10 | |
| Dormoy | M-S | 80 cu.in. | | | | |
| Mummert | M-S | 74 " | | | | |
| Driggs | M-S | 80 " | 326 | 511 | 7.3 | 22.7 |
| Snyder | B-S | | | | | |
| Turner | B-S | 74 " | | | | |
| Heath | B-S | | | | | |
| Brownie I | M-T | 1096 cm³ | 500 | 870 | 4.3 | 29 |
| Brownie II | M-T | 1096 " | 500 | 870 | 4.5 | 29 |
| Cranwell | B-T | 1096 " | 510 | 890 | 3.75 | 29.6 |
| Wee Bee | M-T | 1096 " | 462 | 837 | 4.47 | 25.6 |
| Wood Pigeon | B-T | 1096 " | 439 | 779 | 5.03 | 26 |
| Widgeon | M-T | 1096 " | 450 | 790 | 5.5 | 26 |
| A.N.E.C. | M-T | 1100 " | 415 | 730 | 3.94 | 24.3 |
| Short | M-T | 1096 " | 483 | 850 | 5.05 | 28.3 |
| Sparrow | B-T | 1100 " | 478 | 860 | 3.26 | 28.6 |
| Avis | B-T | 1096 " | 450 | 810 | 3.20 | 27.0 |
| Blue Bird | B-T | 1100 " | 495 | 875 | 3.60 | 29.2 |
| Vagabond | B-T | 1100 " | 527 | 887 | 3.96 | 29.6 |
| Pixie III | M-T | 1096 " | | | | |
| Pixie IIIa | B-T | 1096 " | | | | |

M - Monoplane B - Biplane
S - Single Seater T - Two Seater

Outline drawings of many of the above-mentioned light airplanes are given in N.A.C.A. Technical Memorandums Nos. 261 and 289.

Table I (Cont.)

| Airplane | Type | Engine | High speed | Rate of climb | Ceiling | Miles Gallon |
|---|---|---|---|---|---|---|
| Avro 558 | B-S | 500 cm³ | | | 13,850 | |
| Avro 560 | M-S | 698 " | | | | 87.5 |
| A.N.E.C. | M-S | 698 " | 74 | | 14,400 | |
| Wren | M-S | 398 " | | | | 82.5 |
| Gull | M-S | 698 " | 55.25 | | | |
| Gannet | B-S | 750 " | | | | |
| D.H. 53 | M-S | 750 " | 59.3 | | | 59.3 |
| Viget | B-S | 750 " | 58.1 | | | |
| Poncelet | M-S | 750 " | 58 | | | |
| Peyret | M-S | 750 " | | | 9,400 | |
| Raynham | M-S | 750 " | | | | 65.7 |
| Pixie | M-S | 500 " | 76.1 | | | |
| Hurricane | M-S | 600 " | 58.5 | | | |
| H.P.23 | M-S | 500 " | | | | |
| H.P.25 | M-S | | | | | |
| H.P.26 | M-S | 698 " | | | | |
| Dormoy | M-S | 80 cu.in. | | | | |
| Mummert | M-S | 74 " | | | | |
| Driggs | M-S | 80 " | | | | |
| Snyder | B-S | | | | | |
| Turner | B-S | 74 " | | | | |
| Heath | B-S | | | | | |
| Brownie I | M-T | 1096 cm³ | 70 | | | |
| Brownie II | M-T | 1096 " | 70 | | | |
| Cranwell | B-T | 1096 " | | | | |
| Wee Bee | M-T | 1096 " | 86 | | | |
| Wood Pigeon | B-T | 1096 " | 72 | | | |
| Widgeon | M-T | 1096 " | 72 | | | |
| A.N.E.C. | M-T | 1100 " | 85 | | | |
| Short | M-T | 1096 " | 73 | | | |
| Sparrow | B-T | 1100 " | | | | |
| Avis | B-T | 1096 " | 75 | | | |
| Blue Bird | B-T | 1100 " | 74 | | | |
| Vagabond | B-T | 1100 " | 74 | | | |
| Pixie III | M-T | 1096 " | | | | |
| Pixie IIIa | B-T | 1096 " | | | | |

M - Monoplane B - Biplane
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Outline drawings of many of the above-mentioned light airplanes are given in N.A.C.A. Technical Memorandums Nos. 261 and 289.

PART II.

## Modern Theoretical Aerodynamics as Applied to Light Airplane Design.*

In the first part of this series there is reviewed briefly the results obtained in the development of light airplanes, both in Europe and in this country. Considerable stress was laid on the importance of the mathematical work of the staff of Göttingen University, in that it was largely the foundation of European progress. Like all good things, these theorems are very simple, both to understand and to use.

A strict mathematical proof of Dr. Prandtl's theory is quite difficult and is naturally impossible in a series of this character. Suffice to say that he applies the methods of classical hydrodynamics to fluid flow about a lifting organ, assuming that the fluid in question (air) has no viscosity, causes no friction and is incompressible. None of these assumptions is strictly true, but the deviations are so small and of such character that the truth of the theory may be demonstrated and proved by wind tunnel tests.

If it were possible to visualize the air flow about an airplane in flight the Prandtl theory would be very easy to under-

* Author's Note:- The development of Elementary Aerodynamics in the following pages is necessarily somewhat mathematical. Those readers who do not wish to follow this work may turn to the last page for a summary expressed in a few very simple rules. However, anyone familiar with elementary algebra should easily follow the mathematics as given.

stand. As a wing is drawn through the air an infinite number of air molecules impinge upon its surface. If this wing is exerting a lift it naturally must be forcing these air particles downward, giving rise to the well-known "downwash" observed in numerous wind tunnel and free flight tests. This phenomenon may be demonstrated by a silk cord secured to the trailing edge of an airplane wing. In flight the cord will be seen to maintain an angle with the wing chord considerably greater than the actual angle of attack with the relative wind. This deflection of the air stream is equivalent to the airplane flying at all times in a current of air directed downward. The fact that this downward deflection is caused by the airplane itself in no way invalidates this assumption.

If an airplane is flying in such a downward current, in order to maintain level flight it must have a vertical velocity upward exactly equal to the vertical velocity of the air downward. In other words it must be climbing. This is actually what happens. The airplane is continually climbing away from the air that it has passed over and thereby forced downward. Power is expended in thus causing the airplane to climb. This power necessitated to maintain the airplane in level flight in the downwash induced by its own passage through the air is called induced power. Dr. Prandtl has been able to arrive at a mathematical expression for this proportion of the power required. This formula represents the basis of the so-called Prandtl theory. It has been extended to apply to multiplanes as well as to monoplanes from which the original expression was derived.

Let $W$ = Weight of airplane in pounds = Lift.

$b$ = Span of airplane wing in feet. (Average in case of biplane with uneven wings.)

$V$ = Velocity of flight in miles per hour.

$\rho$ = Density of the air at any altitude relative to that at the ground (always unity or less).

$P_{ind}$ = Induced power required as explained above.

Then $$P_{ind} = \frac{W^2}{3 b^2 \rho V} \text{ for a monoplane} \qquad (1)$$

$$P_{ind} \doteq \frac{W^2}{3.6 b^2 \rho V} \text{ for a biplane (approximately)} \qquad (1a)$$

Formula (1) however does not represent the total power required for flight. As pointed out previously the assumptions under which the induced power has been calculated by Dr. Prandtl do not coincide absolutely with the actual facts. He was forced to ignore the friction of the air on the wings as well as other slight discrepancies. At the present time a wind-tunnel test is the only means available for determining the magnitude of the power necessary to overcome this added wing resistance. Tests on numerous airfoils have shown that the frictional resistance, or Profil Drag as it is called, is very nearly constant for all angles of attack in the ordinary flying range. It increases slightly at the lower and higher angles. Extensive wind-tunnel tests have shown that this Profil Drag does not vary exactly as the velocity squared as ordinarily supposed but at a somewhat lower rate. This gives rise to the so-called Scale Effect mentioned in numerous aeronautical works. The wing Profil Drag is entirely parasitical in its action as it contributes nothing to the usefulness of the airplane. The power expended in overcoming this form of resistance may be called the Wing Parasite Power.

Let $P_{W.P.}$ = Wing Parasite Power

$K$ = Coefficient depending upon the airfoil used. To be determined by wing turned test.

= (Profil Drag of 1 sq.ft. of wing area at 1 mile per hour.)

$S_W$ = Area of wings in square feet.

$$\text{Then } P_{W.P.} = \frac{K S_W V^3 \rho}{375} \qquad (2)$$

In the foregoing paragraphs the power required by the wing alone has been developed. There are always certain other structural parts necessary for bracing or containing the power plant and useful load. These bodies also absorb power when propelled through the air. This proportion of the power required may be called the Structural Parasite Power to differentiate it from the Wing Parasite Power. The magnitude of the Structural Parasite resistance is the most difficult to obtain. Probably the most accurate method is to test a scale model of a proposed airplane in the wind tunnel for resistance at various angles of attack. If a wind-tunnel test is out of the question the resistance of all items exposed to the air stream may be calculated by referring to experimental data on similar shapes. The laboratories of various countries have tested great numbers of fuselages, wheels, wires, struts, etc., and have published the data on those objects in a form convenient for ready use. After the resistance of each item has been found as above, the total resistance is the sum of all the small components. Probably the simplest way to arrive at the magnitude of the Structural Parasite resistance is to estimate it by comparison with airplanes of similar type which have had coefficients experimentally derived by flight test. This is most conveniently done by imagining all the miscellaneous structural items to be replaced by a flat plate of such area that the resistances at any given velocity will be identical. A table of such flat plate areas of equivalent Structural Parasite Resistance may be easily calculated from published tests on different airplanes. When this equivalent flat plate area is determined, whether by tunnel test, calculation, or by estimation, the Structural Parasite Power may be expressed as in formula (3).

Let $P_{S.P.}$ = Structural Parasite Power.

$S_{P.S.}$ = Area of flat plate of resistance equivalent to structural bodies.

$$P_{S.P.} = \frac{.00327\ S_{P.S.} V^3 \rho}{375} \qquad (3)$$

Formulas 1 (or 1a), 2 and 3 may now be added to give an expression for the total Power Required - $P_R$.

$$P_R = \frac{.00327\ S_{P.S.} V^3 \rho}{375} + \frac{K S_W V^3 \rho}{375} + \frac{W^2}{3 b^2 V \rho} \qquad (4)$$

If $\frac{KS_W}{.00327} = S_{P.W.}$ = The area of a flat plate of equal resistance to the wing profil drag.

and if $S_P = S_{P.W.} + S_{P.S.}$

Formula (4) may take this simplified form:

$$P_R = \frac{.00327\ S_P\ V^3 \rho}{375} + \frac{W^2}{3b^2 \rho V} \tag{5}$$

$$P_R = .00000872\ S_P V^3 \rho + \frac{.333 W^2}{b^2 \rho V} \tag{5a}$$

Equation (5) is very simple when compared with the ordinary procedure of calculating the Power Required curve. One of the accepted methods is to start from a tunnel test on the chosen airfoil and apply to it various corrections for aspect ratio, gap chord ratio in case of a biplane, stagger, wing tips, etc. From the chosen wing area and weight the velocity is computed at a series values of the lift coefficient corrected from tunnel test. Then from the values of L/D obtained after corrections at the above lift coefficient the wing drag and then the wing power is computed. The Parasite Power is then calculated and added to that of wing to give values of the Total required at various velocities. If the same quantities were used as in calculating power by equation (5) and if an extension of Dr. Prandtl's theory were applied to correcting for aspect ratio, etc., the curves of Power Required in both cases would be identical. The labor expended, however, in using (5) is infinitely less. This, however, is not the only advantage of the above application of Prandtl's theory. In formula (5) every quantity that affects the power required for flight is shown in its proper relationship to every other. There are no coefficients to confuse and emphasize the wrong quantity. Every item but one is accurately known, assuming that the power is required at a given velocity and air density. The value of $S_p$, the parasite area, is the only quantity that must be determined either experimentally, by calculation or by estimation. This difficulty, however, is experienced by all methods equally. A further advantage lies in the fact that the principles of mathematics may be applied to manipulate equation (5) into different forms and show various laws that have not been clearly expressed previously. This work will not be carried out here, due to the fact that an attempt is being made to keep this series as simple as possible. Suffice to say that by applying the principles of differential calculus the following may be demonstrated.

I. At the speed of minimum power required the Induced Power is three times the Parasite Power.

II. At the speed of minimum drag the Induced Power and Parasite Power are equal.*

Theorem I applies to questions of duration, least sinking speed for a soaring machine and to ceiling, while Theorem II is

* Differentiate (5) with respect to V and place differential equal to zero for the speed of minimum power. Divide (5) through by V and multiply by 375 to reduce to equation of drag. Differentiate this equation with respect to V and place differential equal to zero for the speed of minimum drag.

important for range of flight and best gliding angle. These rules show the very marked influence of induction on airplane performance, especially in the design of light airplanes and gliders. The induced power at any speed and air density is determined solely by the ratio of weight to span, W/b. Herein lies the most important fact relative to Light Airplane design. A span loading, W/b, of 20 pounds per foot on a 500-pound light airplane means but a span of 25 ft. The same value of W/b on a 4000-pound airplane calls for a span of 200 ft. Such a spread is impossible without excessive wing weight and almost impossible maintenance and hangar conditions. The limit of span for 4000-pound airplanes in practical use is approximately 50 ft. Therefore, W/b = 80 pounds per foot. Since the Induced Power varies as $(W/b)^2$ from formula (1), for the 500-pound light airplane this portion of the power required will be 1/16 as great as for the larger airplane. If the propeller efficiencies are the same in both cases the power available, and general performance of the two airplanes would vary somewhat as below:

| 4000-pound Airplane | 500-pound Light Airplane. |
|---|---|
| Span, 50 feet. | Span, 25 feet |
| W/b, 80. | W/b, 20. |
| Power Available, 400 HP. | Power Available, 25 HP. |
| Absolute Ceiling, 19,000 ft. | Absolute Ceiling, 19,000 ft. |
| Rate of Climb, 1200 ft./min. | Rate of Climb, 600 ft./min. |

| 4000-pound Airplane | 500-pound Light Airplane. |
|---|---|
| Span, 50 feet. | Span, 25 feet. |
| W/P, 10 lb. per HP. | W/P, 20 lb. per HP. |
| Parasite Area, 16 sq.ft. | Parasite Area, 1 sq.ft. |
| High Speed, 120 miles per hour. | High Speed, 120 miles per hour. |
| $\frac{\text{Parasite Area}}{\text{Weight}}$, .004 | $\frac{\text{Parasite Area}}{\text{Weight}}$, .002 |

In the foregoing example the Parasite Power has been assumed to vary in the same ratio as the Induced Power. This assumption is not justified by the facts in the case. The wing parasite will probably vary directly as the relative weights of the two airplanes. The structural parasite may or may not vary in some such ratio, probably, however, it will never decrease faster than the ratio of weights. If such be the case the value of $S_p$ for the light airplane becomes 2 sq.ft. and the high speed becomes 95 miles per hour approximately. Very little effect will be noticed in the rate of climb and ceiling, however, since the lowered propeller pitch used with the lower high speed will probably increase the Power Available at lower speeds sufficiently to compensate for an increase of Parasite Power, which has a relatively small effect at lower speeds.

The simple example given brings to light another important fact. In order to obtain the maximum utility out of these airplanes the Parasite Area should be reduced to the lowest possible limit. Parasite is, of course, of prime importance in any airplane; for a light airplane, however, its importance increases in direct proportions to the increase of power loading. It will probably be found impossible to decrease the parasite area beyond a limit of approximately 2 sq.ft. for a 500-pound airplane. Naturally this will lead to a reduction in the high speed over that which would be expected reasoning from the Induced Power reduction alone. This is one of the penalties that must be paid for flight with low power, and should affect the general utility of these airplanes but little when considered in the light of their low first cost and upkeep. To draw a parallel from the automobile industry the most useful and widely sold car manufactured is capable of developing but less than one-half the speed cross country than some of the larger and more expensive automobiles. Its utility in congested traffic, however, compensates in a great measure for such lowered high speed. Likewise the Light Airplane, due to the fact that it can get in and out of smaller areas and possibly paved roads, if necessary, closer in to the center of cities, may make up in the long run for some of the difference in maximum velocity.

Light airplane races with high speed as the only criterion have been somewhat criticized in this country as not furthering development along the proper lines. Such a thought is absolutely without foundations. High speed is the most important single item to be developed provided, however, that the power is not increased and that no sacrifice is made in utility.

An increased high speed (with same power) necessitates a reduction in parasite. Lowering weight and lowering parasite are the two most important problems confronting the light airplane designer today; provided, of course, that neither is done at the sacrifice of first cost, upkeep, or general utility. If the parasite and weight be lowered sufficiently, rate of climb, ceiling, and time to altitude may be increased at will by decreasing the span loading. The design which makes the best high speed may be revised slightly if it be lacking in any of the above particulars and made to out-perform any other design of same power and weight.

Returning to formula (5) it will be seen that no mention has been made of two quantities hithetto thought to be of prime importance in airplane design, namely, wing loading (pounds per square foot of area) and aspect ratio (ratio of span to chord of wing). If the span be constant, wing loading (or wing area) has but little effect upon the curve of Power Required. Its main influence lies in the fact that it controls the wing Parasite Power, formula (2), and also the minimum speed at which level flight may be maintained. It is naturally assumed in application of formula (5) that the wing area is sufficient to maintain level flight at any velocity substituted into the equation. Wing area controls the lower limit of velocity (constant span and airfoil), and to a slight degree the parasite. Aspect Ratio, on the other hand, is a perfectly useless term. Span and area tell the whole story. This is true whether a monoplane or multiplane be under consideration.

A little thought will show wherein lies the fallacy of the belief that rate of climb and ceiling vary as the wing area.

When these relationships were first worked out showing such dependence of performance upon wing area the investigators overlooked the fact that since they were keeping the Aspect Ratio Constant in their calculations they were varying the span as well as the wing loading. The effect obtained was due to the variation in span so produced and not to the wing loading. This is an example of reasoning from an experimental rather than a theoretical basis. The effect was attributed to a cause which in reality acts just the opposite than generally was supposed. With constant span an increase of wing area will decrease ceiling, rate of climb and high speed through the increase of parasite. However, at the same time a lower landing speed will also be obtained.

From Theorem I above defining the speed of minimum power it may be shown that

if $V_{M.P.}$ = Speed of minimum power

$$V_{M.P.} = 10.64 \sqrt[4]{\frac{W^2}{b^2 S_p}} \text{ at the ground.} \qquad (6)$$

The theoretical low speed of the airplane should not be greater than the value given by equation (6) in order that the maximum effect may be realized from the given span loading.

For the 500-pound light airplane investigated above with a value of $S_p$ = 1 sq.ft., $V_{M.P.}$ works out to be 47.7 miles per hour. If the airplane, however, has an $S_p$ of 2 sq.ft., V becomes 40.1 miles per hour. The wing area should be such that in either case flight might be maintained at the speeds given, or preferably, slightly less. Therefore, wing area enters into consideration but entirely in a secondary manner.

If $K_{y\ max}$ = Maximum lift coefficient of airfoil used in lbs. per sq.ft. miles per hr. units.

Then $$S_W = \frac{W}{K_{y\ max}\ (V_{min})^2} \qquad (7)$$

Equation (7) determines the wing area necessary for a required low speed.

Table II lists some of the best American airfoils, giving the value of the maximum lift coefficient as well as the minimum profil drag of the sections. Since the low speed as given by formula (6) is more or less determined by this or other considerations $K_{y\ max}$ should be as large as possible in order that a smaller area may be used with corresponding reductions in wing weight. Similarly, K, the profil drag coefficient should be as small as possible in order that the wing Parasite Power, $P_{W.P.}$ (see formula 2) should be low. Therefore, the ratio of $K_{y\ max}$ to minimum profil drag coefficient, should be a very good criterion for the choice of an airfoil, not considering structural requirements or stability. This ratio also enters into Table II for ready comparison.

| Airfoil | $K_y$ max | $K_{min}$ | $\frac{K_y \max}{K_{min}}$ | Remarks |
|---|---|---|---|---|
| R.A.F. 15 | .0026 | .000025 | 104 | Thin - very good. |
| U.S.A. 27 | .00344 | .0000345 | 99.8 | Medium thick. |
| Gött. 387 | .00366 | .000041 | 89.3 | Medium thick. |
| Gött. 430 | .00328 | .000033 | 102.5 | Medium thick. |
| Gött. 436 | .00307 | .0000313 | 98 | Medium thick. |
| U.S.A.35 B | .00333 | .0000325 | 102.5 | Medium thick. |
| U.S.A.35 A | .00376 | .000044 | 85.5 | Very thick. |
| Clark W | .00291 | .0000294 | 99 | Medium thick. |
| Clark X | .00289 | .0000289 | 99.8 | Medium thick. |
| Clark Y | .00318 | .0000269 | 118.2 | Medium thick - good. |
| Clark Z | .00321 | .000030 | 107.4 | Medium thick - good. |
| U.S.A. 16 | .00274 | .0000229 | 119.5 | Thin - good. |
| Curtiss C-62 | .00233 | .000022 | 106.0 | Thin - racing section. |
| U.S.A. 35 | .00383 | .0000334 | 114.5 | Tapered - cantilever. |
| U.S.A. 45 | .00331 | .0000276 | 120.0 | Tapered - cantilever. |
| Sloane 105 | .00238 | .0000232 | 102.5 | Very thin. |

Power required for flight at any velocity has been investigated with special reference to the light airplane. The power available from the engine-propeller group has not as yet been touched upon. The engine itself is generally determined by considerations of price, availability or race rules. The design of the propeller, however, may have a marked influence upon the general performance through its control to a certain measure of the

Power Available, $P_A$. The Prandtl theory has been extended to apply to propeller design and suggests some very useful theorems especially pertaining to Light Airplane propellers.

In the preceding discussions it has been shown that the ratio W/b should be very small, similarly it may be demonstrated in case of the propeller that the thrust over the diameter should also be as small as possible. Mr. Max M. Munk, in N.A.C.A. Technical Note No. 94, has worked out a formula for propeller diameter, D, based upon this theory.

Let $P_M$ = Power of engine at

$N$ = Revolutions per minute of propeller shaft.

$V_D$ = Velocity in miles per hour at which the propeller efficiency is desired to be a maximum, normally the designed high speed of the airplane.

$D$ = Propeller diameter in feet.

Then $$D = 564\sqrt[3]{\frac{P_M}{NVD}} \qquad (8)$$

If equation (8) gives a diameter such that .0524DN exceeds 820 ft. per sec., the diameter will have to be reduced until that limit is not exceeded. This is due to the fact that as the speed of the propeller tips approaches the velocity of sound the compressibility of the air becomes a noticeable factor and lowers the efficiency very rapidly. Equation (8) will give diameters in excess of present practice, which is based upon the assumptions that 1/2 the diameter divided by the maximum blade width shall be approximately 6. That is, with the diameter above computed, the maximum blade width will be smaller than present practice would allow. Due to the fact that the weight and thrust are low, the stresses imposed upon the light airplane propeller permit this increased ratio of diameter to blade width. The reasoning is similar to that which allows a larger span in proportion to weight for a light airplane than for the larger type.

The propeller used on the D-J-1 was 58 inches in diameter and but $3\frac{1}{2}$ inches maximum width. No trouble whatever was experienced. Weeds, grass, etc., had no appreciable effect except to wear the fabric tips.

The influence of increasing the diameter is two-fold. The slipstream velocity is less and therefore the energy losses are also decreased with a consequent increase in propeller efficiency. The velocity of the slipstream being less and distributed further away from the fuselage causes less interference between the body and propeller. Both of these considerations make for better all around performance.

A numerical example will serve to show more clearly the differences between ordinary practice and diameters given by equation (8).

$V_D$ = 95 miles per hour.

$N$ = 3000 revolutions per minute.

$P_M$ = 25 HP.

$$D = 564 \sqrt[3]{\frac{P_M}{N V_D}}$$

D = 5.5 feet = 66 inches.

A formula derived by H. C. Watts, for propellers of Aspect Ratio 6, give

D = 4.84 feet = 58 inches.

If the maximum blade width in the latter case works out to be 29/6 = 4.84 in., the width, using a 66-inch diameter propeller, is approximately 4 inches or 1/8 of the blade radius, instead of 1/6.

No attempt has been made to propose a method of performance calculation or propeller design. The main intention in mind has been to bring out a few very simple rules important in the design of light airplanes. These ideas are summarized below.

Rule I. Make the ratio of span to weight as small as possible compatible with structural and housing conditions.

Rule II. Build as light as possible.

Rule III. Reduce Parasite to the absolute limit, even at the sacrifice of weight.

Rule IV. Use large diameter, narrow blade propellers.

The next sections* will show by means of a definite numerical example how the different performance characteristics are affected by the variations in the dimensions of a light airplane.

* Will be issued by Committee as a Technical Memorandum in the near future.