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No. 568

CALCULATED EFFECT OF VARIOUS TYPES OF FLAP ON TAKE-OFF OVER OBSTACLES

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SUMMARY

In order to determine whether or not flaps could be expected to have any beneficial effect on take-off performance, the distances required to take off and climb to an altitude of 50 feet were calculated for hypothetical airplanes, corresponding to relatively high-speed types and equipped with several types of flap. The types considered are the Fowler wing, the Hall wing, the split flap, the balanced split flap, the plain flap, and the external-airfoil flap.

The results indicate that substantial reductions in take-off distance are possible through the use of flaps, provided that the proper flap angle corresponding to a given set of conditions is used. The best flap angle for taking off varies inversely as power loading and, to a much smaller extent, varies inversely with wing loading. Apparently, the best take-off characteristics are provided by the type of device in which the flap forms an extension to the main wing as in the case of the Fowler wing and the external-airfoil flap.

INTRODUCTION

The present trend toward very high speeds and higher wing and power loadings in airplane design lends increased importance to the problem of improving take-off performance. Controllable and automatic propellers have proved to be of considerable value in reducing take-off distances but, with these exceptions, little else has been accomplished toward this end.

A number of high-lift devices have been developed to compensate for the effects of high wing loading and clean lines on landing performance. Those of the flap type have proved very satisfactory for use on high-speed airplanes since they not only provide the desired effectiveness in landing but also cause little or no detriment to the maximum speed.

The purpose of this analysis was to determine whether or not such devices might also serve to improve take-off performance. Calculations of the horizontal distance to take off and climb to an altitude of 50 feet were made for a number of assumed cases involving the use of several types of flap and covering wing and power loading conditions corresponding to those encountered in high-speed airplanes.

The types of high-lift devices considered are:

- Fowler wing
- Hall wing
- Split flap
- Balanced split flap
- Plain flap
- External-airfoil flap

These devices were chosen arbitrarily to provide a reasonable number of cases. For each type of device, the size of flap considered was that which would probably be most commonly used in practice. Several flap angles were investigated for each type. Calculations were also made for a hypothetical wing having ideal characteristics providing for the greatest possible reduction in take-off distance. The plain-wing, or flap-neutral, condition was included as the basis of comparison for the various devices. Ranges of wing and power loadings were chosen to include most high-speed conditions.

It is intended in this analysis to provide a comparison among the various devices and conditions considered rather than to present accurate values for individual cases.

METHOD OF ANALYSIS

<u>Assumptions</u>.- The take-offs were assumed to be made at full power throughout, with no wind, and to consist of three phases: first, the accelerated run over the ground at the attitude of least total resistance up to the best

speed for taking off; second, the transition arc, or period of change, of the flight path from that of the ground run to that of the steady climb; and third, the steady climb up to an altitude of 50 feet. The last two phases were assumed to be made at the same speed as the take-off.

It was assumed that an automatic propeller permitting development of full rated engine speed and brake horsepower at all air speeds would be used. It should be noted that the results will apply very nearly as well to the case of a controllable propeller with a single blade-angle setting for the low-speed range since in this range the optimum blade angle varies only slightly. A parasite-drag coefficient of 0.02 was taken for all cases as representative of the high-speed highly loaded type of airplane and was assumed to be independent of angle of attack. A value of 0.05 was used for the coefficient of ground friction corresponding to average landing-field surface conditions. No correction was made for ground effect owing to the difficulty and uncertainty of applying available information on the subject of this work. The probable influence on the results of neglecting this effect is discussed at another point.

The lift and drag characteristics for the hypothetical ideal wing were so chosen as to provide an indication of the limit to which reduction in total take-off distance through modifications to the wing is possible. The profile drag was assumed to be zero and a value of 3.2 was taken for the maximum lift coefficient, as the calculations indicated that higher values of lift coefficient than this would afford little or no added advantage in taking off under normal loading conditions. Probably such a combination of lift and drag characteristics could be approached only with some device incorporating boundary-layer control.

Test data.- The lift and drag characteristics used in the calculations were obtained from wind-tunnel-test data of model wings equipped with full-span flaps of the various types to be investigated (references 1 to 6), the arrangement and dimensions of which are shown in figure 1. The tests were all made in the same wind tunnel but a different system of testing and a different Reynolds Number were used for the plain flap and the balanced split flap from the ones used for the other devices so that they may not be strictly comparable. No correction was made for jet-boundary effect with either test system, but it was found that the results in either case correspond very nearly to an aspect ratio of 5 for free air. The Reynolds Number for the tests of the plain flap and balanced split flap was 1,218,000 and for the other devices 609,000. The Clark Y airfoil section was used for the main wing of all the devices with the exception of the external-airfoil flap, which was fitted to a wing having the N.A.C.A. 23012 airfoil section. With this device the flap is extended in the neutral position instead of being retracted into the wing as in the case of the others. For this work, however, the lift and drag coefficients and wing loading were based on the main-plane area alone rather than on the total area since in this way the minimum drag coefficient with the flap neutral corresponds to that for the plain Clark Y wing, or flap-neutral, condition of the other devices.

Calculations.- The general equation of motion for the airplane during the ground run is:

$$W/g\ V\ \frac{dV}{dx} = T - D - \mu\ (W - L) \qquad (1)$$

where W is the gross weight of the airplane; T, D, and L are the thrust, drag, and lift, respectively, at any instant, corresponding to the speed V; and μ is the coefficient of rolling friction between the wheels and the ground, i.e., the ratio of rolling resistance to wheel loading, assumed to be constant. Since

$$D = C_{D_1}\ \rho/2\ S\ V^2$$

$$L = C_{L_1}\ \rho/2\ S\ V^2$$

where C_{L_1} and C_{D_1} correspond to the attitude maintained during the ground run

and

$$T = T_0 - K\ \rho/2\ V^2$$

where T_0 is the static thrust, and K is the constant of linear variation of thrust with the square of the speed (as explained later), equation (1) may be integrated between the limits $V = 0$ and $V = V_T$, the speed of take-off, to give the equation for the distance covered in the ground run:

$$D_1 = \frac{W/S}{\rho g\left[\left(\mu C_{L_1} - C_{D_1}\right) - \frac{K}{S}\right]} \log_e \left[1 + \frac{\left(\mu C_{L_1} - C_{D_1}\right) - \frac{K}{S}}{\left(\frac{T_o}{W} - \mu\right)\left(\frac{W/S}{\frac{\rho}{2} V_T^2}\right)}\right] \quad (2)$$

The attitude of least resistance during the ground run is defined by the algebraic maximum of the factor $\mu C_{L_1} - C_{D_1}$ and this value was therefore used in the calculations.

The actual motion of the airplane in the transition arc is defined by very complex equations. For this analysis, however, it was considered sufficiently accurate to assume a simple motion as in reference 7 for which the path of the airplane during the transition consists of an arc of constant radius tangent to the ground and extending to the height at which the proper angle of climb is attained.

The radial acceleration during the transition is then:

$$\frac{V^2}{R} = \frac{L_2 - L_1}{W/g}$$

from which $R = \frac{W/g\ V^2}{L_2 - L_1}$

where R is the arc radius,

L_1, the lift required for straight flight.

and L_2, the lift exerted in following the arc.

Since R is constant it may be defined from the conditions at the beginning of the arc as

$$R = \frac{W/g\ V_T^2}{L_2 - W}$$

or

$$R = \frac{2\ W/S}{\rho g}\left(\frac{1}{C_{L_2} - C_{L_T}}\right) \quad (3)$$

It is obvious that the arc radius R and therefore the horizontal distance required in performing the transition becomes shorter as the difference between C_{L_2} and C_{L_T}

increases. In order that this difference shall be as large as possible, C_{L_2} is taken as $C_{L_{max}}$. This procedure may not be valid in some cases where the excess power is very low, that is, where the drag and the wing and power loadings are high. For such cases, however, the transition distance is so short in comparison with the distances covered in the other two phases of the take-off that the error involved is slight. The assumption of an arc of constant radius involves, of course, also the assumption that angle of attack and lift coefficient change instantaneously at the beginning and conclusion of the transition, which although actually not true probably introduces only a small error.

The horizontal distance covered in the transition is given by:

$$D_2 = R \sin\theta = \frac{2\ W/S}{\rho g}\left(\frac{1}{C_{L_{max}} - C_{L_T}}\right)\sin\theta \qquad (4)$$

where θ is the flight-path angle during the subsequent steady climb.

The angle of the flight path during the last phase of the take-off, the steady climb, is determined from

$$\sin\theta = \frac{T - D}{W}$$

for which the thrust T is assumed to act along the flight path, or

$$\sin\theta = \frac{T_o}{W} - \left(\frac{K}{S} + C_{D_3}\right)\frac{\rho/2\ V_3^2}{W/S}$$

Then, since

$$\frac{\rho/2\ V_3^2}{W/S} = \frac{\cos\theta}{C_{L_3}}$$

and $\cos\theta$ may be taken as 1 in view of the generally small values of θ,

$$\sin\theta = \frac{T_o}{W} - \left(\frac{K}{S} + C_{D_3}\right)\frac{1}{C_{L_3}}$$

where C_{L_3} and C_{D_3} correspond to the speed V_3 maintained in the steady climb.

In reference 7 it is shown that to realize the shortest total take-off

$$C_{L_3} = C_{L_T}$$

and therefore

$$\sin\theta = \frac{T_o}{W} - \left(\frac{K}{S} + C_{D_T}\right)\frac{1}{C_{L_T}} \tag{5}$$

The horizontal distance covered in the steady climb is

$$D_3 = \frac{H_2 - H_1}{\tan\theta} \tag{6}$$

where H_2 is the height to be cleared (50 feet) and H_1 is the height attained in the transition, or

$$H_1 = R\,(1 - \cos\theta)$$

In the determination of the thrust relations for use in the equations, the automatic propellers were assumed to permit full rated engine speed and brake horsepower at all air speeds. Propeller diameters giving maximum efficiency at top speed were determined, according to the method and information of reference 8, for a number of conditions involving various values of maximum speed and brake horsepower. The thrust characteristics in the low-speed, take-off range for these conditions were derived from data given in reference 9.

For a given propeller the variation of thrust from the static condition was found to be very nearly linear with the square of the velocity in the take-off range and can therefore be expressed as

$$\Delta T = K\,\rho/2\,V^2$$

Moreover, for a series of propellers designed for the same top speed the value of K varies directly with brake horsepower

or

$$K = B \times \text{b.hp.}$$

where the factor B depends on the top speed V_{max}. Then

$$\Delta T = B \times \text{b.hp.} \times \rho/2\,V^2$$

Likewise the static thrust T_0 was shown to vary directly with brake horsepower, for a given top speed, so that

$$T_0 = A \times \text{b.hp.}$$

where A is also a function of V_{max}.

Thus, the thrust at any speed in the take-off range for any condition becomes

$$T = \text{b.hp.}\ (A - B\ \rho/2\ V^2) \qquad (7)$$

The relations between the factors A and B and maximum speed are shown in figure 2(a).

At maximum speed the equation of forces is

$$\frac{T_{V_{max}}}{W} = \left[C_{D_o} + C_{D_p} + \frac{4}{\rho^2 \pi\ \text{A.R.}} \left(\frac{W/S}{V_{max}^2}\right)^2 \right] \frac{\rho V_{max}^2}{2\ W/S}$$

where A.R. is the effective aspect ratio, C_{D_p} the parasite-drag coefficient, and C_{D_o} the minimum wing profile-drag coefficient. The value of $C_{D_o} = 0.010$ was taken from full-scale test data since this corresponded more closely to high-speed conditions than the value 0.015 determined by the low-scale tests from which the characteristics of the high-lift devices were obtained.

It was found that $T_{V_{max}}$ also varies directly with brake horsepower for a given top speed

so that
$$\frac{T_{V_{max}}}{W} = \frac{C}{W/\text{hp.}}$$

where C is a function of V_{max} as shown in figure 2(a).

From these equations the relation between W/S, W/hp., and V_{max} may be determined. This relationship is shown in figure 2(b). It is then possible to determine the values of the factors A and B to correspond to given wing and power loading conditions.

The equations for the various phases of the take-off become in their final form:

Ground run:

$$D_1 = \frac{W/S}{\rho g \left[(\mu C_{L_1} - C_{D_1}) - B \frac{W/S}{W/hp.}\right]} \log_e \left[1 + \frac{(\mu C_{L_1} - C_{D_1}) - B \frac{W/S}{W/hp.}}{\left(\frac{A}{W/hp.} - \mu\right) C_{L_T}}\right] \tag{8}$$

Transition:

$$D_2 = \frac{2\ W/S}{\rho g}\left(\frac{1}{C_{L_{max}} - C_{L_T}}\right)\left[\frac{A}{W/hp.} - \left(B \frac{W/S}{W/hp.} + C_{D_T}\right)\frac{1}{C_{L_T}}\right] \tag{9}$$

Steady climb:

$$D_3 = \frac{H_2 - \frac{2\ W/S}{\rho g}\left(\frac{1}{C_{L_{max}} - C_{L_T}}\right)\left[1 - \cos \sin^{-1}\left(\frac{A}{W/hp.} - \left[B \frac{W/S}{W/hp.} + C_{D_T}\right]\frac{1}{C_{L_T}}\right)\right]}{\tan \sin^{-1}\left[\frac{A}{W/hp.} - \left(B \frac{W/S}{W/hp.} + C_{D_T}\right)\frac{1}{C_{L_T}}\right]} \tag{10}$$

For each set of conditions several values of C_{L_T} with corresponding values of C_{D_T} were assumed in order to determine the minimum total distance for that condition.

RESULTS

The minimum total take-off distances for all the devices and conditions considered are listed in table I. Figures 3 and 4 show the effect of variation of flap angle on the total take-off distance for the Fowler wing and the Hall wing, respectively. In figure 5 the flap angles giving the shortest total take-off distance are plotted against power loading for three wing loadings for each of the high-lift devices considered. The total take-off distance at the best flap angles for all the devices is plotted against power loading for three wing loadings in figures 6, 7, and 8. Curves for the plain-wing, or flap-neutral, condition (for the external-airfoil flap) and for the ideal wing are also included in these figures for comparison. In figure 9, the ground run, transition, and climb for take-off at best flap angles are plotted separately against power loading for one wing-loading condition. The plain-wing, or flap-neutral, condition also is shown here for comparison.

Although not of primary importance to the comparisons, it may be of some interest to note the lift coefficients corresponding to the best take-offs. For the Fowler wing and external-airfoil flap, the shortest total distance with the flaps deflected to their best angle is apparently realized when the take-off is made at a lift coefficient of about 78 percent of the maximum, regardless of the loading condition. For all the other devices considered, the lift coefficient giving the shortest take-off distance, although independent of wing loading, varies from about 82 percent of the maximum lift coefficient at the lowest power loading to about 89 percent at the highest.

DISCUSSION

The extent to which the total take-off distance is influenced by the angle of the flap may be seen in figures 3 and 4. There is a fairly definite minimum on all the curves; therefore, in order to derive the greatest possible benefit in taking off for a given set of conditions, the flap should be set at, or very close to, the proper angle to correspond to those conditions. This consideration is particularly important at the higher wing and power loadings for which the take-off distance increases more abruptly than at lower loadings with variation of flap angle from the optimum value. The effect may be more critical with one type of device than with another as shown by the differences in the curves for the Hall and Fowler wings, which represent the extremes of variation of all the devices considered; in any case, however, the effect is sufficiently marked to deserve considerable attention.

Figure 5 shows that the variation in best flap angle with power loading may be fairly large. The magnitude of this variation differs considerably among the several devices but its trend is very nearly the same; in all cases the best flap angle decreases with increasing power loading. The best flap angle varies with wing loading in the same manner but to a much smaller extent than with power loading. Apparently no general conclusions can be drawn as to the proper flap angle to be used for a given set of conditions as it varies rather widely among the different devices and would probably vary considerably with different flap sizes for the same device.

Figures 6, 7, and 8 indicate that appreciable savings in total take-off distance may be expected through use of any of the high-lift devices considered when operating at their optimum flap angles. With a given device and wing loading the percentage reduction in distance from that required with the plain-wing or flap-neutral condition decreases very nearly linearly with an increase in power loading. On the other hand, for a given device and a given power loading, the percentage reduction is practically constant for all wing loadings.

Of the particular form of devices considered, the Fowler wing and external-airfoil flap appear to be by far the most promising, both requiring very nearly the same take-off distance except at high power loadings where the distance for the latter is somewhat shorter. As the take-off distance for the flap-neutral condition of the external-airfoil flap is considerably less than for the plain-wing condition (corresponding to flap neutral with the Fowler wing) the actual reduction in take-off is greater with the Fowler wing. For the Fowler wing the reduction ranges from 44 percent at the lowest power loading to 27 percent at the highest. For the external-airfoil flap the reduction from the flap-neutral condition varies from 36 to 21 percent. With the plain Clark Y wing as the basis of comparison, the reduction with the external-airfoil flap is between 42 and 29 percent. There is little difference between the Hall wing and split flap in total take-off distance, the reduction in both cases over the distance required for the plain wing ranging between 24 and 11 percent. Although the results for the plain flap and the balanced split flap are not strictly comparable with those for the other devices, a separate comparison should be valid. Of the two, the balanced split flap gives the shorter take-off for all conditions, the reduction for this device varying from 30 to 16 percent with power loading. The reduction provided by the plain flap is between 22 and 12 percent.

For the ideal wing the reduction in total take-off distance from the plain-wing condition is approximately 50 percent for all loading conditions, being slightly greater than this at low power loadings and slightly less at the high values. This value may be considered as the limit to which such reduction is possible.

Owing to the neglect of ground effect, these estimates of the reductions in take-off distance gained with the various devices are probably somewhat conservative. Since the influence of ground proximity on a wing is essentially to increase its effective aspect ratio (reference 10), the resultant reduction in induced drag would be considerably greater with the high-lift devices than with the plain wing, thus tending to reduce the take-off distance more for the former case than for the latter and hence increase the advantage of the high-lift devices. There is some evidence to the effect that nearness to the ground produces increased lift, particularly at low angles of attack, but information regarding this phenomenon is of such a nature as not to permit a prediction of the effect that it would have on the results of this analysis.

Some consideration should likewise be given to the possible effect of wind on the comparisons. This effect may be considered as the summation of the effects of a wind of constant velocity and a corresponding wind velocity gradient with altitude (reference 11). It may be seen that ordinarily the time required to take off and climb to a given altitude will be longer, in proportion to the horizontal distance covered, with the high-lift devices than with the plain wing. Consequently, the effect of a steady wind, which is roughly proportional to the time required, will result in a greater percentage reduction in distance with the high-lift devices than with the plain wing. Calculations have indicated that the effect increases the percentage reduction in total take-off distance between that for the plain wing and that for the high-lift devices by a small amount. The wind gradient, the effect of which depends on the rate of climb, would usually be of greatest benefit to the plain-wing condition. Its effect is, however, less than that of the steady wind so that the overall effect of wind would slightly increase the advantage of the high-lift device.

It is interesting to note from figure 9, which shows the effect of the various devices on the separate phases of the take-off at a wing loading of 16.3, that practically all the difference between the total take-off distance with the flaps operating at their optimum angles and with the flaps neutral may be accounted for by the difference in ground run. Although the distance covered in the steady climb is less with the flap neutral than with the flap deflected to its best angle, the distance required in performing the transition is correspondingly greater so that in general, the distance covered from the instant the airplane leaves the ground until it attains an altitude of 50 feet is very nearly the same in either case. It should be remembered, however, that the flap angle giving the shortest total take-off distance will not ordinarily correspond to that giving the shortest ground run so that the maximum reduction in the ground run probably would not be a true indication of the maximum reduction in the total take-off distance.

CONCLUSIONS

1. Substantial reductions in the distance required by an airplane to take off and climb to an altitude of 50 feet should be possible through the use of flaps.

2. It is necessary to use the proper flap angle corresponding to a given loading condition in order to realize the greatest advantage to be gained with the flaps.

3. The optimum flap angles for take-off vary inversely as the power loading and in the same manner but to a much less extent with wing loading.

4. The flap arrangement for which the flap forms an extension to the main wing, as with the Fowler wing and external-airfoil flap, appears to provide the best characteristics for take-off.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 24, 1935.

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TABLE I

MINIMUM TOTAL DISTANCE IN FEET TO TAKE OFF AND CLIMB TO 50 FEET

Wing loading (W/S)			29.4	29.4	29.4	21.7	21.7	21.7	16.3	16.3	16.3
Power loading (W/hp.)			15.0	11.0	8.0	15.0	11.0	8.0	15.0	11.0	8.0
Maximum speed (V_{max})			194	221	245	176	202	225	160	181	205
Device	Flap angle degrees	$C_{L_{max}}$									
Plain wing	-	1.26	3410	2545	2065	2525	1840	1490	1875	1360	1080
Fowler wing	10	2.10	2550	1715	1360	1865	1260	985	1415	945	725
	20	2.50	2550	1610	1230	1810	1170	875	1375	865	645
	30	2.75	2785	1635	1155	1945	1170	820	1455	865	610
	40	2.83	3660	1780	1205	2455	1275	840	1740	930	625
Hall wing	10	1.63	3060	2110	1690	2235	1540	1240	1665	1145	905
	20	1.84	3560	2115	1595	2545	1520	1140	1835	1110	835
	30	1.95	14700	2495	1630	8330	1715	1165	3290	1230	850
Split flap	15	1.59	3010	2125	1715	2205	1565	1250	1670	1170	910
	30	1.87	3760	2105	1580	2585	1510	1130	1880	1110	835
	45	2.07	∞	2510	1590	13700	1740	1115	3535	1205	825
Balanced split flap	15	1.56	2875	2135	1740	2110	1550	1235	1570	1140	905
	30	1.78	2960	1985	1545	2135	1445	1120	1595	1065	820
	60	2.06	4770	2035	1495	2865	1460	1050	1940	1065	775
Plain flap	15	1.51	3050	2220	1795	2210	1605	1290	1660	1200	945
	30	1.70	3370	2160	1675	2460	1545	1205	1800	1150	873
	60	1.85	∞	2960	1810	10650	1905	1230	3370	1320	885
(Neutral)	-4	1.44	3055	2220	1840	2210	1620	1325	1685	1230	965
External-airfoil flap	20	2.55	2460	1575	1205	1760	1145	860	1330	850	640
	30	2.73	2920	1650	1205	2040	1195	835	1495	870	625
	40	2.76	4520	1860	1245	2765	1305	865	1900	935	640
Ideal wing	-	3.20	1775	1240	980	1305	915	695	1020	695	525

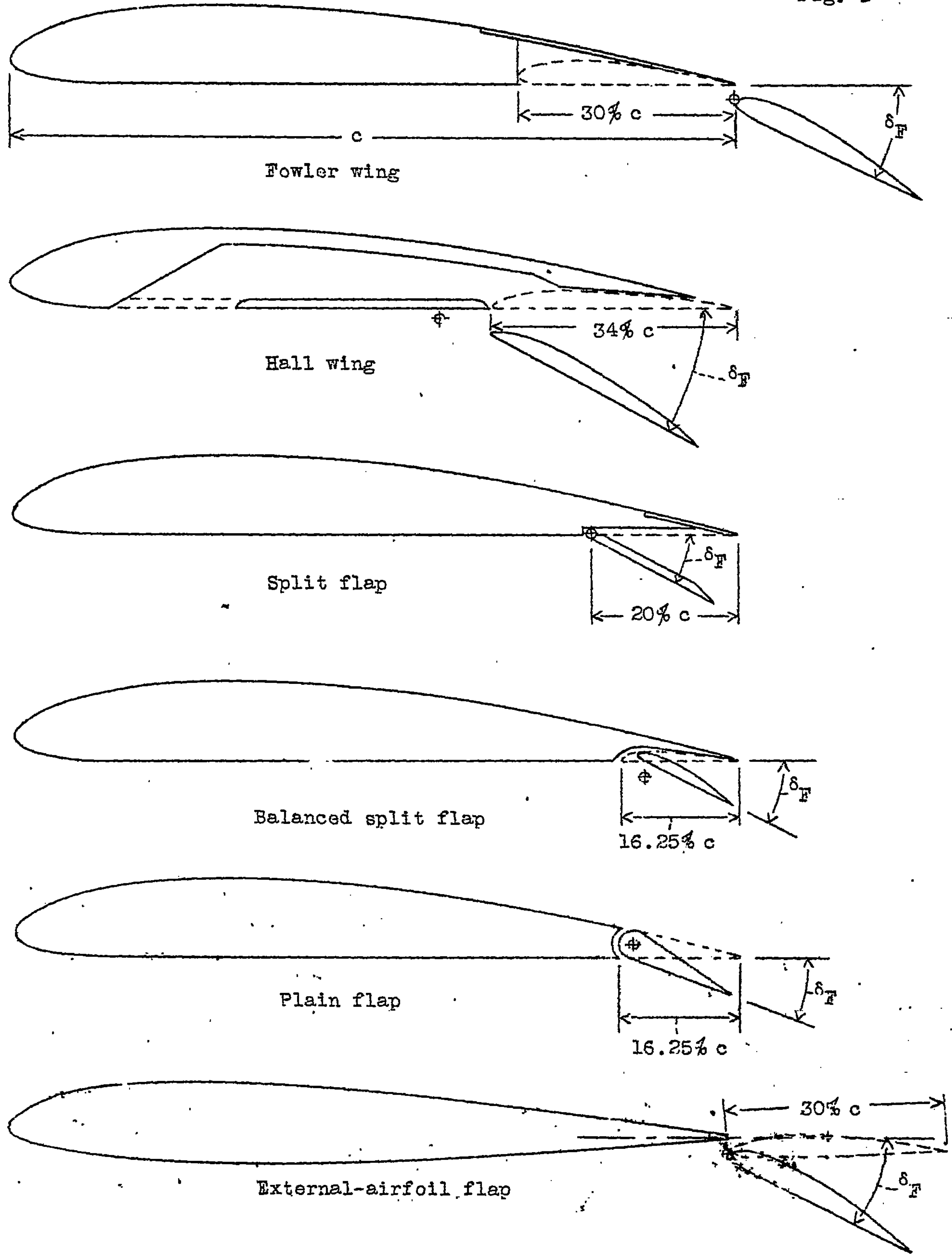

Figure 1.- Arrangement and dimensions of the various types of flaps.

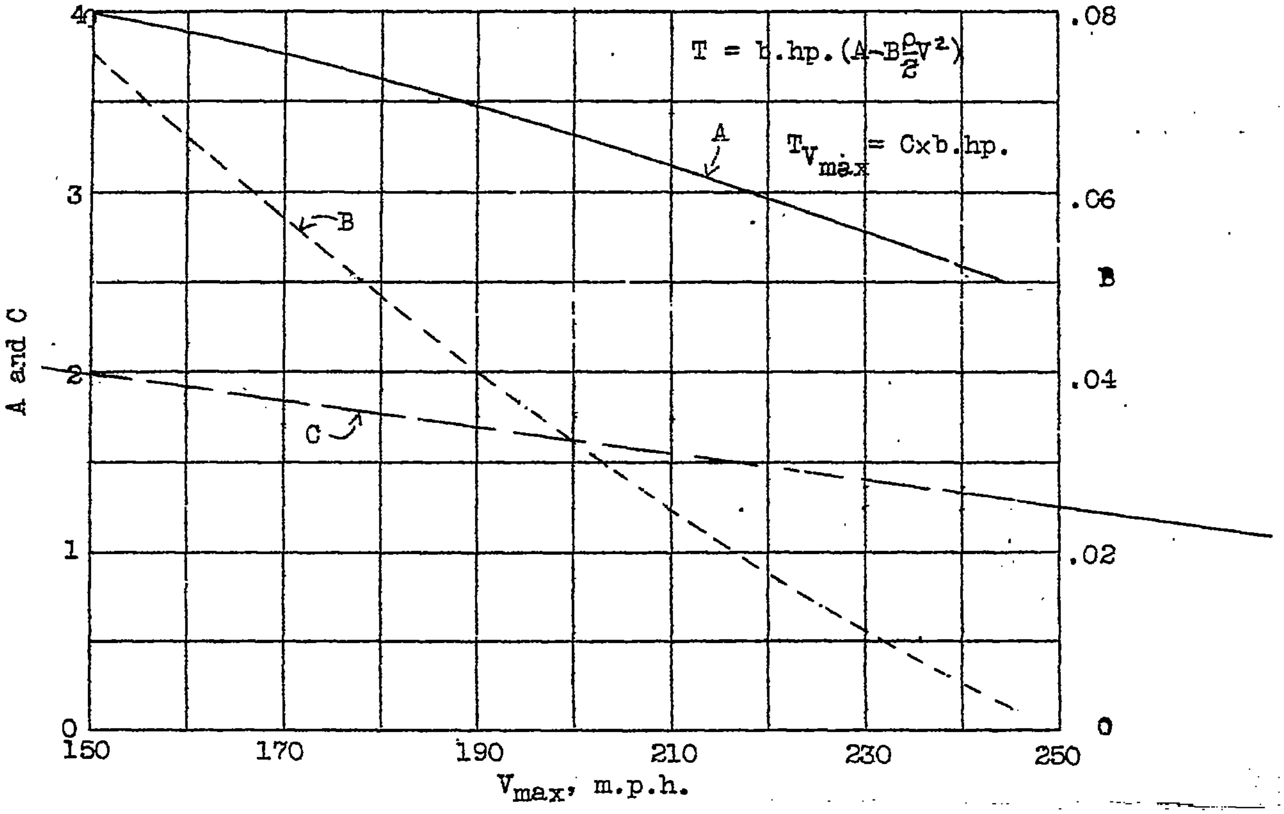

Figure 2a.-Thrust relations for automatic propellers.

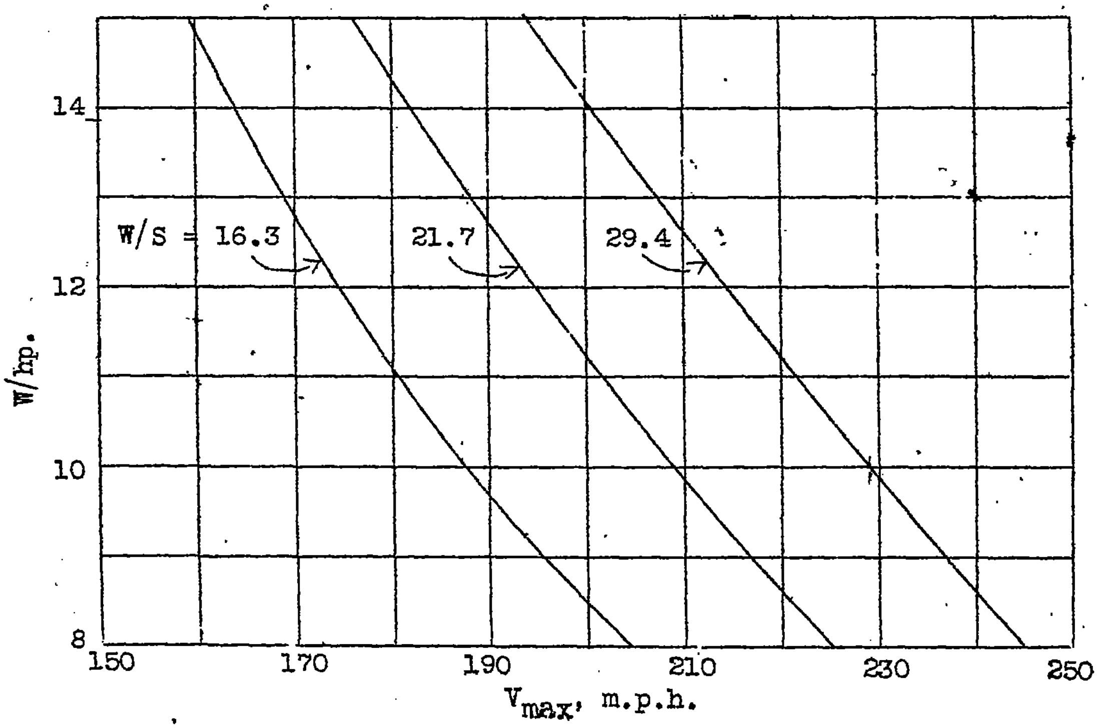

Figure 2b.- Relation between wing loading, power loading, and maximum speed.

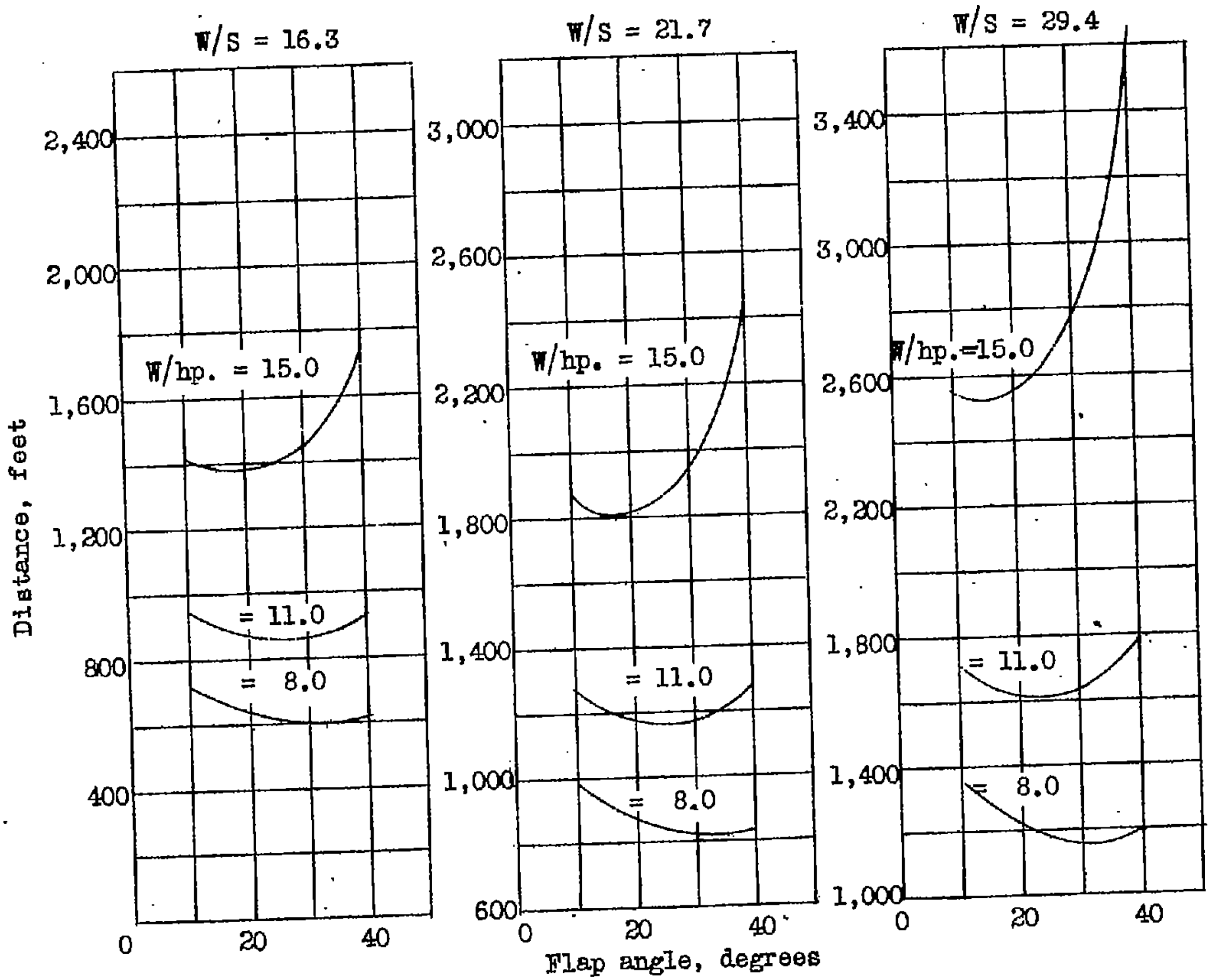

Figure 3.-Variation of total take-off distance with flap angle for the Fowler wing.

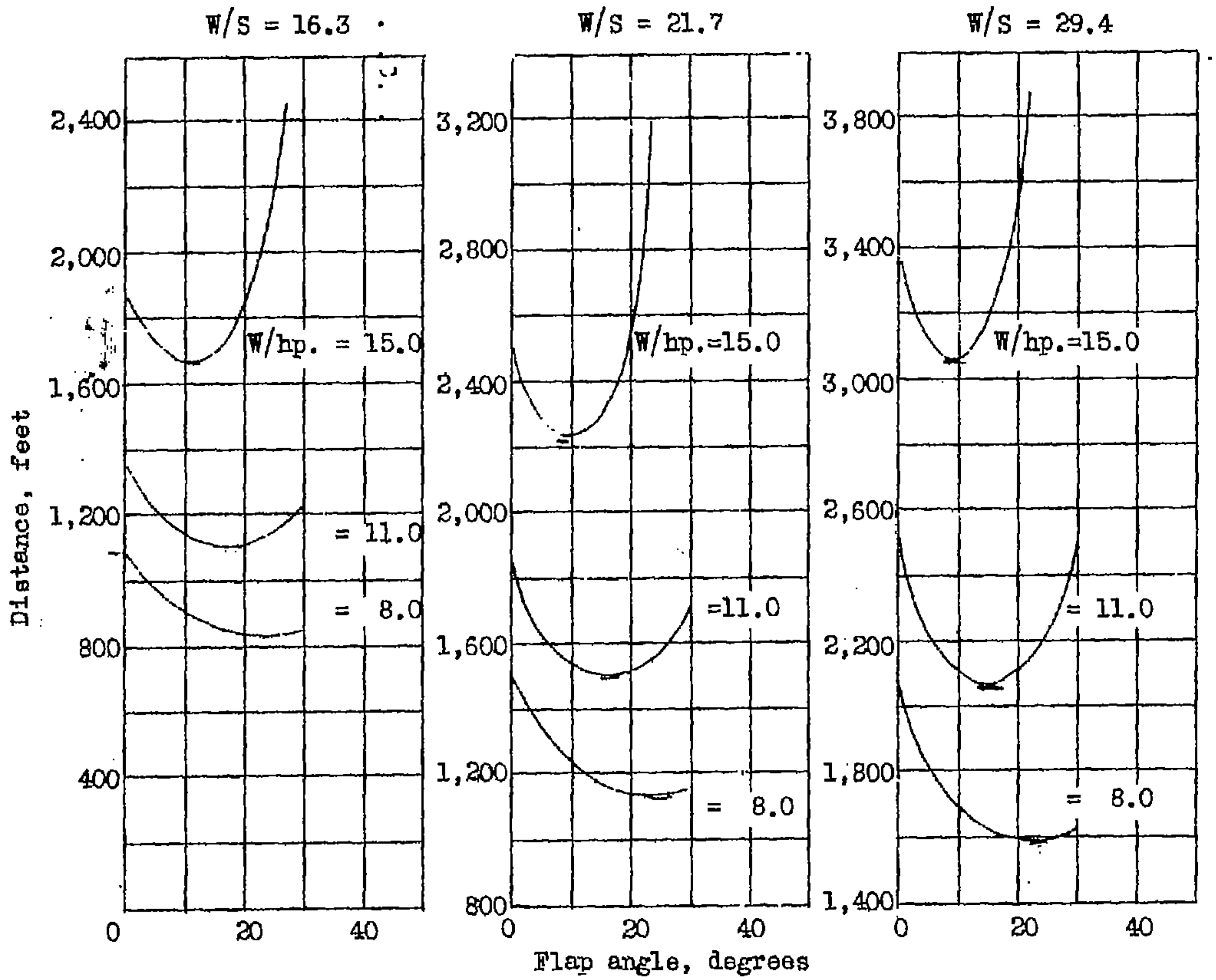

Figure 4.-Variation of total take-off distance with flap angle for Hall wing.

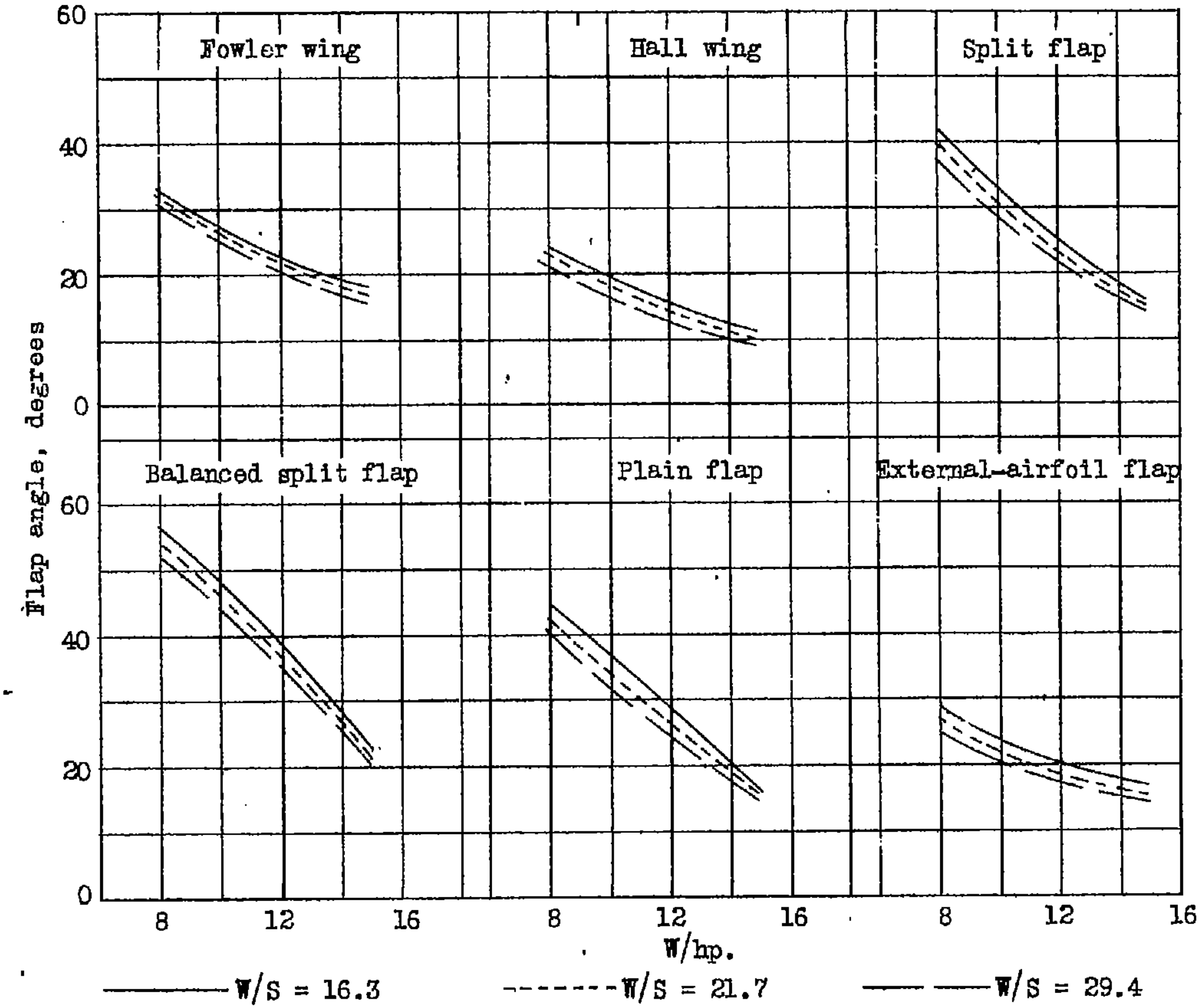

Figure 5.-Variation of best flap angle with power loading W/hp. and wing loading W/S.

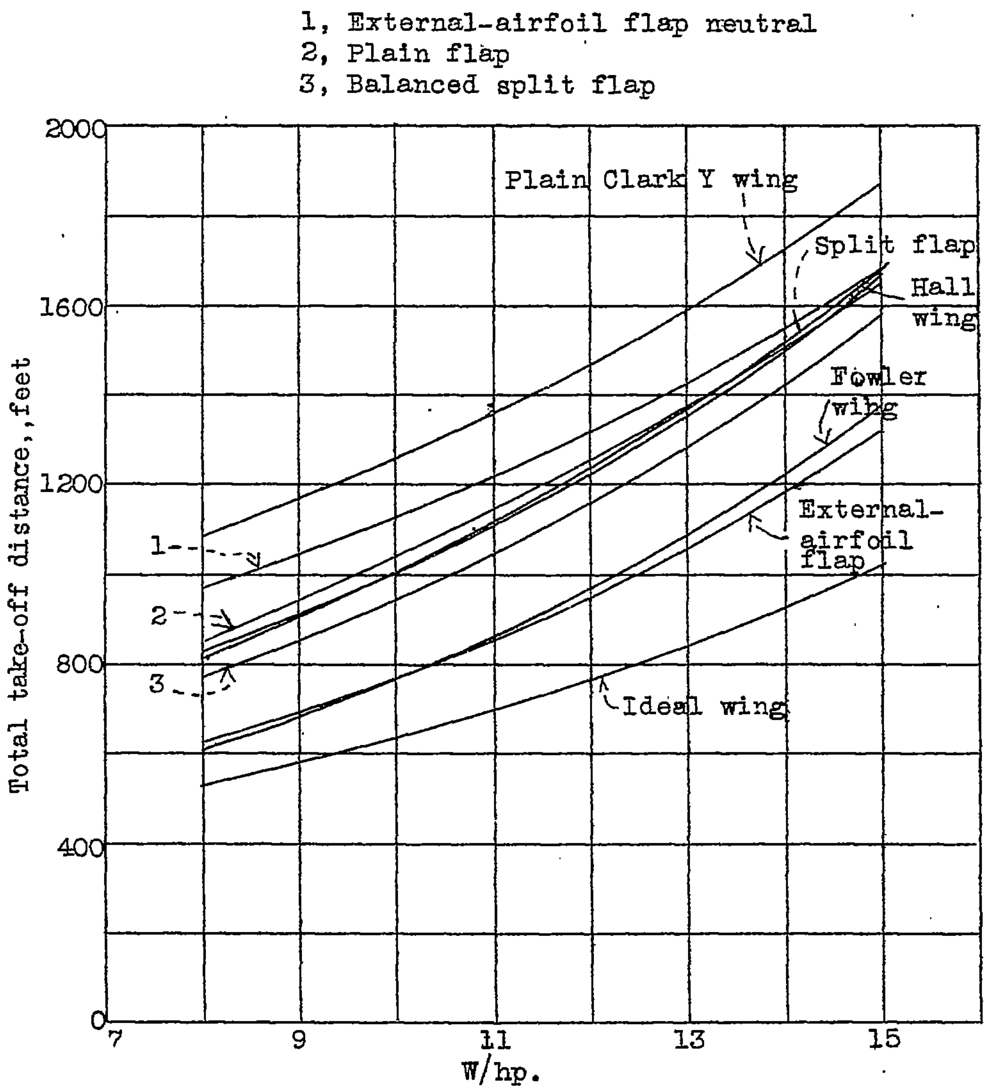

Figure 6.-Variation of total take-off distance at best flap angle with power loading. (Wing loading, W/S = 16.3)

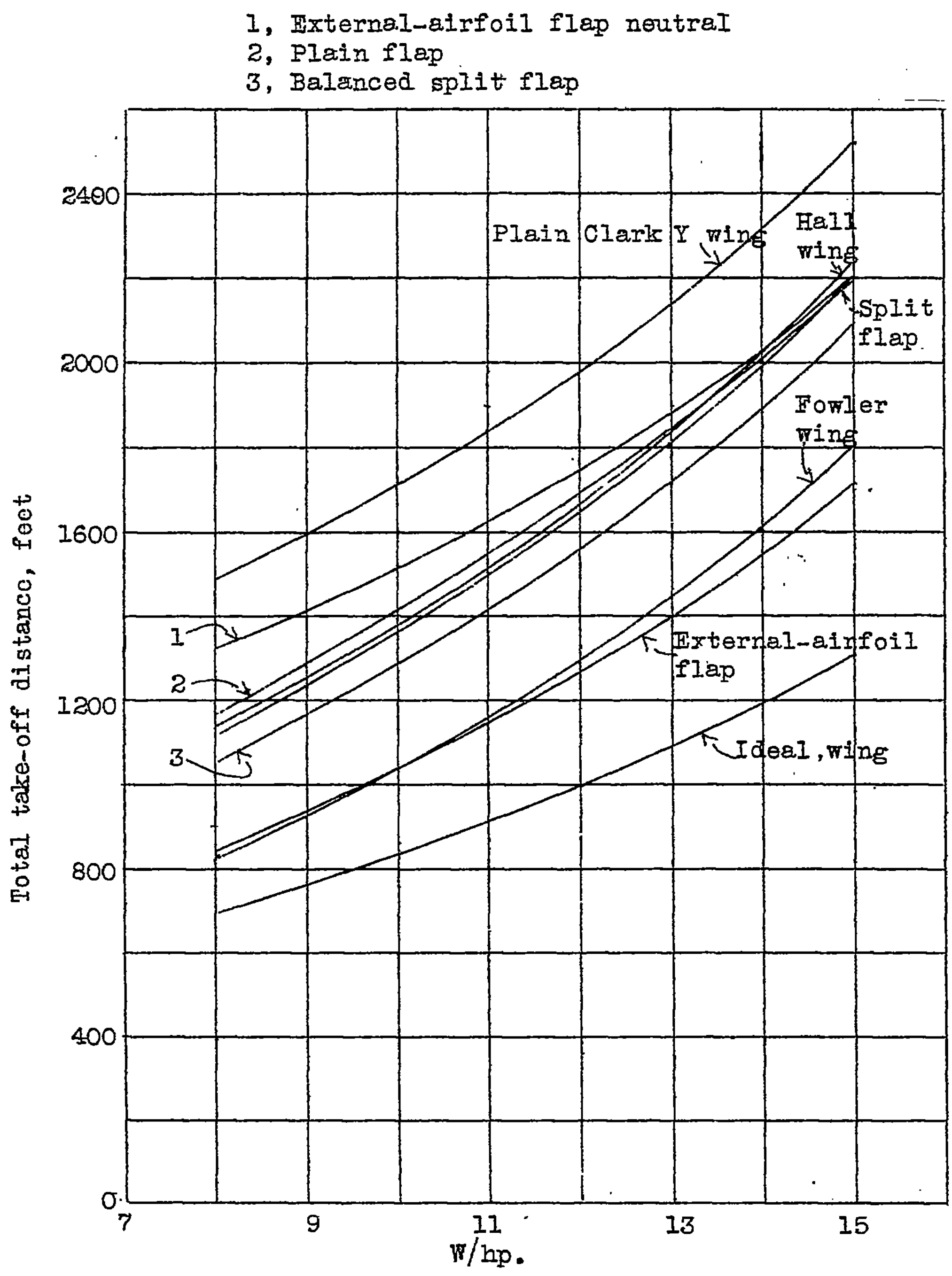

Figure 7-Variation of total take-off distance at best flap angle with power loading. (Wing loading, W/S = 21.7)

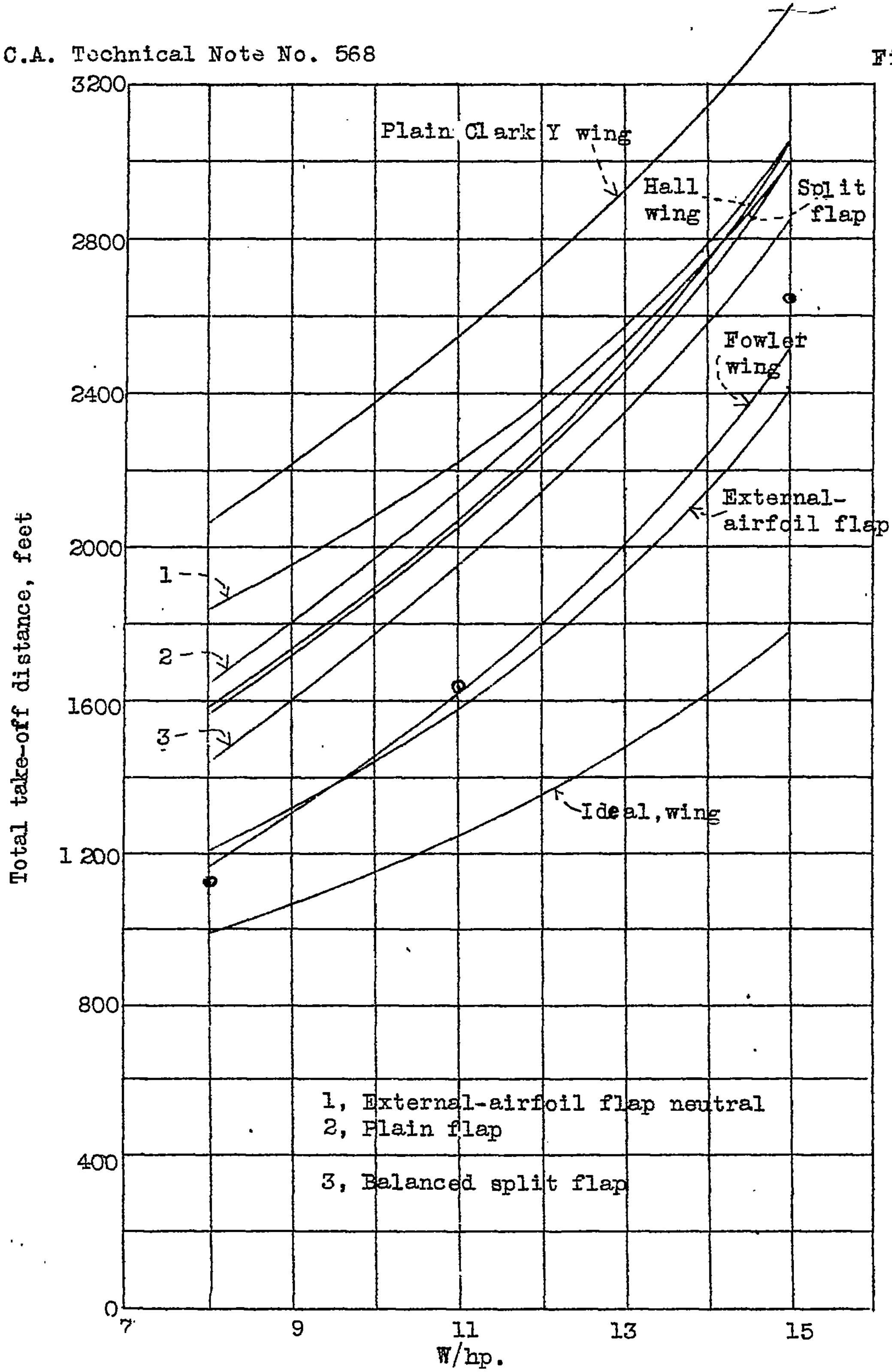

Figure 8.-Variation of total take-off distance at best flap angle with power loading. (Wing loading, W/S = 29.4)

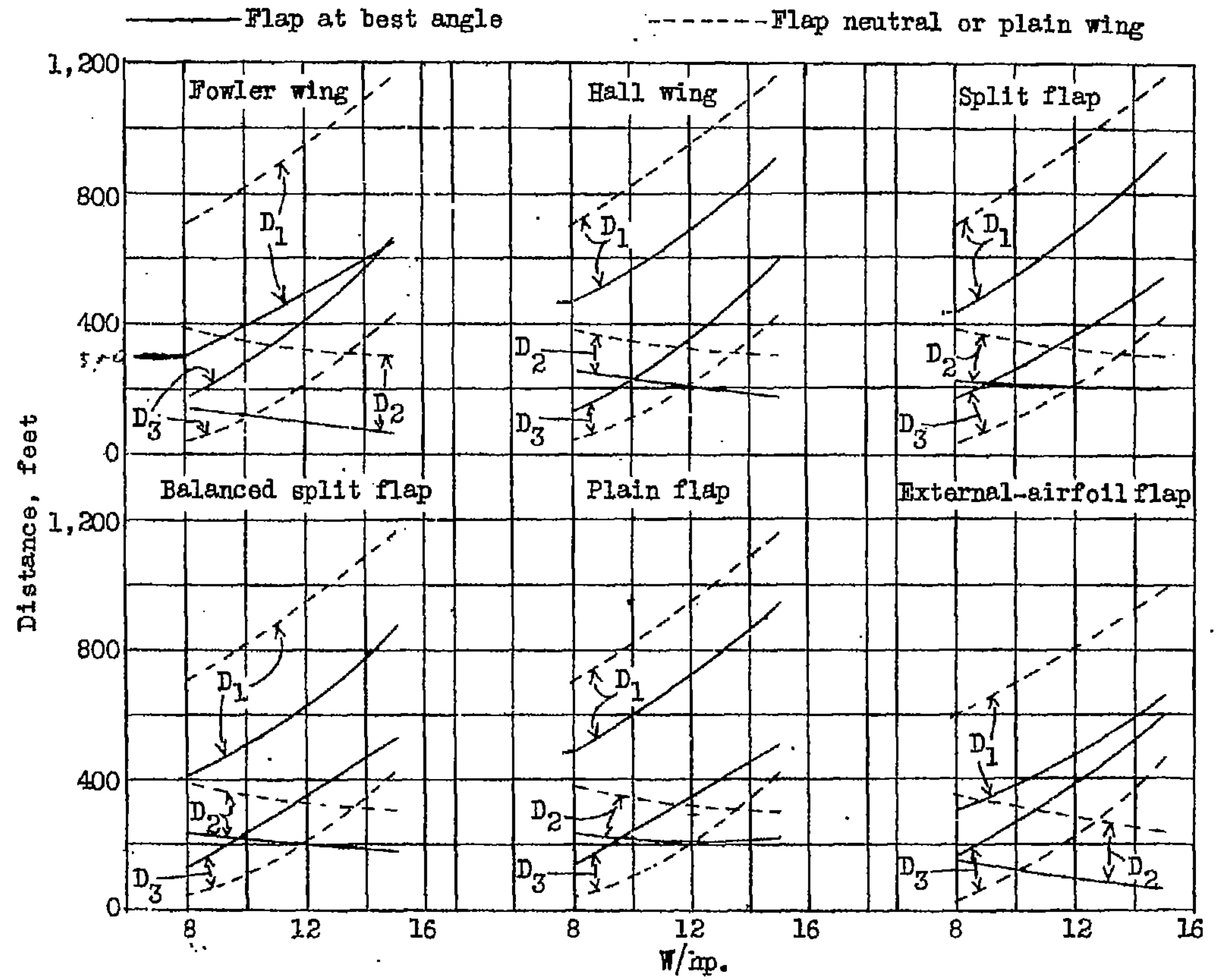

Figure 9.-Variation of distance covered in the different phases of the take-off at best flap angle with power loading. (Wing loading, W/S = 16.3).