TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 216

VARIABLE PITCH PROPELLER.

By Enrico Pistolesi.

From L'Ala d'Italia, March-April, 1923.

July, 1923.

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VARIABLE PITCH PROPELLER.*

By Enrico Pistolesi.

The importance of the variable +itch propeller is due to the well-known fact that a constant pitch propeller is adapted to only one flight condition or, at most, to a very restricted range. If, for example, a propeller is adapted for horizontal flight at sea-level, it is not perfectly adapted for climbing nor for flight at a higher altitude.

The disadvantage of such imperfect adaptation is more or less serious, according to the engine employed and the altitude range. It is least for normal engines (without supercharger), the power of which decreases with decreasing air density, small for an airplane with a low altitude limit and greater for an airplane with a high altitude limit.

The imperfect adaptation is usually manifested by variations in the revolution speed (R.P.M.) of the engine, i.e. a propeller, capable of giving the normal R.P.M. under one condition of flight, gives too many or too few R.P.M. under other flight conditions. In the former case, the fuel consumption, and consequently the engine torque, must be reduced by bringing the angular velocity of the engine within suitable limits. In the latter case, the low R.P.M. cannot be increased in any way. In either case, there is a

* From L'Ala d'Italia, March-April, 1923, pp. 65-71.

loss of available power, because one of the two power factors, Q and Ω, is smaller than what the engine is able to furnish. (Q indicates the engine torque and Ω the angular velocity.)

For obviating this disadvantage, there are only two means available: either to vary the R.P.M. of the propeller by means of a gear shift, as in an automobile, or by varying the shape of the propeller, so as to adapt it to the changing speed of the airplane.

The former method presents manifest disadvantages, not only due to the weight and complexity and the necessity of disengaging the propeller for every change of the power transmission ratio, but especially because it would result in erratic undulating flight. There is today no mechanical device capable of effecting a gradual change in speed, without loss of power.

The latter method has the advantage of greater simplicity and perfectly uniform acceleration, which enables an almost perfect adaptation of the propeller to the airplane under all conditions of flight. The shape of a propeller may be altered by varying the diameter or pitch or the width of the blade.

The last-named method is by far the most difficult and is therefore not generally taken into consideration, though it has been demonstrated that the most perfect theoretical solution of the problem of adaptation would be by means of the simultaneous and coordinated variation of the diameter and pitch. Attempts have been made to vary the width of the blade by means of two propellers on the same shaft so adjusted that one may partially cover the other.

Doubtless, however, the best solution is by varying the pitch, which is accomplished by rotating the propeller blades about their longitudinal axis.

If β designates the angle of attack of any given section of the blade in its normal position, the angle of attack, after the blades have been rotated through an angle of ϵ in either direction about their longitudinal axis, will be $\beta \pm \epsilon$. Since the pitch P_R of the given section, with reference to the radius R, is

$$P_R = 2 \pi R \tan \beta,$$

the pitch in the new position will be

$$P'_R = 2 \pi R \tan (\beta \pm \epsilon).$$

Even if P_R were the same for all sections (uniform pitch propeller), it would not hold true for P'_R. It has, however, been demonstrated that the total pitch, after the rotation of the blades, may be assumed to be approximately the pitch of the section at 0.7 of the radius.

Varying the pitch, therefore, puts us in possession of a whole set of propellers, all having the same diameter but different pitches.

I will avoid long calculations, and will endeavor to show the advantage offered by variable pitch with the aid of diagrams representing graphically the results of the calculations.

For this purpose, I have taken, as my starting point, propeller No. 96 of the National Advisory Committee for Aeronautics, experimented on by W. F. Durand and E. P. Lesley in the aerodynamic laboratory of Leland Stanford University. The results were published in the N.A.C.A. reports No. 30 (Experimental Research on Air Propellers II, 1919) and No. 141 (Experimental Research on Air Propellers V, 1922).

This propeller has the following characteristics: blade of uniform width and equal to 0.15 R, with flat-faced sections (one of the most common for propellers and very efficient) and a uniform pitch ratio of 0.7 in the standard setting. Aside from this setting, the propeller was tested at -6°, -4°, $+4^\circ$, 8°, 12°, 16°, 20°, considering as positive the angles corresponding to an increase in pitch.

Figure 1 gives the functional diagrams τ and κ the propeller in the various positions, being

$$\tau = \frac{T}{\rho\ R^4 \cdot \Omega^2}$$

$$\kappa = \frac{C}{\rho\ R^5\ \Omega^2} = \frac{P}{\rho\ R^5\ \Omega^3}$$

in which T is the thrust, C the torque, P the power (in kg-m/sec), ρ the density of the air, R the radius of the propeller, Ω the angular velocity. The coefficient of velocity is taken as the abscissa

$$\gamma = \frac{V}{R\ \Omega}$$

in which V is the velocity of the airplane in m/sec. The coefficients τ, κ and γ are non-dimensional.

For example, let us assume that the propeller has a diameter of 2.8 m (9.2 ft), and that the engine furnishes a torque Q, which, for simplicity, we will consider constant and equal to 150 kg-m (1085 lb-ft)* with a maximum normal** R.P.M. of 1700. The power corresponding to the above values of Ω and Q is 356 HP.

Fig. 2 shows how the R.P.M. (N) varies with the velocity (V) for a constant pitch propeller with a rotation angle of zero. At sea-level it ranges from 1470 R.P.M. at 80 km/hr (49.7 mi/hr), to 1890 R.P.M. at 240 km/hr (149 mi/hr).

For other altitudes, everything depends on the law of decrease of the engine torque Q with increasing altitude. If the engine torque at sea-level is designated by Q_0 and a decreasing function of the altitude by μ, we have $Q = Q_0 \mu$.

For the purpose of this investigation, we have taken into consideration two diverse cases: the first, ("motore normale,") is the case of the normal engine for which it is assumed that the torque diminishes according to a function of the relative density δ, which coincides in form with the law of decrease of the relative pressure in standard atmosphere. In this case $\mu = \delta^{1.235}$.

We then have:

Altitude ft	0	13123	26247	39370
Altitude m	0	4000	8000	12000
δ	1	0.669	0.429	0.253
μ	1	0.609	0.352	0.192

*The variability of the engine couple with the R.P.M. causes no important change, but only a slight complication in the research work and its results.

**That is to say, it can only be slightly exceeded for a very short period of time.

The second case is that of a supercharged engine. We might have taken the limiting case in which the engine torque remains constant for variations in the altitude, but we considered it more practical and instructive to assume that, by the effect of the supercharging, the torque at 12000 m (39370 ft) is reduced only to one-half, instead of to one-fifth, as for the normal engine. We then have:

Altitude ft	0	13123	26247	39370
Altitude m	0	4000	8000	12000
δ	1	0.669	0.429	0.253
μ	1	0.900	0.750	0.500

Thus, we see, in Fig. 2, that at an altitude of 12000 m (39370 ft), for example, the R.P.M. ranges from 1290 at 80 km/hr (49.7 mi/hr), to 1610 at 200 km/hr (124.3 mi/hr) for a normal engine, and from 2050 R.P.M. at 80 km/hr (49.7 mi/hr) to 2340 at 240 km/hr (149 mi/hr), for a supercharged engine. With a supercharged engine, even at an altitude of only 8000 m (26247 ft) the R.P.M. is excessive, ranging from 1925 at 80 km/hr (49.7 mi/hr) to 2240 at 240 km/hr (149 mi/hr).

This already demonstrates the truth of our contentions. Of course, in order to keep the R.P.M. below the 1700 limit, it is necessary to diminish the engine torque by throttling, which causes considerable loss of power. By varying, instead, the pitch of the propeller, the R.P.M. is kept normal, without diminishing the engine torque and, consequently, without loss of power.

In order, however, to make the demonstratiom clearer, it is thought best to calculate in four cases (1. normal engine with fixed pitch propeller; 2. normal engine with variable pitch propeller; 3. supercharged engine with fixed pitch propeller; 4. supercharged engine with variable pitch propeller) the flight data of a hypothetical airplane with the following characteristics:

Full load $W = 2500$ kg (5511.6 lb)

Wing area $S =$ 53 sq.m (570.5 sq.ft)

which gives a wing loading of 47.2 kg/m² (9.67 lb/ft²) and a load of 7 kg (15.4 lb) per HP.

The polar of the airplane is shown in Figs. 3 and 4, in which the ordinates and abscissas are respectively

$$R_y = \rho_o \, S \, X_y \qquad\qquad R_x = \rho_o \, S \, X_x$$

Together with the polar of the airplane, there is traced, in various cases and for various altitudes, the polar of the propeller, which serves as a basis for the calculation of the flight data of the airplane, by a method published by us in 1919* and which has been again proposed (with some further elaborations, but with less accuracy and less general applicability) by G. Delanghe in an article in "Technique Aeronautique."**

The polar of the propeller is a curve which has for abscissas the values of T/V^2 and for ordinates the values of W/V^2.

* "Teoria e costruzione delle eliche." Lectures delivered in a course for aeronautic designers at the Turin Polytechnic Institute under the auspices of the "Direzione Sperimentale Aviazione," Rome, 1919, pp. 175 and following.

** A new nomogram for utilizing directly the polar of an airplane for calculating its performances. Technique Aeronautique, December 15, 1922.

If the engine gives a constant torque, as we have assumed, the passage from one altitude to another is made simply by multiplying the polar ordinates by $1/\mu$. This holds true for a fixed pitch propeller and when the R.P.M. is not subject to limitations.

When the propeller has a fixed pitch, but the R.P.M. is limited and, as in the case under consideration, is kept constant above a certain altitude by varying the engine torque, there is, for every value of γ, at whatever altitude, a corresponding value of V and hence the abscissas and ordinates of the polar of the propeller are simply proportional to $1/\delta$.

If the propeller has a variable pitch, it will first be necessary to trace, in the field of the characteristic curves of Fig. 1, the curves which join the points of the τ curves corresponding to the points of equal ordinates of the κ curves.

In other words, for any given R.P.M., at any altitude, there is a definite value of the coefficient of torque κ and, consequently, for every angle of attack of the propeller, there is a definite value of τ. The curves designated in Fig. 1 by the symbol τ^* were thus traced. Curves are here traced for altitudes of 0, 4000, 8000 and 12000 meters in standard atmosphere, both with a normal and a supercharged engine. The τ^* curves descend as the altitude increases for a normal engine, since the number of R.P.M. tends to decrease, and ascend for a supercharged engine, because the number of R.P.M. tends to increase.

This being the case, there is, for every value of V at any altitude, a corresponding value of $\gamma = V/R\,\Omega$, and, consequently, of τ^* and T. It is therefore possible to trace the polar of the propeller in various cases.**

Regarding the use of this polar, we will mention briefly:

1. The intersection of the polar of the propeller, for a given altitude, with the polar of the airplane corresponds to horizontal flight at the given altitude.

2. The altitude limit (ceiling) is the altitude at which the polar of the propeller becomes tangent to the polar of the airplane.

3. For any point of the polar, the speed of the airplane at that angle of attack and at the given altitude is obtained: by drawing from the chosen point the parallel to the axis of the abscissas until it meets the polar of the propeller (Fig. 3); by drawing from the latter point the perpendicular to the axis of the abscissas; and, lastly, by connecting the foot of this perpendicular with the chosen point on the polar of the airplane. The angle formed by this connecting line and the perpenducular to the axis of the abscissas is the angle of climb φ. The speed along this path is determined by the value of R_y. The vertical velocity is the product of the speed on the trajectory multiplied by $\tan \varphi$.

In this manner the flight data were calculated in the four cases under consideration and the results are represented graphically in Fig. 5.

It is known, even with normal engines, that the advantages of

** The numbers inscribed on the polars of the propeller in Figs. 3 and 4, as also the values of γ, are the values $V/ND = \pi \gamma$, derived in a very direct manner from the results of the American experiments.

using a variable pitch propeller are considerable, there having been obtained: an increase of 10 km/hr (6.2 mi/hr) in horizontal speed at low altitudes (between 198 (650) and 208 meters (682 ft)); an increase of 0.4 m/sec (1.31 ft/sec) (from 3.7 to 4.1) in climbing speed at low altitudes and of 0.25 m/sec (.82 ft/sec) at 4000 meters; and a raising of the altitude limit by 300 m (984 ft) (from 5200 (17060) to 5500 meters (18045 ft)). The climbing times were affected as follows:

To	1000 m 3281 ft	From	5' 3"	to	4' 32"	Gain	0' 31"
"	2000 m 6562 ft	"	11' 33"	"	10' 24"	"	1' 9"
"	3000 m 9842 ft	"	20' 54"	"	18' 36"	"	2' 18"
"	4000 m 13123 ft	"	36' 54"	"	31' 24"	"	5' 30"
"	4500 m 14764 ft	"	51' 24"	"	41' 36"	"	9' 48

As regards the horizontal speed at various altitudes, they coincide in the two cases at an altitude of about 3900 meters (12795 ft), above which there is an increasing advantage in favor of the variable pitch propeller amounting to 8 km/hr (4.96 mi/hr), (from 167 to 175 km/hr) at 5000 meters (16404 ft). The advantages would be greater for a swifter airplane with a higher ceiling.

The advantages are very evident with a supercharged engine. Any comment would be superfluous, since the diagrams speak for themselves.

If, for the sake of comparison, we simply take the horizontal speed at 7000 meters (22966 ft), which is 166 km/hr (103 mi/hr), (the maximum speed obtainable with a supercharged engine and variable pitch propeller), we find that the ceiling passes from 7200 meters (23622 ft) to 9950 meters (32644 ft) and the climbing times are affected as follows:

To	1000 m / 3281 ft	From	4' 38"	to	4' 11"	Gain	0' 27"
"	2000 m / 6563 ft	"	9' 20"	"	8' 41"	"	0' 39"
"	3000 m / 9842 ft	"	14' 36"	"	13' 36"	"	1' 0"
"	4000 m / 13123 ft	"	20' 30"	"	19' 0"	"	1' 30"
"	5000 m / 16404 ft	"	29' 0"	"	25' 6"	"	3' 54"
"	6000 m / 19685 ft	"	44' 6"	"	32' 18"	"	11' 48"
"	7000 m / 22966 ft	"			40' 36"		

The diagrams of Fig. 5 furnish the material for many interesting remarks, but we shall purposely abstain from them, in order not to lengthen this article unnecessarily.*

Thus far we have spoken principally of airplanes, but the utility of variable pitch propellers for airships is no less evident. The latter have a greater range of speeds than airplanes and hence everything that has been said in connection with air-

* It is noted that the commonly accepted hypothesis of a proportional variation of climbing speed with altitude differs considerably from the results of strict calculation.

planes applies all the more forcibly to airships. Moreover, the utility of variable pitch propellers for airships is demonstrated, as it were, by historical considerations, by the fact that the first Italian variable pitch propellers were employed on airships. Of course, in the adoption of variable pitch propellers on airships there was some uncertainty, fully warranted at that stage of technical aeronautics, regarding the pitch required for the perfect adaptation of propellers to airplanes, but this has nothing to do with the evident utility of the propeller itself. We may say, rather, that it shows another advantage, very practical but not negligible on this account. This is the possibility of avoiding, by its own means, the necessity for the repeated attempts to adapt the propeller to the airplane, which are still often necessary, notwithstanding the progress already made.

Our airships, variable pitch propellers (of metal) were also used for reversing the pitch and thus obtaining a negative or retarding thrust. Would a similar application on airplanes be desirable? Such use would offer the following advantages:

a) The possibility of stopping the airplane soon after it touches the ground and, consequently, of reducing the size of the landing field and of facilitating emergency landings;

b) The possibility of further reducing the necessary landing space by artificially reducing the fineness ratio of the airplane.

In order to appreciate this point, it is necessary to remember that very "fine" airplanes must volplane at a small angle, in order not to acquire too great speed. This requires a long space free from obstructions (hills, tall buildings, etc.) around the field. Aside from this, after an airplane has flattened out and begun horizontal flight over the field, before landing, if its drag is very small, it requires a long time (and a correspondingly long distance) before its speed is sufficiently reduced to enable landing.

It follows, from these simple considerations, that, in order to facilitate landing, ability to create drag would be very useful, not only at the instant of landing, but also during the preceding descent.

In order to create such a drag, there are various possible methods, as, for example, surfaces ordinarily concealed in the fuselage and disposed in the direction of the wind, which are exposed at the right moment in the direction perpendicular to the wind.*

One invention (that of Col. Buongiovanni) reverses the direction of rotation of the propeller, requiring clock-work and a friction joint. The method, however, which best combines simplicity and efficacy, appears to be the reversal of the propeller pitch.

Naturally, it is necessary to consider the case in which the pilot finds himself obliged, at the last moment, to give up landing, because of the sudden appearance of some obstacle. It then becomes necessary to restore the normal pitch at once. This can be done by the engine itself through some suitable mechanism, not difficult to apply, while the reversal, not being so urgent, can be effected by hand.

*The editor of the aeronautic department of this magazine, "Piero Magni," has invented a device of this kind.

The chief disadvantages are: the influence of the negative thrust on the longitudinal stability* and aerodynamic characteristics of the airplane. In other words, the pilot feels that he has under his control an airplane aerodynamically different. This may cause disadvantages. Like other disadvantages, they may result from insufficient promptness in restoring the pitch in case of need.

It seems to us that all such disadvantages would be eliminated by the proper training of the pilots and that, in any event, the advantages would constitute an ample compensation.

In order, however, to have a propeller capable of functioning well with reversed pitch, it would be necessary to take special precautions, both in the distribution of the pitch at various distances from the axis and in the shape of the sections, for which the double convex shape would be well suited (Fig. 6).

It should, however, be noted that the double convex shape has the disadvantage of slightly reducing the efficiency of the propeller when functioning in normal pitch. It is known that such a retarding force can attain high values, even to half the weight of the airplane. This tends to prevent excessive speeds in diving and constitutes, therefore, an additional element of safety.

This retarding force, which can be shown to be almost independent of the pitch and largely dependent on the diameter, width of blade and <u>shape of the sections</u>, is greatest when the profile of the sections is such as to give the highest values of drag with

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* This is a question of increasing the already existing instability of the airplane in which the center of gravity lies outside the line of thrust, when the engine is accelerated or retarded.

relation to the value of the thrust; in other words, high values of X_x for $X_y = 0$. Such are the strongly cambered concaved-convex sections. The double convex sections, especially when symmetrical, yield, on the contrary, the minimum retarding force. This disadvantage would be offset, however, by the possibility of obtaining the desired retarding force by reversing the pitch.

In any event, the foregoing discussion shows the importance of the aerodynamic problems connected with the use of propellers of variable and possibly reversible pitch.

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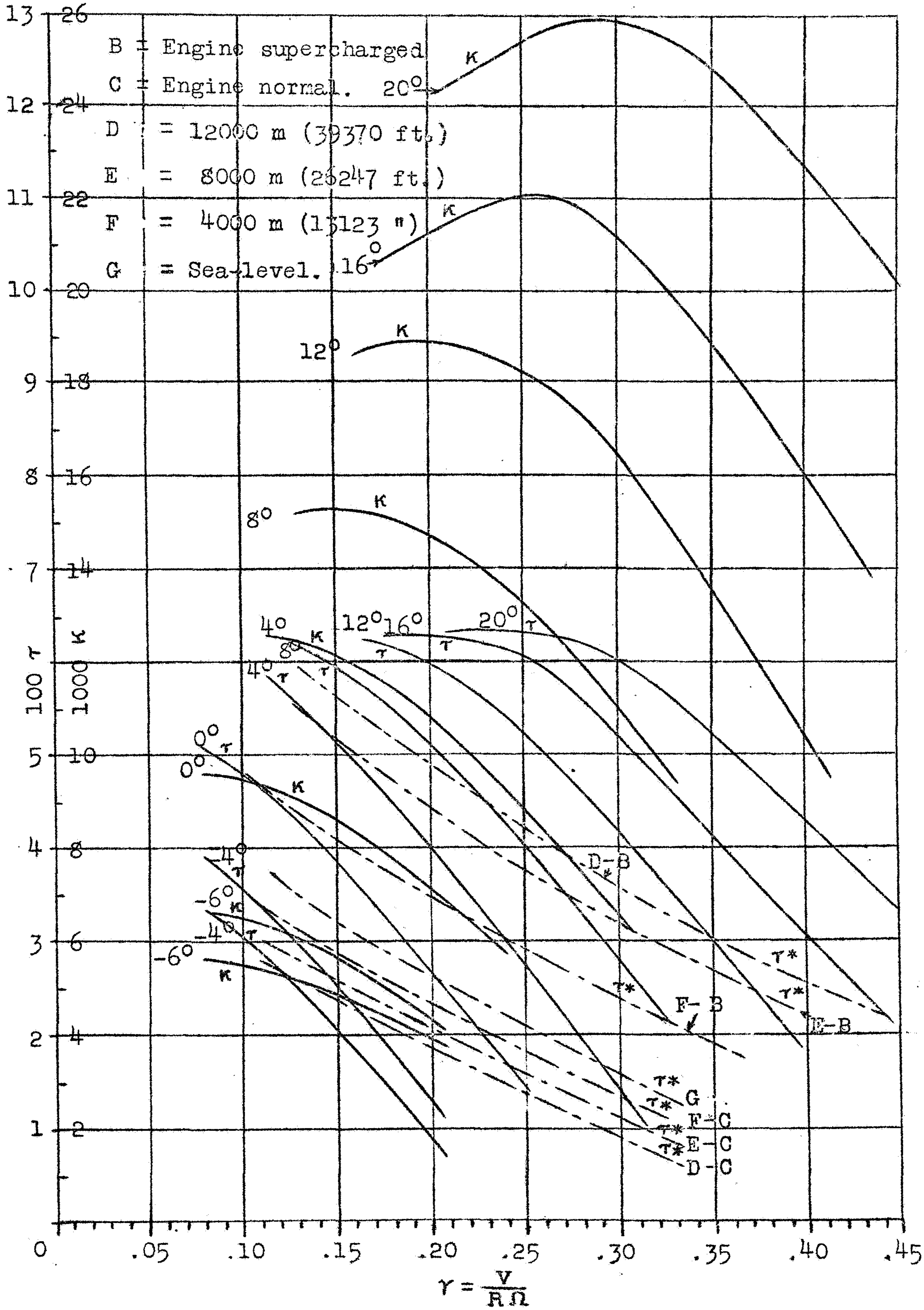
B = Engine supercharged
C = Engine normal.
D = 12000 m (39370 ft.)
E = 8000 m (26247 ft.)
F = 4000 m (13123 ")
G = Sea-level.
20°
16°
12°
8°
4°
0°
-4°
-6°
κ
τ
τ*
D-B
F-B
E-B
G
F-C
E-C
D-C
100 τ
1000 κ
13
12
11
10
9
8
7
5
4
3
2
1
0
26
24
22
20
18
16
14
10
8
6
4
2
.05
.10
.15
.20
.25
.30
.35
.40
.45
$\gamma = \frac{V}{R\Omega}$

Fig.1.

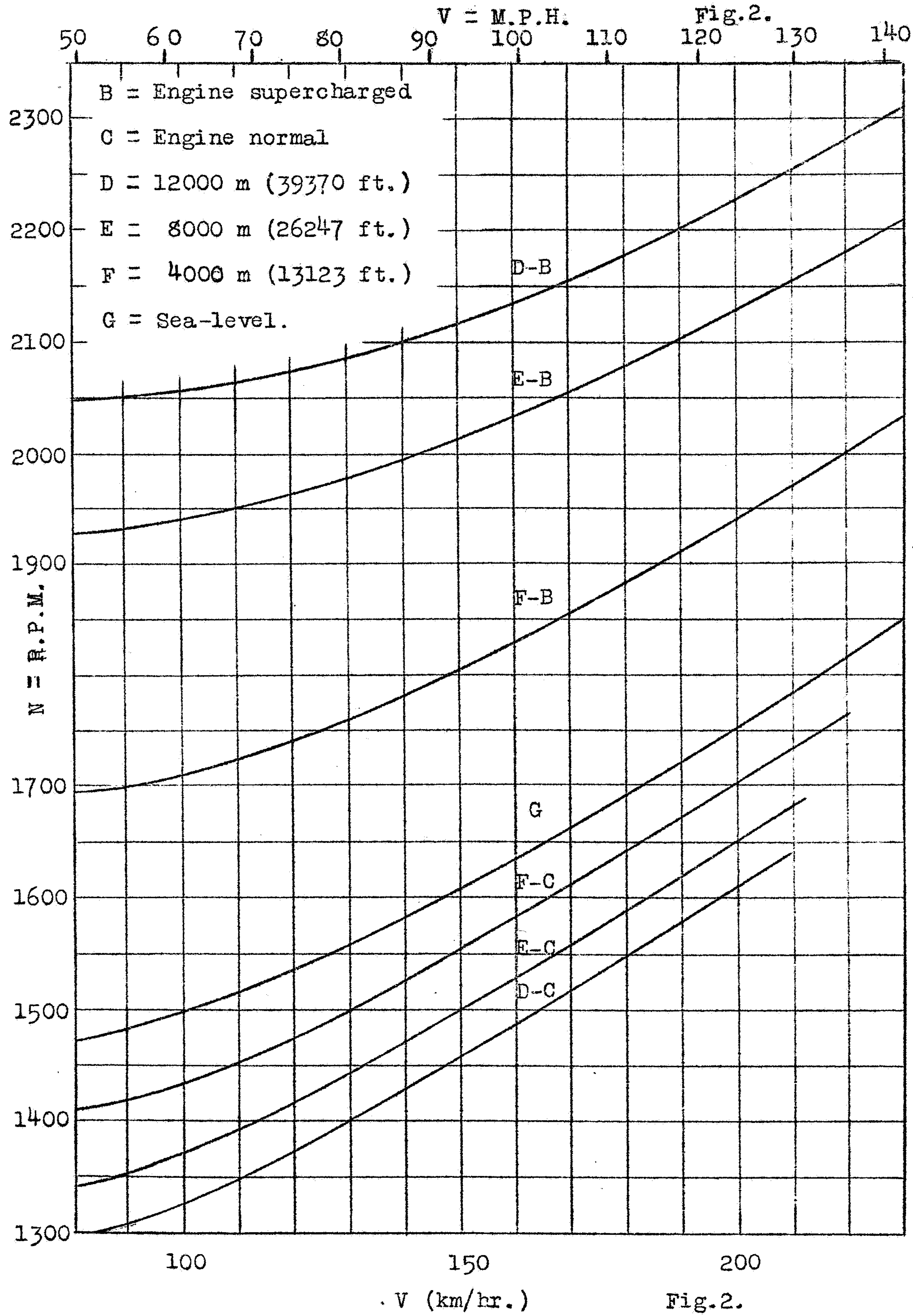
V = M.P.H.
50
60
70
80
90
100
110
120
130
140
B = Engine supercharged
C = Engine normal
D = 12000 m (39370 ft.)
E = 8000 m (26247 ft.)
F = 4000 m (13123 ft.)
G = Sea-level.
D-B
E-B
F-B
G
F-C
E-C
D-C
N = R.P.M.
2300
2200
2100
2000
1900
1700
1600
1500
1400
1300
100
150
200
V (km/hr.)

Fig.2.

Fig. 3.

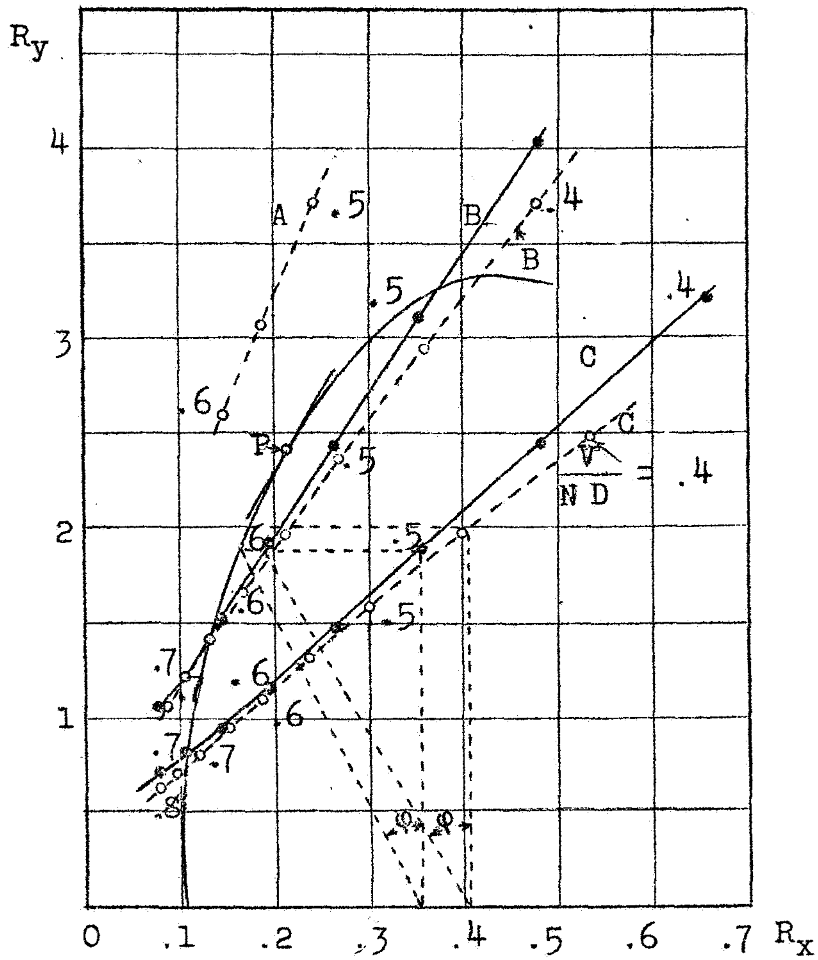

Fig. 3. Cases 1 & 2 normal engine.

A = 8000 m. (26247 ft.)

B = 4000 m. (13123 ft.)

C = Sea-level

——————• Fixed pitch propeller

- - - - - - -o Variable pitch propeller

Figs.4. & 6.

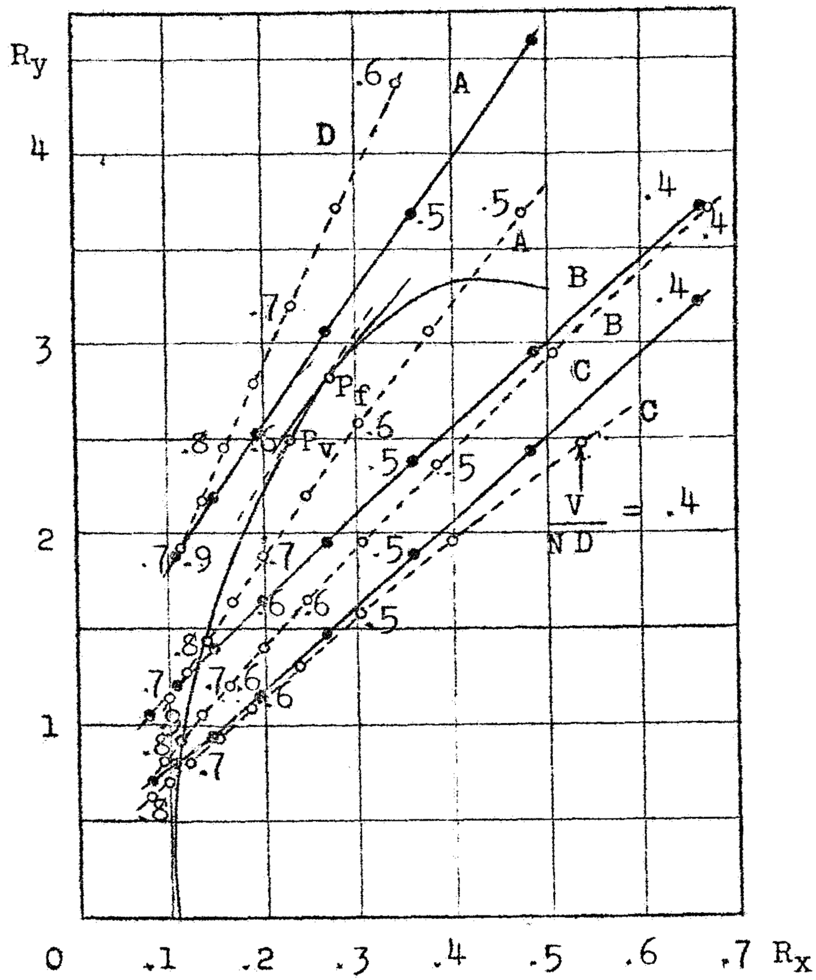

Fig.4. Cases 3 & 4 supercharged engines.

D = 12000 m (39370 ft.) C = Sea-level

A = 8000 m (26247 ft.) ———————• Fixed pitch propeller.

B = 4000 m (13123 ft.) - - - - - - -o Variable pitch propeller

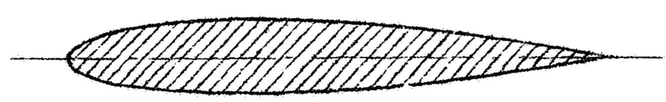

Fig.6.

Fig.5.

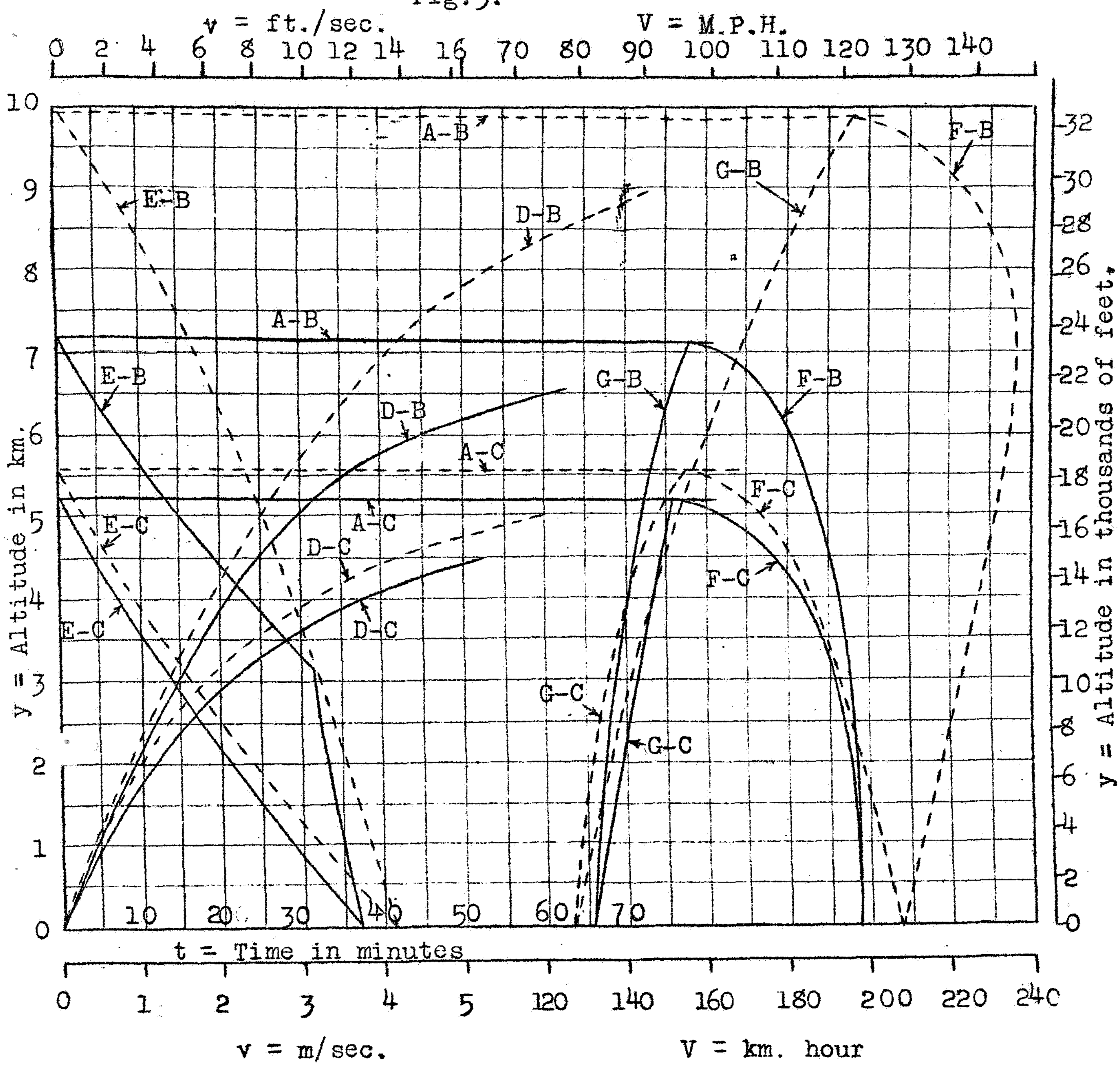

Fig.5.

———— Fixed pitch

- - - - - - Variable pitch

A = Altitude limit

B = Engine supercharged

C = Engine normal

D = Climbing time

E = Assending speed

F = Horizontal speed

G = Climbing speed