NOTICE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 275.

RECENT RESEARCHES IN AIRSHIP CONSTRUCTION - I.*

Forces of Flow on a Moving Airship and the Effect of the Control Surfaces.

By H. Naatz.

I am taking the liberty to inform you regarding aerodynamic experiments with airship models, in order to show that the aerodynamics of the airship merit more attention than they have hitherto received. The problems as to how an airship can best be stabilized and steered and to what stresses it is subjected in the air, are so important as to determine in large measure the future development of airships much more than formerly when velocities of 30-35 meters (98-115 feet) per second were not known and the effects of the air flow were not so great. The science of aerodynamics, when systematically applied, is able to give important information. The L.F.G. ("Luft-Fahrzeug Gesellschaft") and the L.Z. (Luftschiffbau Zeppelin") have been working on these problems for years. Recently they have also been taken up by the "Lustuv". The information which I have the honor of presenting to you, comes largely from the L.F.G. and "Lustuv," which generously gave me access to their very valuable records.

*From "Berichte und Abhandlungen der Wissenschaftlichen Gesellschaft für Luftfahrt" (a supplement to "Zeitschrift für Flugtechnik und Motorluftschiffahrt"), March, 1924, pp. 50-55.

I will begin this discussion of the air forces by illustrating well-known phenomena with the simplest possible examples. Fig. 1 shows how an elongated body (not necessarily streamlined) behaves in an airstream. If it (which we must consider as being without weight) is held by a cord attached to its head, it will assume an oblique position with respect to the airstream and also to the plane of the diagram and will circle on the surface of the indicated cone. This phenomenon has long been known. Professor Von Parseval was probably the first to call attention to the fact that the resulting air force must be outside of the body. How this is to be conceived is shown by Fig. 2, in which the body is provided with a rod projecting from its head, with a cord attached to the end of the rod. The location and direction of the resultant air force is here indicated, as in the first case, by the taut line, only the inclination of the body to the airstream is smaller. In order to reduce this inclination to zero, the rod must be made considerably longer, as shown in Fig. 3. Here the resulting air force lies in the axis of the body and causes no circling. The point A may be considered as the center of resistance of the body. Since an airship, however, moves in such a way that it can turn, at any time, about an axis passing through its center of gravity, we must regard its center of gravity as the point at which it is, to a certain extent, drawn in toward the flow. Then, however, the body is unstable and will always swing in a circle. It is manifest that control surfaces are absolutely essential and must, indeed, be quite large. We must, at least to some extent, counterbalance the air force by a new supplementary force located nearer the center of gravity. As to just how near, I will explain shortly. We will first consider which control plane is the most effective. Should the control surfaces be located, as customary, in the two principal meridian planes or are other arrangements also effective, such, for example, as a box enclosing the rear end of the airship or so-called multiplane control surfaces, above, below and on the sides? If a model is made of light airtight fabric, inflated with air and weighted, so that its center of gravity coincides with its center of rotation and then allowed to fall in calm air from a considerable height (e.g., in a hangar) with its head downward, it either describes a path to one side and falls flat on the ground or it falls vertically and strikes on its head, according to how well it is stabilized by the attached pieces of pasteboard. If the experiment is repeated with differently shaped and located pieces of the same total area, it will be found that the maximum stability is obtained with the customary simple arrangement in meridian planes at right angles to each other. After this primitive experiment has already shown us the best method, our belief in it will be still further confirmed by wind tunnel experiments with models. We can demonstrate the effect of the control surfaces by testing the model, both with and without them, and comparing the results. The difference is then due to the control surfaces. Professor Prandtl and Dr. Fuhrmann, who (in 1910) first tried such experiments, found that the lateral force of a pair of stabilizers on the body of an airship was 60% greater than the lateral force of the same surfaces placed adjacent to each other without the intervening body. Hence, the airship body has a great influence on this lateral force or its coefficient C_n. I have still further investigated this effect and find that it differs according to the shape of the airship and that it varies greatly according to the position of the stabilizers on the hull. If a pair of triangular fins (Fig. 4) is applied first at the rear end of the hull, then farther forward and then still farther forward, a great increase in the lateral force is observed. In Fig. 4 the coefficient C_n is represented diagrammatically over the successive positions of the rear edges of the fins. The same figure gives the Fuhrmann values, as likewise the values for a differently shaped hull, which we will also consider. The points of application of the lateral forces to the fins are also given for the shape 1505. They scarcely change their position with the change in the inclination α. If we multiply the values of C_n by the distances of these points from the center of displacement S, we obtain the curves in Fig. 5, which give the stabilizing value of one and the same pair of fins in different locations and at different inclinations. From these it follows that the maximum stabilizing effect is obtained with the fins in the position 0.15 L. Even in position II (0.1 L), where the fins project but slightly beyond the maximum diameter of the hull, the stabilizing effect is very great. The coefficient C_n, according to Fig. 4, here attains, with $\alpha = 15^\circ$, the value 109, which is about 2.5 times as great as it would be if the fins were joined without the intervention of the hull. This is still greater than Dr. Fuhrmann obtained. To what this is due and in what way the hull exerts such an influence, it is difficult to determine. It appears that the shape of the hull is the deciding factor, since I have not found greater values on differently shaped hulls. This 1505 shape exhibits still further advantages. It has the quite high volumetric efficiency of 0.645 and the very low coefficient of drag of 2.1 on the bare hull, whereas the best Fuhrmann shape gives 2.24, though with a lower wind velocity.

For the strength computation, it is important to know whether the large lateral forces are exerted entirely or only partially on the fins. Therefore we performed experiments at Göttingen, in which the forces exerted on the fins were separated and measured directly. It was found that, with arrangement II of Fig. 4, only 73% of the C_n values fell on the fins, so that the balance obviously fell on the hull. We were able, moreover, to determine the center of pressure of this 73%. Fig. 6 shows a location which scarcely changes with a change in the inclination. Its nearness to the hull indicates that the pressure on the fin is not uniform, but decreases toward the free edges. Fig. 7 roughly represents this pressure. It is plotted at right angles to the hull, as a so-called "triangular loading."

The problem of the rudder is, of course, closely related to that of the fins, for which reason we will consider it here. We will consider it here. We will take a triangular fin, cut off portions of different sizes according to Fig. 8, and rotate them about the dividing lines A_1, A_2, A_3. For the different rudder deflections β we then measure the air forces exerted on the whole model and compare the results. The curves are plotted in Fig. 9. In the diagram, C_n applies to the entire control surface consisting of fin and rudder. The load must also be considered as distributed over both rudder and fin, since the center of pressure usually lies in front of the rudder axis, especially for large deflections of the rudder. The distance varies from one-half to the whole depth of the rudder. According to Fig. 9, the coefficient C_n increases with the depth of the rudder, but neither directly as the depth nor as the ratio $F_r : F$. Moreover, the effect of the rudder on the hull-shape 1692 is quite different. For small deflections of the rudder, it is not as great as for the shape 1505. It increases considerably, however, for $\beta = 30\text{-}40^\circ$, while for the shape 1505 it does not substantially increase above $\beta = 20^\circ$. This fact should be taken into consideration in evaluating the rudder deflections. The maneuverability of the airship should be such as never to require a rudder deflection of more than 20°. Later we will have the opportunity to discuss this condition more thoroughly.

If the rudder deflections β are combined with the inclinations α of the hull to the airflow, the result will be practically the same as for airplanes, namely, that the inclination of the airflow will have little effect on the rudder action. In fact, it is only above $\alpha = 12^{\circ}$ that the effect of the rudder will increase about 20%. In practice, it is therefore safe to assume that the effect of the rudder is the same for all inclinations α.

The fin shown in Fig. 8 is the best for comparative experimental purposes. When it is necessary, however, for practical reasons, to employ balanced rudders, the compensating surfaces should extend into the fin, after the manner of rudders on seaships.

We will now pass to the second problem of the stabilization of an airship, namely, the size of the fin and rudder. We can also make this clearer by means of an example and choose, as the nearest to actuality, the hull 1692, which approaches nearest, in its cross-section, to the pear-shape of nonrigid airships and possesses the principal accessories, such as the walkway and cars. We will first test its air force without elevator. We will, for the time being, give our attention only to the horizontal stabilizer and the elevator, because they are the more important. Fig. 10 shows the location and direction of the resulting air forces. It is manifest that the air force at 0° inclination is directed downward, but that the tip of the Fuhrmann enveloping curves lies above the body. The case would not be essentially different, if a pair of horizontal fins of certain dimensions $\frac{F}{V^{2/3}} = 0.2975$, were applied at the equator (Fig. 11), although the new resultants should be nearer the center of buoyancy of the body. In straight-ahead flight, the airship would nose up, since the propellers are underneath. The ease with which this tendency can be remedied is illustrated by Fig. 12, in which the horizontal fins have been elevated 1.8°. This not only shifts the center of drag to the resulting propeller axis, but also makes the air force, at 0° inclination of the airflow, nearly parallel to the airship's axis, thereby reducing the lift to zero. This is important, since horizontal flight with a stabilized airship would not otherwise be possible. A similar result could likewise have been obtained with an elevator deflection of $\beta = 5^\circ$ and would have affected the drag of the airship still less. From the experimental results, which are always somewhat uncertain on account of the smallness of the model, we can deduce an increase of 0.1 in the value of the coefficient C_n by means of the described adjustment and 0.02 by means of the 5° deflection of the elevator. Which of these two methods is chosen depends on how much the axis of resistance or drag must be lowered. Under certain conditions both means must be employed. At any rate, the example shows that it is not necessary, as formerly, to elevate the propeller by the application of a complicated technical device, but that it may be located where it appears best for other reasons and be offset by lowering the axis of drag.

If we wish to discuss stabilization still further, geometrical presentation will no longer suffice and we must resort to diagrams. First of all, we must know the curves of the air-force moments with respect to the center of buoyancy. Fig. 13 gives the moment curves of three different airship models without control surfaces and also the airship shape 1692 with the last-mentioned control surfaces. The effect of these surfaces on model 1692 is readily recognizable, although the stability is represented only outside of the field of $\alpha = -19^\circ$ to 13°. Regarding the other model, shape 1505, it may be remarked that its instability, although greater without control surfaces, could be reduced to the same level with such surfaces, which are smaller than for the shape 1692 with $\frac{F}{V^{2/3}} = 0.2375$. A hull which is somewhat fuller in the stern is more easily stabilized, although without control surfaces it is less stable than a hull which is more pointed at the stern.

We now return to our airship shape 1692 and ask whether we can tolerate its lack of stability with the control surfaces $\frac{F}{V^{2/3}} \simeq 0.3$. This depends first on what can be accomplished with the elevator. Hence the moments of the elevator forces must also be plotted. It is first advisable to compute the moments of the model with control surfaces with respect to another point, namely, the intersection point of the axis of gravity with the resulting propeller axis, in order to eliminate the moment of the propeller thrust from the diagram. The elevator moments are not difficult to convert if the coefficients C_n and C_t and the lever arm are given, only they must be computed with respect to the volume of the airship, which can be done as follows: The elevator moment is

$$M_r = C_n\ F\ e\ q - C_t\ F_r{}'h\ q$$

in which e = distance from center of pressure on the elevator to the center of buoyancy, for the shape 1692 = $1.48\ V^{1/3}$; h = distance between propeller axis and center of buoyancy, for the shape 1692 = $0.37\ V^{1/3}$. Since $F = 0.2975\ V^{2/3}$ and $F_r = 0.0427\ V^{2/3}$, we thus obtain

$$M_r = (0.44\ C_n - 0.0162\ C_t)\ V\ q = C''_m\ V\ q.$$

These C''_m curves are carried, for various β deflections, both upward and downward from the basic curve and constitute a set of similar parallel curves (Fig. 14), which give us the answer in a clear manner. At first glance, we see that the airship, if turned up or down, can be brought back to the zero point by elevator deflections up to 15°. On the other hand, any desired inclination can be produced, although, for the most part, the elevator must be reversed, e.g., for 4° inclination upward toward the airflow, the elevator must be inclined about 7° downward. Gravity equilibrium is not considered in this diagram, because it is subject to pitching, according to the condition of the airship, and, at high speeds, is of very subordinate importance. In the stabilization of the airship, when the problem is to restore the airship to the zero point in any case, gravity equilibrium should be regarded only as an auxiliary and the control surfaces should be so dimensioned as to render it possible, at any time, to restore the ship to the zero position independently of gravity equilibrium, but with the aid of elevator deflections not exceeding 20°. In this connection, a limit must be set to the elevator deflection, because, as we have already seen, the effect of the elevator does not always increase above $\beta = 20^\circ$. If this rule is applied to the case in Fig. 14, the control surfaces appear to exceed the desired area. The question thus arises as to whether the stabilizers and elevators can not be made smaller. If this question is made to depend on the effect of the control surfaces in oscillations of the airship about the transverse horizontal line passing through the center of gravity (pitching), e.g. in nosing up as the result of some disturbance, the tedious computations tell us nothing new, namely, that the larger the horizontal fins are, the slower the pitching motions will be. No minimum limit can be set, however, so that only one consideration remains, namely, as to whether, with larger or smaller control surfaces, all changes in the trim of the airship, due to increasing or decreasing the load, can be offset aerodynamically, i.e., by varying the lift during flight. This question is a very important one anyway, and we will therefore go into it more thoroughly by considering the following example. If the airship is either too heavy or light in the tail, middle, or nose, how much can it rise or sink in the individual cases with no further assistance than a maximum 20° deflection of the elevators? It suffices, if we can in all cases give the known coefficient C_n (or more correctly $C_n/\cos\alpha$), but (and this is the important point) the loss in speed, through assuming an oblique position, must be taken into consideration. In solving this problem, we proceed in such a manner that we take from the diagram of moments the C_m value, e.g., for $\alpha = 6^\circ$ and $\beta = 20^\circ$ and divide it by the corresponding C_n value from the diagram of the lateral forces. We multiply the result by $V^{1/3}$ of the airship of certain given dimensions according to Fig. 15 and thus obtain the location of this C_n or $C_n/\cos\alpha$ value. First, however, we compute the $C_n/\cos\alpha$ value for the lower speed. In each instance this reduction factor must be obtained from the formula

$$\left(\frac{v}{v_o}\right)^2 = \left[\frac{C_t(\text{to } \alpha = 0,\ \beta = 0)}{C_t(\alpha,\beta)+C_n(\alpha,\beta)\tan\alpha}\ \cos\alpha\right]^{2/3}$$

It is found by assuming that the power of the engine is the same when the airship is inclined as when it is horizontal, which is sufficiently accurate. Fig. 15 shows the aerodynamic balancing capacity (if we may venture so to call it) of various control surfaces, in which only the areas of the fins are changed, in order to determine whether there there is any gain from enlarging the fins alone. The static stability is not considered in the diagram. Allowance may, however, be made for it by imagining the balancing capacity extended the distance e according to the expression

$$A\ e = \alpha\ V\ e\ \sin\Phi$$

in which V = volume of gas; α = its lift per cubic meter; e = distance between center of gravity and center of buoyancy; Φ = inclination of airship.

A comparison of the curves shows that the enlargement of the fins beyond $\frac{F}{V^{2/3}} = 0.3$ gives no special advantage, because, with larger fins, the balancing capacity is smaller forward than rearward. An airship, however, requires greater balancing capacity forward, because it is larger there. Consequently, fins with $\frac{F}{V^{2/3}} = 0.3$ best meet this requirement.

We finally gave our attention only to the shape 1692, but, in order to establish universal laws, we would need to investigate other shapes also. It would take us, however, too far, were we to attempt to give all the results here. Hence we must content ourselves with stating that we, for example, would have obtained the same result with control surfaces of the size $\frac{F}{V^{2/3}} = 0.2375$ on the shape 1505, as with $\frac{F}{V^{2/3}} = 0.3$ on the shape 1692 with the same elevator area, namely, $\frac{F_r}{V^{2/3}} = 0.0428$ (Fig. 16).

By combining all these considerations, we come to the following conclusions:

1. The stabilization of an airship must be carried at least so far that the airship can be brought back from any inclination to its zero position with an elevator deflection of not over 20°, independently of its static stability.

2. The stabilization also depends on what balancing capacity is required, e.g., very low position of center of gravity of air-

ship and small speed.

This minimum stabilization is attained with control surfaces of the magnitude

$$\frac{F}{V^{2/3}} = 0.2 \text{ to } 0.3 \quad \text{and} \quad \frac{F_r}{V^{2/3}} = 0.04 \text{ to } 0.043$$

according to the shape of the airship and the location of the control surfaces.

Lastly, it should be noted that all different airship shapes have different air forces and different fin effect. Hence, aerodynamic experiments furnish the best means of determining the flight characteristics.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

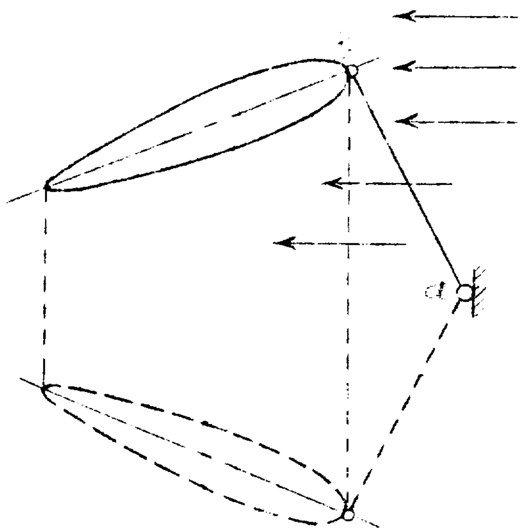


Fig. 1

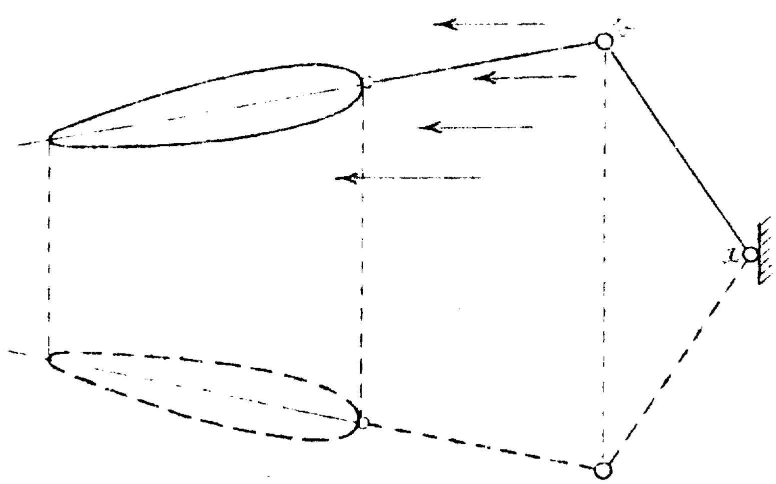


Fig. 2

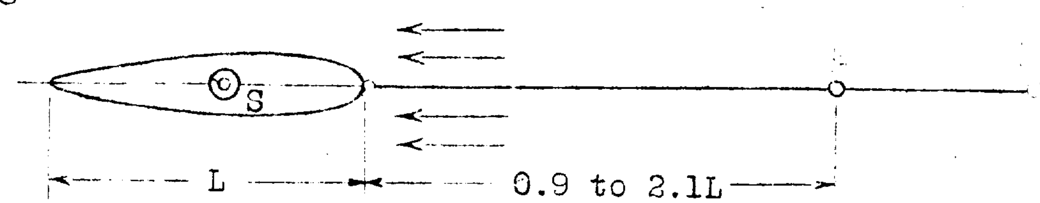
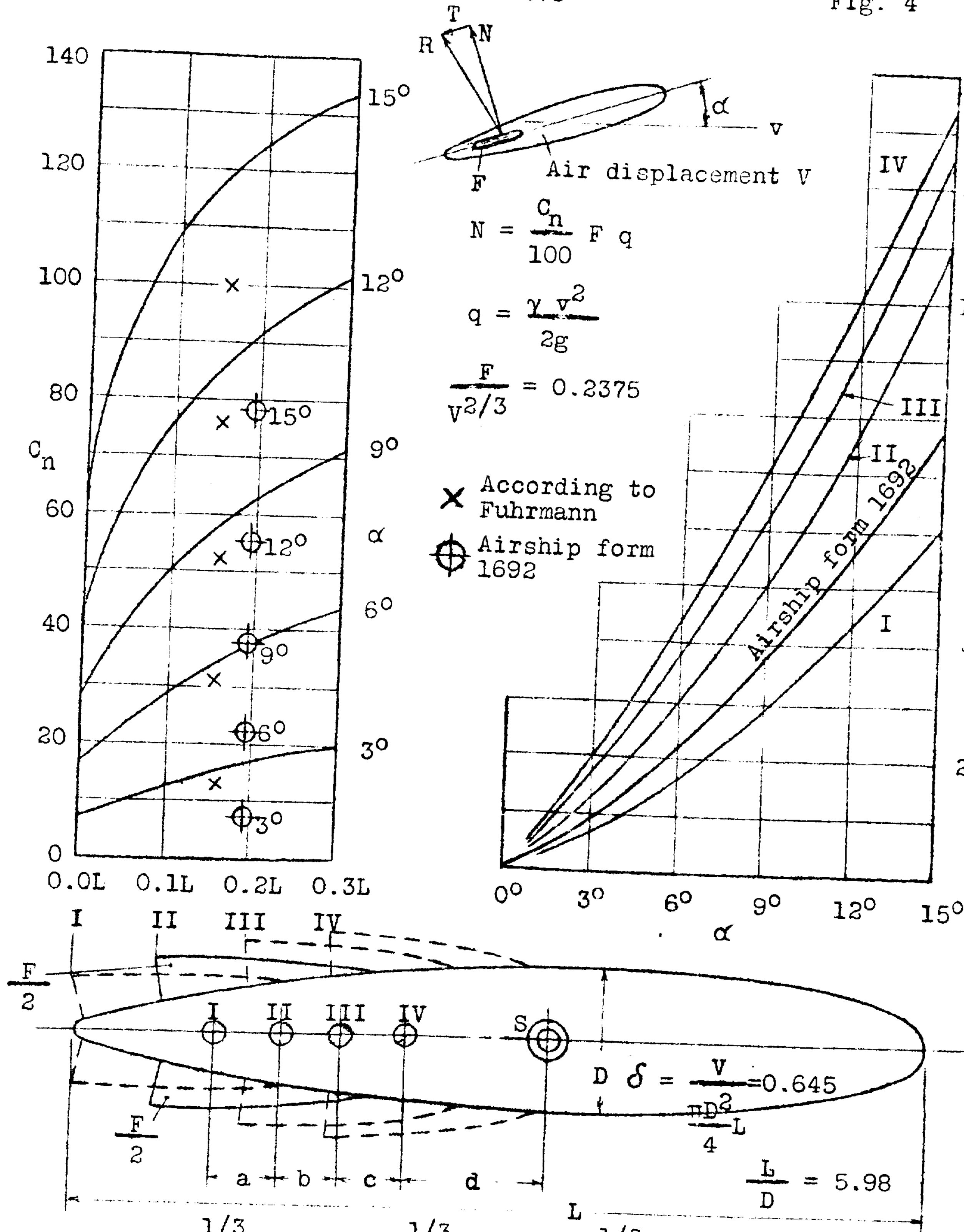
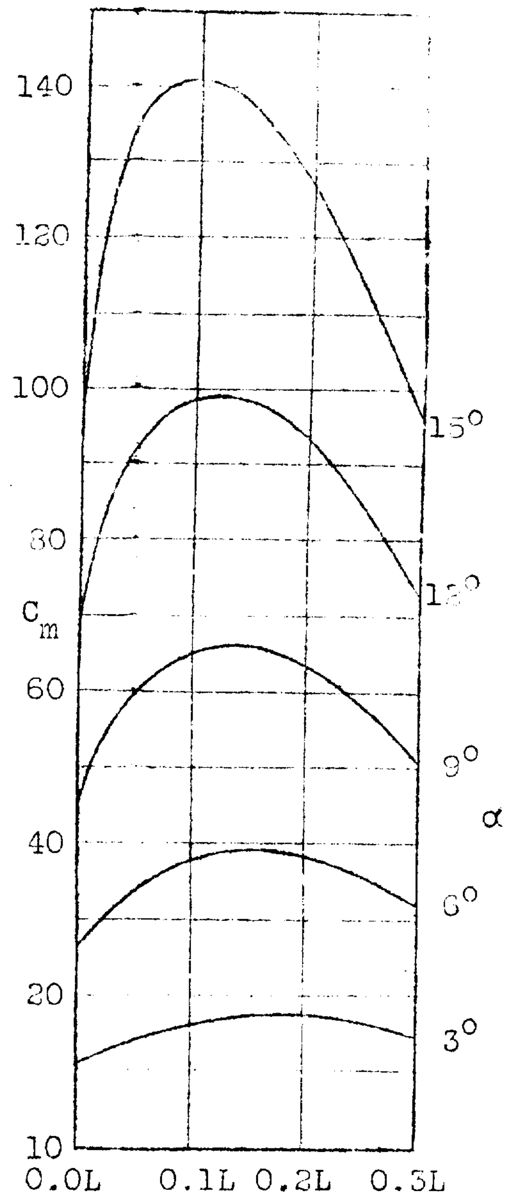


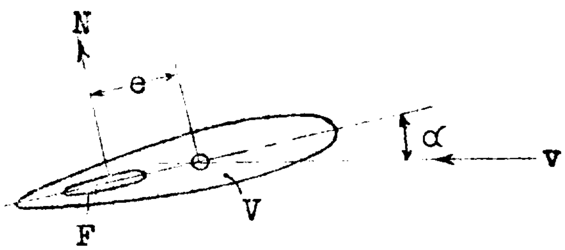
Fig. 3



$a = 1.60\ V^{1/3}$ $b = 1.293\ V^{1/3}$ $c = 1.01\ V^{1/3}$ $d = 0.714\ V^{1/3}$

Fig. 4 C_n values of control surfaces with respect to their position





$$M = N\,e = \frac{C_n}{100}\,F\,q\,e\;;\quad q = \frac{\gamma\,v^2}{2g}$$

$$M = \underbrace{\frac{C_n}{100}\,\frac{e}{V^{1/3}}}_{C_m}\,V^{1/3}\,F\,q = \frac{C_m}{100}\,V^{1/3}\,F\,q$$

For airship form 1505

$$\frac{L}{D} = 5.98\;;\quad \delta = \frac{V}{\frac{\pi D^2}{4}L} = 0.645$$

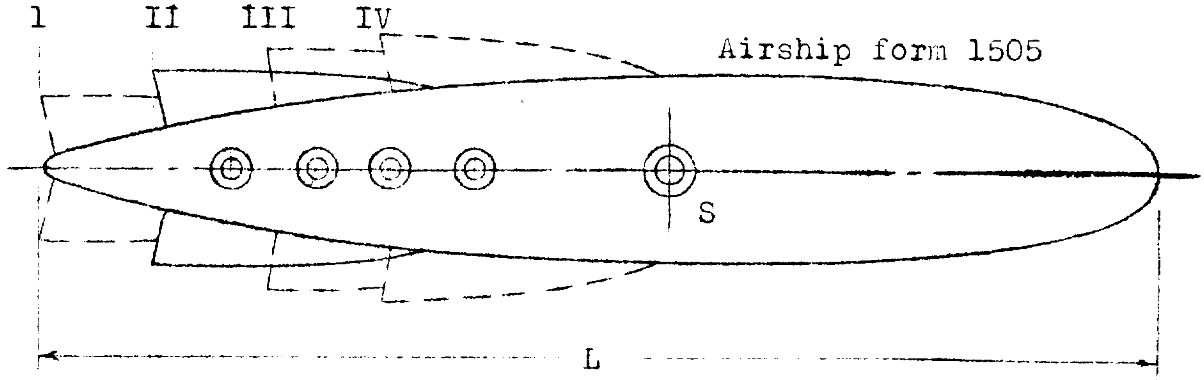


Fig. 5 C_m values of control surfaces with respect to their position

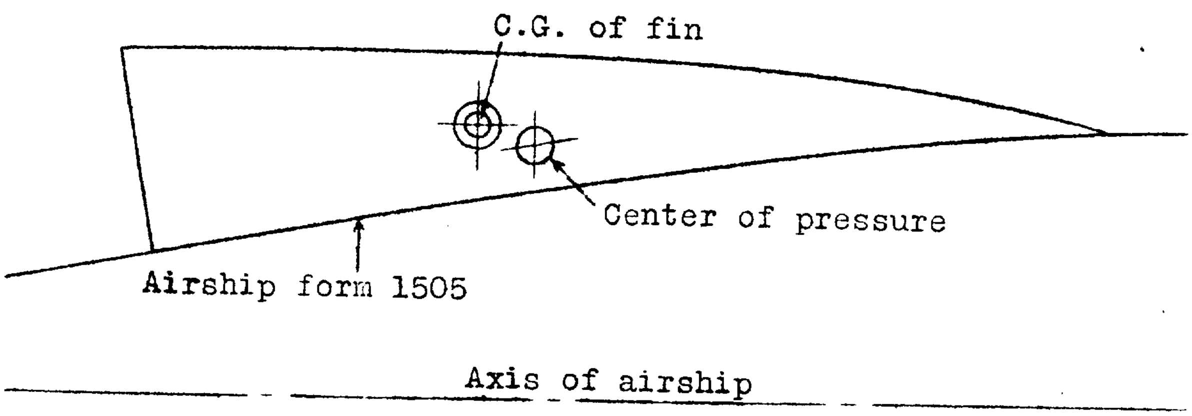


Fig. 6

Mean load of fin
$p=0.73C_nq=C_n'q$

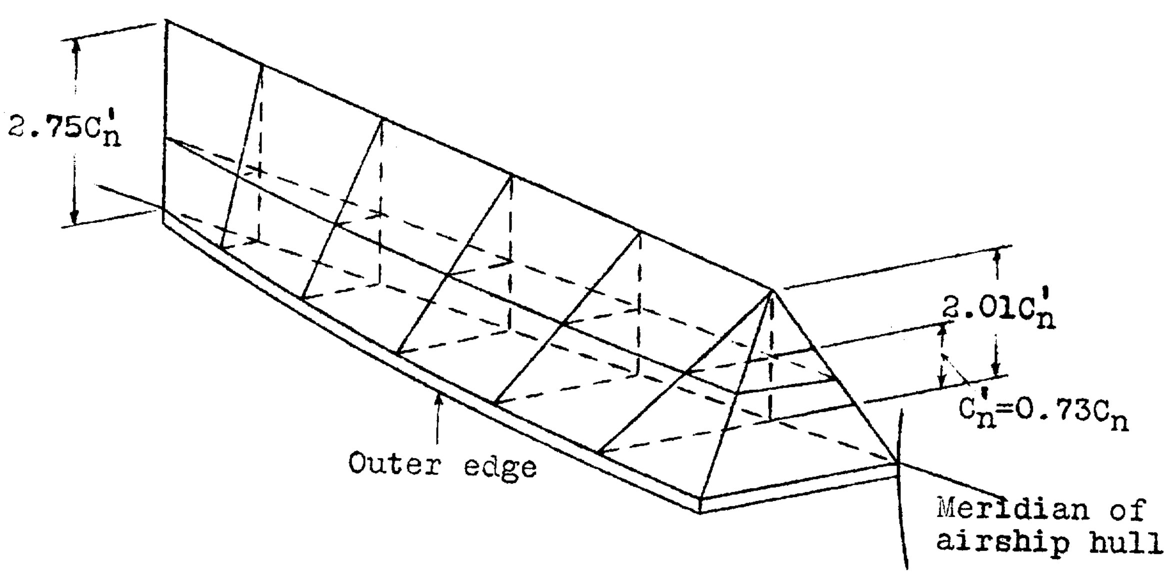


Fig. 7 Pressure distribution on control surfaces

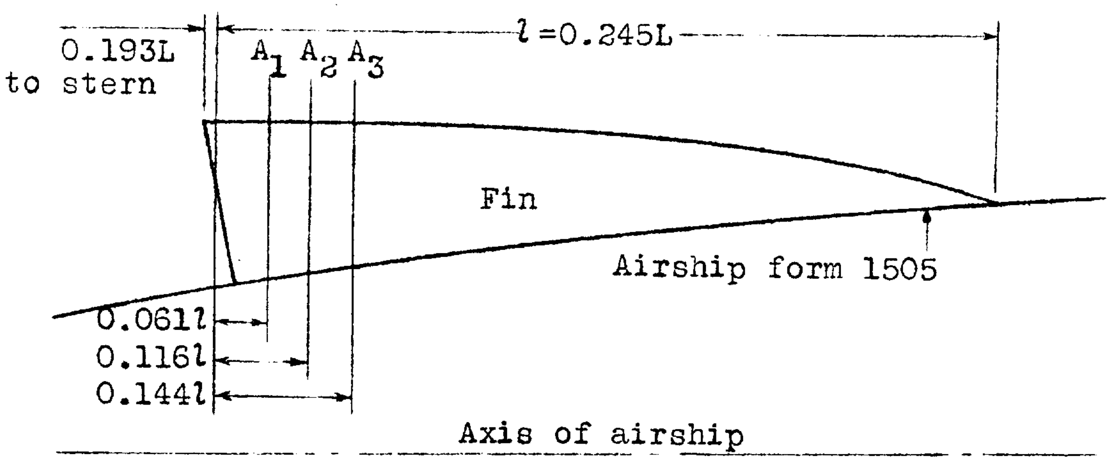

0.193L
to stern
A1 A2 A3
l =0.245L
Fin
Airship form 1505
0.061l
0.116l
0.144l
Axis of airship

Fig. 8

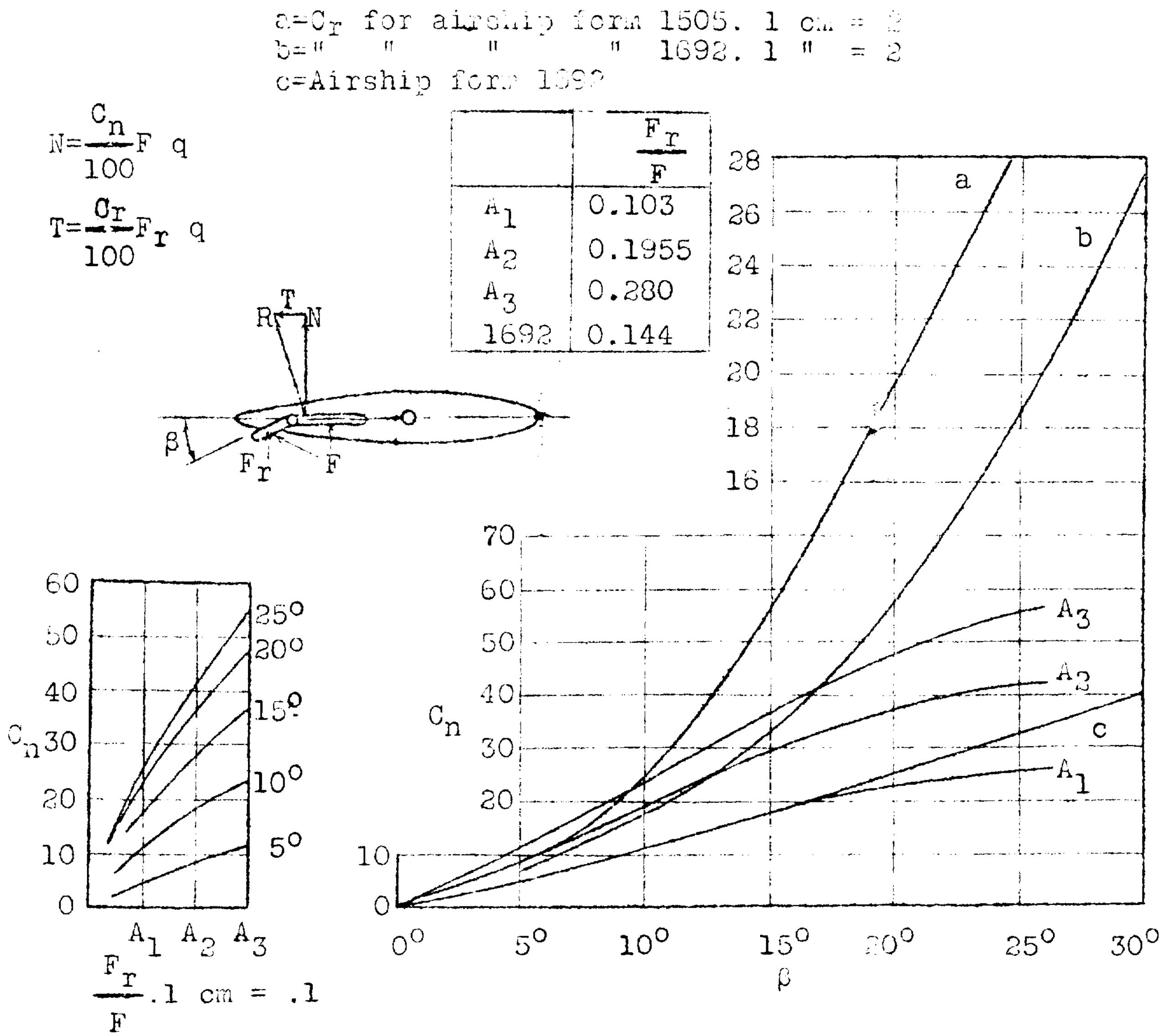


Fig. 9 C_n and C_r values of rudder

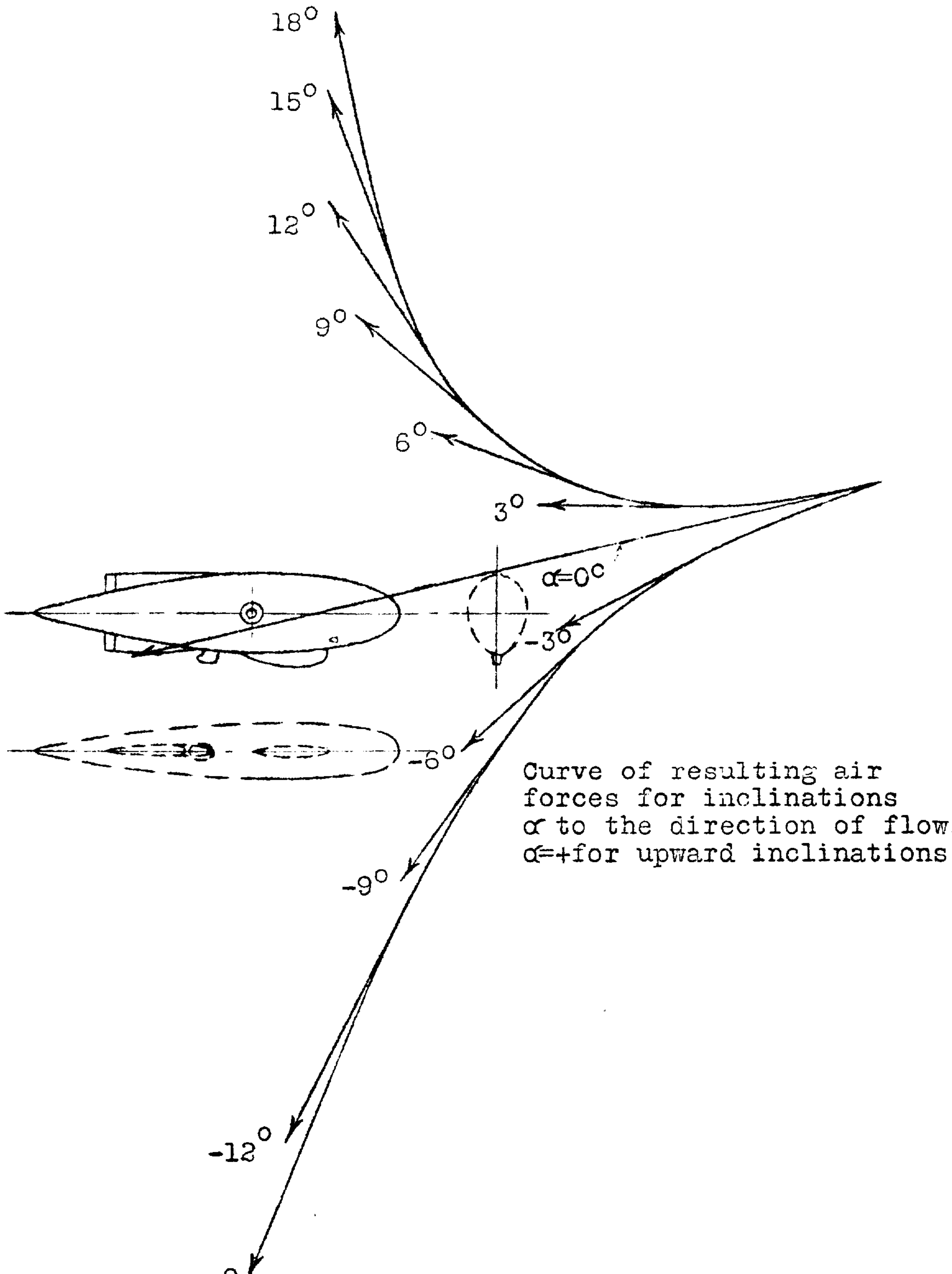


Fig. 10 Airship form 1692 without horizontal tail surfaces

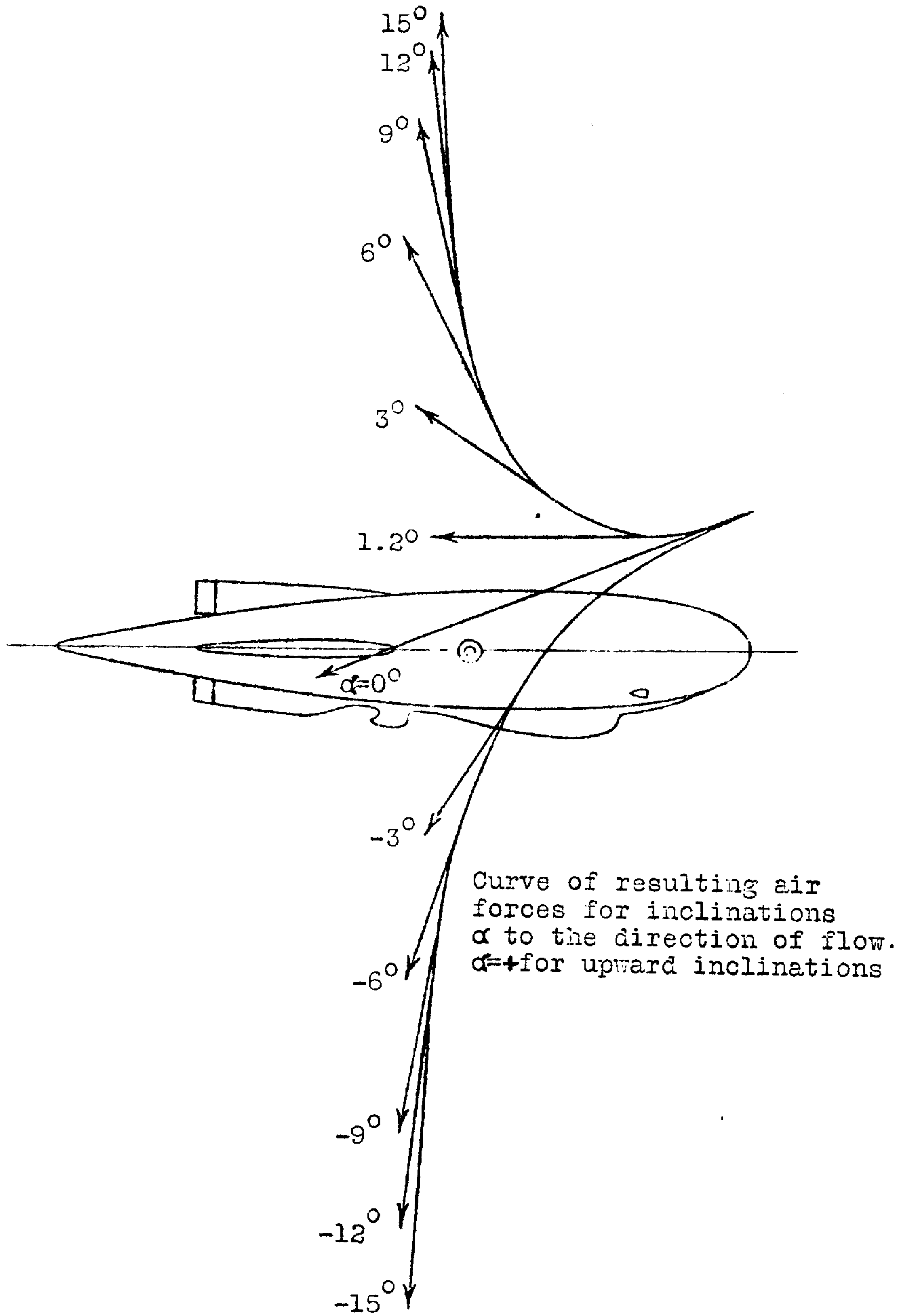


Fig. 11 Airship form 1692 with horizontal tail surfaces in the principal axis

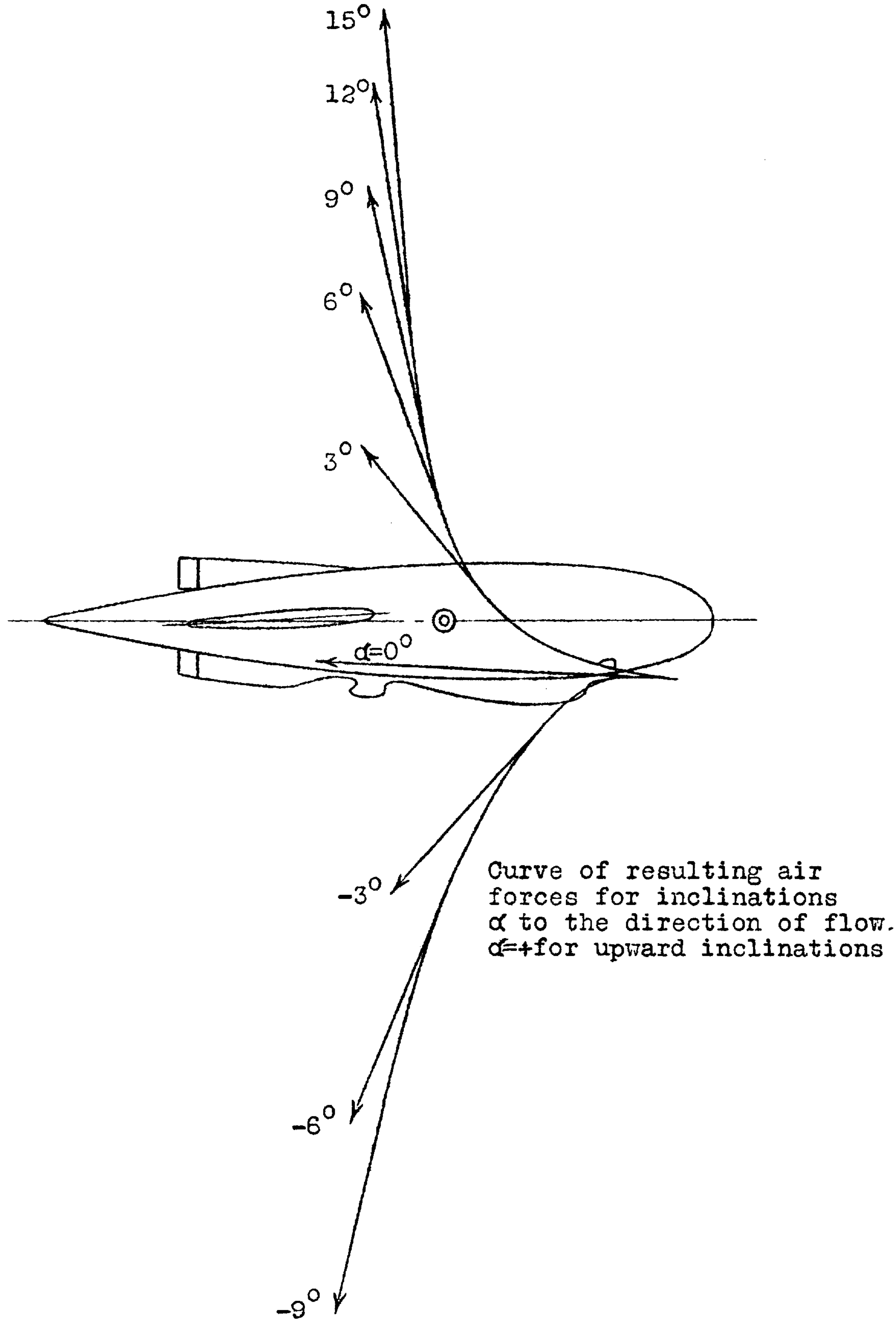


Fig. 12 Horizontal tail surfaces elevated 1.8° with respect to the airship axis.

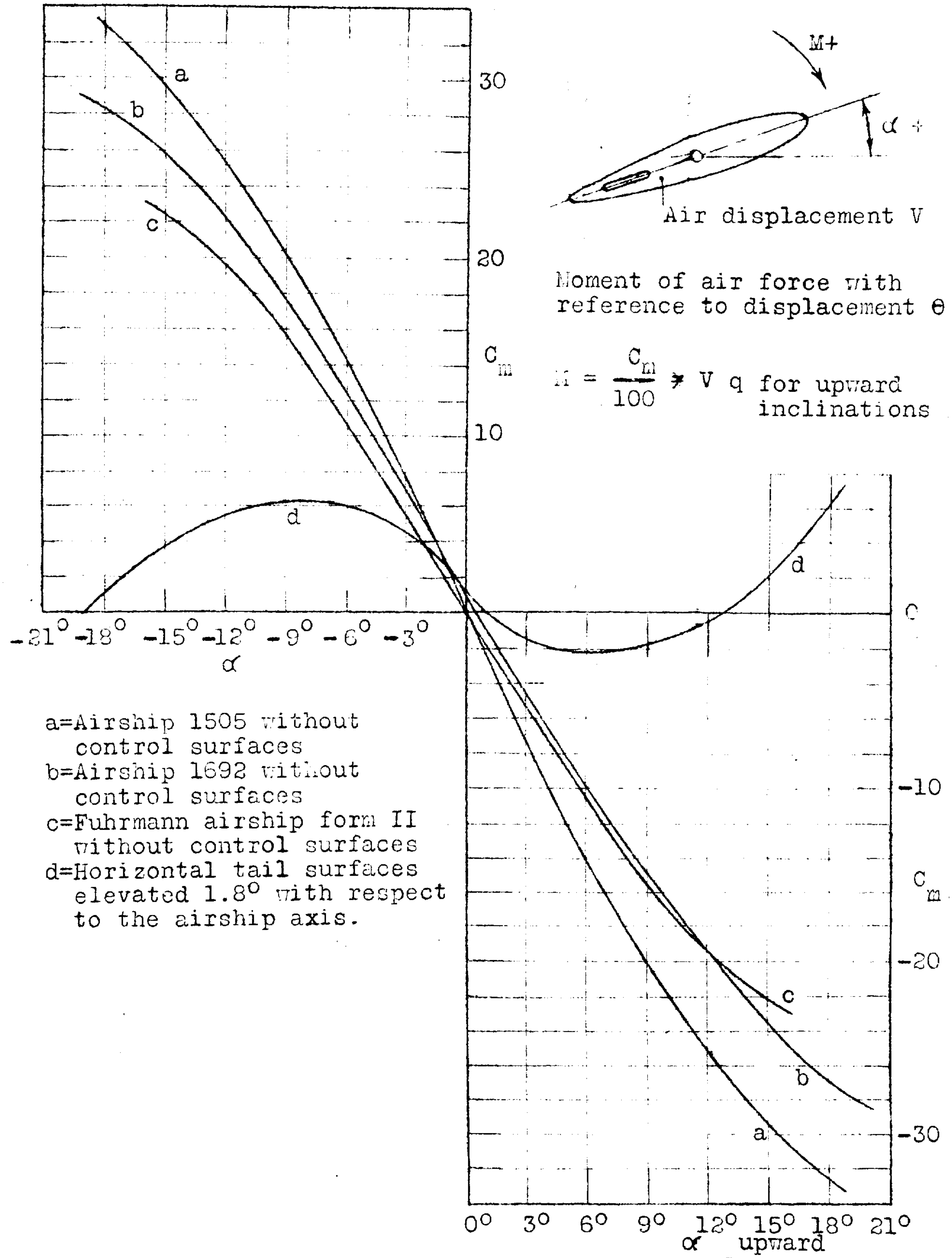


Fig. 13 C_m values of airship hull without control surfaces.

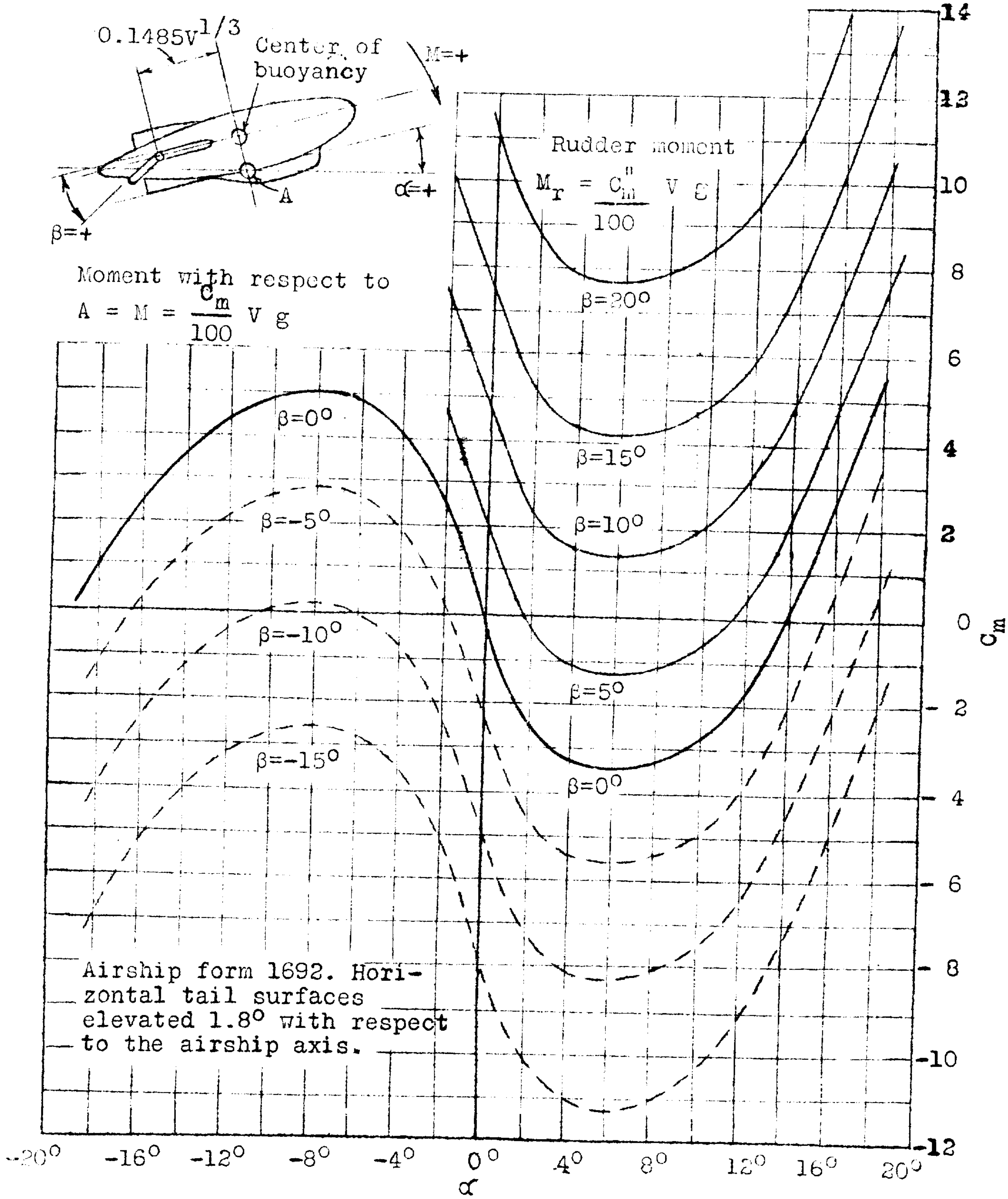
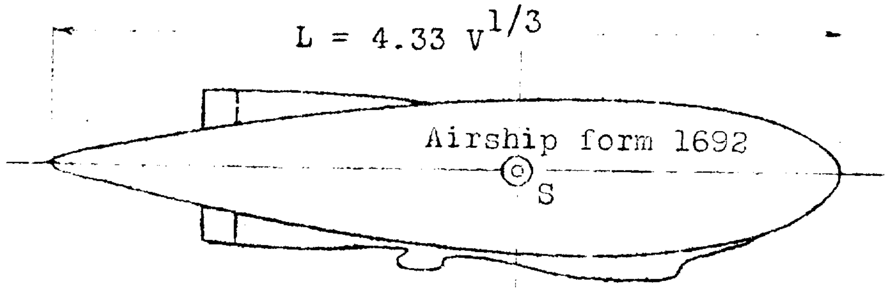


Fig. 14 C_m values of airship hull with control surfaces



Location and magnitude of maximum lateral force with rudder deflections $\beta = \pm 20^\circ$

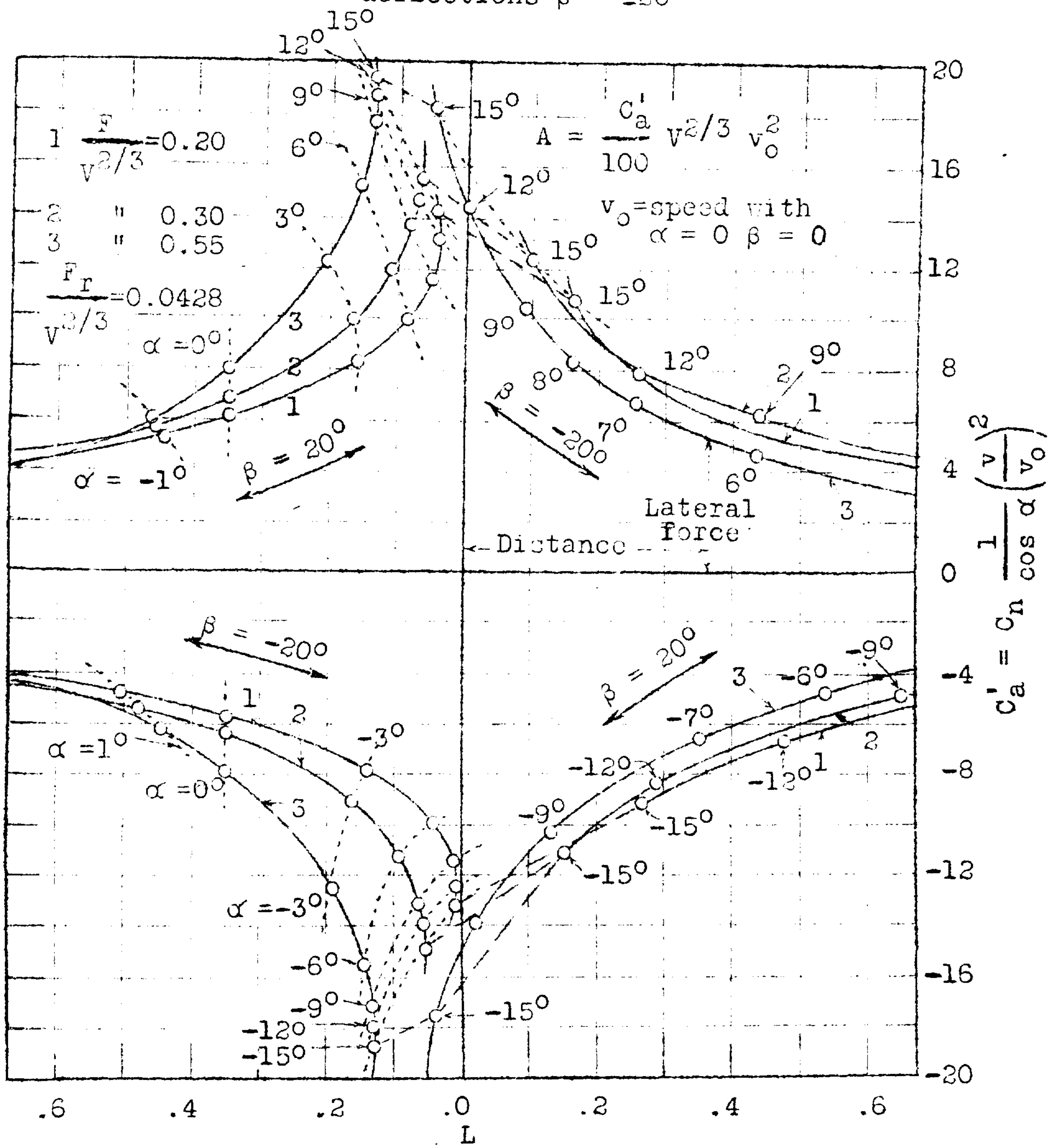


Fig. 15

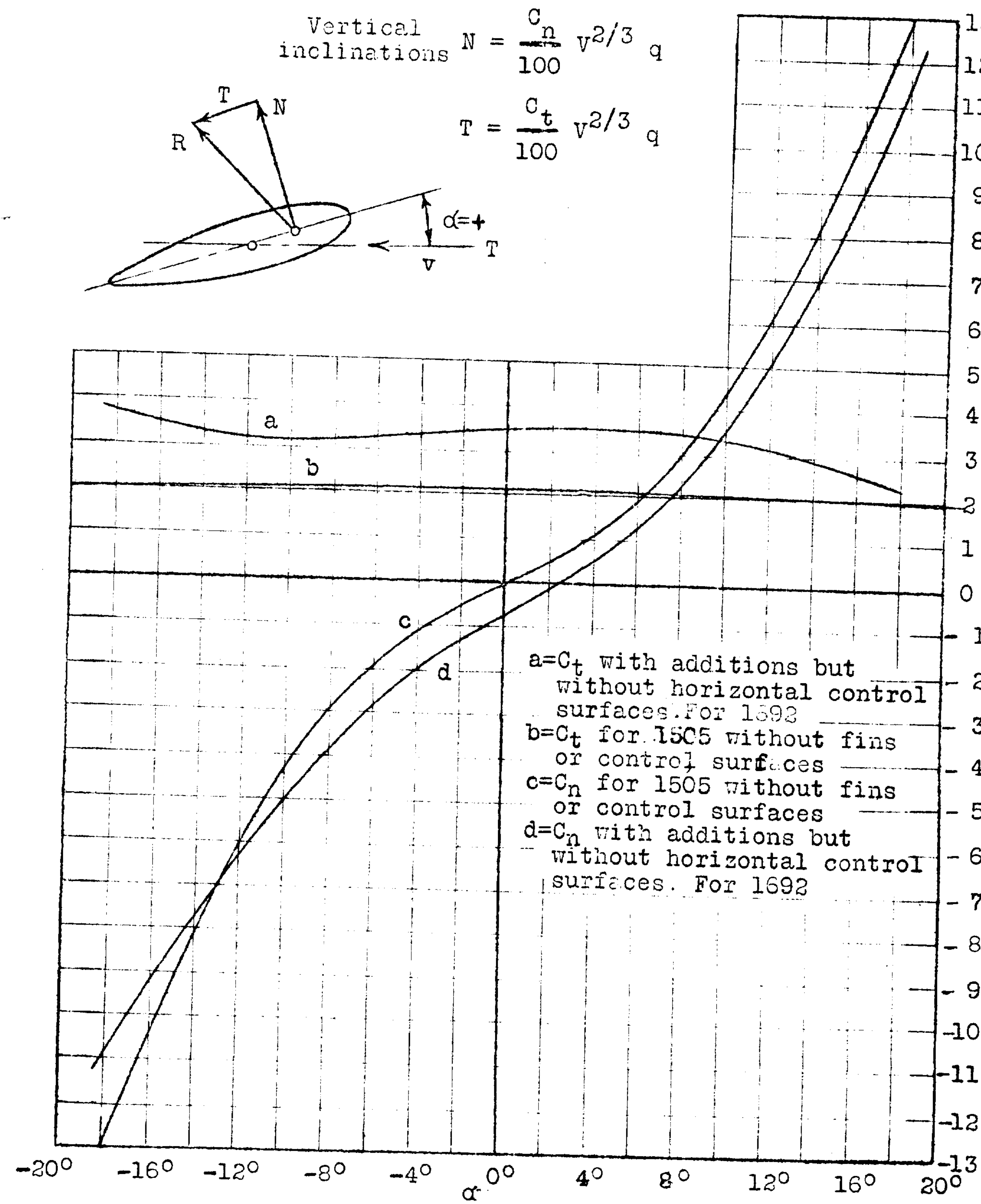


Fig. 16 Airship forms 1505 and 1692 without horizontal control surfaces