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SUMMARY

This report is divided into three parts. The first part (Sections I through IV) is a summary of the results of a literature survey conducted on the general topic of towed vehicle systems. The second part (Section V) is an analytical development which demonstrates that one of the fundamental assumptions which most investigators have made (considering the tow cable's tangential frictional force to be negligible) is incorrect. The third part (Section VI) is a bibliography.

I. INTRODUCTION

Since the problem areas encountered are quite similar the survey covers

both airborne and submersible systems. Briefly, the conclusion of the survey

is that much work remains to be done (both theoretically and experimentally)

before a significantly greater level of understanding than currently exists is

achieved in the area of towed vehicles.

No attempt is made herein to indicate the many and varied areas of

applicability for the solution of the towed vehicle problem; especially since

many applications in this era of heavy government support of research are class-

ified. Rather, a general description of the technical problem areas is presented.

Also, in an effort to enable the reader to follow the evolutionary path of the

many investigators brief abstracts are given for some of the references in the

bibliography, Section VI. The bibliography is by no means an attempt to list

all of the numerous references found, for they are extensive in number and in

the large most have not contributed significantly to furthering the state of

the art. Rather it represents a sampling from which the interested reader can,

hopefully, obtain an appreciation of the magnitude and scope of the problem area.

One of the odd features of this topic area is that relatively few of

the research reports written on towed vehicles have been published in journals.

This feature has resulted in vast duplication of effort; especially in the last

five years during which time agencies of several governments have been supporting

research efforts in the area of the stability of towed vehicles.

II. GLAUERT'S MATHEMATICAL MODEL

Most researchers tend to duplicate (both by intent and inadvertently)

the works of Glauert [1, 2] who published his papers on the stability of an

airborne non-lifting towed vehicle in rectilinear motion in 1930 and 1934
respectively.

Glauert's analyses incorporate flexible cables and make the assump-
tion of straight, level flight in which the cable moves from one equilibrium
shape to the next (an instantaneous displacement) while the towed vehicle behaves
dynamically. Another assumption made by Glauert, which like the above, later
investigators have also adopted is that the cable drag is perpendicular to the
cable. That is, there exists no skin friction component. This greatly simpli-
fies the equations which determine the shape of the cable. However, quoting
from Glauert, "Further investigation is necessary to examine the dynamical
effects on the wire (cable) which are ignored in the present analysis."

Glauert's investigations were directed towards developing stability
criteria for both longitudinal and lateral perturbations for an assumed equilib-
rium position for non-lifting bodies. His results are presented parametrically;
the parameters being combinations of cable length, cable weight, towed body
weight, ratio of drag of cable to drag of towed body, and angle of inclination
of cable. He did not attempt to couple the longitudinal and lateral stability
problems.

Of the many investigations which followed Glauert's work the most
significant contribution was made in 1947 by L. Landweber and M. H. Protter
[3] . It is equally significant that this paper has gone completely unnoticed
by subsequent researchers and as a consequence none of the investigations conducted
since yield results delicate enough to be termed better than "adequate." The
main contribution of [3] is that the authors included the tangential friction
force of the towing cable in their mathematical model and, using measured quan-
tities for this force, demonstrated that the equilibrium configuration of the
system is altered appreciably by the tangential drag. Some completely independent

studies have been made in recent years on this problem, but they fail to achieve the elegance of [3] and consequently never demonstrate the importance of the tangential drag. Landweber and Protter did not glean all of the useful information which can be obtained from a slight modification of their mathematical model. Specifically, they failed to formulate a moment equation which is non-trivial. In Glauert's case the moment equation is trivial because his mathematical model reduces to a system of concurrent forces. The results of [3] are presented in what might be termed a complicated form because the authors resorted to numerical means to solve the resulting equations. In Section V we, with computer solution in mind, derive the basic equations and present them in a very simple form. We also develop the moment equation referred to above. Equally important is that the illustrative examples given in [3] are for water whereas the results of our study are illustrated for air.

III. SOME OTHER TYPES OF INVESTIGATIONS

An unfortunate waste was created by the excessive duplication of effort by the many investigators. The mathematical models which they used are very much similar to Glauert's; which is quite understandable sans the benefit of the experience of the others (especially Landweber and Protter). This has resulted in models which are necessarily crude (Glauert emphasizes this) to facilitate the mathematics. Accordingly, the results are at best of a first order approximation. However, the model(s) have proven to be adequate for determining some of the fundamental problem areas; a fact which is borne out by experimental work. For example Shanks [5, 6, 7, 8] has done a considerable amount of research on the lateral stability of towed, lifting airborne vehicles. Shanks' efforts differ from most other investigations in that he seeks ways of stabilizing an unpiloted towed vehicle (a difficult analytical undertaking)

rather than accepting a given confguration and determining (parametrically) regions of unpiloted stability for it.

Perhaps the most unusual (and most pessimistic) paper written concerning the stability of towed vehicles is that of Söhne [9] , who was a glider pilot in World War II. His theoretical study was his dissertation (1947). "... blind towed flight of long duration is impossible. If the towing airplane is lost sight of, the pilot of the towed airplane is forced usually after a few seconds to release the towline." One must keep in mind that this paper was written prior to the "electronics age."

As indicated above a number of investigations have been conducted with the towing environment being water. See references 10 through 12 and 15 through 26. However, many of these studies have placed primary emphasis on the towed vehicle (hydrofoils, instrument packages, etc.); the system analysis being of passing interest to the investigators. Even those reports which are concerned with the system prove to be less searching studies than some of the studies conducted with airborne vehicles, although once more [3] is an exception to this criticism. The latter criticism stems mainly from the investigators reluctance to make any concession for the difference in media from Glauert's work. For example [10] is virtually a duplication of a small part of Glauert's work. Nevertheless, despite their many shortcomings the authors of [11, 12] made the only reasonable attempt uncovered in this survey to analyze a towed vehicle in a turn. They do this considering fully submerged hydrofoils, for which they establish stability criteria. It is of interest to note that no experimental projects were initiated to verify their findings.

IV. BASIC PROBLEM

The basic system of concern in the study of the towed vehicle problem

consists simply of a towing vehicle, a cable and the towed vehicle, which can be lifting or non-lifting.

Focusing on one of the several logical starting points in the analysis of the airborne system, the cable connection to the towing vehicle, the complexity of the general problem becomes evident. All the reports studied begin with the assumption that the dynamic properties of the towing vehicle are completely known and that its flight pattern is stable. Any other assumption, such as the towing craft moving through a region of turbulence is, in effect, to place a forcing function on the cable. This, of course, would create traveling waves in the cable making the analysis of the system (the cable dynamics superimposed upon the dynamics of the towed vehicle) quite complex. It is obvious, of course , that the forcing function can also originate at the connection of the towed vehicle to the cable. It has been argued [13] that for low velocities (approximately 200 mph at sea level) that the traveling wave damps out and can be neglected. The entire problem of high subsonic velocities and supersonic velocities has not been investigated analytically. The transition velocity range would no doubt prove to be an interesting study.

Reference [14] carries Glauert's work one significant step further by showing that there exists a critical (unstable) speed range. It is interesting to note that the authors of [14] were very apologetic, stating that they were not aware of and thus for the most part duplicated Glauert's work.

Reference [13] aside from being a fair review of the state of the art, sans [3] , contains as its main contribution parametric studies of the longitudinal and lateral stability of lifting bodies both coupled and uncoupled. This is accomplished by studying the equations of motion (using linear theory) on an analog computer.

The literature does not contain any reference to the study of towed

elastic bodies. The aeroelastic analysis of lifting bodies in free flight remains a complex problem to analyze. An extreme but relatively simple case, the structural stability of a right circular cylindrical shell (missile) with arbitrary boundary conditions under the action of a longitudinal pulsating load, is receiving considerable attention in the literature. Thus, it is seen that this small, significant portion of the overall system is not easily attacked or solved.

Nevertheless, the ultimate problem to pursue is the stability of a three dimensional, multi-degree of freedom, damped, elastic, towed vehicle, both lifting and non-lifting, considering both rectilinear motion and turns. The state of the art is such that we are a long way off from being able to make a meaningful analytical analysis of this problem. The fundamental mathematical model must be improved incrementally, supported by a parallel experimental effort.

V. EQUILIBRIUM CONFIGURATION AND TENSION OF A LIGHT FLEXIBLE CABLE IN A UNIFORM FLOW FIELD.

In this section we present the results of our study of the effect of a cable's tangential drag force on the orientation of a tow vehicle system, demonstrating that the skin friction force is not a negligible effect as most investigators, sans proof, have assumed. The equations developed should prove to be a valuable starting point in future investigations to determine stability criteria for the system, and equally important they can be used by practicing engineers to obtain more accurate estimates of cable shapes.

Two fundamental categories into which tow vehicle studies may be divided are light (negligible weight) and heavy cables. In that our purpose was to display the effect of skin friction and in that in most cases the weight of the cable is negligible in comparison to that of the body being towed we confined the study to the case of the light cable. More important, this assumption aided in simplifying the resulting equations so that attention was properly

focused on the effect of skin friction. The other assumptions made were steady-state aerodynamics, constant tow vehicle velocity, equilibrium configuration for the tow cable (hence system), and the airplane and towed vehicle were assumed to be rigid bodies. The last assumption allowed for constant values of lift and drag to be employed for the towed vehicle when in straight flight at a constant speed. These assumptions are discussed at length in many of the reports listed in the bibliography and will not be repeated herein.

Figure 1 is a sketch of the system analyzed, defining a few of the variables which appear in the development below.
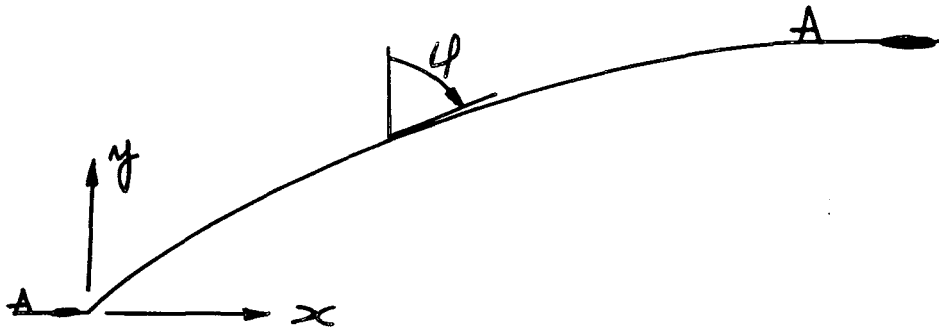

Figure 1 - TOW VEHICLE SYSTEM

A free body diagram of a generic segment of the cable of length ds is shown in Figure 2.
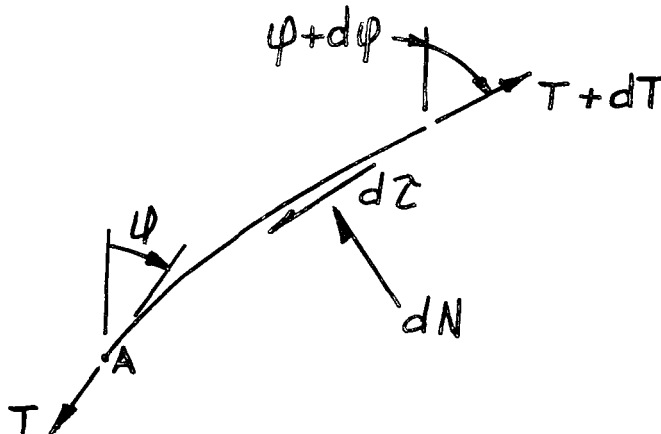

Figure 2 - FREE BODY DIAGRAM

Summing forces in directions tangent and normal to the cable at point A we obtain after making a small angle assumption on $d\varphi$

$$d\tau = dT \qquad (1)$$

and

$$T d\varphi - dN = 0 \qquad (2)$$

Let us write the tangential drag per unit length as

$$d\tau = f(\varphi) ds \qquad (3)$$

and the normal component per unit length as

$$dN = g(\varphi) ds \qquad (4)$$

where $f(\varphi)$ and $g(\varphi)$ are experimentally determined and are functions of the velocity of the cable. It turns out that $g(\varphi)$ can be expressed as

$$g(\varphi) = K \cos^2\varphi$$

where K, of course is a function of the velocity of the cable. Thus Eqn. (4) may be rewritten as

$$dN = K \cos^2\varphi \, ds \qquad (5)$$

It facilitates computations to leave (3) in its present form for now.

We will now formulate the governing differential equation for the determination of cable shapes. Placing (5) into (2) we obtain

$$T d\varphi - K \cos^2\varphi \, ds = 0 \qquad (6)$$

T may be determined by placing (3) into (1) and integrating. Thus,

$$T = \int f(\varphi) ds + c \qquad (7)$$

Hence, from (6) and (7) we obtain

$$\left(\int f(\varphi)ds + c \right) d\varphi - K \cos^2\varphi \, ds = 0 \qquad (8)$$

Dividing (8) by $d\varphi$ yields

$$\int f(\varphi)ds + c - K \cos^2\varphi \frac{ds}{d\varphi} = 0 \qquad (9)$$

Taking $\frac{d}{ds}$ of (9)

$$f(\varphi) - \frac{d}{ds}\left(K \cos^2\varphi \frac{ds}{d\varphi} \right) =$$

$$f(\varphi) + 2K\cos\varphi\sin\varphi - K \cos^2\varphi \frac{d\varphi}{ds} \frac{d^2s}{d\varphi^2} = 0$$

or

$$\frac{d^2s}{d\varphi^2} - q(\varphi) \frac{ds}{d\varphi} = 0, \qquad (10)$$

where

$$q(\varphi) = \frac{f(\varphi) + 2K\cos\varphi\sin\varphi}{K \cos^2\varphi} \qquad (11)$$

Using Eqn. (10) and the geometric relations

$$dx = \sin\varphi \, ds \qquad (12)$$

and

$$dy = \cos\varphi \, ds \qquad (13)$$

it is easy to make comparative studies between Glauert's model which neglects the effects of skin friction and our mathematical model which, of course, includes the effects of skin friction. However, before doing that let us develop one more valuable equation by selecting a slightly altered mathematical model; that

is, another free body diagram.

Let O be the center of gravity of the towed body which was assumed to be a particle. Hence the center of gravity is the geometric center and lies on the cable. Thus, we have the free body diagram shown in Figure 3.
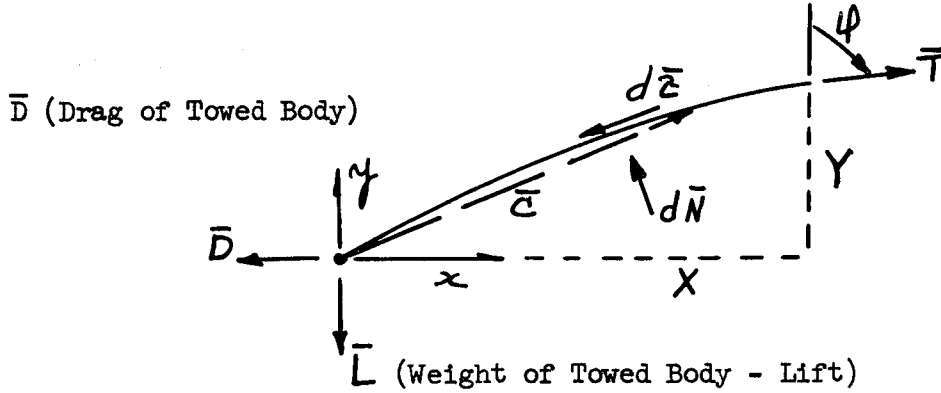

Figure 3. - MODEL FOR MOMENT CALCULATION

In Figure 3 $\bar{c}$ represents the position vector measured from O to any point on the cable. Thus,

$$C = x\bar{\imath} + y\bar{\jmath} \tag{14}$$

The cable force $\bar{T}$ may be written as

$$\bar{T} = T(\sin\varphi\,\bar{\imath} + \cos\varphi\,\bar{\jmath}) \tag{15}$$

Similarly we may form

$$d\bar{\tau} = d\tau(-\sin\varphi\,\bar{\imath} - \cos\varphi\,\bar{\jmath}) \tag{16}$$

and

$$d\bar{N} = dN(-\cos\varphi\,\bar{\imath} + \sin\varphi\,\bar{\jmath}) \tag{17}$$

Taking moments about point O we have

$$\sum M_o = 0 = \bar{c} \times \bar{T} + \int_0^s \bar{c} \times (d\bar{\tau} + d\bar{N}) \tag{18}$$

Placing Eqns. (14) through (17) into (18) we obtain

$$T\left(X\cos\varphi - Y\sin\varphi\right) + \int_0^S \left\{ \frac{d\tau}{ds}\left(-x\cos\varphi + y\sin\varphi\right.\right.$$

$$\left.\left. + \frac{dN}{ds}\left(x\sin\varphi + y\cos\varphi\right)\right\} ds = 0 \right.$$

where X and Y are as defined in Figure 3 (say the point of contact with the towing vehicle). We can now replace T, dN and $d\tau$ in the last equation by using Eqns. (2), (3) and (5). The result is

$$K\cos^2\varphi \frac{ds}{d\varphi}\left(X\cos\varphi - Y\sin\varphi\right)$$

$$+ \int_0^S \left\{ f(\varphi)\left(-x\cos\varphi + y\sin\varphi\right) + K\cos^2\varphi\left(x\sin\varphi + y\cos\varphi\right)\right\} ds = 0 \tag{19}$$

Eqn. (19) allows for the complete determination of a cable configuration for a given physical problem. The potency of the equation is self evident. In our next report we will develop a more general equation taking the cable weight into account. Therefore, we will not dwell on the moment formulation herein.

Let us now return to Eqns. (10) through (13). Define $\gamma = K/T_0$ where T_0 is the tension in the cable at $\varphi \equiv 0$. Thus, nondimensionalizing the lengths s, x and y we obtain

$$\left. \begin{array}{l} \sigma = s\gamma \\ \xi = x\gamma \\ \eta = y\gamma \end{array} \right\} \tag{20}$$

Placing (20) into (10) we obtain

$$\frac{d^2\sigma}{d\varphi^2} - f(\varphi)\frac{d\sigma}{d\varphi} = 0 \tag{21}$$

The boundary condition necessary to integrate Eqn. (21) is obtained from Eqn. (6). We have defined

$$T_o = T\big|_{\varphi=0}$$

Therefore from (6) in nondimensional form we have

$$\frac{d\tau}{d\varphi}\bigg|_{\varphi=0} = 1$$

as the boundary condition. Using this boundary condition Eqn. (21) was integrated by computer using a Runga Kutta scheme and the resulting curves for cable shapes were plotted.

Intuitively one would expect the tangential drag to increase with velocity and tend to force the cable to approach a straight line configuration in the limit. Hence to illustrate the importance of the frictional force we have selected an extremely low velocity for our illustrative example. To this end experimental data was taken from [4] which was measured in a flow of 40 ft./sec. Thus by a curve fitting process $f(\varphi)$ was computed to be

$$f(\varphi) = 0.0134\left(\frac{\varphi}{\pi}\right) + 0.0072\left(\frac{\varphi}{\pi}\right)^2 - 0.0504\left(\frac{\varphi}{\pi}\right)^3$$

Figure 4 contains comparative curves for the case where the drag of the towed vehicle is negligible. Thus it is solely a theoretical result. The zero towed body drag produces a vertical tangent at the point of contact of towed vehicle and cable.

Figure 5 contains comparative curves for an arbitrary set of input data of drag and lift for the towed body which results in an angle φ at the cable-towed vehicle connection of 0.6 radians.

The significant difference in the curves of Figures 4 and 5 is entirely

due to the effect of tangential drag. Physically, when one eliminates this effect he, in essence, is making the assumption that the tension throughout the cable is constant. Thus, there is but one possible cable configuration for the Glauert case. It is a fair first approximation and mathematically Glauert's equations are easier to work with than the equations developed above but as the study shows the Glauert results are not sufficiently delicate for accurate work.

FIGURE 4

EFFECT OF CABLE SKIN FRICTION WHEN TOWED BODY HAS NEGLIGIBLE DRAG.

TANGENTIAL DRAG CURVE

GLAUERT"S CURVE

$\eta = \dfrac{c}{h}$

$\xi = \dfrac{x}{c}$
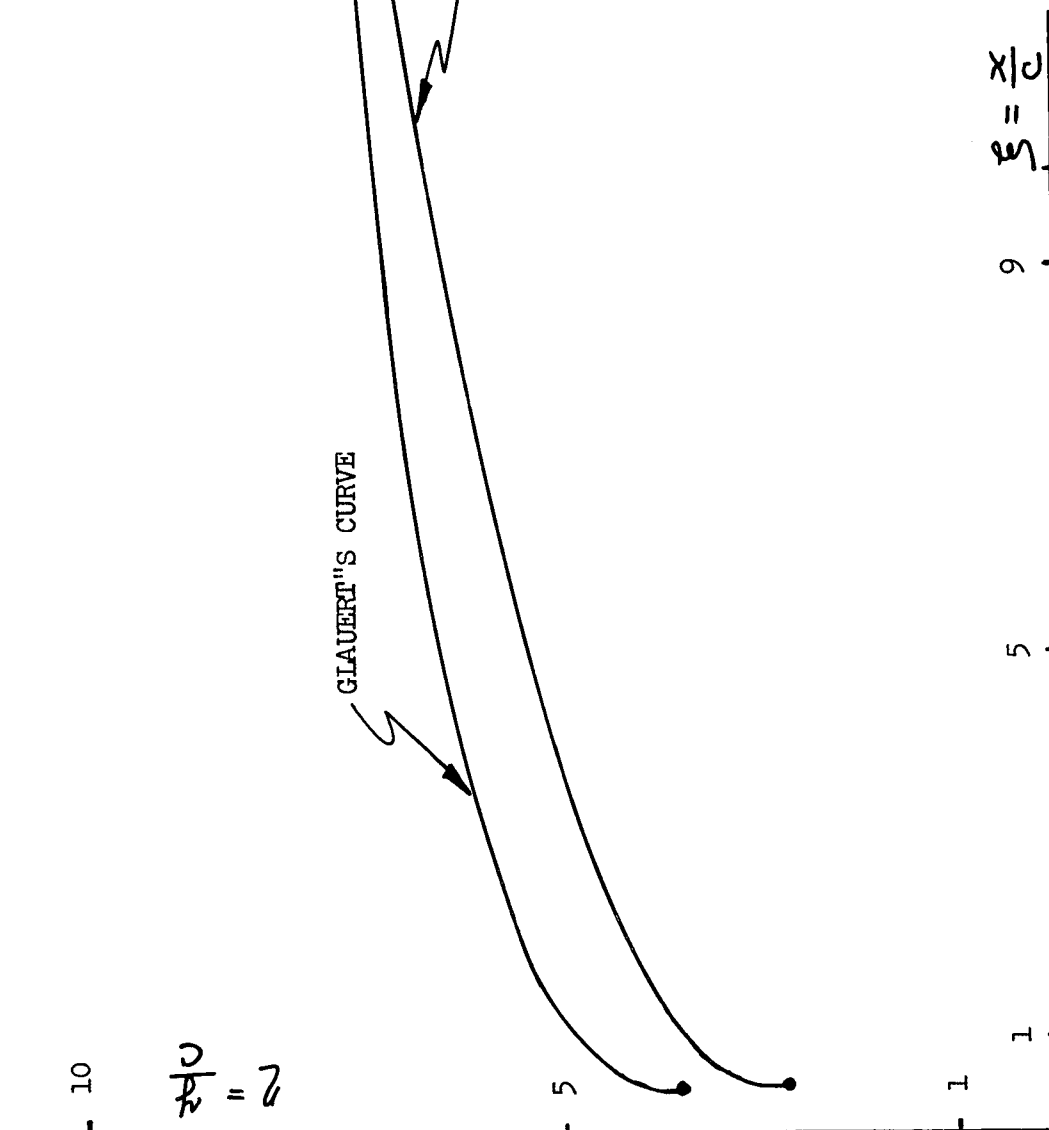
Note: C equals the length of cable whose normal drag is equal to the tension [Glauert's case] .

FIGURE 5

COMPARATIVE STUDY FOR A TOWED LIFTING BODY
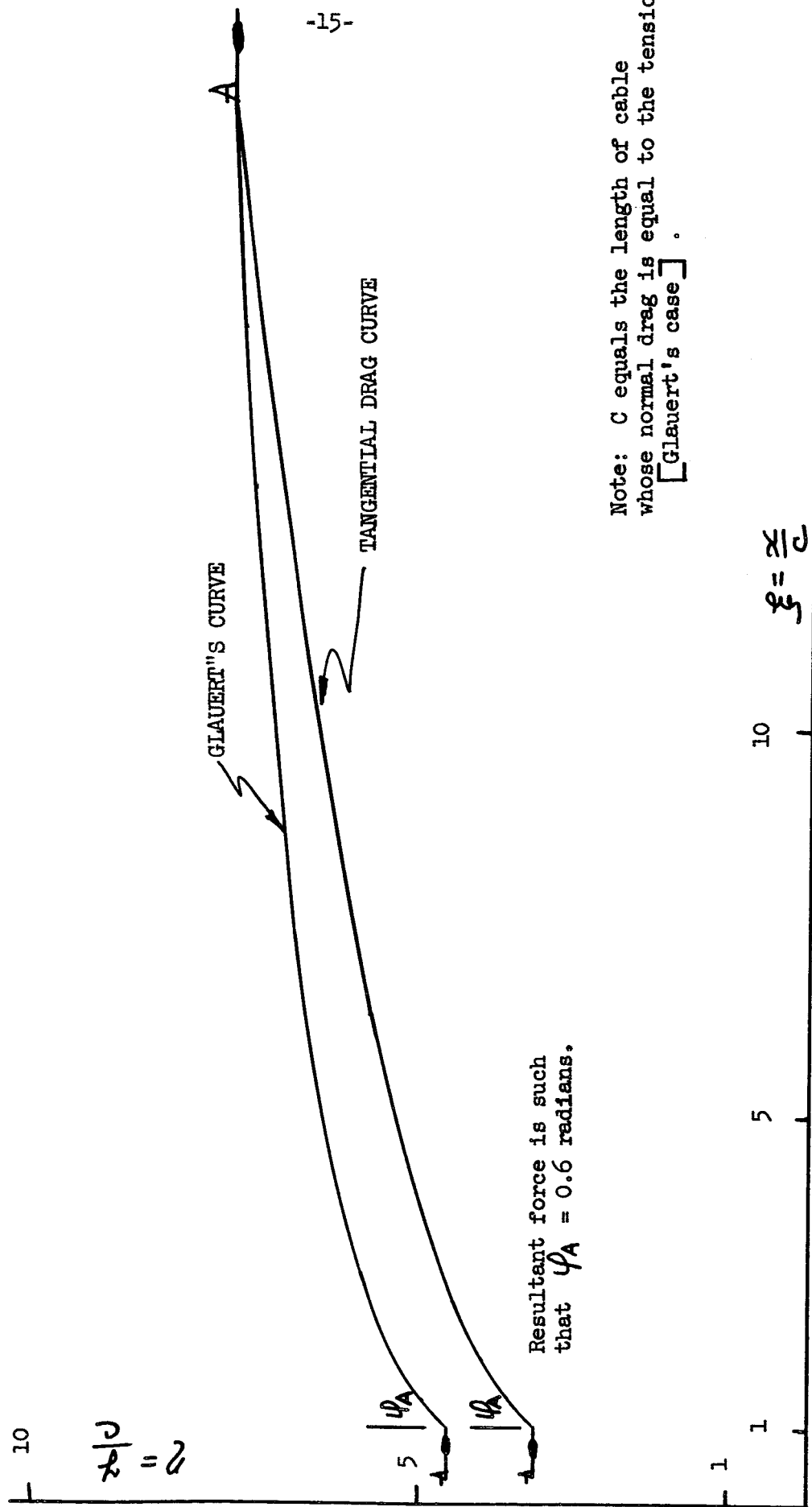
GLAUERT'S CURVE

TANGENTIAL DRAG CURVE

$\eta = \dfrac{T}{c}$

$\xi = \dfrac{x}{c}$

Resultant force is such that $\varphi_A = 0.6$ radians.

Note: C equals the length of cable whose normal drag is equal to the tension [Glauert's case].

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