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Review of theoretical studies on a trawl

by

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In trying to understand how fishing gear works the problems that arise are usually connected with the difficulties of making measurements on the gear. The use of specially designed instruments have provided many answers but the question arises whether an approach based on hydrodynamical theories could be of any help in supplying an additional basis for interpretation of results? The only attempts to answer this question have been made by some Japanese scientists and this review will discuss their work and other possible developments. It has been made at the suggestion of my colleague Mr. W. Dickson and the frequent discussions with him are gratefully acknowledged.

In problems of this kind, the usual method is to break down the complex structure into various simple parts which are amenable to mathematical treatment. Such simple forms will often be idealisations of the actual components and they will be considered separately. The results obtained will give expressions for the forces acting on each part for all possible dimensions, angles of attack and speeds of current. It is this knowledge of all the relevant variations which make such results useful since, when each structure is then considered as part of a trawl, estimates can be given of the forces acting on it, forces which are often not directly measurable in the trawl.

It is obvious that the value of the process depends on the degree of realism in the correspondence between the idealised forms and the actual parts of the net represented. It also depends on the amount of interaction, when recombined in the trawl, of parts which have been considered separately. These are the factors which must be borne in mind when attempts are made to construct suitable theoretical formulae.

Of the simple forms for which hydrodynamic data are available, two are important in relation to a trawl. Firstly there are the results for circular cylinders which can be used for the warps, for the main ropes and for the twine of the net. Secondly, data for flat plates are relevant to the action of trawl boards.

The Net.

The Japanese experiments have been concerned mainly with finding the drag on rectangular pieces of net at various angles to the flow. The formulae for this drag have been based on the forces thought to act on a single piece of twine. The idealised picture, shown in Fig. 1, consists of a cylinder of unit length inclined at an angle θ to the flow and with the force acting on it split into resolutes N normal to the cylinder and S along it.

The available results for the magnitudes of these components will be mentioned first together with the possibility of applying them to a trawl. This will provide a basis for discussing the Japanese work.

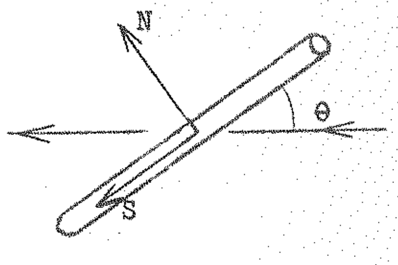

Fig. 1.

Briefly the results are as follows:

$$N = D \sin^2 \theta \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where D is the drag when the axis of the cylinder is perpendicular to the direction of flow and

$$D = \tfrac{1}{2} . \rho . v^2 . d . C_D \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where ρ is the density of the fluid, d is the diameter of the cylinder, v is the velocity of the cylinder relative to the fluid and C_D is the drag coefficient. The drag is put in this form (see Goldstein, 1938) because C_D then depends only on a dimensionless number R, the Reynolds number, equal to $v.d/\nu$, where ν is the kinematic viscosity (this is the normal viscosity divided by the density). For a cylinder the dependance of C_D on R has been found experimentally (see Goldstein, 1938) and the relation (1) has also been tested several times (Glauert, 1934; Kullenberg, 1951; Kawakami and Tubota, 1953).

The dependance of S on θ is not nearly so well known but the form usually suggested is

$$S = \frac{1}{2}\rho\, v^2 d\, C_s \cos^2\theta \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where C_s, like C_D, will depend on R, but in this case very little is known about its value. Both C_s and C_D will also depend on the surface roughness of the cylinder, the effect probably being greater for C_s than for C_D. Kullenberg, for a wire, suggests $C_s = 1/15\ C_D$ while Kawakami and Tubota, for a rope, take $C_s = 1/10\ C_D$.

These are the available results and it is probable that for values of θ near 90^o, when N is the dominant component, they will be quite realistic. For lower values of θ they will not be so useful since it can easily be shown (see Appendix) that for a small but non-zero value of θ they give a minimum drag and zero lift, Fig. 2, and this is unrealistic. This is unfortunate since, in a trawl, much of the net (and also the warps) is at a small angle to the main direction of flow. Thus the application of the available results would seem, a priori, to be limited.

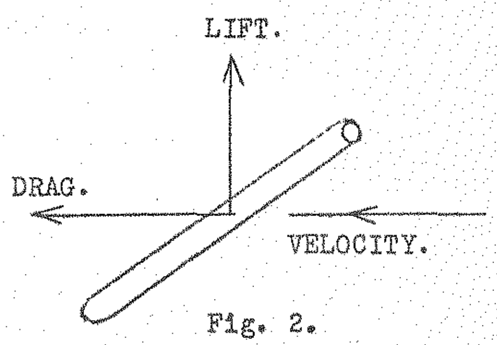

Fig. 2.

Other difficulties are raised however, when one comes to consider the twine built up into a piece of netting. These may be expressed as follows:- a single piece of twine can be taken as a one dimensional object in a three-dimensional flow of water and the disturbance of this flow will not be great: on the other hand a net, in this sense, can be considered as two-dimensional and will have a much greater effect on the flow. This means that the angle at which the water approaches a piece of twine in the net will not be the same as the angle of the undisturbed flow. Thus to apply the previous formulae to each piece of twine one would need to know at what angle the flow approached it and this obviously raises quite a few problems.

Turning to the Japanese work, this started with experiments by Terada, Sekine and Nozaki (1915), and by Tauti, Miura and Sugii (1925) on nets having the shape shown in Fig. 3. Attempts to provide a theoretical explanation of the values of the drag were made by Miyake (1927) who performed further experiments of the same type, and by Tauti (1934a). Lastly, experiments and an accompanying interpretation were made by Fujita (1953) for a net fixed only at the two sides A and A^1 (Fig. 4).

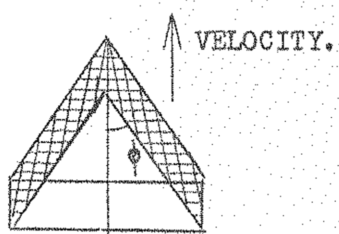

Fig. 3.

Terada et al. said that their results showed that the resistance of the net was proportional to the area of all the legs and knots projected on a plane perpendicular to the direction of motion (i.e. drag $\propto$ sin ϕ). Miyake used this as the basis for a formula in terms of the angle between meshes, length of meshes and angle of net to flow.

Tauti et al (1925) said that their results showed proportionality with o (rather than with sin ϕ as Terada et al. said). Tauti (1934a) tried to establish this theoretically by starting with the assumption that the force on a piece of twine was perpendicular to the twine and proportional to its area projected perpendicular to the flow. In the terms used in the initial discussion, this is to say that

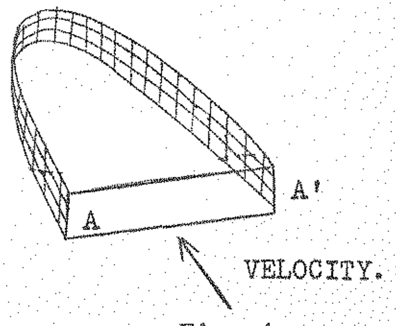

Fig. 4.

$$N \propto \sin\theta,\ S = 0$$

On this basis Tauti showed that the drag was proportional to $\sin^2 o$ and he considered this to have proved his point since $\sin^2\phi$ is a better approximation to $\phi/90$ than $\sin\phi$.

The most important feature of this argument is that neither Miyake nor Tauti use the expressions for the forces on a piece of twine given by (1) and (3). Thus neither can claim to be based on the normally held theory.

This fact may be related to the second difficulty that has been stated, which is that a net of the shape shown in Fig. 3 may considerably alter the lines of flow. These flow-lines might take the form shown roughly in Fig. 5. Then the expression for the drag of the whole net might be of some form similar[1] to Miyake or Tauti's

These results are expressed as twice the drag on each half. Consider one half by itself - the flow lines might be as shown in Fig. 6 which gives quite a different picture from that of Fig. 5. Thus the drag for this case would not be the same as for the half part in Fig. 5. This shows the dependence of the drag on the particular circumstances in which it is measured:

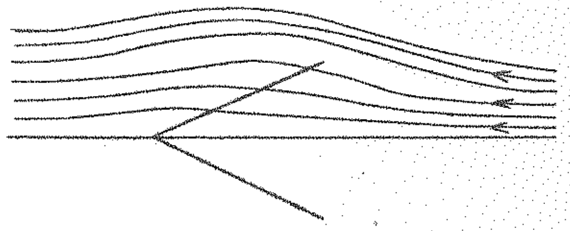

Fig. 5.

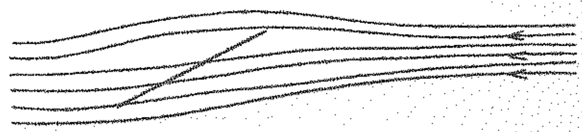

Fig. 6.

The same criticisms apply to Fujita's work. He uses the forms

$$N \propto \sin\theta$$
$$S \propto \cos^2\theta$$

and states his results as a graph of a drag ratio r/r_o against l/a (see Fig. 7) where $r = r_o$ when $l = a$. To get his experiments to fit his theory he has to introduce function of θ, which is supposed to account for the "interference" of neighbouring cords. This function and the form for N are derived in a previous paper, which is not at present available, but there is not apparently sufficient explanation of this interference to justify the use of the equations in other situations - for example when the meshes have their usual diagonal form, which they did not have in Fujita's experiments, see Fig. 4.

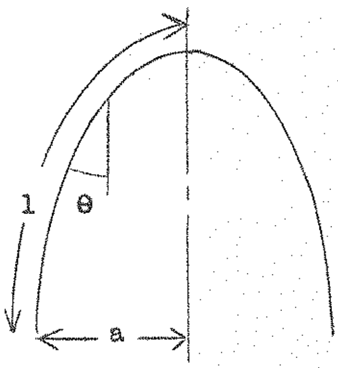

Fig. 7.

These criticisms may seem to be unduly severe but regard must be paid to the difficulties which beset this type of approach, difficulties which might be compared to those found in aerodynamics where extensive experimental work and much mathematical development were required before adequate theories could be evolved. The value of this Japanese work is to raise the questions and illustrate the difficulties that can be expected.

Thus the first problem is whether long term research of this kind is worth undertaking. The Japanese experiments dealt only with the drag but the force at right angles to the direction of flow[2] should also be measured. This force is as important as the drag since it has the effect of keeping the meshes, and thus the net, open.

Measurements of these forces for varying speeds, shapes and sizes of pieces of netting would undoubtedly form a link between a more fundamental approach and actual measurements on trawls. Such experiments would require suitable water

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1) The results of their experiments are not particularly coherent and it is difficult to decide whether either formulation is satisfactory.

2) This force is known technically as the 'lift' although it may not be necessarily upwards in direction.

channels, special equipment and considerable preparation. Further there are the special difficulties inherent in this kind of work which is still, to some extent, an art (1).

The Trawl Boards.

Apart from the net itself, the trawl board is the other main feature of the trawl to which theoretical knowledge might be applied and about which informatio would be useful.

The board can be considered as a rectangular flat plate and the process of idealisation could be carried further by taking the rectangular plate to be a section of an infinite strip and so ignoring edge effects. The few experimental results available are given in Fig. 8 Attempts to fit these results from theoretical considerations (such as Raleigh's formula) have not been successful. The only feature of the results which agrees with these theories is that, except at small angles, the force on the plate is at right angles to the plate.

It will be seen that the region of maximum lift, 30° to 40°, is about that at which trawl boards are often believed to operate.

The variations of the two curves in the region 0-20° is probably due to delay in separation of the wake from the infinite strip which is masked in the other curve by the edge-effects.

This delay in separation is accentuated by the use of an aerofoil profile and is illustrated in Figs. 9 and 10. Before separation there is a high lift/drag ratio which is sharply descreased by the turbulent wake at larger angles of attack.

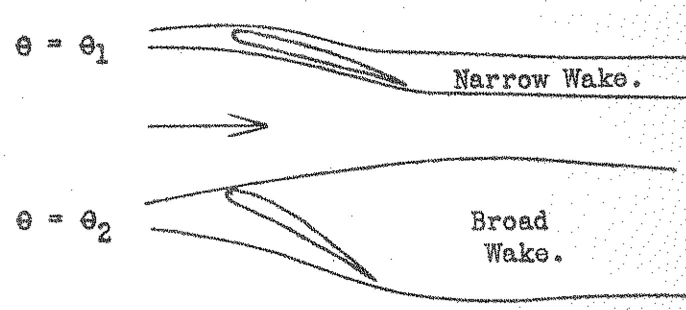

Fig. 9.

Thus suggestions for the use of 'aerofoil' boards depend upon the board moving at an angle θ_1 with the advantage of a small drag. The difficulty is that this effect is very dependant on the exact angle θ_1 - too small an angle and the lift falls off, too large, (e.g. θ_2), and the advantage is lost. But changes of speed, of warp length, of bottom conditions will tend to change the angle of attack and thus lose any advantage over the flat board working at maximum lift where the large drag is accepted as a necessary concomitant.

One Japanese paper (Kobayashi and Takahashi, 1951) deals with the relations between the lift and drag of a board and the loads in the warp and sweep. However they use an inadequate theoretical formula and give no experimental evidence. This type of approach might be helpful in interpreting the measurements of spread, load and speed which can be taken with comparative ease on board ship.

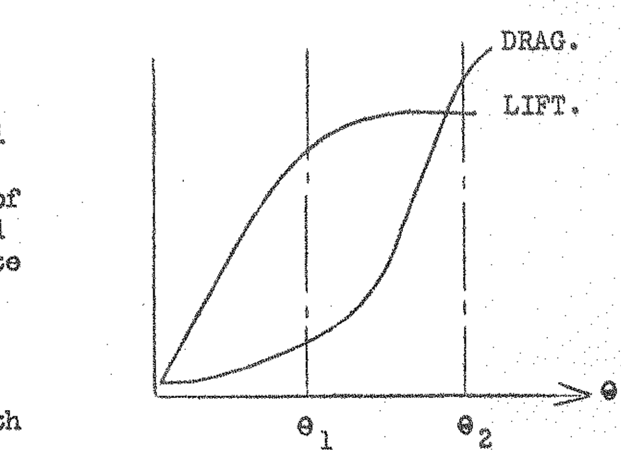

Fig. 10.

Modelling

One approach to the study of the trawl lies in the use of models. In the construction of the model and the interpretation of the results, the need is to know the relations holding between model and full scale. To demonstrate the problems raised the simple case will be considered of a wire with a load at its end being dragged through the water. Consider one of the equations governing the shape of this wire at P.

$$\frac{T}{\delta} = N + W.\cos\theta$$

Where T = tension
N = drag per unit length normal to the wire
W = weight
δ = radius of curvature.

1) See the section on modelling.

Consider a model of this where the length and diameter d are reduced by a factor p. Then, if the same material is used, the weight per unit length, W, will be reduced by p^2. This governs the reduction which is necessary in the other terms to keep the value of θ the same. Now the force N is of the form

$$N = \frac{1}{2}\, p\rho\, v^2\, d.C_D \sin^2\theta$$

Assume that C_D is constant; then for N to be reduced by p^2, V^2 must be reduced by p, i.e., V by $p^{\frac{1}{2}}$. Further T must be reduced by p^3. This affects the 'boundary conditions' which in this case is the load T_o at the end of the wire. T_o must be reduced by p^3 in such a way that θ_o is unchanged. This means that the weight and drag of the load must both be reduced by p^3.

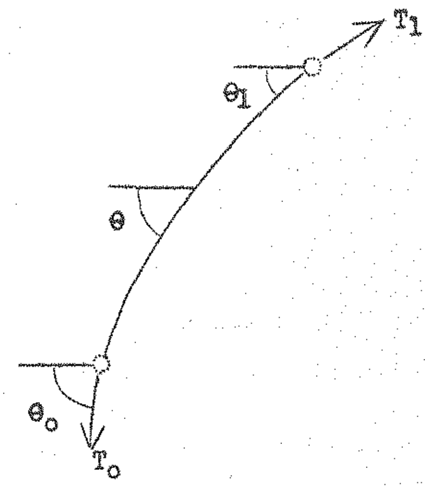

Fig. 11.

If this is done then one would expect to find that, for the model, the angle θ_1 is the same as for the full scale and the load T_1 is p^3 of the full load.

This type of modelling is called "inertial modelling" since it is governed by the effect of reducing the weight of the wire. It has depended on the assumption underlined, i.e. on C_D being constant. Now earlier it was stated that C_D is constant when the Reynold's number $R = \frac{vd}{\nu}$ is constant. This means that when d is reduced by a factor p, v must be increased by p^{-1} if the Reynold's number is to remain constant. This is known as 'Reynold's modelling'.

Thus v decreased by $p^{\frac{1}{2}}$ for inertial modelling

v increased by p^{-1} for Reynold's modelling

Obviously the two effects cannot be accounted for at the same time. The decision to use a certain scale for a particular case is largely dependent on a combination of experience and expediency.

"Inertial modelling" is the basis of the paper by Tauti (1934b) on this subject and the effects of changes in Reynold's number are ignored. Inertial modelling is necessary for a model trawl since the shape is controlled to a large extent by the relative weight of the various parts (floats, sinkers, etc.), but the changes in the drag coefficients will tend to introduce factors which will mean that comparison of results between model and full scale will not be in strict proportion.

To illustrate this, consider the wire in the previous example.

The value of C_D as a function of R is shown in Fig. 12. Now if the values of R for model and full scale lie between 10^2 and 10^5 then inertial modelling will be satisfactory, but it will break down if either value of R lies outside this range.

This result might be applied to the net if one supposes that drag coefficient of the net varies in the same way as the coefficient of each twine. For such twine moving at three knots, $R = 3.10^3$ and $C_D = 0.9$. Using $^1/_{10}$ scale gives approximately 10^2 for R and $C_D = 1.4$. This is already a 50% increase and so $^1/_{10}$ scale would appear to be a limit for a satisfactory model. There will also be scale effects of this kind on floats, boards, and on the bottom friction and for these the variations with R are not known.

Experiments with model nets have been made by Japanese workers. In particular a fairly extensive series of experiments were made by Nomura and Yasui (1953) studying various types of net and using the rules of modelling suggested by Tauti.

Considering one net, they used a model of an 'ordinary otter trawl' apparently rigged as for round-fishing. The scale was 1/30 and only the scaled-up results are given. At a speed of three knots the drag of the net was about 2 tons and this value seems reasonable. However, this net left the bottom at the scale equivalent of less than 2 knots and at 3 to 4 knots its gape was between 3-5 ft.

It does not seem probable that any commercial trawl would have such poor characteristics and it is possible that the difference between the behaviour of the model and that expected of a full scale net could be due to the very large change in scale.

Thus it appears that experiments with small scale models may not be of use in giving quantitative results. This would mean that water channels would not be used and larger scale models would have to be towed in the open sea with observations by frogmen or such other means as may be available. Small scale models may however still provide useful qualitative results. Thus the Japanese experiments show that, due to the decrease in headline height, the increase of resistance with speed occurs in a ratio less than the square of the velocity which is the expected ratio for rigid structures.

There are two questions which might receive partial answers from experiments in water channels. These are concerned with the stream lines round and through a net. At present there is no knowledge of such lines and models would provide pictures which could not be obtained in any other way. Thus one would want to know what changes occur when the net goes from mid-water on to the bottom. Such results would be relevant to experiments on particular pieces of netting discussed earlier. They could also be of interest to discussions of the behaviour of fish in front of the net. Further one could perhaps discover whether changes in drag off and on the bottom could be due not only to the direct friction of the bottom but also to the effect of the bottom in changing the lines of flow.

Appendix.

A rope dragged through water will be straight since the forces acting on it are everywhere the same. For a rope which has no weight in water its angle to the flow should be zero. The equations for the lift and drag on such a rope are-

$$D = N \sin^3 \theta + T \cos^3 \theta$$

$$L = N \sin^2 \theta \cos \theta - T \cos^2 \theta \sin \theta$$

$$\frac{\partial D}{\partial \theta} = 3 \sin \theta \cos \theta \;(N \sin \theta - T \cos \theta)$$

$$= 0 \quad \text{for } \tan \theta_o = \frac{T}{N}$$

$$\frac{\partial^2 D}{\partial \theta^2} > 0 \text{ for } \theta = \theta_o$$

$$L = o \text{ for } \theta = \theta_o$$

Thus according to the equations the cable would have a stable position at all speeds at $\theta = \theta_o$ but this is physically impossible.

For the value $C_s = 1/10\ C_D$ (see page 2)

$$\theta_o = 6^o$$

The range in which the equations are inadmissable might be several times this value of θ_o.

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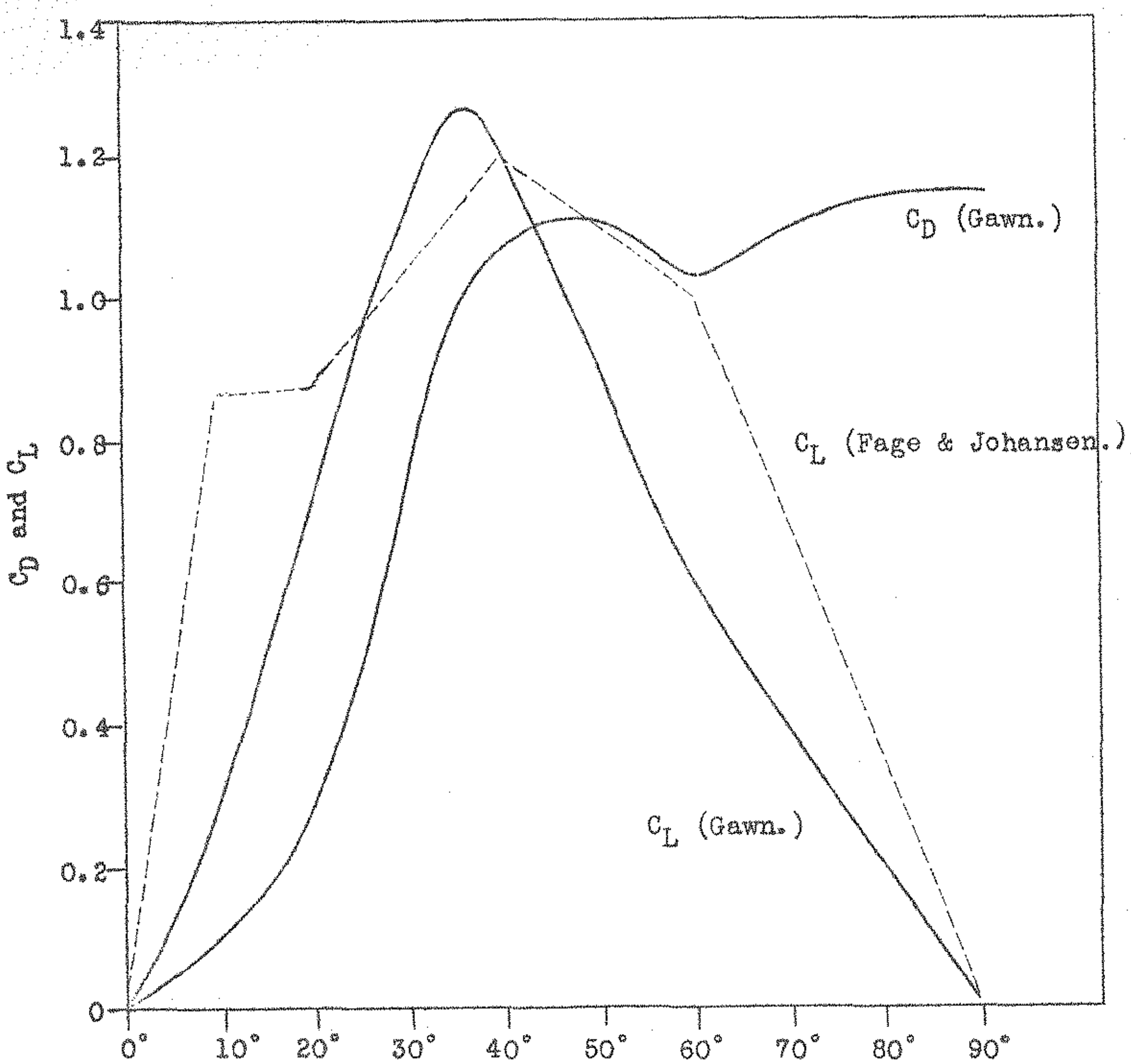

Fig. 8. Lift and Drag Coefficients for flat plates.

——— Gawn (1943): rectangular plate with breadth equal to half the length.

- - - - - Fage and Johansen (1928): for an infinite strip.

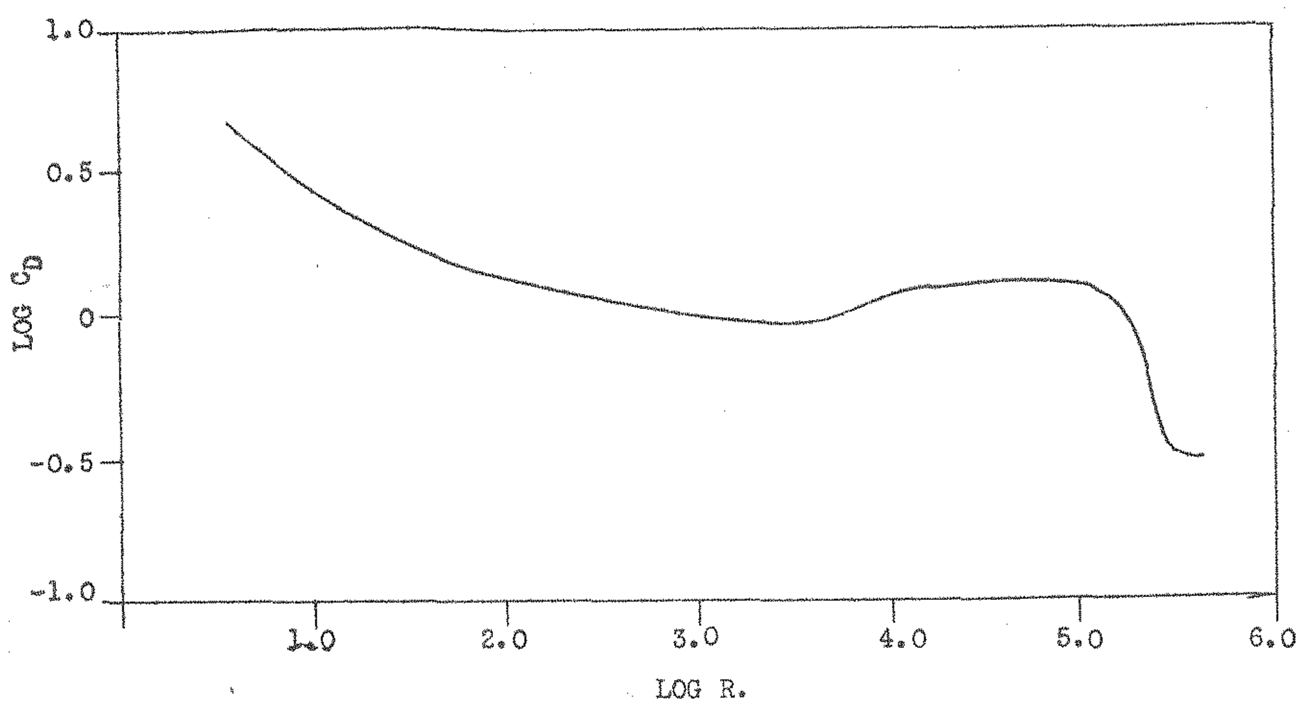

Fig. 12. Change of drag coefficient with Reynold's number. (see Goldstein (1938) p. 15.)