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STRAKE/DELTA WING INTERACTIONS AT HIGH ANGLES OF ATTACK

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ABSTRACT

The method of vortex discretization is used to analyze the interaction of the vorticity generated by a strake, with the flow over a delta wing. The validity of the approach is first established by making comparisons with established methods for dealing with delta wings, after which compound delta planforms are discussed. An understanding of the favorable interference effects normally associated with this type of configuration is obtained and results are presented to quantify the expected lift increments resulting from the strake interaction.

ACKNOWLEDGEMENTS

This report came about as the result of a visit by one of the authors (MIGB) to the Joint Institute for Aeronautics and Acoustics at Stanford University. The author is grateful to Professor K. Karamcheti for affording him that opportunity.

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INTRODUCTION

In recent years there has been a great deal of interest shown in the close coupled strake-wing configuration for military aircraft. This arises because of the improvement afforded in the high angle of attack characteristics of the aircraft. The improvement comes from the favorable interaction of the flow generated by the strake with the flow over the main wing.

It is well-known that for highly swept wings with sharp leading edges at incidence to a stream, the flow separates near the leading edge. A shear layer, in the limit of infinite Reynolds number, a vortex sheet, springs from the sharp edge and under the influence of its own vorticity rolls up into a spiral vortex lying above the wing. The resulting flow pattern is quite different from the attached flow picture, which is amenable to analysis by classical techniques. It seems in the present context, that not only does this separated flow produce substantial vortex lift but the strake vortices interact favorably with the wing flow field.

In order to calculate the aerodynamic forces which arise in the flows with leading edge separation, a number of models have been put forward. In general, the methods rely on the approximations associated with slender body theory, that is, the assumption that the flow gradients in the axial direction are small compared with those in the cross plane. The approach adopted by Brown and Michael (1954) for flow over a delta wing was to regard all the vorticity shed by the wing as being concentrated in vortex cores connected to sharp leading edges by force free vortex sheets of zero strength. Any vorticity shed by the wing is instantaneously convected into the cores.

Generalizations of this method developed by Mangler and Smith (1959) and Smith (1968) consisted of an inviscid model in which the rolled up shear layer was approximated by a concentrated vortex core, as in the Brown and Michael study, connected to the leading edge by a non-uniform force free vortex sheet. This showed a marked improvement over the isolated vortex approach in that the pressure peak over the upper surface of the wing was more accurately predicted.

The computational effort required in the above models were quite small by modern standards.

More recently, techniques which avoid the simplifying assumptions of slender body, or conical flow and utilize the modern high speed computers have been developed. In particular a nonlinear discrete vortex method has been presented by Atta, Kandil and Nayfeh (1977) to account for leading edge separation and which is also capable of dealing with the full three dimensional unsteady flow. The method essentially reduces the problem to the determination of the strengths of bound vortex filaments connecting the vortex lattice lines closest to the leading edge to the starting vortex.

The aim of the present investigation is to try to obtain some understanding of the complex flow interaction which arises between the rolled up shear layer on the strake and the flow over the main wing. Vorticity fed from the strake will influence the vorticity shedding rate from the leading edge of the main wing and also affect the way in which the shear layer over the main wing rolls up. The detailed aerodynamics of the system are regarded as being of secondary importance although comparisons of pressure coefficient over the wing with previous theoretical results and experiment are made.

The slender body approximations are used in the present approach and under these circumstances the steady flow over the strake wing combination becomes equivalent to an unsteady two dimensional flow problem past a growing plate. The method of vortex discretization for this problem consists of replacing the shear layer by a distribution of line vortices the dynamics of which can be determined using the powerful tools of two-dimensional potential flow theory. It must be remembered that in the three dimensional flow, the vortex lines would be curved and consequently would have a self-induced velocity which was logarithmically infinite. However, in a real problem, the singular vortex line cannot exist and this self-induced velocity is in fact limited by the effective non zero radius of the vortex tube. For the present problem therefore, an estimate of the self-induced velocity can be based on a vortex tube radius which is equal to a viscous diffusion length appropriate to the discrete time step. Then the requirement is that the self-induced velocity of the vortex be negligible compared with the velocity induced at the vortex by the other vortices and the stream. This restriction on the time step is not at all serious owing to the fact that the singularity in the self-induced velocity is logarithmic and so the approximation that the vortices can be regarded as infinite straight line vortices is valid.

The method of vortex discretization applied to two-dimensional flow problems was first introduced by Rosenhead (1931) and since that time many authors have taken advantage of the inherent simplicity of the method to tackle the difficult problems involving separation from sharp edges. In particular with the advent of the modern computer the method received a great deal of attention. A substantial review article by Clements and Maull (1975) outlines many of the varied applications. Fink and Soh (1974) have critically reviewed the method and highlight a source of error which may arise from the contribution to the velocity from the principal-value integrals implicit in the numerical scheme. However, they point out that this can be avoided providing the vortices are at the centre of the segment of the shear layer which they are supposed to represent. They therefore proposed a redistribution of vorticity at each time step. However, Sarpkaya (1975) has concluded, after reworking some of his problems, that this refinement was hardly justified.

Moore (1974) has drawn attention to rather more fundamental drawbacks of the method which arise essentially because a vortex sheet is unstable. The problem occurs when neighboring vortices get too close, so that induced velocities of the vortices are extremely high. An examination of Kaden's (1931) results indicated to Moore that any attempt to replace the sheet near its tip by discrete vortices was inadequate. He therefore amalgamated neighboring vortices on the inner spirals to obtain smooth roll up. However, as he points out, some results showed evidence of Kelvin-Helmholtz instability and amalgamation causes instantaneous changes in the velocity field so that it is possible that this approach may aggravate this type of instability. Another device employed by Chorin and Bernard (1973) to avoid the difficulties encountered when vortices came closely together was the vortex cut-off region which ensured that the induced velocities remained bounded.

In using the method of vortex discretization it is necessary to determine the strength of the individual vortices and their generation point. Many workers have relied on experimental data to choose the most appropriate generation point and then the Kutta condition applied at the sharp edge determines the vortex strength. The present authors (1977) used an approximate expression for the rate of vorticity shedding which in conjunction with the Kutta condition gave two equations for the determination of both the vortex strengths and the generation points.

METHOD

The problem analyzed is that of a compound delta wing at incidence α to a stream of speed U. It is easily seen from the analysis that the restriction of delta wings is not strictly necessary, although they are the only type considered in the present report. The apex angles of the strake delta and wing are denoted by $2\beta_1$ and $2\beta_2$ respectively. A Cartesian coordinate system is set up in which z^1 is measured along the axis of the wing and x is perpendicular to the wing; the geometry is shown in Figure 1.

Since the flow is inviscid and irrotational, except at discrete points, the velocity potential ϕ must satisfy

$$\nabla^2\phi = 0$$

subject to the condition of zero normal velocity on the wing. Under the assumptions of slender body theory, ϕ may be written

$$\phi = \Phi + U_\infty \cos\alpha \; z^1$$

where $$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} = 0$$

and $$\frac{\partial\Phi}{\partial x} = 0$$

The equivalent unsteady problem is that of a plate of height $s(t)$ placed normal to a stream of speed $U_\infty \sin\alpha$. This can be obtained from the steady flow problem simply by observing that z^1 is essentially the time coordinate, in fact $z^1 = U_\infty \cos\alpha \; t$, and the local semi-span $s(z^1)$ of the wing can be written

$$S/U_\infty \sin\alpha = s_1 t \qquad t \leq t_0 \qquad \text{say}$$

$$\text{and} \qquad S/U_\infty \sin\alpha = s_2(t - t_0) + s_1 t_0 \qquad t > t_0 \tag{1}$$

where $s_1 = \tan\beta_1/\tan\alpha$ and t_0 is the time corresponding to the strake/wing junction.

Now, concentrating on the unsteady flow problem in the $z(= x + iy)$ plane, it is convenient to map the region $y > 0$ excluding the cut $x = 0$, $0 < y \leq s$ into the upper half of the $\zeta(=\xi + i\eta)$ plane using the transformation

$$\zeta = \sqrt{z^2 + s^2} \tag{2}$$

In the z-plane, vortices are to be shed from a point z_G close to the tip of the plate where $x_G = 0$, $y_G = s + \varepsilon/2$ so that ε can be regarded as the mean thickness of that part of the shear layer shed from the tip which the discrete vortex is supposed to represent. This corresponds to vortices being released in the ζ plane from a point ζ_G close to the origin into a stream of speed $U_\infty \sin\alpha$ parallel to the ξ-axis. After η vortices have been released, the complex potential can be written

$$\omega(\zeta) = -U_\infty \sin\alpha\, \zeta + \frac{1}{2\pi} \sum_{j=1}^{n} K_j \left\{ \ln(\zeta - \zeta_j) - \ln(\zeta - \bar{\zeta}_j) \right\} \qquad (3)$$

where account has been taken of the image system of vortices and K_j is the strength of the j^{th} vortex which is at $\zeta = \zeta_j$.

Because vortex paths do not correspond in the ζ, and z-planes, it is necessary to use Routh's rule to determine the complex vortex velocities $(-u_r + iv_r)$ in the z-plane. Hence,

$$-u_r + iv_r = -U_\infty \sin\alpha + \frac{1}{2\pi} \sum_{\substack{j=1 \\ j\neq r}}^{n} K_j \left[\frac{1}{\zeta_r - \zeta_j} - \frac{1}{\zeta_r - \bar{\zeta}_j} \right] \frac{z_r}{\zeta_r}$$

$$+ \frac{iK_r}{4\pi} \frac{s^2}{\zeta_r^2 z_r} - \frac{1}{2\pi} \frac{K_r}{\zeta_r - \bar{\zeta}_r} \frac{z_r}{\zeta_r} \qquad (4)$$

where ζ_r corresponds to z_r and z_r is the position of r^{th} vortex in the z-plane. At any instant in time this equation gives the vortex velocities thus allowing the individual vortices to be convected and the new distribution established. It remains to examine the way in which the vortices are generated.

For a flat plate normal to a uniform stream, Fage and Johansen (1927) have verified experimentally that the vorticity flux is approximately $\frac{1}{2}q_+^2$ where q_+ is the speed of the outer surface of the shear layer adjacent to a mainstream flow. Hence, if K_n is the strength of the vortex released over an interval Δt , a slight modification of this appropriate to the present problem is

$$\frac{K_n}{\Delta t} = \frac{1}{2}\left|\frac{dw}{dz}\right|^2_{z = i(s+\varepsilon)} - \frac{1}{2}\left|\frac{dw}{dz}\right|^2_{z = is} \tag{5}$$

At the sharp edge $z = is$, the Kutta condition is imposed to make the velocity there finite, this implies that there is a stagnation point at $\zeta = 0$. Using equation (3) this gives

$$K_n = -\eta_G \left(\pi U_\infty \sin\alpha + \sum_{j=1}^{n-1} \frac{K_j \eta_j}{\xi_j^2 + \eta_j^2}\right) \tag{6}$$

where, using the transformation (2), $\eta_G = \sqrt{s\varepsilon + \varepsilon^2/4}$.

Equations (5) and (6) may be solved to determine K_n and the corresponding value of ε .

The fluid velocity (u, v) at any point except the singular points in the flow can be found from equations (2) and (3) and is given by

$$-u + iv = \left\{ -U_\infty \sin\alpha + \frac{1}{2\pi} \sum_{j=1}^{n} K_j \left[\frac{1}{\zeta - \zeta_j} \quad \frac{1}{\zeta - \zeta_j}\right]\right\} \frac{z}{\zeta} \tag{7}$$

In order to evaluate some of the aerodynamic properties of the wings, it is necessary to find the pressure distribution over the surface of the wing. The non-zero velocity component v in the cross flow plane can be found from equation (7) and is

$$v = -\frac{U\,y\sin\alpha}{\xi} - \frac{y}{\pi\xi}\sum_{j=1}^{n}\frac{K_j\,\eta_j}{\xi^2 - 2\xi\xi_j + \xi_j^2 + \eta_j^{\,2}} \qquad \begin{array}{c} -s \le \xi \le s \\ y = \sqrt{s^2 - \xi^2} \end{array} \tag{8}$$

where $\xi < 0$ for the lower surface and $\xi > 0$ for the upper surface. From equation (3) the velocity potential can be found and its time derivative evaluated, bearing in mind that the only time dependent part of Φ arises through the vortex positions.

Thus

$$\frac{\partial\Phi}{\partial t} = \frac{1}{\pi}\sum_{j=1}^{n} K_j \frac{u_j\,[\eta_j A_j + (\xi - \xi_j)B_j] + v_j\,[(\xi - \xi_j)A_j - \eta_j B_j]}{[(\xi - \xi_j)^2 + \eta_j^2]\;[\xi_j^2 + \eta_j^2]} \tag{9}$$

where $A_j = x_j\xi_j + y_j\eta_j$ and $B_j = y_j\xi_j - x_j\eta_j$,

Using Bernoulli's equation

$$-\frac{\partial\Phi}{\partial t} + p + \frac{1}{2}\rho v^2 = \text{a constant} \tag{10}$$

and equations (8) and (9), the pressure distribution on the wing can be calculated.

In the present work, the fact that no length scale exists for the delta wing problem has not been incorporated into the analysis. As a result there is no self-similar development of the flow and when a comparison was made between the strake-on and strake-off configurations, it was felt that to be consistent, the length scale for both problems should be the same and therefore taken from the strake-on case. The difficulty in adopting what might be regarded as a more rigorous approach is that the numerical scheme does not remain stable for a sufficiently long time.

RESULTS AND CONCLUSIONS

It is important, before any detailed results concerning the strake wing interaction are presented, to compare the present method with the well established method of Smith. Smith's results give a detailed picture of the rolled up vortex sheet and also give a location for the concentrated core. However, his analysis was based on the conical flow approximation so that it was necessary, in the present calculations, to assume that the flow had become approximately similar at chordwise stations before the comparisons were made. In Figure 1(a), (b) the vortex roll-up along two delta wings with $s_1 = s_2 = 1$ and 2/3 respectively is shown, the total number of vortices shed on the final spiral is 59 in each case. Reference to equation (1) shows that the larger values of s_1, s_2 can be interpreted, not only as indicating a larger apex angle of the wing if the incidence in the two cases is the same, but, alternatively, for the same wing represents a smaller angle of attack. Thus, the reason for the more extensive vortex spiral in the $s_1 = s_2 = .7$ case is evident.

In order to make a detailed comparison with Smith's results, it is necessary to reproduce his type of flow model, namely one and half spirals in the shear layer and a concentrated vortex core. This was done after 49 vortices had been released by amalgamating the inner 24 vortices into their vortex centre. The results are shown in Figure 2a and b, where it can be seen that good agreement between the two methods should be the same and therefore taken from the strake-on case. The difficulty in adopting what might be regarded as a more rigorous approach is that the numerical scheme does not remain stable for a sufficiently long time.

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In order to make a detailed comparison with Smith's results, it is necessary to reproduce his type of flow model, namely one and half spirals in the shear layer and a concentrated vortex core. This was done after 49 vortices had been released by amalgamating the inner 24 vortices into their vortex centre. The results are shown in Figure 2a and b, where it can be seen that good agreement between the two methods is achieved overall, but the centre of the vortex core on the present calculation, although at approximately the same height, lies farther inboard. Smith pointed out that his predicted lateral position of the core was in error by about 6% of the semi-span of the wing so the present calculations look particularly promising. In Figure 3, the pressure distribution over the wing surface is compared with both Smith's results and the experimental data of Fink and Taylor (1966). Two curves from the present calculations are shown, one corresponding to no amalgamation of vortices and the other to the amalgamation of twenty four vortices as mentioned above. The results clearly show the increased sharpness of the pressure peak resulting from the concentration of vorticity. Overall, the results show a broader suction peak spreading further inboard giving good qualitative agreement with the experiment. However, the pressure rise as the leading edge is approached is overestimated by the theory.

Having established that the method is capable of producing realistic results for the case of the delta wing, attention can now be focussed on the strake wing interaction problem. It must be stressed that the numerical procedure used requires rather fine tuning in order to avoid the instabilities which frequently arise with this method. It is worthwhile to examine the reason for this difficulty as it has a direct bearing on the results to be presented for the strake wing problem. As mentioned in the Introduction, Moore has suggested that the system is susceptible to Kelvin-Helmholtz instabilities which can be triggered by any perturbation to the system. He found evidence that repeated amalgamation of vortices, by producing instantaneous changes in the velocity field, made this type of instability on the system more apparent. Clearly, any discrete numerical scheme is continually producing instantaneous changes to the system but in the present context the extra complication which arises from continually changing geometry aggravates this situation. In particular, when there is a sudden change in a parameter value e.g. where the problem is enormously increased. This means that at this stage, it is necessary to limit the cases considered to ones where the ratio s_1/s_2 is no more than 2.

Nevertheless, in the extreme case the results (Figure 4) show the development of an instability after about thirty five vortices have been released. Figure 5 shows the same flow with a change in time step at the discontinuity of slope of the wing which has succeeded in stabilizing the numerical procedure. Another example of the vortex roll up is shown in Figure 5b where $s_1 = .5$ and $s_2 = .8$. The experimental results of Lamar (1978) and Luckring (1978) show that for high angles of attack, there appears to be only one vortex system over the main wing.

Although it is not going to be possible to examine the practical situations where s_1/s_2 is substantially more than 2, the results shown in Figure 4 do begin to show the way in which the interaction between strake vortex and flow over the wing produces an improvement in lift characteristics. By comparing the shapes of the rolled up shear layers at the same span (A in Fig. 4, B in Fig. 1(a)) for the two cases, i.e. corresponding to strake on and strake off configurations, it can be seen that the rolled up shear layer is dragged inboard by the strake vortex. On the face of it this would suggest a substantial increase in the coefficient of lift per-unit chord C_{LS} at this span since the total vorticity at this station is greater with the strake on than with the strake off. However, reference to Figure 6 where the surface pressure distributions for the two cases are plotted, shows that this is not the case. This is because the center of vorticity at the span corresponding to the strake wing junction, although in approximately the same lateral position for the two cases, is about one and a half times further from the wing surface with the strake on. It is necessary to go further along the wing before the favorable interaction becomes apparent in the form of an increase in C_{LS}. This is shown in Figure 7 where the C_{LS} with the strake on becomes greater than the strake off value at about two strake chords from the vortex of the strake. It must be borne in mind that the contribution of C_{LS} to the overall C_L of a wing would be weighted by the local span. Such curves are shown in Figure 8 where it is worth noting that the deviation from a straight line through the origin is a measure of the non-conical nature of the flow.

It seems likely that this preliminary investigation of the influence of a strake on the flow characteristics over a slender wing is worth extending to gain further insight into this complex phenomenon. Clearly the restriction to delta like geometry is not necessary and also cambered aerofoils could be analyzed. However, it is felt, intuitively, that one of the most important benefits which might arise from the addition of a close coupled strake is the delay in the vortex breakdown over the main wing. In general, the highly swept strake will produce a stable vortex which may under suitable conditions, tend to stabilize the inherently less stable vortex over the main wing. Indeed there are indications from recent experimental results[14] that this may be the case.

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LIST OF FIGURES

Figure 6 Comparison of pressure distribution over delta wing with strake on and strake off; ——— strake on, - - - - - strake off.

(a) $s = 1.12\ s(t_o)$ (b) $s = 1.80\ s(t_o)$

Figure 7 Comparison of C_{LS} for strake on/strake off configurations

Figure 8 Comparison of C_{LD} x local span for strake on/strake off configurations

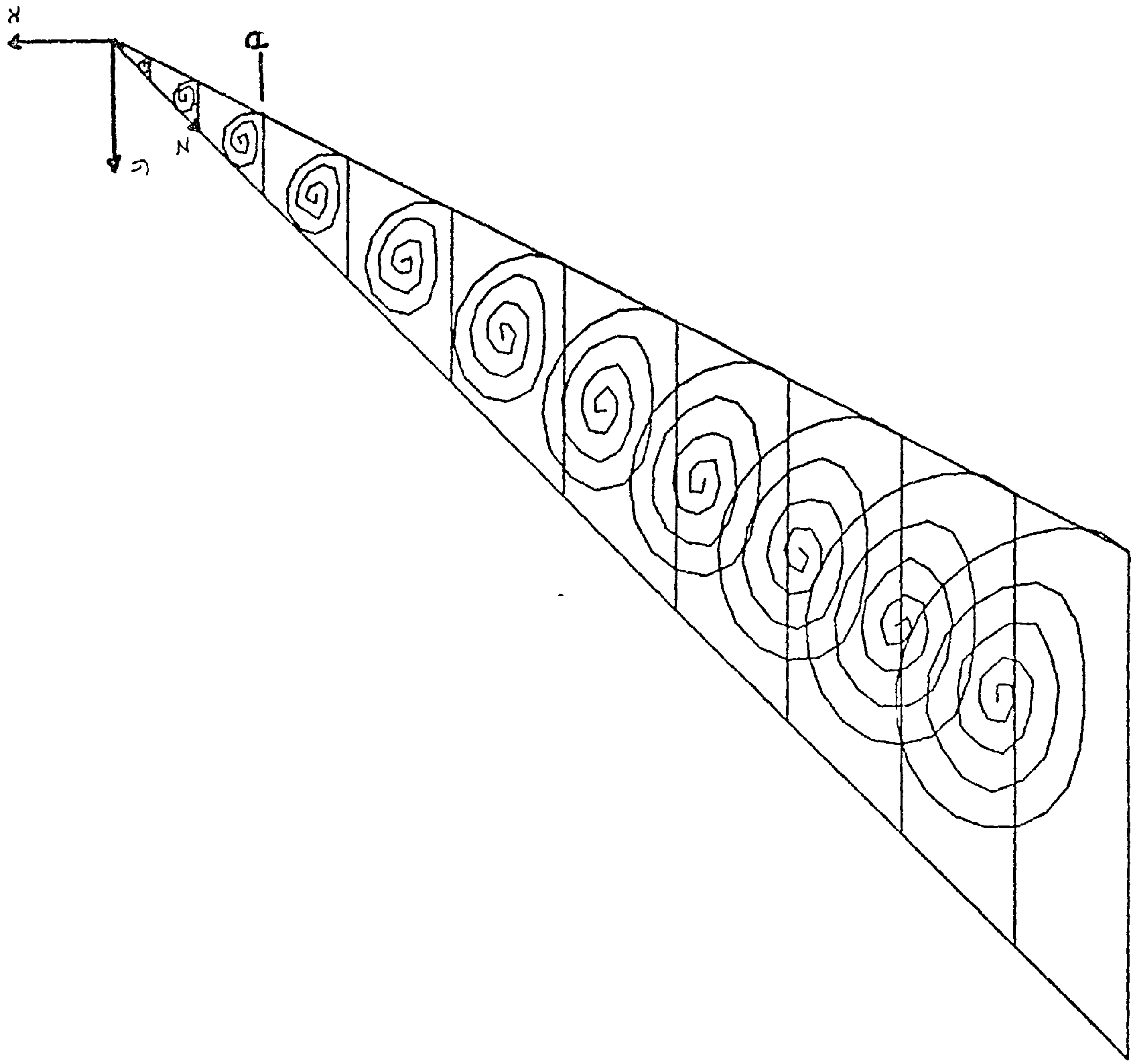


Figure 1a.

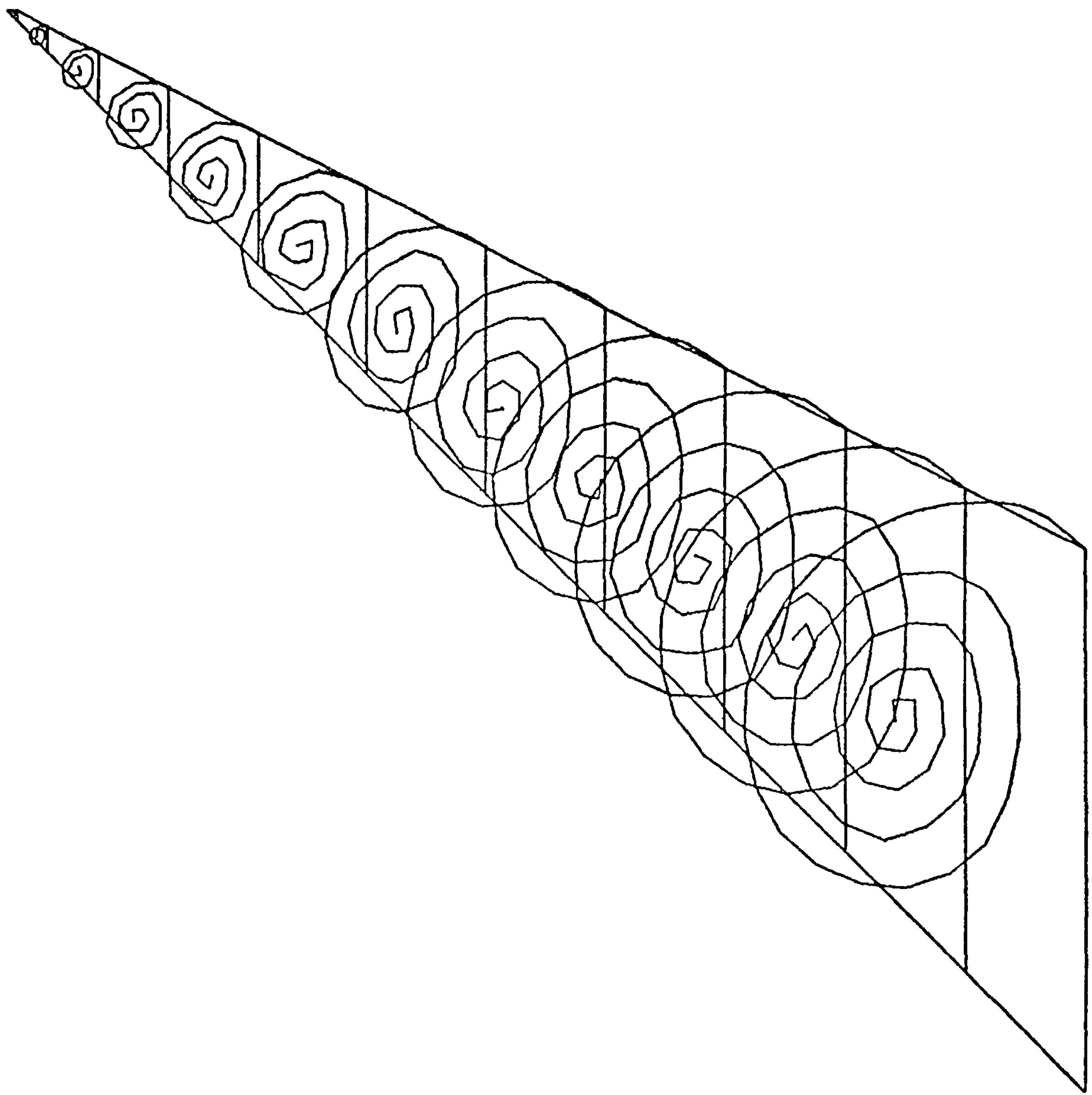


Figure 1b.

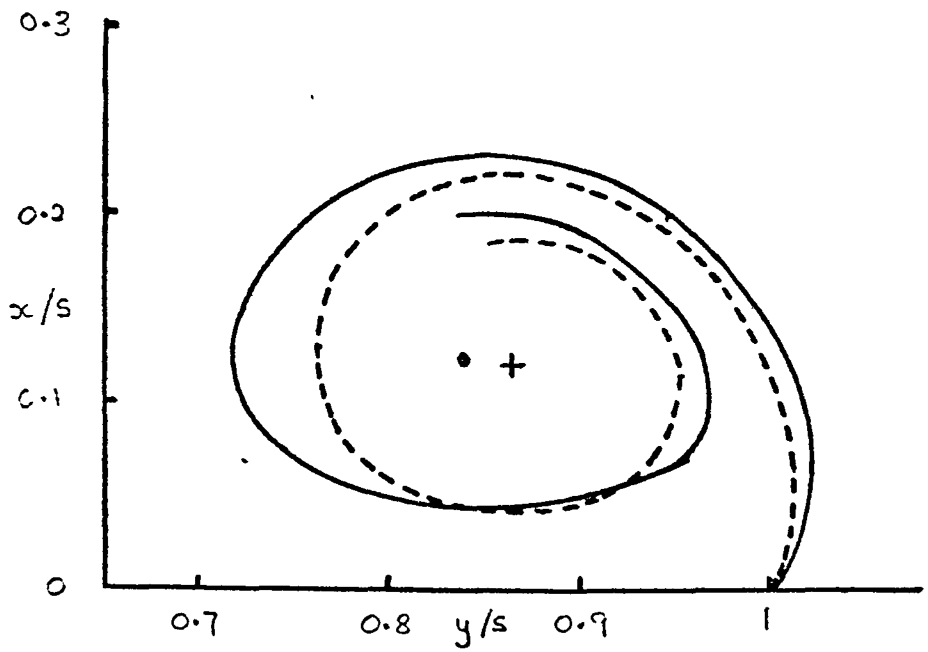
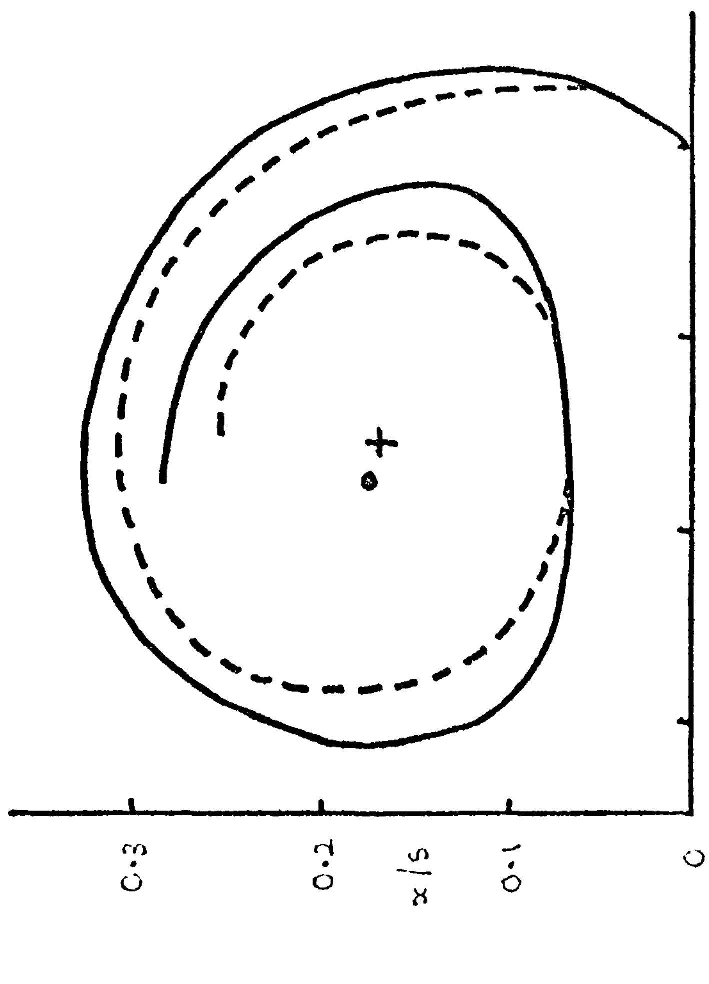


Figure 2a.



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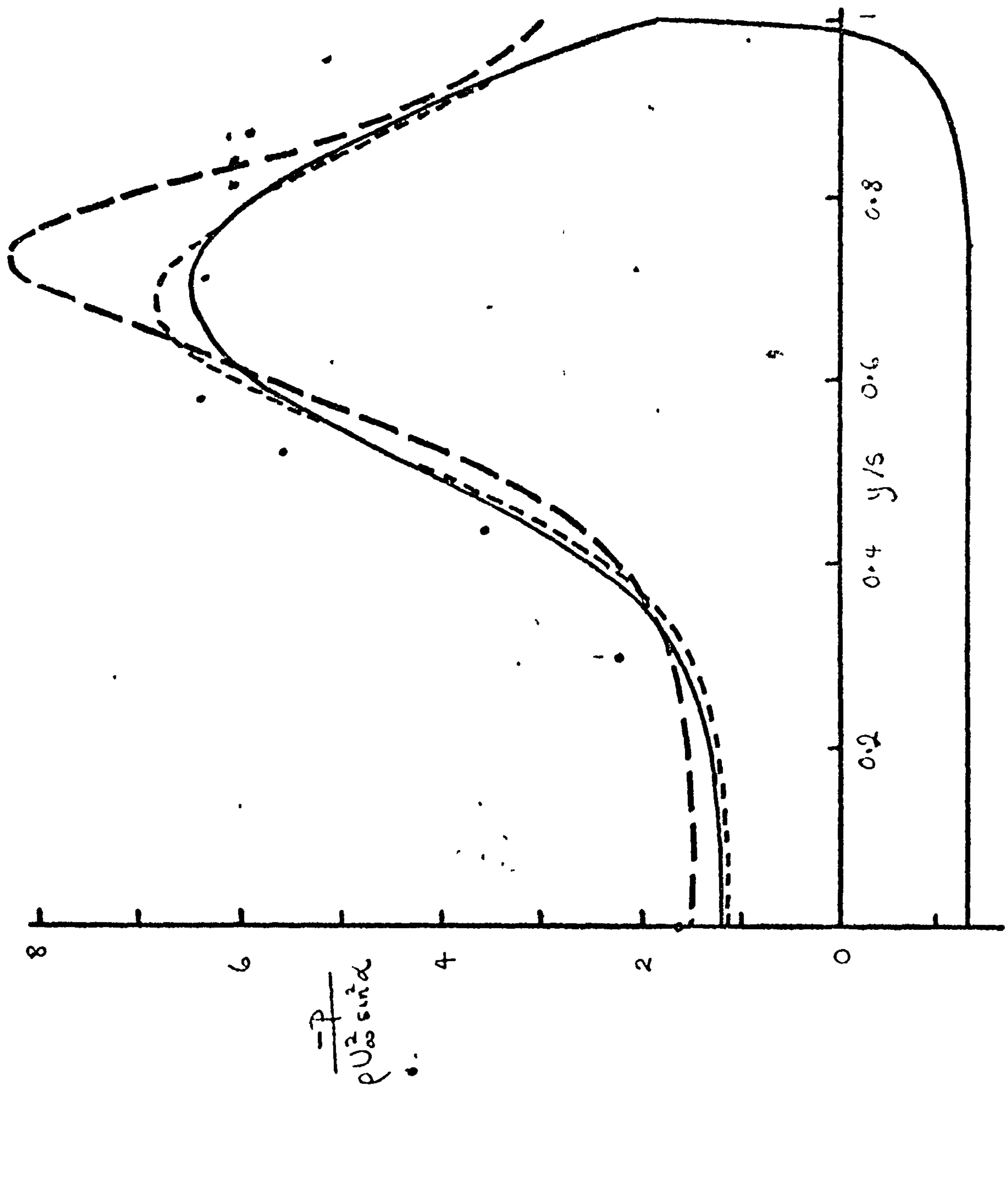

Figure 3.

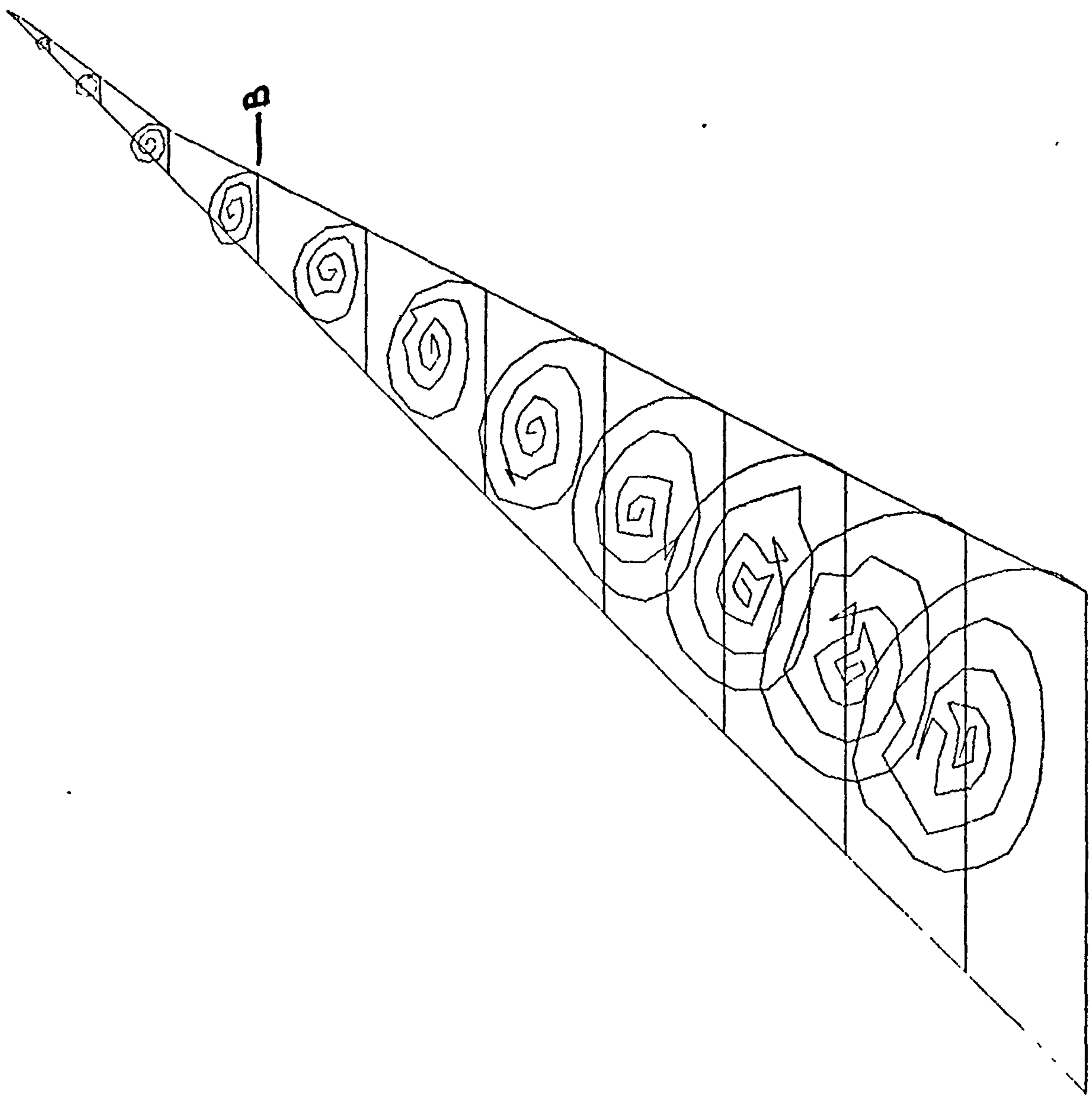

Figure 4.

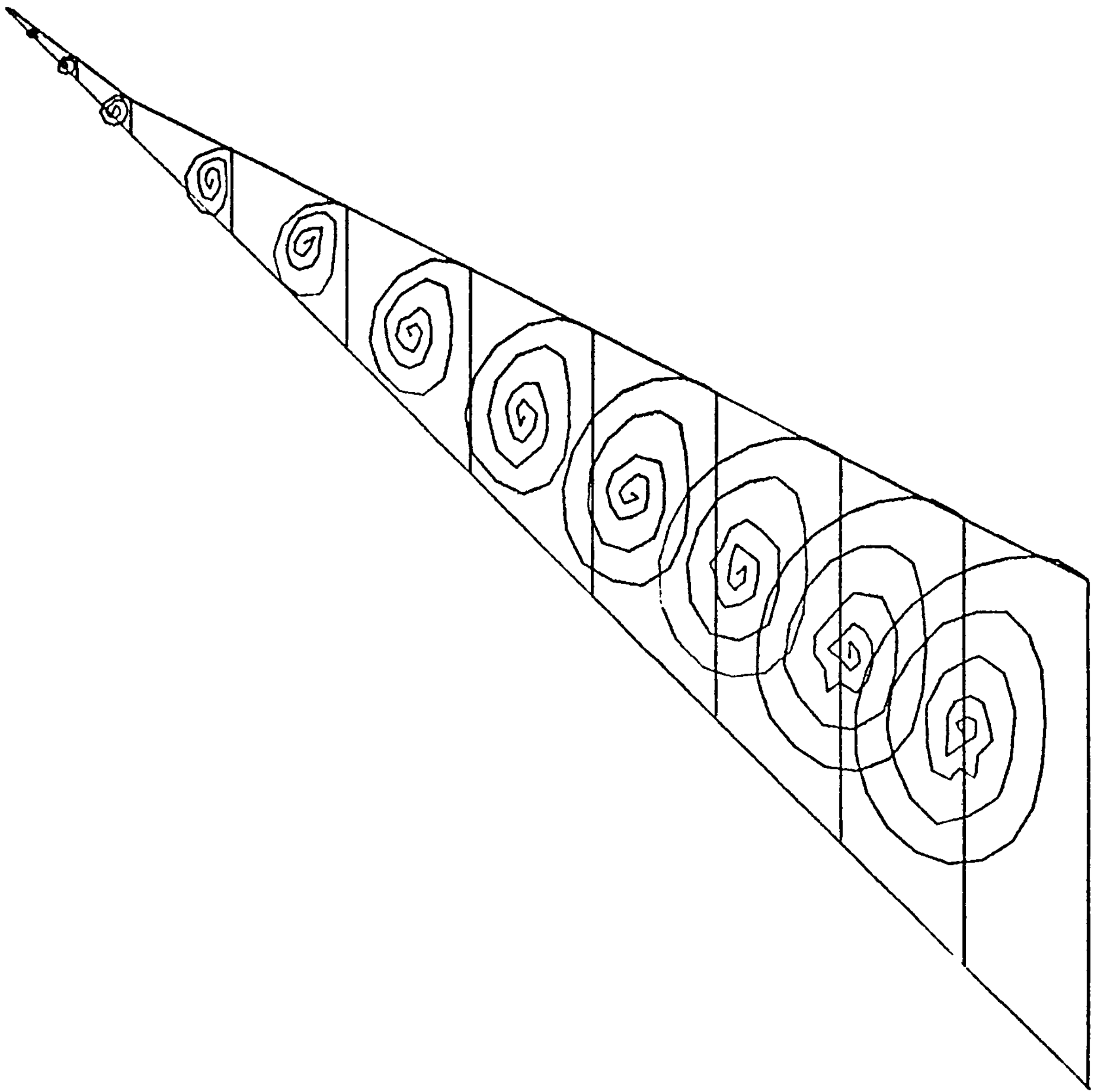

Figure 5a.

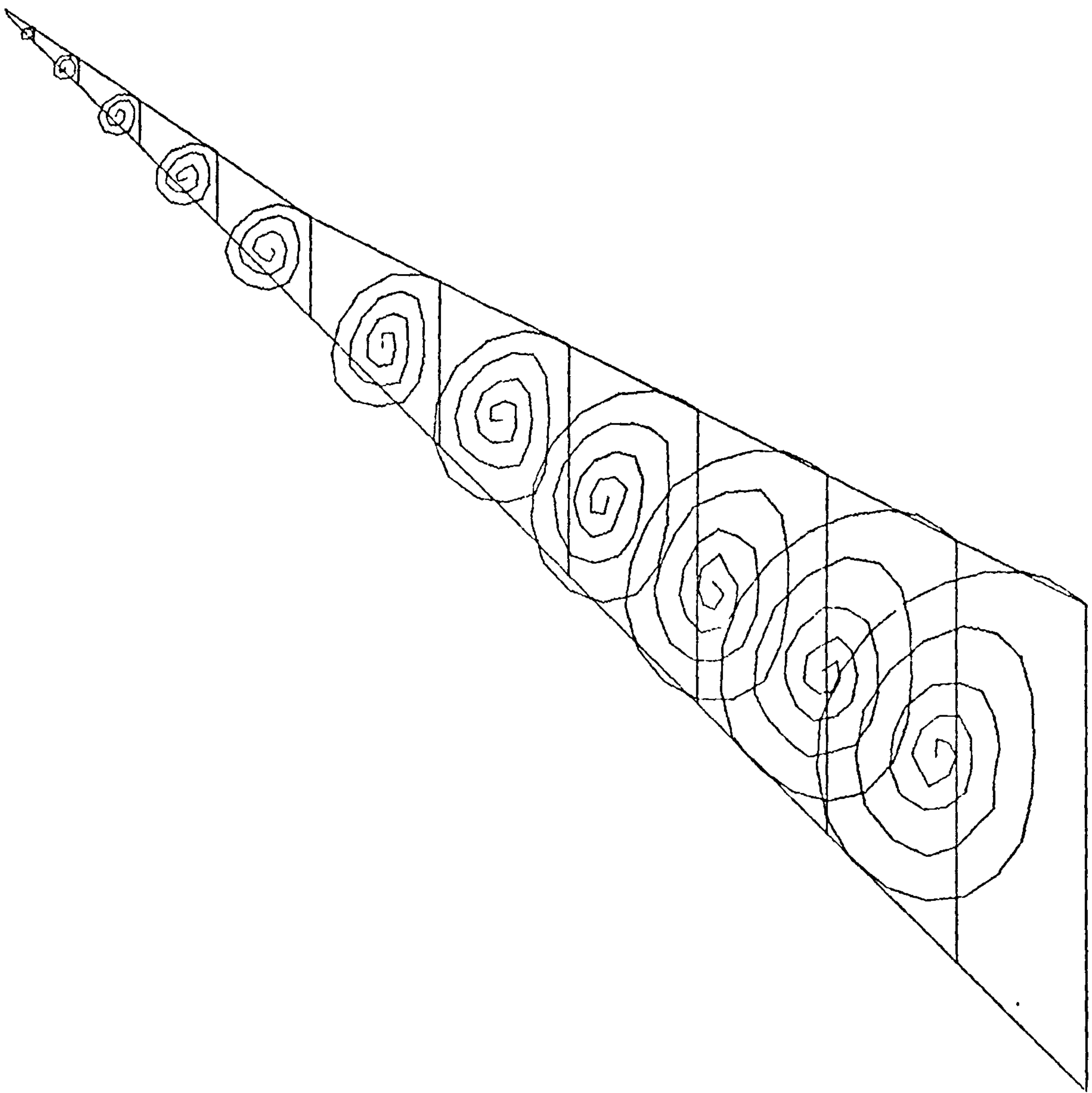

Figure 5b.

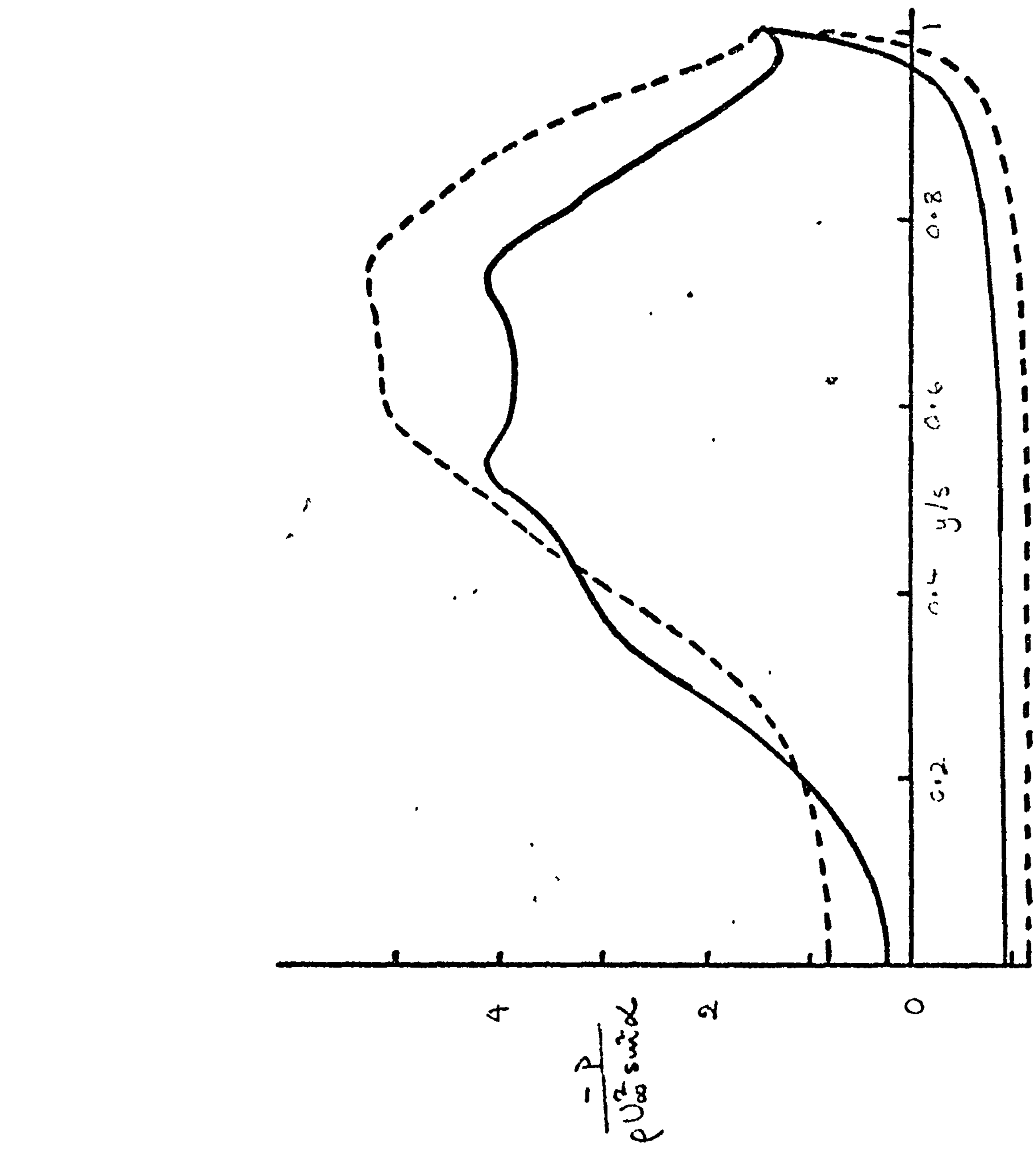

Figure 6a

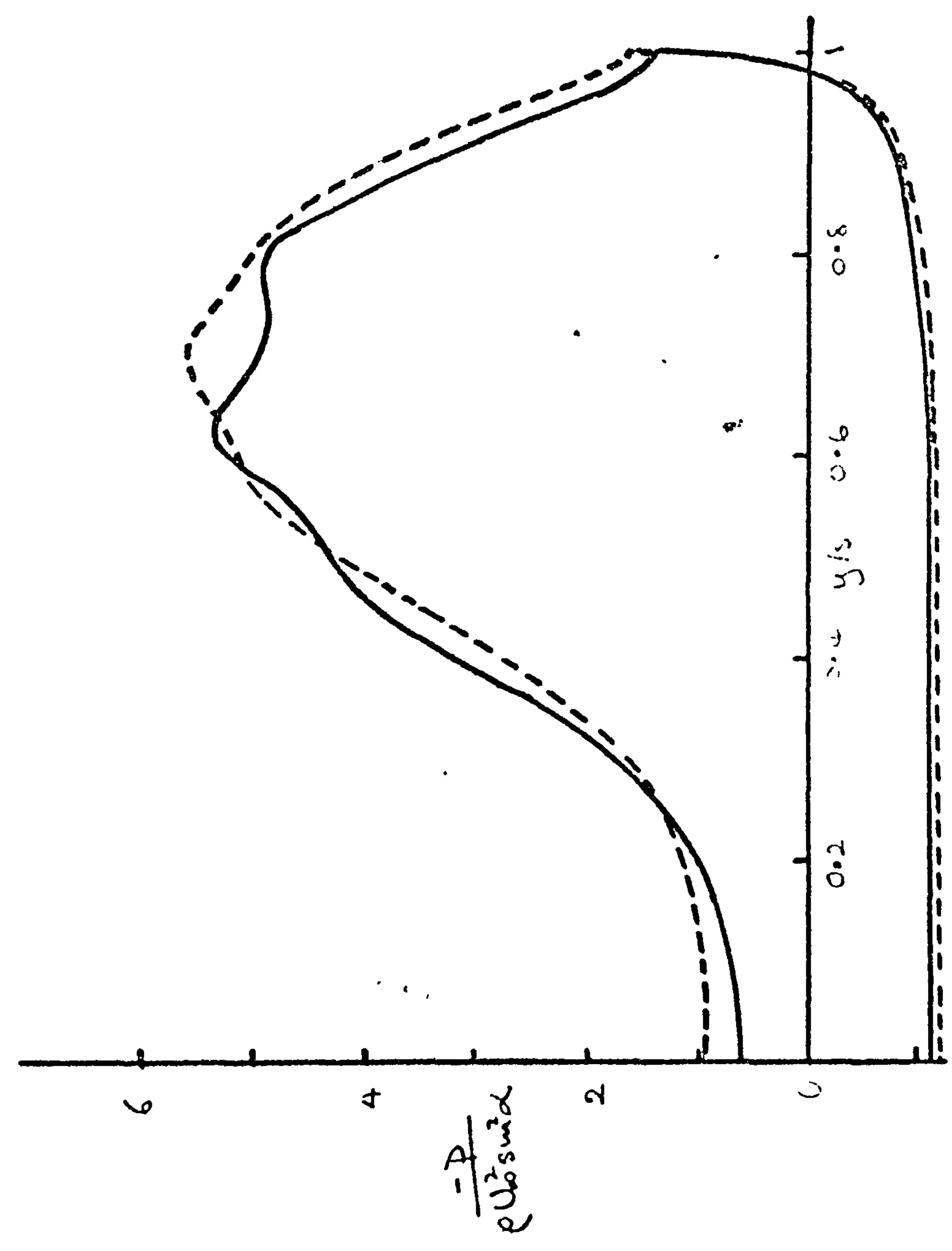

Figure 6b.

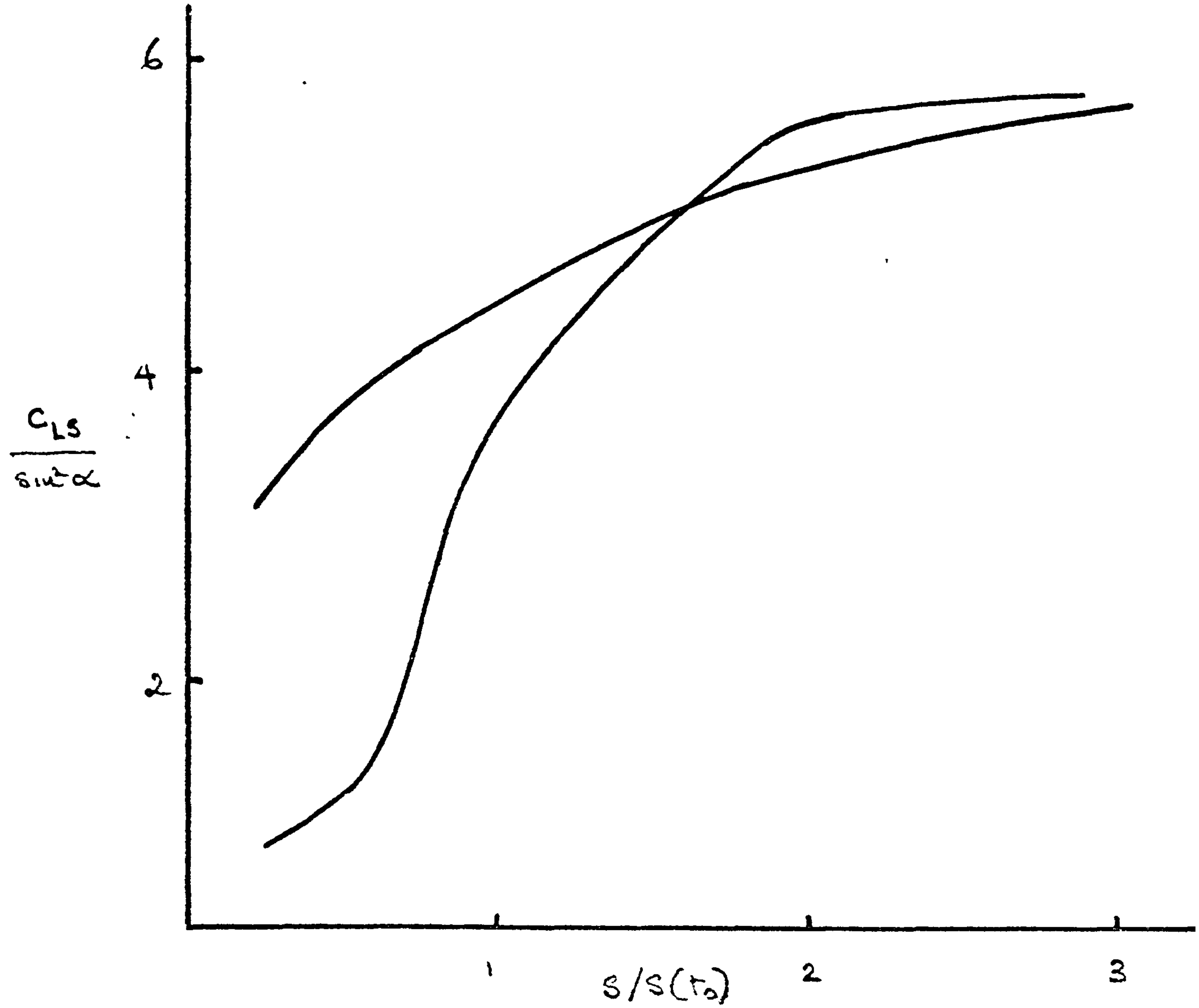

Figure 7.

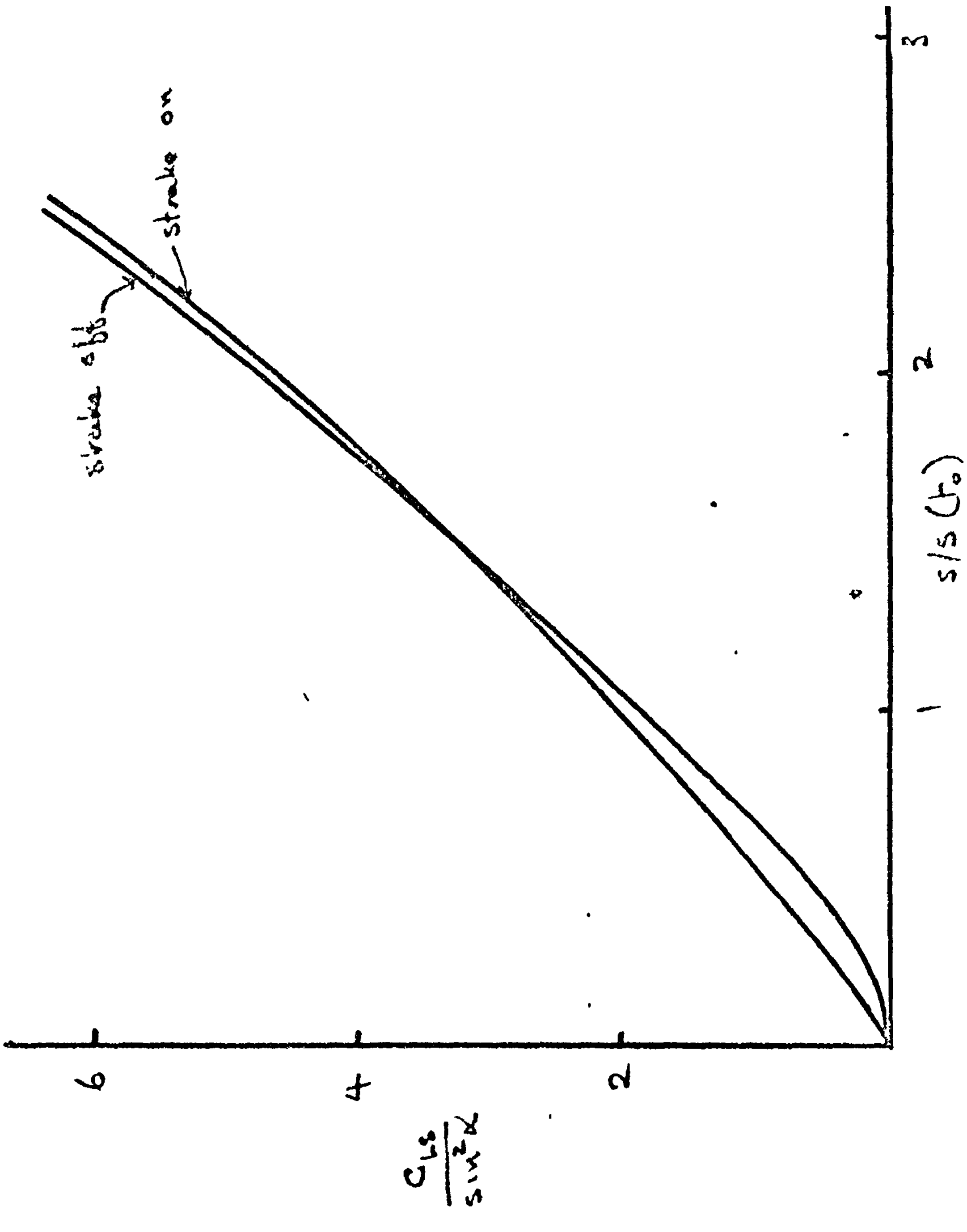

Figure 8.

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