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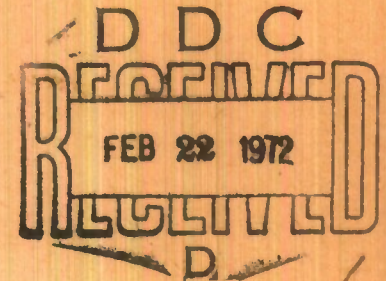
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

BASIC TECHNIQUES DIVISION

R.A.R.D.E. MEMORANDUM 14/70

Subsonic wind tunnel tests on the use of streamers to stabilize the FOIL bomblet [C]

R. K. Fancett, Ph.D., D.I.C.

W. A. Clayden, B.Sc., A.R.C.S.

Fort Halstead
Kent.

CONFIDENTIAL

March,
1970

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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 14/70

Subsonic wind tunnel tests on the use
of streamers to stabilize the FOIL bomblet

R.K. Fancett, Ph.D., D.I.C. } (D4)
W.A. Clayden, B.Sc., A.R.C.S. }

Summary

        The aerodynamics of a FOIL bomblet stabilized by streamers was studied in
a small subsonic wind tunnel. For this investigation the size and shape of the
streamers was based upon an earlier parametric study of the drag of isolated streamers.

        The reduction in drag of a streamer operating in the bomblet wake was
measured and measurements were also made of the static and dynamic stability and spin
damping. These measurements were compared with results obtained for a similar bomblet
stabilized with a conventional fin. It is shown that whilst streamers may provide
adequate static stability and spin damping, the dynamic stability at small angles of
incidence is poor compared with fins though streamers may be as effective as fins in
damping out very large angles of incidence.

Approved for issue:

        S.W. Coppock, Principal Superintendent, 'D' Division

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Notation

a	static margin of the fin tail centre of pressure related to body centre of gravity
A	area (cm^2)
b	calibre of cylinder enclosing the fins
C_{DA}	drag coefficient based on streamer area, $l \times s$
C_{DO}	drag coefficient based on bomblet frontal area
C_l	rolling moment coefficient ($= $ rolling moment$/\frac{1}{2}\rho U^2 A_b d$)
C_{lp}	spin damping coefficient $\left\{ = \partial C_l / \partial \left(\frac{pd}{2U}\right) \right\}$
C_m	pitching moment coefficient about the centre of gravity ($=$ pitching moment$/\frac{1}{2}\rho U^2 A_b d$), positive nose up
$C_{m\alpha}$	$= \partial C_m / \partial \alpha$
$C_{mq} + C_{m\dot\alpha}$	pitch damping coefficient $\left\{ = \partial C_m / \partial \left(\frac{qd}{2U}\right) + \partial C_m / \partial \left(\frac{\dot\alpha d}{2U}\right) \right\}$
C_N	normal force coefficient ($=$ normal force$/\frac{1}{2}\rho U^2 A_b$)
$C_{N\alpha}$	$= \partial C_N / \partial \alpha$
d	bomblet calibre (cm)
g	acceleration due to gravity (m/s^2)
FR	streamer fineness ratio ($= l/s$)
I_l	bomblet moment of inertia in roll ($kg.m^2$)
I_m	bomblet moment of inertia in pitch ($kg.m^2$)
l	streamer length (cm)
n	number of fins
p	spin rate (rad/s)
q	pitch rate about a fixed axis of rotation (rad/s)
r	radius of the streamer point of attachment (Fig. A2)
r_G	distance from streamer attachment point to body centre of gravity (Fig. A1(a))

Re   Reynolds number

s   streamer width (cm)

t   time

U   free stream velocity (m/s)

u   local velocity (m/s)

w   streamer weight per unit area (g/m^2)

x_{CG} centre of gravity distance from the bomblet face

x_{CP} centre of pressure distance from the bomblet face

y   distance normal to the bomblet longitudinal axis

α incidence

$\dot{\alpha}$ rate of change of incidence (rad/s)

ρ air density (kg/m^3)

Subscripts

b   body

f   one fin

M   mean value during "residual" motion phase

o   initial value

s   streamer

t   complete fin tail

∞ free-stream conditions

Superscript

−   mean value

1. INTRODUCTION

Projectiles are normally either stabilized gyroscopically or aero-dynamically by the use of fins. Stability may also be achieved by a drag device attached to the rear end of the projectile such that the restoring moment produced by the drag force is larger than the overturning aerodynamic moment on the projectile. For a variety of reasons to be discussed later the drag force may conveniently be applied by the use of streamers. The use of streamers is not new and has been applied in the past to primitive throwing spears and a type of grenade used in the first world war. Drag stabilization is not normally used because of the enhanced drag, but for certain types of sub-projectiles dispersed from a parent vehicle the enhanced drag is not necessarily a disadvantage, particularly if the sub-projectile contains a shaped charge. Indeed in some cases the enhanced drag may be an advantage since the impact velocity is reduced and the effective stand-off distance may be increased for a given fuze system. The use of streamers as an alternative to fins to stabilize sub-projectiles can lead to improved packing density and the ability to withstand high accelerations during the launch phase of the parent warhead. This latter ability is of particular importance for gun-launched warheads. There may also be a marginal cost reduction. Because of the above advantages the aerodynamics of a streamer stabilized FOIL bomblet was studied to provide sufficient information for preliminary systems analysis and assessment purposes and the results are reported in this memo.

In addition to providing adequate static stability the streamers must also ensure that large launch disturbances and spin rates are damped to an acceptable level, say an incidence of less than $\pm 10°$ and a spin rate of less than 10 revolutions/sec. Very large initial spin rates may occur if the parent warhead is spin-stabilized or it is spun at the end of its trajectory to disperse the bomblets.

The tunnel tests were aimed at providing sufficient information on static and dynamic stability and spin damping with streamers to enable a near optimum solution to be chosen for the given design. Whilst typical launch velocities may vary from subsonic to supersonic the tests reported here were undertaken in the subsonic tunnel since the aerodynamic behaviour of the bomblet is of most interest at low velocities just before impact ($\simeq 50$m/s). It is hoped to extend the work to supersonic velocities with the aid of a small intermittent tunnel which is being assembled from existing components.[*] Most of the tests were undertaken with a configuration similar to that proposed for the bomblets of the FOIL artillery rocket but much of the work and the apparatus will be applicable to shell dispensed bomblets. The approach to the problem has been largely experimental because of the complex behaviour of streamers but an elementary theoretical treatment has been attempted for some aspects. For purposes of comparison some measurements of static and dynamic stability and spin damping have been made with bomblets stabilized with fins.

* It is not possible to test streamer devices in the continuously running supersonic tunnel since the streamer material will not survive the violent flapping motion for a sufficient time for the tunnel to run up to speed.

Before attempting to make measurements on a complete device a number of preliminary tests were undertaken to measure the drag of streamers alone to obtain some information concerning the dependence of drag on parameters such as size, shape, weight per unit area and velocity. The results of this study will be published in a forthcoming RARDE memo. These preliminary experiments were deemed necessary in order to obtain some information on scaling as the only relevant information in the literature was aimed at the drag of advertizing streamers towed behind light aircraft in 1930 [1].

As mentioned earlier drag devices other than streamers may be used for stability and some tests were undertaken with drogues. Whilst these devices yield adequate static and dynamic stability it is doubtful if they can be attached to the bomblet to provide sufficient spin damping.

2. STATIC STABILITY AND DRAG

Measurements have shown that the drag of a streamer is sufficiently high to stabilize a typical bomblet shape. This section describes measurements made to estimate the reduction of streamer drag due to the wake behind the bomblet body and the static stability of a bomblet stabilized with fins or various drag devices including streamers and drogues.

2.1 Tunnel

The tests were made in the 0.46 metre (18in) square subsonic tunnel described in detail by Clayden [2]. The tunnel has a closed working section and an open circuit and is driven by an upstream radial blower. The tunnel was not provided with a speed control before these tests were undertaken because for reasons of economy the blower was driven by an A.C. motor originally obtained for another purpose. However during the course of the tests it was found that an adequate speed control could be obtained by simply reducing the area of the inlet to the blower and the tunnel was operated at nominal speeds of 14, 21, 32 and 37 m/s (46, 67, 105 and 125 ft/s) yielding Reynolds numbers from 0.95 to 2.52 x 10^6 per metre (0.29 to 0.77 x 10^6 per ft).

2.2 Models and data reduction

A 3.81 cm (1.5in) calibre shaped charge bomblet model with a body geometry shown in fig. 1 was used for the reduction in streamer drag and stability measurements. The centre of gravity was located 0.75 calibres aft of the front face.

The two frontal probes consisted of a 0.25 calibre disc tripod mounted from the front face of the basic body at stand-off distances of 0.75 and 1.5 calibres (referred to as geometries (a) and (b) respectively). The fin tail (configuration A) had three straight fins of cropped delta planform made of 1.6mm (0.063in) thick perspex with a leading edge angle of 45° and overall radial height and chord of 0.58 and 1.57 calibres respectively.

The streamers (configuration B, fig. 1) were made of terylene (w = 134 g/m²).

Earlier streamer results showed diminishing returns of the streamer drag coefficient with fineness ratio and the choice of this parameter was dictated by practical considerations of the streamer area. Two main streamer combinations were studied each with the same total area to body cross section area ratio of 5.5; two streamers 0.33 calibres wide and 6.5 calibres long were mounted off axis in a radial plane to give a height to their outer edges of 0.5 calibres and three streamers, each having a length and width 4.4 and 0.33 calibres respectively, were attached to the circumference of the bomblet afterbody.

Two other types of drag stabilizer were investigated, namely a plastic hemisphere cap with 25% porosity and a thin copper cone-cylinder drogue with a trailing terylene 'wind sock' (configuration C in fig. 1). They were attached to the model axis by three strings in the form of a tripod connected via a swivel to a single string attached to the model base to give a stand-off distance of 2.67 calibres.

Properties (ie weight, pitch inertia etc.) of the main bomblet configurations are included in table 1. As the bomblet may be launched at large incidence, measurements of lift and pitching moment were required up to angles of 90° which are outside the scope of the three-component balance and a simple one-component balance was made for the purpose. It consisted of a 4.8mm (≃0.19in) diameter brass rod mounted transversely across the tunnel working section supported at each end by low-friction ball races to allow it to rotate freely. The model was rigidly mounted to the rod and positioned at the tunnel centre line. The ends of the rod extended outside the tunnel sides through air-tight plugs and the model could be maintained at a fixed incidence during a run by balancing the aerodynamic pitching moment with a scale pan and weights supported over a 5.04cm (2 in) diameter pulley. A pointer, clamped to the rod and able to traverse an incidence scale, was used to measure incidence. The model was supported at its centre of gravity and rebalanced at a position ahead of it to give the aerodynamic moment and normal force as a function of incidence. Tare forces due to friction in the balance were measured and found to be negligible.

The static measurements of $\partial C_m/\partial\alpha$ $(=C_{m\alpha})$ were checked by allowing the model and its support to oscillate freely in the bearings and measuring the frequency. The pitching moment was then obtained from the relationship.

$$- M_{G\alpha} = 4\pi^2 \ f^2 \ I_m \tag{1}$$

where f is the frequency, I_m the moment of inertia, and $M_{G\alpha}$ the pitching moment curve slope about the centre of gravity.

A dural model, twice the scale of the model used on the one-component balance and with a probe of 1.5 calibre stand-off distance was used to measure the effect of body wake on the streamer drag. It was supported on a three-component semi-conductor strain gauge balance [3]. Four fibre glass streamers (w = 100 g/m²), 0.25 calibres wide and with fineness ratios up to 16 were attached to the bomblet off axis in two orthogonal radial planes by means of small fins to give a height to their outer edges of 0.5 calibres.

2.3 Results and discussion

The drag of the bomblet with and without the four radial streamers is shown in fig. 2 where C_{DO}, the drag coefficient based on the maximum body frontal area is plotted for the incidence range $-1.25° \leqslant \alpha \leqslant 14°$. The drag coefficient of the body alone is 1.35 and is independent of incidence within $\pm 4\%$. The addition of the 1.5 calibre probe to the body drastically reduces the drag due to the lessening of the aerodynamic force on the bluff face of the body caused by the flow separation from the probe tip. However C_{DO} increases with incidence from 0.67 at $\alpha = 0°$ to 0.94 at $\alpha = 14°$. The increment of C_{DO} due to the streamers (FR=16) is constant at 0.5 to within $\pm 10\%$. The variation of C_{DO} for the streamers with fineness ratio is given in fig. 3 for zero incidence and shown to be linear (ie C_{DA} = constant) for 0<FR<6. This result differs from measurements made with unshielded streamers in which C_{DA} decreased with increasing fineness ratio. This suggests that the relative efficiency of the body-shielded streamers increases with their length due to the rise in the wake dynamic pressure close to the bomblet's base. For FR>6 the body shielded streamers exhibit the same behaviour as the unshielded streamers, C_{DA} decreasing with increasing fineness ratio.

Profiles of the non-dimensional dynamic pressure in the bomblet wake at three positions from the bomblet base show the mean value acting on the streamers to be constant and 60% of the free-stream value (see fig. 4). Fig. 5 shows the corresponding deficit in the effective drag coefficient of the streamers. The ratio of drag coefficients for the body-shielded streamers to those in the free-stream, k $(=C_{DA}/C_{DA\infty})$, increases with the fineness ratio to a constant maximum value of 0.5 for fineness ratios greater than 6 and the results suggest that the loss of streamer drag effectiveness is almost entirely due to the loss of dynamic pressure in the wake.

Measurements of $C_{N\alpha}$, $C_{m\alpha}$, and static margin $(X_{CP}-X_{CG})/d$ of the bomblet with the 0.75 calibre probe in the incidence range $0° \leqslant \alpha \leqslant 30°$ are given in figs. 6 and 7 for the body alone and with the fin and three circumferential streamer stabilizers. The body alone is statically stable in the range $-22.5° < \alpha < 22.5°$, positive incidence producing negative normal force; the value of $(C_{N\alpha})_{\alpha \to o}$, was -0.69 per rad. In this case the static margin is negative, the centre of pressure position being 0.5 calibres ahead of the body centre of gravity. This effect is attributable to the body behaving essentially like a disc ie. the aerodynamic characteristics are dominated by the bluff front face of the body. The same behaviour was observed in a series of low speed wind tunnel tests made on a similar bomblet shape at R.A.E. [4].

The pitching moment coefficient of the body alone, plotted in fig. 7 is linear for $0° < \alpha < 10°$, with $C_{m\alpha}$ = -0.57 per rad. This is similar to a value of $C_{m\alpha}$ = -0.58 per rad. measured for a similar bluff body at a Mach number of 1.72. However the result is thought to be fortuitous and it is expected that compressibility effects would cause the high speed aerodynamic characteristics to differ from the low speed values.

Within the scatter of the experimental data the normal force acting on the body with the three circumferential streamers attached varies linearly with incidence (fig. 6), the value of $C_{N\alpha}$ being 2.12 per rad. for $0° < \alpha < 20°$. This linear behaviour was expected because of the constant drag force of the streamers which are always immersed in the body wake for the range of incidence studied. The fin stabilized body exhibited the same linear variation of C_N with incidence for α up to $30°$ and the value

to a static margin of 1.33. As expected this value does not agree with the measured static margin of the body-plus-fin due to the not insignificant normal force acting on the body itself and the fact that the tail is immersed in the body wake. However, the predicted value of $C_{m\alpha}$ = -4.29 per rad. agrees well with the measured value. This is probably because the fin is a more efficient lifting surface than the equivalent span plane surface used in the prediction of $C_{m\alpha}$ thus compensating for the loss of dynamic pressure in the body wake. The second prediction was obtained from a simplified method proposed by Simmons [5] for estimating the stability characteristics of finned projectiles. Whereas the predicted static margin agreed quite well with experiment the calculated normal force coefficient, taking into account such effects as fin taper and boom diameter, was considerably less. However it is emphasized that the method is meant to apply strictly to long slender projectile shapes and not the blunt body considered in this paper. $C_{m\alpha}$ was also obtained from measurements of the frequency of pitching oscillations for the bomblets with fins, circumferential and radial streamers and drogues and the results are tabulated in table 1. The values of $C_{m\alpha}$ agree with the static measurements made on the one-component balance to within 6% and 20% for the fin and three streamer stabilized bomblets respectively. The two radial off-axis streamers provide the highest restoring moment of the streamer combinations studied $C_{m\alpha}$ having approximately the same value as that produced by the fins. This increased efficiency is due to the enhanced drag obtained by mounting them near the edge of the body wake. The streamers provided better static stability than both the porous hemisphere cap and 'wind sock' drogues. The hemisphere cap was particularly poor due to its inability to remain stable in the body wake. Due to this erratic behaviour the results are not listed in the table.

3.   DYNAMIC STABILITY

The investigation of section 2 has shown that streamer stabilized bomblets are statically stable at low speeds. However, before such a combination can be regarded as feasible, it is necessary to ensure that the initial pitching motion caused by initial release disturbances is damped sufficiently rapidly to provide near-normal impact (say within ± 10°).

The tests reported below are concerned primarily with the pitch damping efficiency of streamers. As in section 2, the results are compared with those obtained for bomblets with fins. An approximate calculation method is used to predict the pitch damping of the finned bomblet. Measurements of the dynamic stability are used to estimate the distance for large disturbances to damp down (typically to half the initial amplitude) for typical launch conditions.

3.1   Models and data reduction

The bomblet model described in section 2 was used for the dynamic stability measurements and, as before, the air speed was held constant at 32m/s (105 ft/s). The main model configurations tested were those with the fin tail and three circumferential streamers as stabilizers, the former with both the 0.75 and 1.50 calibre probes and the latter with the 0.75 calibre probe only.

The models were supported at their centres of gravity on a one degree-of-freedom pitch rig and released from an angle of 90°. The residual motion was recorded on a high speed cine' film (250 frames/s) from which the pitch damping was calculated. The frictional torque of the pitch rig was assumed to be negligible compared to the damping moment for large oscillations and ignored in the data analysis. The damping is expressed in the form of a pitch damping coefficient $C_{mq} + C_{m\dot{\alpha}}$ where

$$C_{mq} + C_{m\dot{\alpha}} = \partial C_m / \partial \left(\frac{qd}{2U}\right) + \partial C_m / \partial \left(\frac{\dot{q}d}{2U}\right) \tag{3}$$

and the aerodynamic damping moment is obtained from the relationship

$$-(M_q + M_{\dot{\alpha}}) = 4 I_m f \lambda \tag{4}$$

where λ is the logarithmic decrement of the damped oscillations {defined as $\frac{1}{n} \log_e \frac{\alpha_1}{\alpha_{n+1}}$} and n is the number of successive peak to peak half cycles (see fig. 9).

3.2 Results and discussion

The bomblet response in pitch to an initial release disturbance of $\alpha_0 = 90°$ is shown in fig. 9 for the first 1.3 seconds of the pitching motion. Figs. 9(a) and (b) show the oscillations of the fin and streamer stabilized bomblets with the 0.75 calibre probe to be convergent, taking approximately 0.43 and 0.21 seconds respectively for the amplitudes to decay to half of their initial values for oscillations less than 30°. Qualitatively it may be seen that pitch damping with streamers is an erratic process but nevertheless they appear to be as effective as the fins for damping large oscillations. For small incidences the bomblet motion is undamped with both streamers and fins and continues to execute small oscillations. The streamer result is suggested by the equation derived in appendix 1(a) for the pitch damping of streamer stabilized bodies.

The log decrements of the amplitude decays are shown in fig. 10. An interpolated best fit was used for the streamer data due to the erratic damping for incidences less than 15°. The pitch damping of both the fin and streamer stabilized bomblets is not constant being most rapid for large oscillations and decreasing to a constant magnitude for $\alpha < 30°$ where, for the fin stabilized bomblet, the motion may be regarded as simple harmonic. The pitch damping coefficients of the fin and streamer stabilized bomblets (which were calculated for $\alpha < 30°$) agreed to within 10% having values of -12.78 and -11.55 per rad. respectively and both configurations damp down to a mean residual oscillation of $\pm 5°$ which is within the angular deviation specified by design requirements. However, the damping reliability of the streamers

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is suspect for small oscillations where the fluctuating component of the streamer drag force has been shown to be sufficient to affect the dynamic aerodynamic characteristics of the complete bomblet. The predicted value of C_{mq} = -11.4 per rad. for the fin stabilized bomblet (obtained from the approximate calculation method of appendix 1 (b) using eqn. (2) of section 2 for $C_{N\alpha}$ and assuming the centre of pressure of the fin tail to be at the quarter-chord position) agrees well with experiment, underestimating the measured value by 11%.

The dynamic stability of the fin stabilized bomblet is greatly reduced by replacing the 0.75 calibre probe with the 1.5 calibre probe. Figs. 9 and 10 show that, although the decay and damping frequencies are similar for both configurations for oscillations greater than 25°, the dynamic stability of the bomblet with the longer probe decreases at lower angles, the configuration becoming virtually undamped for $\alpha \leqslant 15°$. The dominant influence of the probe length on the dynamic characteristics of the bomblet for small oscillations (where the damping moment provided by the fin tail is relatively small) is thought to be due to the manner in which the separated flow from the probe tip affects the bomblet body. The results suggest that, whereas the fully separated shear layers shed from the shorter probe are stable, the 1.5 calibre probe has sufficient length to cause a dynamically unstable separation which produces severe destabilizing moments. Robinson et al [6] calculated flow stability boundaries for a bluff body with a probe for a range of probe length and Mach number which they compared with some experimental data. An extrapolation of their results to M=0.2 shows that the critical probe length at which the flow becomes unstable is approximately 1.5 calibres.

It may be shown that the pitching frequency of a body is proportional to velocity and the ratio of the amplitudes of two successive oscillations is independent of velocity. The damping is conveniently expressed in terms of distance and calculations for the fin and streamer stabilized bomblets show that the oscillations damp to half the initial value after a distance of typically 12 metres (40ft).

Of the two chute devices studied the 'wind sock' provided very effective damping down to an angle of 2.5° but severe oscillations of up to ± 90° were observed with the hemisphere cap. The cap was ineffective due to its inability to remain in the body wake, and in this respect behaved like most parachute devices which tend to move towards high velocity when situated in a shear flow.

4.   SPIN DAMPING

4.1   Apparatus

The spin damping was obtained by a free rotation technique. To avoid support interference the spin damping of the bomblet with fins was measured with a 7.62 cm (3 in) calibre model on a rear sting support, fig. 11(a). This support was also tried for a bomblet with streamers but as was anticipated the streamers tended to wrap around the sting and a front support {fig. 11(b)} was used for the streamer tests reported below. The finned model was also tested on the front support to determine if interference from the front support was significant. The forward end of the front sting was covered with a disc of the same size as on the spinning model.

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The spin velocity was obtained from a tachometer which consisted of a series of small permanent magnets which rotated with the model and a stationary coil attached to the support. The output from the coil was fed via an amplifier to a recording galvanometer and spin velocity versus time was obtained from the galvanometer record. The initial spin of a few hundred r.p.m. was imparted to the model by hand or with a piece of twine wrapped around the body.

The spin damping moment was obtained from a knowledge of the decay of spin velocity with time and the moment of inertia of the rotating model, due allowance being made for the friction of the bearings and aerodynamic damping produced by the body and probe.

4.2   Fin results

The spin damping moment of the model with fins is plotted in fig. 12 as a function of the spin rate in non-dimensional form. The spin damping coefficient C_{lp} is the ratio of the spin damping moment to the spin rate suitably non-dimensionalized.

C_{lp} is defined as $C_{lp} = \dfrac{\partial C_l}{\partial \left(\frac{pd}{2U}\right)}$ where $C_l = \dfrac{M}{\frac{1}{2}\rho U^2 A_b d}$. This is a useful

definition when the spin damping moment is linear with spin rate. However when the damping is due to streamers the linearity will not necessarily occur as explained below and for this memo we define $C_{lp} = C_l / \frac{pd}{2U}$. The spin parameter, $\frac{pd}{2U}$, is the ratio of the circumferential velocity to the axial velocity and, for values of less than 0.1, $\frac{pd}{2U}$ is approximately equal to the angle between the fin and the airstream at a radius of $d/2$. Typical initial values of $\frac{pd}{2U}$ are 0.03 for a shell dispensed bomblet and 0.01 for a rocket dispensed bomblet. The results in fig. 12 show that within the experimental error there is no significant dependance upon spin rate, velocity or the method of support. The mean value of C_{lp} due to the fins is 0.65. To compare this value with previous results the spin damping coefficient is recast using a single fin area as a reference area thus

$$C_{lp,f} = \frac{M}{\frac{1}{2}\rho U^2 \ A_f b \ \left(\frac{pb}{2U}\right) n} \tag{5}$$

where b is the diameter of the cylinder enclosing the fins and n the number of fins then

$$C_{lp,f} = \frac{A_b}{A_f} \left(\frac{d}{b}\right)^2 \frac{C_{lp}}{n} = 0.4 \ C_{lp} \tag{6}$$

and the mean value of $C_{lp,f} = 0.26$. This value may be compared with values of $C_{lp,f}$

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obtained for mortar bombs [7] which vary from 0.13 for shaped fins with holes in them to 0.30 for rectangular fins. An empirical correlation given by Dearden [8] yields $C_{lp,f} = 0.14$ which is significantly less than the measured value.

4.3   Streamer results

When a bomblet with streamers attached is spun rapidly in an airstream the centrifugal force will cause the streamers to fly out from their unspun position with the result that the damping moment will probably be enhanced. Thus the damping may depend not only on the spin parameter but also on a centrifugal parameter. The ratio of the centrifugal force to the aerodynamic force is defined as $G = \dfrac{wp^2 \, r}{g} / \frac{1}{2}\rho U^2$ where r is the radius of the point of attachment of the streamers.

Assuming that for a practical case streamers are made from a material similar to heavy sailcloth (576 g/m²); $G \simeq 0.03$ for a shell launched bomblet and 0.0006 for a rocket launched bomblet. Taking a simple model the steady shape of the streamers may be calculated when under the combined action of aerodynamic and centrifugal loads (see appendix 3) and it may be shown that when $G \leqslant 0.01$ the centrifugal force is unimportant. This conclusion is confirmed by the results of fig. 13.

Measurements were made of the spin damping coefficient for the bomblet model shown in fig. 11(b) with 3 terylene streamers of various weights and lengths rigidly attached to the bomblet tail. Because of the unsteady behaviour of the streamers the repeatability of the results was not as good as that achieved with the fins. The results in fig. 12 show that the spin damping coefficient of 3 streamers of 33.0 x 2.54 cm (13 x 1.0in) and 576 g/m² (0.118 lb/ft²) terylene is almost twice as large as the fin value for spin rates sufficiently low for centrifugal forces to be unimportant. Within the scope of the limited data the results in figs. 14 and 15 show that C_{lp} is proportional to the length and weight per unit area of the streamer. The results in fig. 12 together with some additional results obtained from a record in which the initial spin rate was about 2,000 r.p.m. are replotted in fig. 13 as a function of the centrifugal parameter. Fig. 13 shows that C_{lp} increases significantly with the spin rate as expected but that the increase probably occurs at higher values of G than will be achieved in practice.

4.4   Theory

If it is assumed that the spin damping moment is due solely to the resolved component of the drag of the streamers then C_{lp} may be easily calculated (see appendix 3) and is given by

$$C_{lp} = 2n \; C_{DA} \frac{A_s}{A_b} \left(\frac{r}{d}\right)^2 . \tag{7}$$

When due allowance is made for the reduced drag of the streamers because of the wake the above expression underestimates the measured value of C_{lp} by as much as an order of magnitude in the case of the heavy streamers. This surprising result is probably partly accounted for because the streamers are rigidly attached to the base with the result that the material of the streamer which is close to the base is not aligned

with the stream and so has a sideways force on it which opposes the spin motion.
Another factor which might contribute to the increased drag of the streamer when
behind a spinning body is that as it flaps in a plane through the model axis so the
angle of incidence will vary and hence increase the drag. A third explanation is
that whilst the free end of the streamer will tend to align itself with the flow
direction the end attached to the model will be moving in slow base flow and hence
will be at large incidence.

4.5 Time for spin decay of bomblet

Knowing the value of C_{lp} the time or distance for the spin of a real bomblet
to decay may be readily calculated by using

$$\frac{p}{p_o} = e^{-kt}$$

where
$$k = \tfrac{1}{2}\rho U^2 \; \frac{A_b d^2}{2UI_1} \; C_{lp} \qquad\qquad (8)$$

Assuming that the velocity is constant then t may be replaced by x/U and the
distance for the spin to decay by a given factor is independent of velocity. For
example taking $C_{lp} = 1$, $d = 5.08$ cm (2.0 in) and $I_1 = 4.39$kg.m^2 (0.15lb.in^2) then the
distance for the spin rate to decay to $1/e$ is 43 metres (90 ft).

5. EXPERIMENTS WITH A THREE DEGREE-OF-FREEDOM APPARATUS

Much information concerning the behaviour of a complicated projectile may
be obtained from a wind tunnel by releasing the model to fly freely in the working
section. This method has the advantage that support interference and bearing friction
are completely eliminated, but the technique is difficult to apply except when the
aerodynamic forces and moments are large and the inertias of the model are small or
when the working section is vertical. To yield quantitative information the motion of
the projectile is recorded in some manner and computer programmes are then used to fit
the observed motion with a tricyclic motion theory and thus in principle at least all
relevant forces and moments are obtained.

5.1 Apparatus

An alternative to the free-flight technique is to use a pivot which allows
the model to rotate freely about its C.G. When the model has a large base (eg. a cone)
this is comparatively easy as the model may be sting mounted and execute large
oscillations. For models which are very slender or have tails supported by narrow booms
a sting support cannot be used and a more complicated support is required such as is
shown in fig. 16. This system of pivoting the model which was used for the present
tests was based on a design developed by Charles et al [9]. The nose and tail are
rigidly attached together and are allowed to roll freely in bearings

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supported by a non-rolling portion of the body. The non-rolling portion of the body is supported on a yoke by small ball bearings and is allowed to pitch freely. The yoke is supported on a vertical rod covered by a streamlined shroud which houses bearings to allow the rod to rotate about its axis. With this support the model may roll and yaw through 360° but is constrained to pitch within ± 30°. It also limits the models which may be tested to those having an axisymmetric centre portion. The fact that the centre portion cannot roll is not considered serious for the present tests since the body will probably lie in separated flow.

When the present investigation was undertaken the technique of fitting the observed motion with a tricyclic theory was not available and instrumentation to give a direct reading of pitch, yaw, and roll angles had not been developed. Nevertheless it was thought that much information concerning the dynamic behaviour of the bomblet could be obtained with the apparatus since the behaviour of a projectile in a wind tunnel freely supported about its centre of gravity gives a close approximation to the same projectile in free-flight because the small plunging motion of the C.G. in free-flight is not considered significant.

The basic bomblet shape was tested on the three degree-of-freedom apparatus with the C.G. of the model, shown in fig. 16, close to the estimated position of the C.G. of the FO1L bomblet. The external dimensions of this model were identical to the one used for the spin damping tests apart from a smaller boat-tail angle and a truncated re-entrant cone. These modifications were necessary to accommodate the pivot which was designed for another purpose. Four combinations of bomblet body probes and tails were tested and these are listed in table 2. For most combinations a film at 100 c/s was taken to record the motion of the bomblet after being released with a large angle of pitch or yaw and also the 'residual' motion which resulted after the large disturbances had been damped out. The 'residual' motion was filmed at various tunnel speeds. For some tests the finned model had small tabs attached to the rear of the fins which were bent over to give varying amounts of spin and again the subsequent motion was filmed. The tabs were adjusted until spin-yaw resonance occurred.

5.2 Results

The films were analysed to yield values of $C_{m\alpha}$, $C_{mq} + C_{m\dot{\alpha}}$ and the mean value of the pitch or yaw angle during the 'residual' motion phase, $\bar{\alpha}_M$. These values are tabulated in table 2. Two films were measured in more detail to give the motion of the projectile as a function of time after being released at a large angle of incidence. These results are shown in fig. 17 and give a quick visual comparison between the damping behaviour of a fin and streamer stabilized projectile and demonstrate the erratic behaviour of the latter. Measurements of $C_{m\alpha}$ and $C_{mq} + C_{m\dot{\alpha}}$ may be obtained more simply by other methods and these values were merely obtained as a check on previous measurements, however the three degree-of-freedom rig is particularly valuable in as much as it demonstrates that even though the bomblet is statically stable at angles of incidence between 0° & 90° and large pitch and yaw disturbance are rapidly damped nevertheless the bomblet has a significant value of $\bar{\alpha}_M$ which is presumably a result of dynamic instability at small angles of incidence. The results show that for a finned bomblet $\bar{\alpha}_M \simeq 5°$ for a probe length of 0.75 calibres and $\bar{\alpha}_M \simeq 10°$ for a probe length of 1.5 calibres. These values are in qualitative agreement with measurements made

on the one degree-of-freedom rig, and are probably acceptable for a practical design. On the other hand the bomblet stabilized with streamers has a value of $\bar{\alpha}_M \simeq 15°$ to $20°$ which might be excessive.

The behaviour of the streamer stabilized bomblet was very erratic and the value of $\bar{\alpha}_M$ must be treated with caution as occasionally pitch angles as large as $30°$ were observed when the bomblet was in the 'residual' motion phase. The absolute values of $C_{mq} + C_{m\dot{\alpha}}$ shown in table 2 are probably not very meaningful because of the non-constant damping and because of a difference in behaviour between the pitch and yaw planes. The values of $C_{mq} + C_{m\dot{\alpha}}$ obtained in the pitch plane are believed to be high because of the tendency for the pitching motion to damp rapidly whilst the yawing motion is built up (fig. 17) thus more reliance is placed upon the values obtained in the yaw plane. Fortunately, as shown in section 3, precise values of $C_{mq} + C_{m\dot{\alpha}}$ are not required because the large disturbances are damped out very rapidly. Within the admittedly poor experimental accuracy however the results show that fins and streamers damp out large disturbances equally well.

The bomblet body with a 0.75 calibre stand-off probe was also tested without fins or streamers as the static tests gave results which suggested that it should be stable. When released at near zero incidence the bomblet body executed about 7 or 8 undamped oscillations and when the amplitude of the oscillations increased to about $15°$ the model became unstable and turned sideways on to the flow. The bomblet body alone thus has the property of being statically stable up to incidences of $15°$ and dynamically unstable.

The filmed tests with the bomblet stabilized with streamers were performed with 3 streamers 33.0 x 2.54 cm (13 x 1 in) in size and weighing 576 g/m² (0.118 lb/ft²). Qualitatively the tests showed that large pitch and yaw oscillations were quickly damped down and then the model continued to execute oscillations with apparently random amplitude of up to about 20°. Taking this combination of streamers as a standard a number of variations were tested in an attempt to improve the poor dynamic stability. These consisted of using longer and shorter streamers, different numbers and also attaching the streamers on a support as sketched in fig. 16. The qualitative results are given in the accompanying table 3. The tentative conclusions from this test were that, of the combinations tested, the original combination of streamers appeared to be better than most with possibly a marginal improvement when the length was increased to 43.2 cm (17 in).

6. CONCLUSIONS

The aerodynamics of a streamer stabilized FOIL bomblet have been studied at low speeds to determine the feasibility of using streamers for a practical design. Before examining the behaviour of the projectile-streamer combination a number of preliminary measurements were made on isolated streamers to extend information on drag and flutter frequency to relevant values of fineness ratio and weight per unit area for the present problem. The results of this study will be published in a forthcoming RARDE memo.

The reduction in drag of a streamer in the wake behind a bomblet shape was

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measured and a correction factor is given to allow for the wake effect. The static stability of the bomblet fitted with fins and various types of streamers was measured and the results show that adequate static stability may be obtained with streamers of a sufficiently small size to be practical though typically the restoring moment of the streamers was only one half of that due to fins. The restoring moments of both fins and streamers were predicted with simple empirical methods.

The dynamic stability of the bomblet was investigated with one degree and three degree-of-freedom rigs and the streamers were as effective as the fins in damping large initial incidences. However, due to the shape of the nose the bomblet was found to be dynamically unstable at small pitch angles. The fins damped the oscillations to within 5° to 10° depending on the length of probe whereas the streamer stabilized bomblets reached a residual motion phase in which they oscillated with random pitch angles of 15° to 20° and sometimes as much as 30°. Several streamer combinations were tested in an attempt to improve the poor dynamic stability but without much success.

The spin damping properties of streamers were obtained by allowing a freely spinning model to damp down and the measurements show that the spin damping properties are surprisingly good and that it is possible to achieve higher spin damping with streamers than fins.

A few measurements were also made with other drag devices such as drogues but whilst these can provide adequate static stability and in some cases dynamic stability, it was not thought that they could provide spin damping to the required degree and consequently these devices were not studied in detail.

Whilst the advantages of using streamers to stabilize the bomblet geometry used for the present tests may not outweigh the disadvantages, (ie. the poor dynamic stability), nevertheless it is quite likely that with a different geometry and much higher launch accelerations appropriate to a gun fired container the reverse may be true. It is therefore recommended that some further work be undertaken on the use of streamers at transonic and supersonic Mach numbers.

The limited measurements made with the fin-stabilized bomblet showed that whilst the static stability did not depend significantly upon the probe stand-off distance the bomblet was dynamically unstable at small angles of incidence and the extent to which this happened depended significantly upon the stand-off distance. This effect is not understood in detail and since the lethality of the warhead could be impaired if the bomblet executed large oscillations in the terminal phase it is recommended that further tests be undertaken to obtain the dynamic stability as a function of probe size, stand-off distance, and fin size.

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TABLE 1

Static stability coefficients for various bomblet configurations (U=32m/s)

Model	0.75 calibre probe fin tail	1.50 calibre probe fin tail	0.75 calibre probe 3 circumferential streamers	1.50 calibre probe 3 circumferential streamers	1.50 calibre probe 2 radial streamers	1.50 calibre probe "wind sock" drogue	Remarks
Configuration	A(a)	A(b)	B(a)(i)	B(b)(i)	B(b)(ii)	C(b)(ii)	
Weight (g)	54.0	51.8	42.2	40.0	41.7	40.0	
C.G. posn, x_{CG}/d	0.77	0.77	0.67	0.63	0.70	0.77	
Pitch inertia (kg.m²)(x10⁵)	5.81	6.51	2.71	3.78	5.08	3.78	Measured with a bifilar suspension method.
Frequency, f (c/s)	6.39	6.0	6.25	5.35	6.67	3.77	
$C_{N\alpha}$/rad.	4.41	-	2.12	-	-	-	Static pitch tests
$C_{N\alpha}$/rad.	2.09	2.09	-	-	-	-	Simmons prediction
Mean static margin $(x_{CP} - x_{CG})/d$	0.85		0.68				Static pitch tests
Mean static margin $(x_{CP} - x_{CG})/d$	1.1	1.1	1.43				Simmons prediction
$-C_{m\alpha}$/rad.	4.19	-					Static pitch tests
$-C_{m\alpha}$/rad.	3.95	3.95	1.77	1.81	3.79	0.9	Dynamic tests
$-C_{m\alpha}$/rad.	2.30	2.30					Simmons prediction
$-C_{m\alpha}$/rad.	4.29	4.29					3 diml. airfoil theory.

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TABLE 2

Summary of results from 3 degree-of-freedom apparatus

Model	Velocity m/s	$C_{m\alpha}$	$-(C_{mq} + C_{m\dot\alpha})$	$\bar{\alpha}_M$
Body 0.75 calibre probe	30	0.22	Dynamically unstable	-
Body 0.75 calibre probe fins	21 28 37	4.8 4.8 4.9 _____ 4.7	Residual motion (undamped)	)) 5°)
	29 29 29	4.4 4.7 4.9	17 Pitch 12.4 Pitch 5.9 Yaw	Damped motion
Body 1.50 calibre probe fins	14 20 30 37	4.6 4.3 4.3 4.2 _____ 4.4	Residual motion (undamped)	)) 10°)
	30 30	4.5 4.5	16.5 Pitch 3.6 Yaw	Damped motion
Body 0.75 calibre probe Three circumferential streamers	15 29 37	3.2 1.9 2.8 _____ 2.5	Residual motion (undamped)	)) 15° - 20°)
	30 30	2.4 2.4	7.3 Pitch 7.1 Yaw	Damped motion

       Undisturbed or 'residual' motion is defined as the oscillatory motion which the bomblet retains after large disturbances have been damped. When the bomblet is stabilized with fins the amplitude of this oscillatory motion is constant.

       Damped motion is defined as the process whereby large initial disturbances in the pitch and yaw plane are damped down to the 'residual' motion.

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TABLE 3

Qualitative effect of streamer configuration on dynamic stability

Streamer combination	Comment
3 Streamers, 33.0 x 2.54 cm, 576 g/m² attached as shown in fig. 16 Position (1)	Standard
3 Streamers, 16.5 x 2.54 cm, 576 g/m² attached as shown in fig. 16 Position (1)	Worse
3 Streamers, 49.5 x 2.54 cm, 576 g/m² attached as shown in fig. 16 Position (1)	Marginal improvement
6 Streamers, 16.5 x 2.54 cm, 576 g/m² attached as shown in fig. 16 Position (1)	Worse
3 Streamers, 33.0 x 2.54 cm, 57 g/m² attached as shown in fig. 16 Position (1)	Statically unstable
3 Streamers, 33.0 x 2.54 cm, 576 g/m² attached to support as shown in fig. 16 Position (2)	Similar to standard

Pitch damping

1(a)   Streamers (Fig. A1(a))

Consider a body with a moment of inertia I_m stabilized with two streamers at positions shown in fig. A1(a). If the body has an angular velocity of $\dot{\alpha}$ the restoring moment due to the bottom streamer which has a drag of $D/2$ when $\alpha = \dot{\alpha} = 0$ is given by

$$M_1 = \frac{D}{2} \left\{ \frac{U + u_1}{U} \right\}^2 r \sin(\alpha+\theta) \tag{1}$$

where u_1 is the increment in velocity of the streamer due to the angular velocity. Similarly for the upper streamer

$$M_2 = \frac{D}{2} \left\{ \frac{U + u_2}{U} \right\}^2 r \sin(\alpha-\theta) \tag{2}$$

The motion of the body is given by

$$I_m \ddot{\alpha} + M_1 + M_2 = 0 \tag{3}$$

and

$$u_1 = r \dot{\alpha} \sin(\alpha+\theta)$$
$$u_2 = r \dot{\alpha} \sin(\alpha-\theta) \tag{4}$$

Substituting eqns. (1), (2) and (4) into (3) yields

$$I_m \ddot{\alpha} + \frac{D}{2} \left\{ \frac{U + r \dot{\alpha} \sin(\alpha+\theta)}{U} \right\}^2 r \sin(\alpha+\theta)$$

$$+ \frac{D}{2} \left\{ \frac{U + r \dot{\alpha} \sin(\alpha-\theta)}{U} \right\}^2 r \sin(\alpha-\theta) = 0 \tag{5}$$

If θ and α are both small this reduces to

$$I_m \ddot{\alpha} + \frac{2 Dr^2 (\theta^2+\alpha^2)}{U} \dot{\alpha} + Dr\alpha = 0 \tag{6}$$

which gives a damped oscillation with the damping term proportional to $(\theta^2+\alpha^2)$. This equation suggests that the damping will be improved if θ is as large as possible and in a practical situation this implies attaching the streamers as far off axis as possible. The equation also shows that in an extreme case where the streamers or drag devices are attached to the body on the axis the damping coefficient will be proportional to α^2 and the damping process will be ineffective for small oscillations.

1(b)   Fins (Fig. A1(b))

Assume that the model is oscillating about its C.G. which is fixed in space (ie. the wind tunnel case), that the damping is due to the tail alone and that the tail is unaffected by the downwash of the body.
The equation of motion of the body is given by

$$I_m \ddot{\alpha} + M = 0 \tag{1}$$

When the incidence is α and the angular velocity is $\dot{\alpha}$ the effective incidence of the tail is $\alpha + \dfrac{\alpha a}{U}$

and the restoring moment M is then given by

$$M = \frac{\partial N}{\partial \alpha} \left(\alpha + \frac{\dot{\alpha} \, a}{U} \right) a \tag{2}$$

Substituting eqn. (1) into (2) yields

$$I_m \ddot{\alpha} + \frac{\partial N}{\partial \alpha} \frac{a^2}{U} \dot{\alpha} + \frac{\partial N}{\partial \alpha} a \, \alpha = 0 \tag{3}$$

This is the equation of motion of a damped harmonic oscillation in which the damping moment is $- \left(\dfrac{\partial N}{\partial \alpha} \dfrac{a^2}{U} \dot{\alpha} \right)$ and this term may be non-dimensionalized to yield the usual damping coefficient since $q = \dot{\alpha}$

$$C_{mq} = \frac{\partial C_m}{\partial \left(\frac{qd}{2U} \right)} = - \frac{\partial \left(\frac{\partial N}{\partial \alpha} \frac{a^2}{U} \frac{\dot{\alpha}}{\frac{1}{2}\rho U^2 A_b d} \right)}{\partial \left(\frac{qd}{2U} \right)} = - 2 \frac{a^2}{d^2} C_{N\alpha} \tag{4}$$

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Shape of streamers attached to a spinning body

(Fig. A2)

Assume that the streamers take up a steady position such that centrifugal forces are balanced by the aerodynamic forces, the angle between the streamer and axis, θ, is small and the pressure coefficient is given by $\frac{\partial C}{\partial \theta}p\ \theta$.

$$dT = \tfrac{1}{2}\rho U^2\ \frac{\partial C}{\partial \theta}p\ \theta^2 \tag{1}$$

where T is the tension

Equating the aerodynamic, centrifugal and body forces gives the relationship

$$\frac{wp^2}{g}\ (y+r) = dT\ \theta\ +\ \tfrac{1}{2}\rho U^2\ \frac{\partial C}{\partial \theta}p\ \theta \tag{2}$$

Eliminating dT from (1) and (2) yields

$$\frac{wp^2}{g}\ (y+r) = \tfrac{1}{2}\rho U^2\ \frac{\partial C}{\partial \theta}p\ \theta^2\ +\ \tfrac{1}{2}\rho U^2\ \frac{\partial C}{\partial \theta}p\ \theta \tag{3}$$

If we now let $\qquad G^* = \dfrac{wp^2 r}{g\tfrac{1}{2}\rho U^2}$ and $\theta = \dfrac{dy}{dx}$

Then, ignoring high order terms in $\dfrac{dy}{dx}$, eqn. (3) becomes

$$G\left(\frac{y}{r} + 1\right) = \frac{\partial C}{\partial \theta}p\ \frac{dy}{dx} \tag{4}$$

and the solution is

$$\frac{y}{r} = \exp\left\{\frac{G}{\frac{\partial C}{\partial \theta}p}\ \frac{x}{r}\right\} - 1 \tag{5}$$

This simple analysis demonstrates that the appropriate non-dimensional scaling parameter for the spinning streamers is $\dfrac{wp^2 r}{g} \Big/ \tfrac{1}{2}\rho U^2$.

For small values of G eqn. (5) may be written as

$$y = Gx\Big/\frac{\partial C}{\partial \theta}p \tag{6}$$

* G is called the centrifugal parameter.

when $y/x \ll 1$ it will probably not be necessary to scale the centrifugal parameter, G, and since $\frac{\partial C}{\partial \theta}p \simeq \pi$ for long streamers then this occurs when $G < 0.03$ say. This argument is substantiated by the results of C_{lp} which rise above a constant value when G exceeds 0.01.

Spin damping due to streamers

(Fig. A3)

The spin damping moment is calculated by resolving the drag force of the streamer and ignoring effects of wake and centrifugal force. Assume n streamers of area A_s are pin jointed at a radial distance r from the axis, then the folling moment M is given by

$$M = n \, Dr \, \frac{pr}{U} \quad (\text{if } \frac{pr}{U} \ll 1). \tag{1}$$

Defining $C_{lp} = \dfrac{C_l}{\dfrac{pd}{2U}}$ where $C_l = \dfrac{M}{\frac{1}{2}\rho U^2 A_b d}$ \hfill (2)

and $\qquad D = C_{DA} \, \tfrac{1}{2}\rho U^2 A_s$ \hfill (3)

Substitution of (1) and (3) into (2) yields

$$C_{lp} = 2n C_{DA} \, \frac{A_s}{A_b} \left(\frac{r}{d}\right)^2 \tag{4}$$

FIG. 1

0.25 d DIA

d=3.81 cm DIA

45°

0.58 d RAD

0.19 d RAD

23°

4.8 mm SLOT

20°

0.75 d

1.30 d

0.50 d DIA

0.17 d DIA

1.50 d

1.63 d

3.20 d
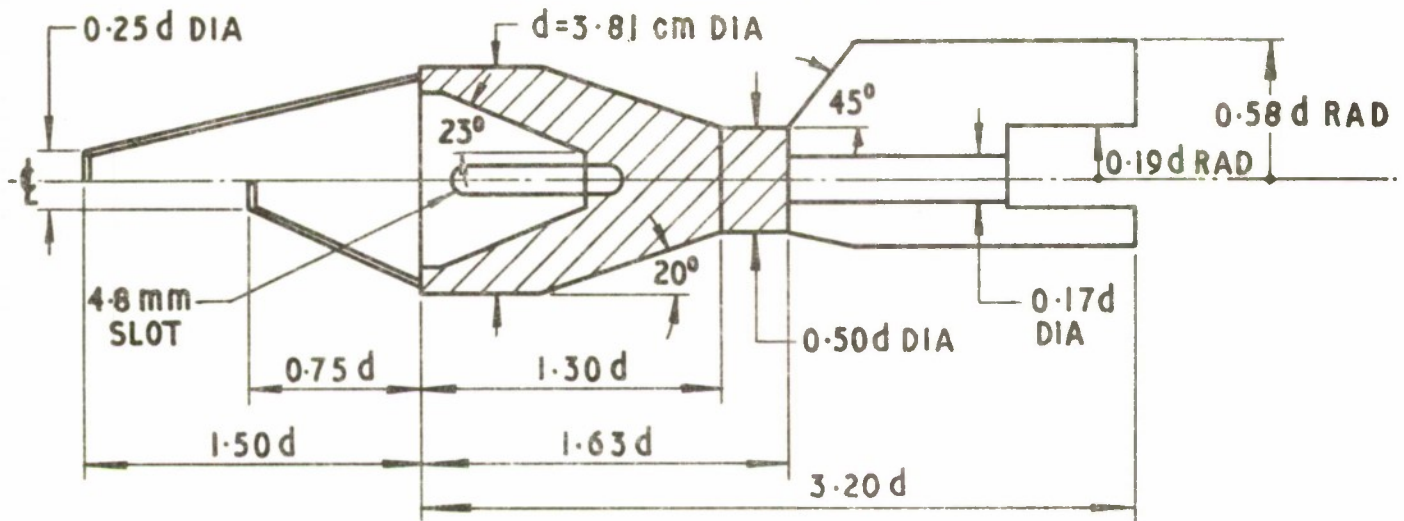
CONFIGURATION A: FIN TAIL

0.33d

4.40 d

0.33d
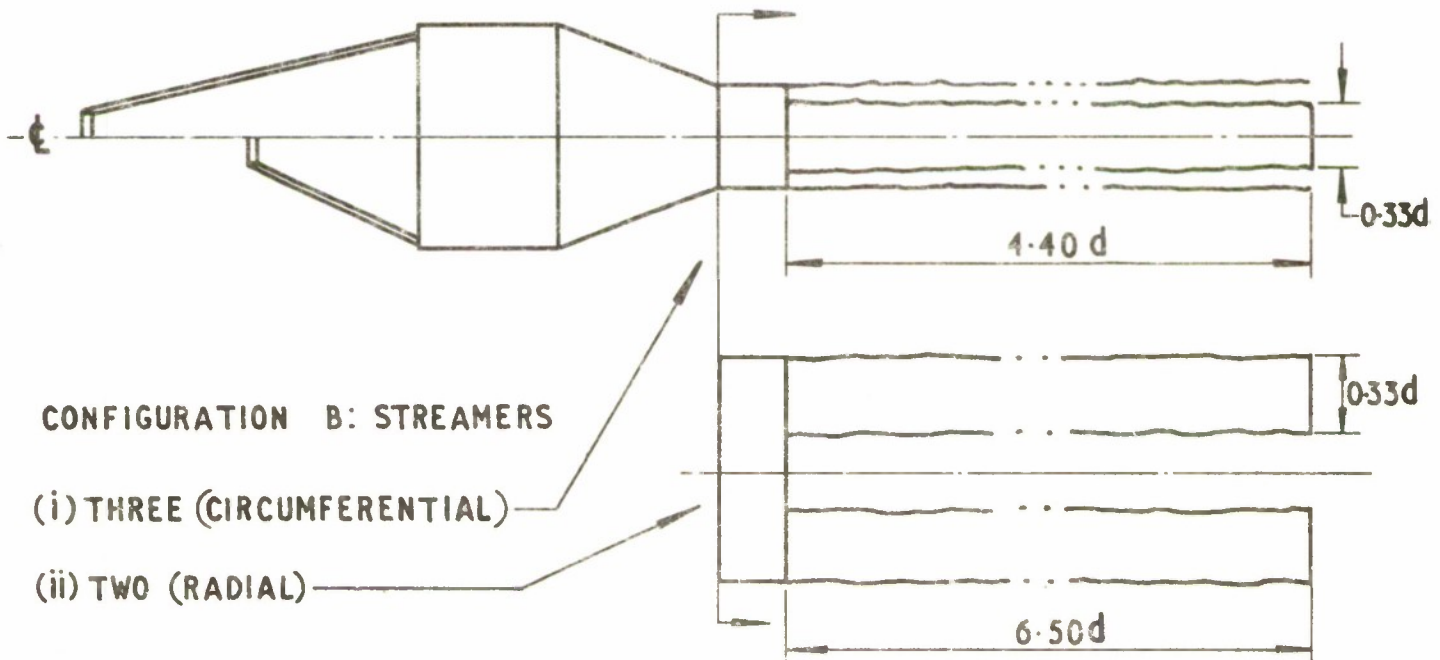
CONFIGURATION B: STREAMERS

(i) THREE (CIRCUMFERENTIAL)

(ii) TWO (RADIAL)

6.50 d

20°

d

(i) HEMISPHERE CAP
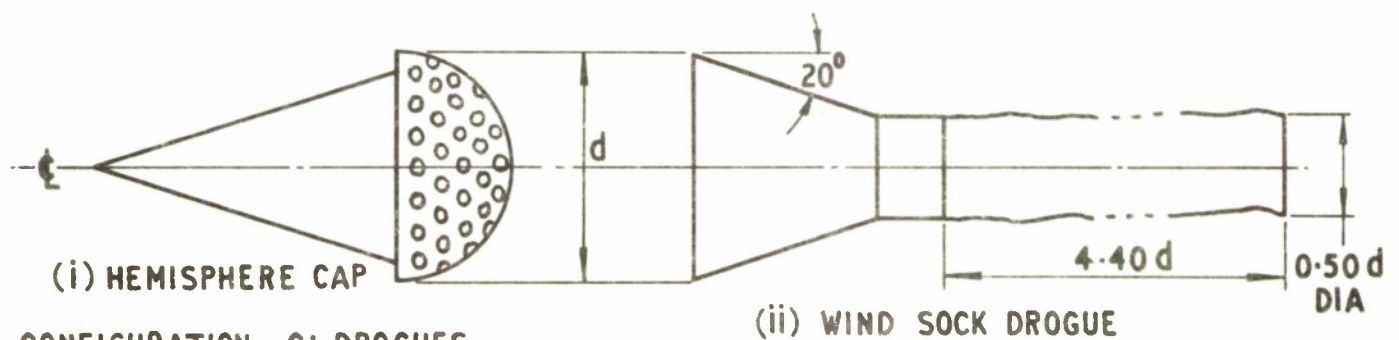
CONFIGURATION C: DROGUES

(ii) WIND SOCK DROGUE

4.40 d

0.50 d DIA

FIG.1 BOMBLET PITCHING MODEL WITH RANGE OF STABILIZERS
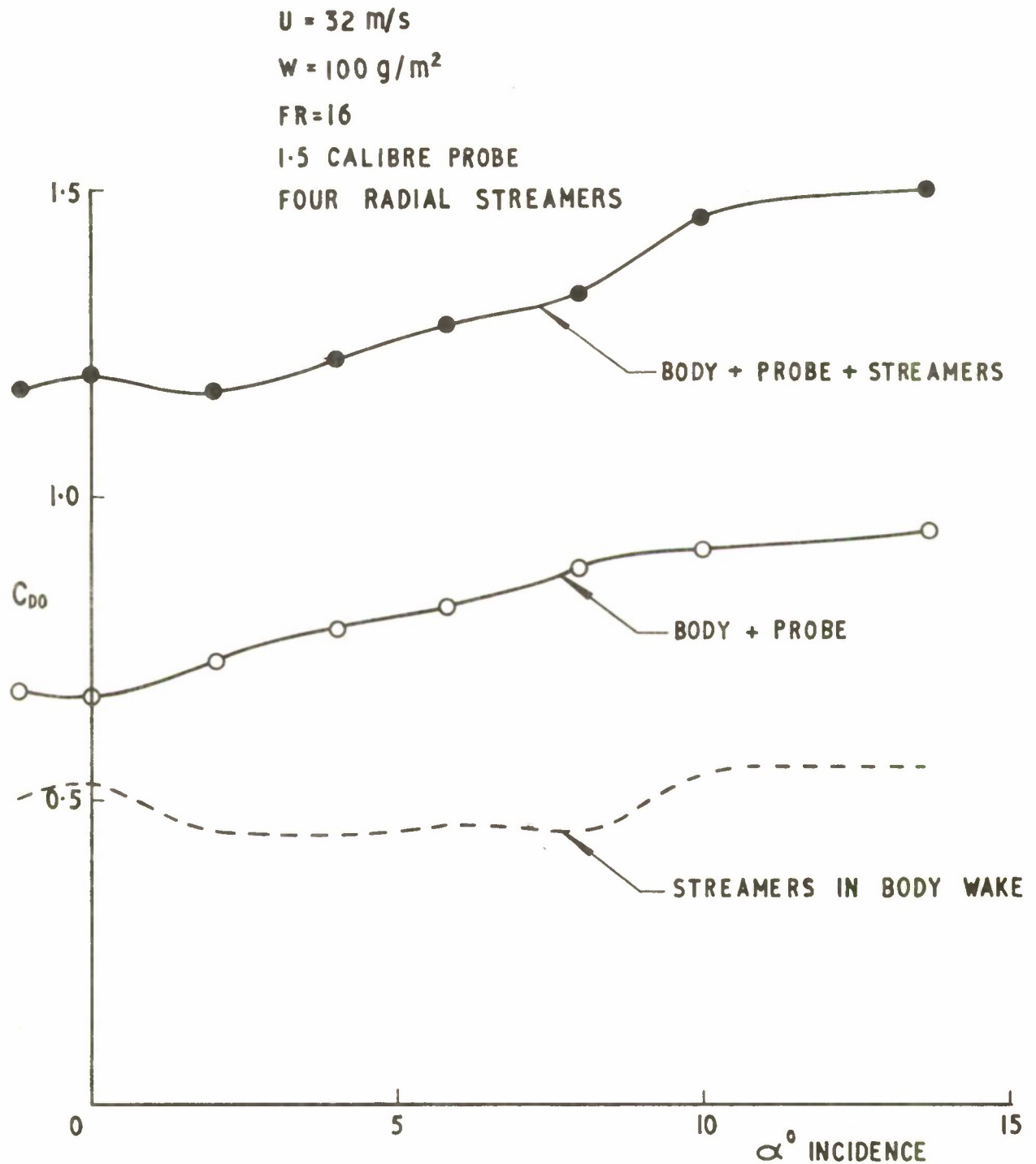
FIG.2   DRAG CHARACTERISTICS OF BOMBLET WITH AND WITHOUT STREAMERS

FIG. 3

ZERO INCIDENCE

$U = 32$ m/s
$w = 100$ g/m^2
FOUR RADIAL STREAMERS

LINEAR VARIATION
C_{DA} = CONSTANT

C_{DO}

FR
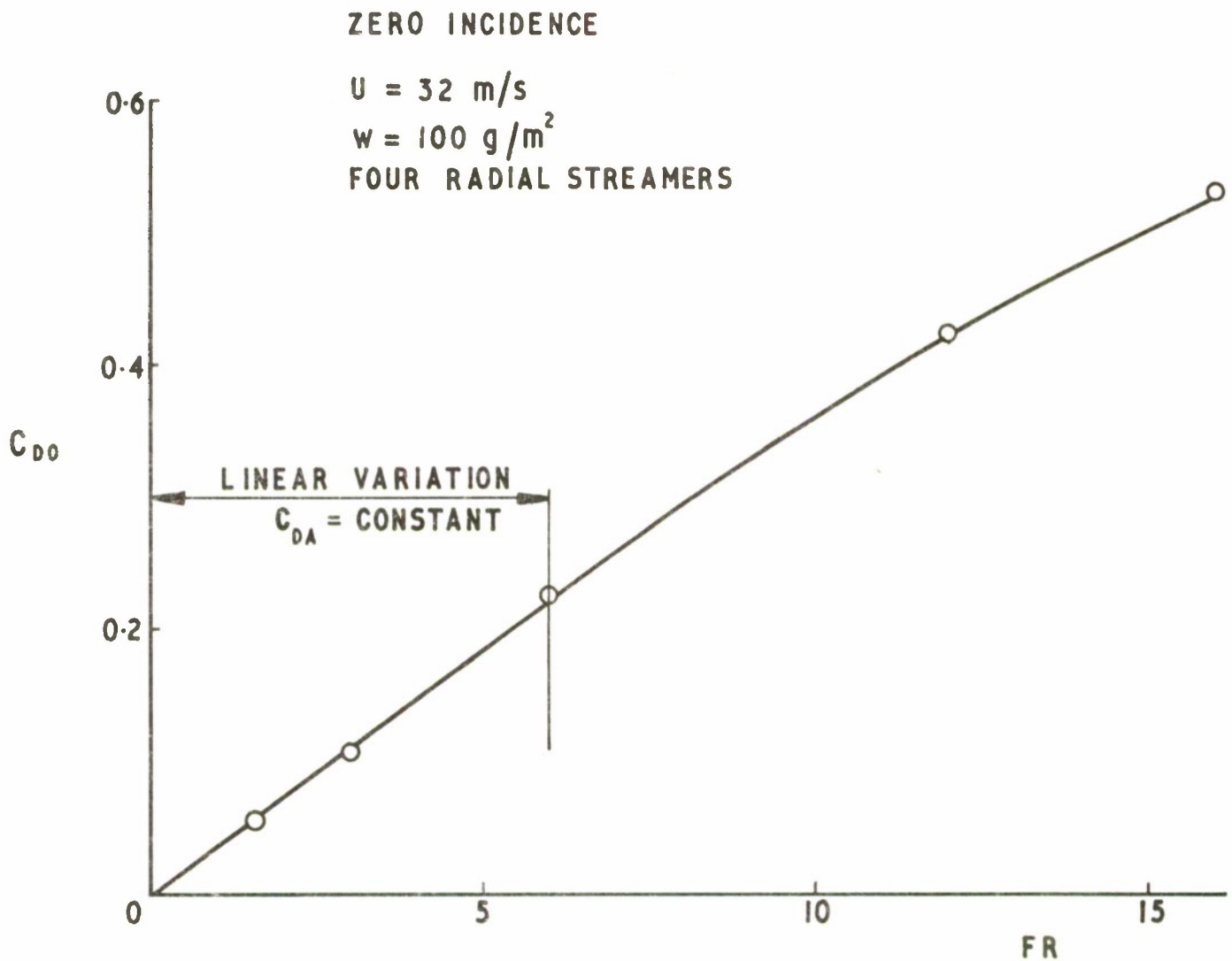
FIG. 3   INCREMENTAL DRAG OF BASE - MOUNTED STREAMERS
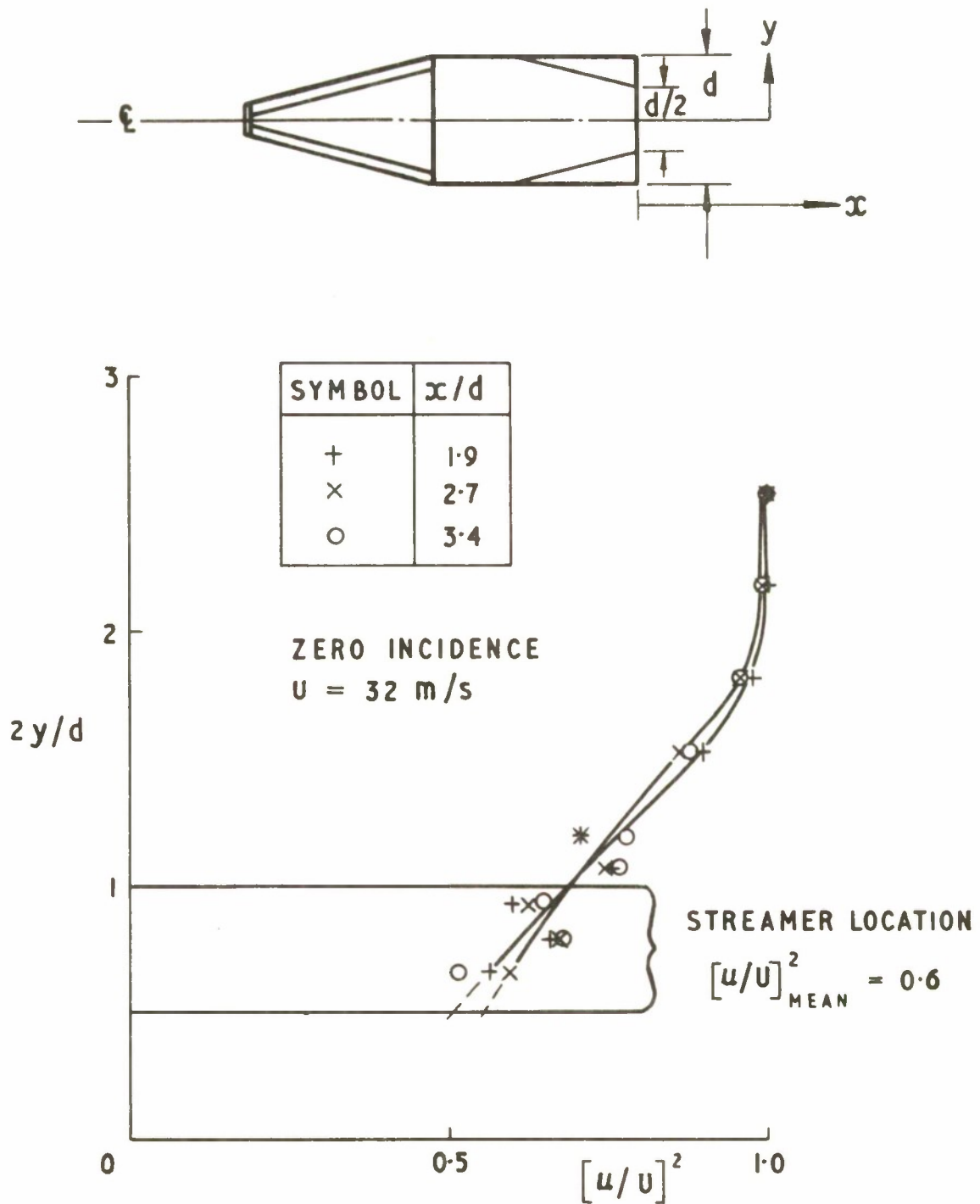
FIG.4   DYNAMIC HEAD PROFILES OF BOMBLET WAKE

ZERO INCIDENCE

$U = 32 \text{ m/s}$
$w = 100 \text{ g/m}^2$

FOUR RADIAL STREAMERS
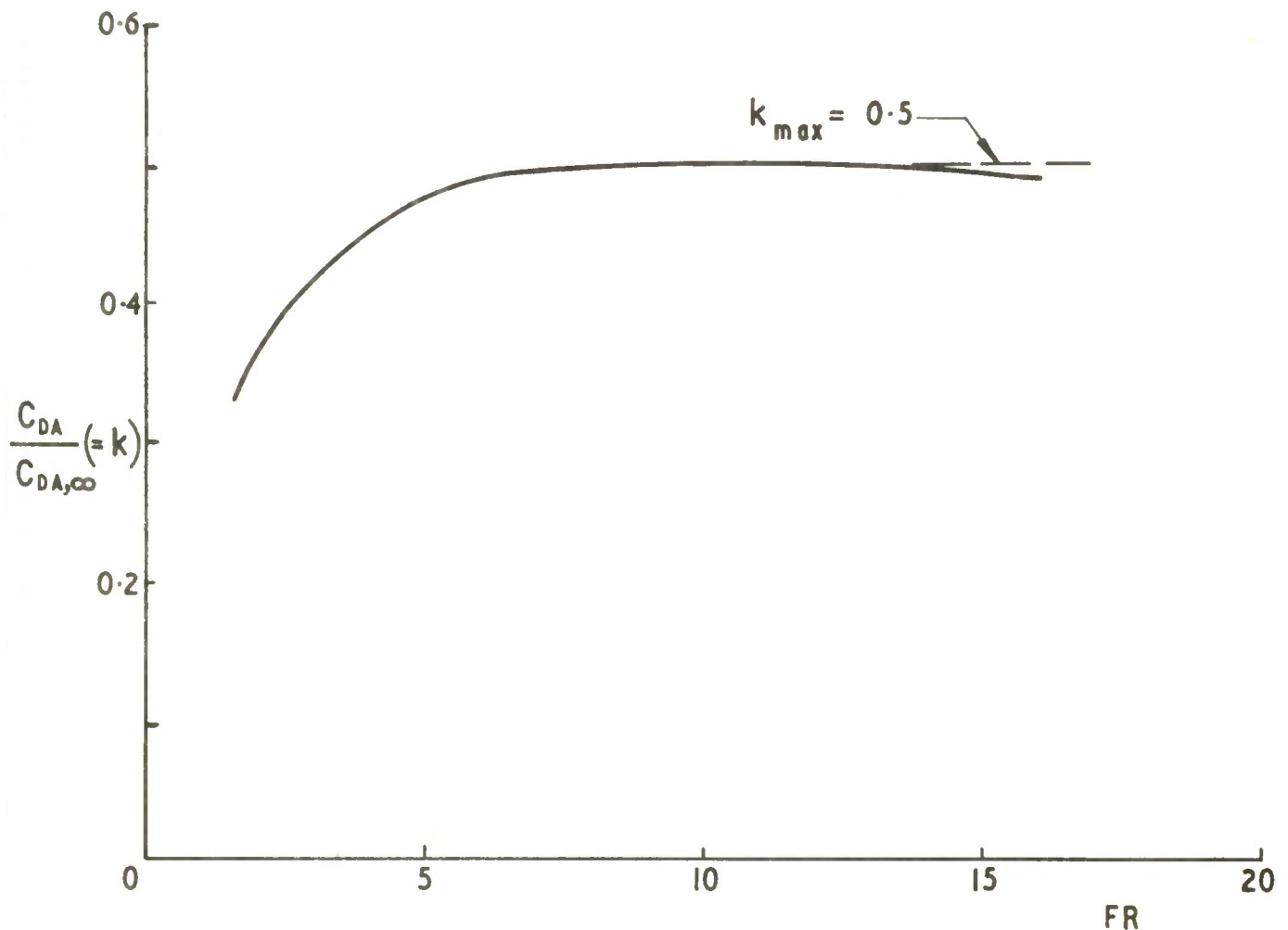
FIG. 5   LOSS OF STREAMER EFFECTIVENESS IN BOMBLET WAKE

SYMBOL	CONFIGURATION	$(C_N\alpha)_{\alpha \to 0}$
△	BODY ALONE	−0.69/RAD
□	BODY + STREAMERS	2.12/RAD *
○	BODY + FIN	4.41/RAD

* THREE CIRCUMFERENTIAL STREAMERS (SEE FIG. 1)
N.B. 0.75 CALIBRE PROBE
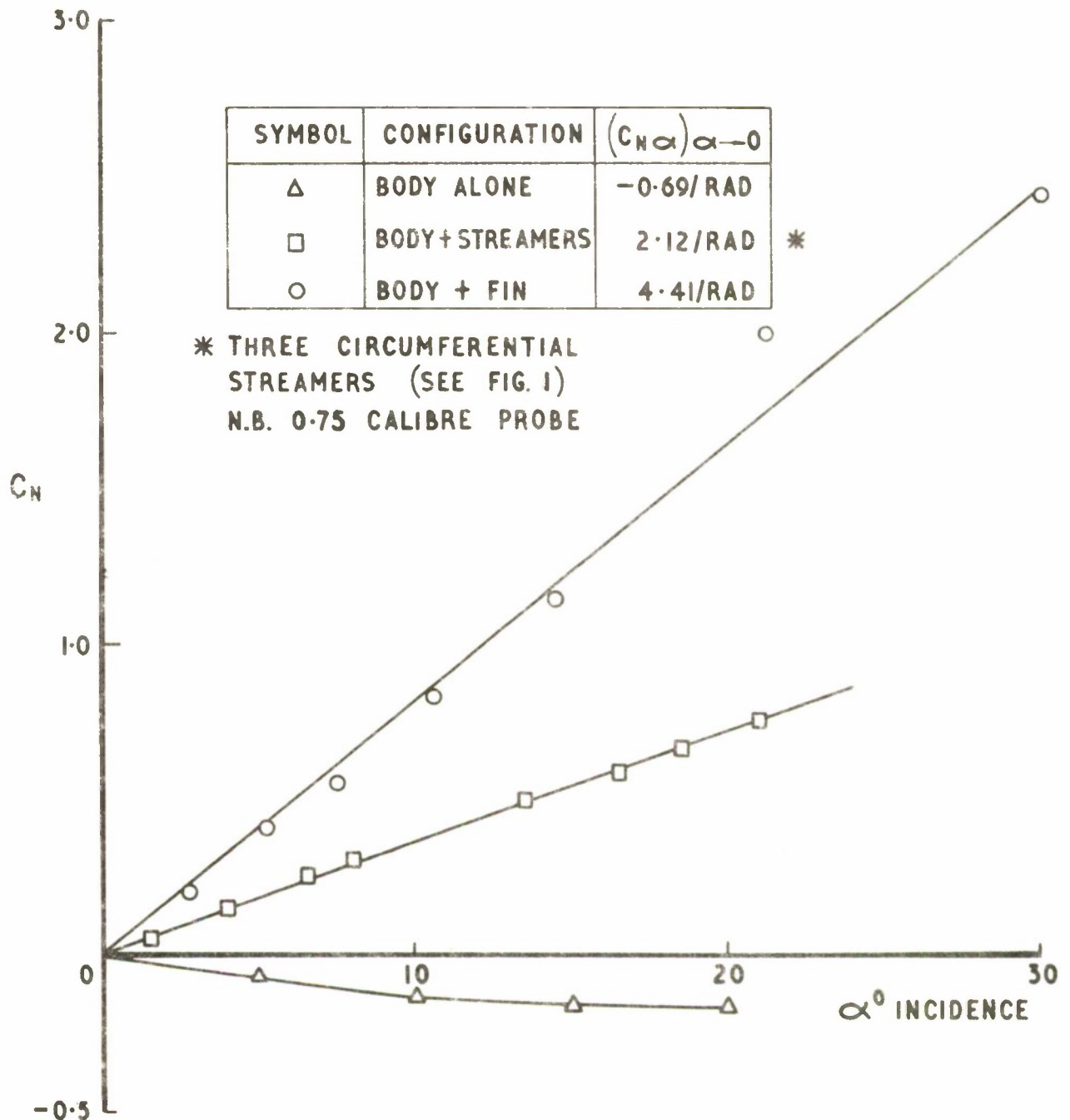
FIG. 6   VARIATION OF BOMBLET NORMAL FORCE COEFFICIENT WITH INCIDENCE (U−32m/s)
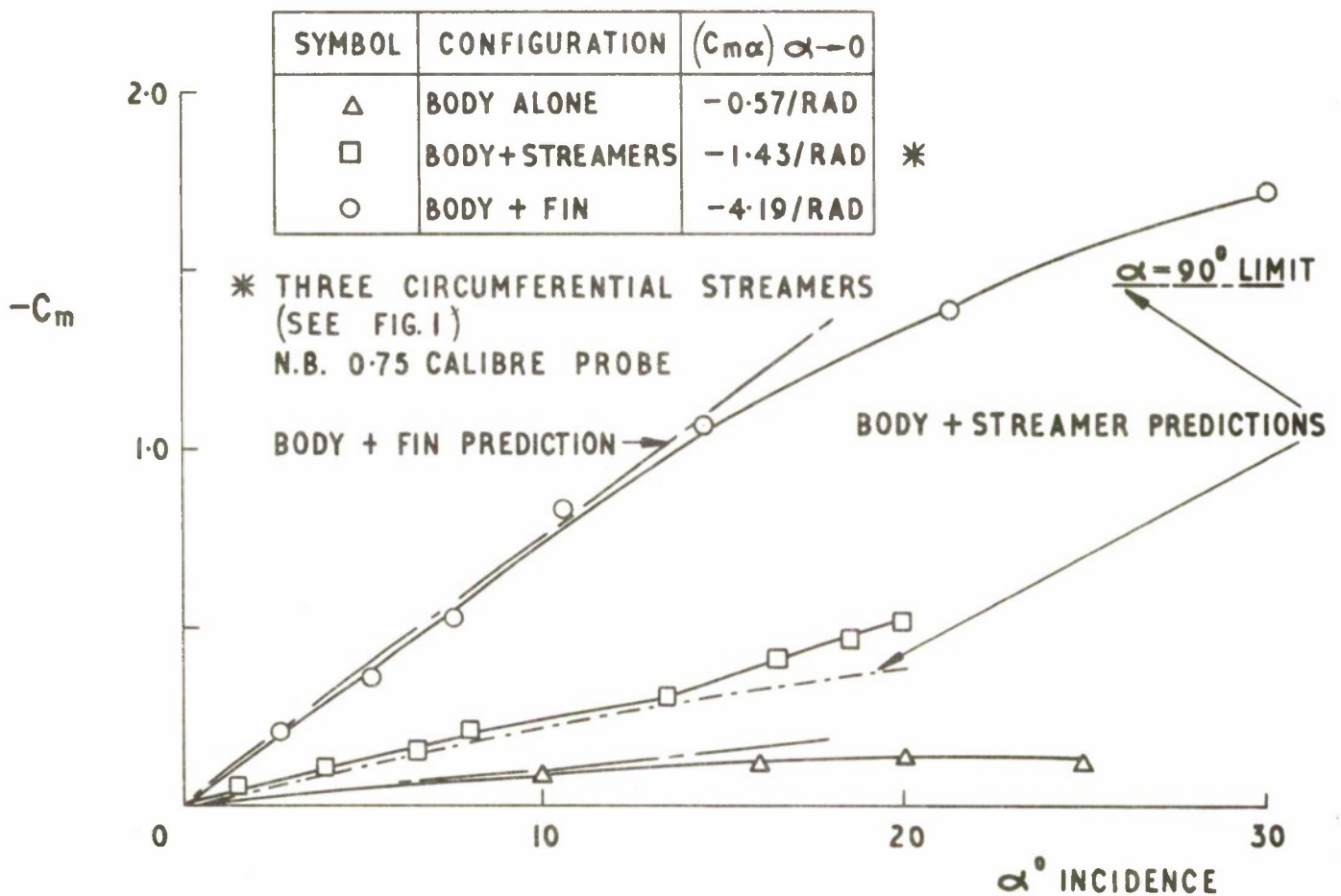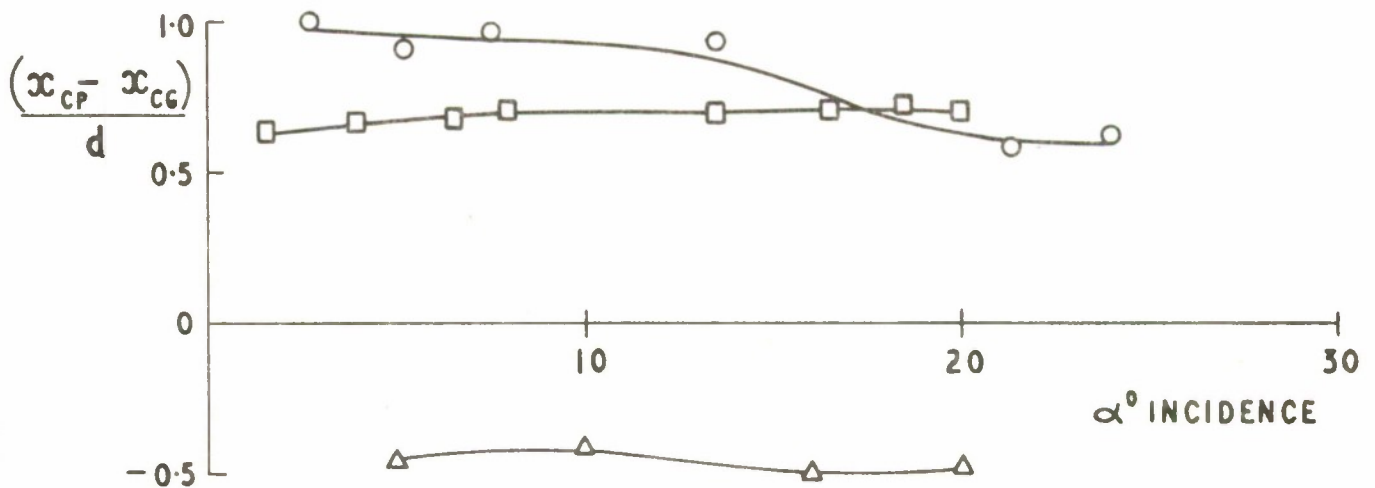
FIG. 7 VARIATION OF BOMBLET STATIC MARGIN AND PITCHING MOMENT WITH INCIDENCE (U-32 m/s)
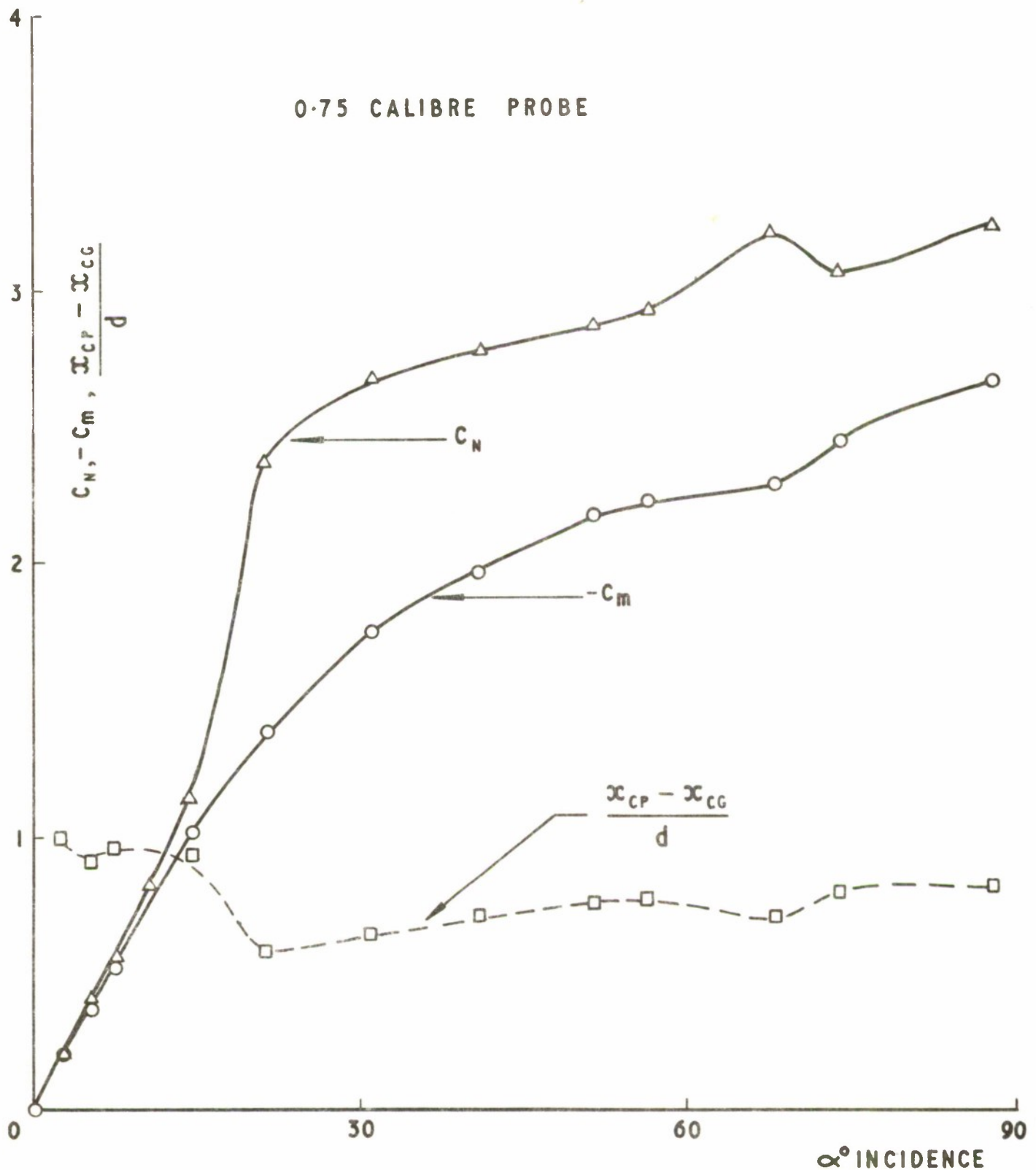
FIG.8 STATIC STABILITY COEFFICIENTS OF FIN STABILIZED BOMBLET (U = 32 m/s)

DAMPS TO ± 5°

FOR $\alpha < 30°$: $\lambda = 0.13$, $f = 6.38$ c/s

$-(C_{m_q} + C_{m_{\dot{\alpha}}}) = 12.78$ PER RAD

(a) FIN STABILIZED, 0.75 CALIBRE PROBE

UNSTEADY DAMPING FOR $\alpha < 15°$

DAMPS TO ± 5°

INTERPOLATED DATA FOR $\alpha < 30°$: $\begin{cases} \lambda = 0.26 , \quad f = 6.25 \text{ c/s} \\ -(C_{m_q} + C_{m_{\dot{\alpha}}}) = 11.55 \text{ PER RAD} \end{cases}$
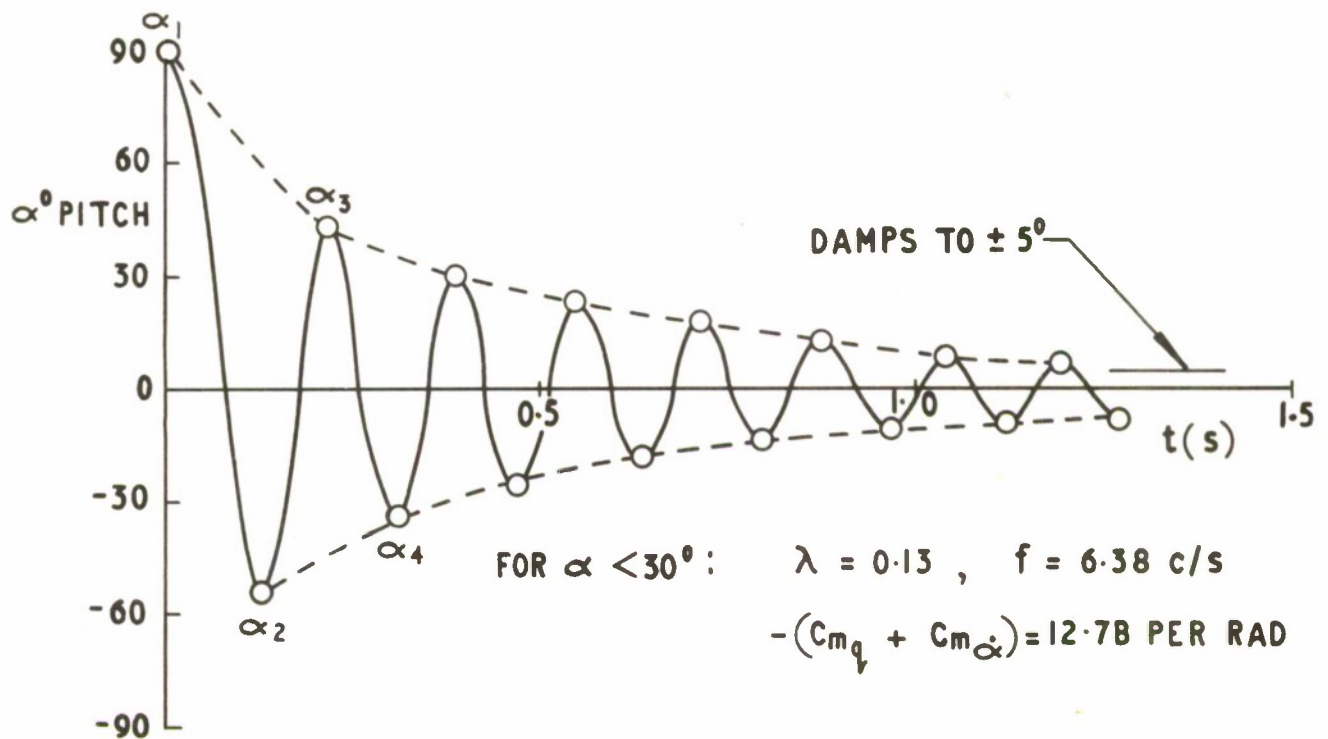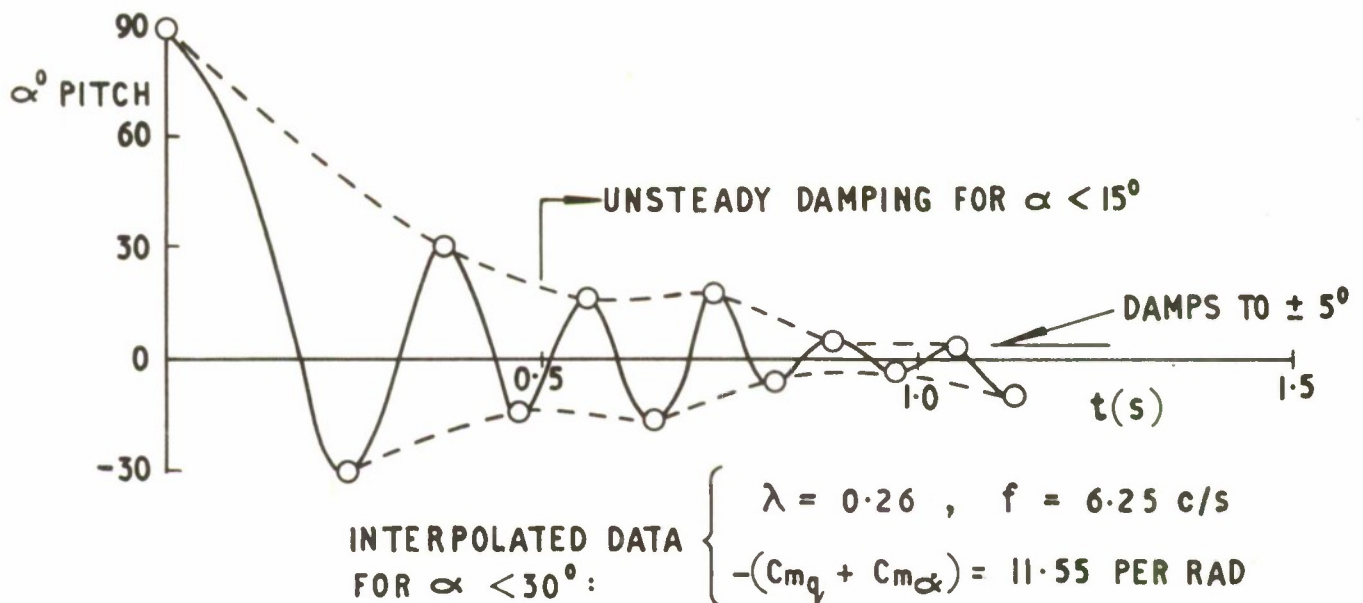
(b) 3 STREAMER STABILIZED, 0.75 CALIBRE PROBE

FIGS. 9 (a)(b)   BOMBLET RESPONSE TO AN INITIAL RELEASE
DISTURBANCE IN PITCH (U = 32 m/s)

POOR DAMPING
FOR $\alpha < 15°$

DAMPING NOT CONSTANT
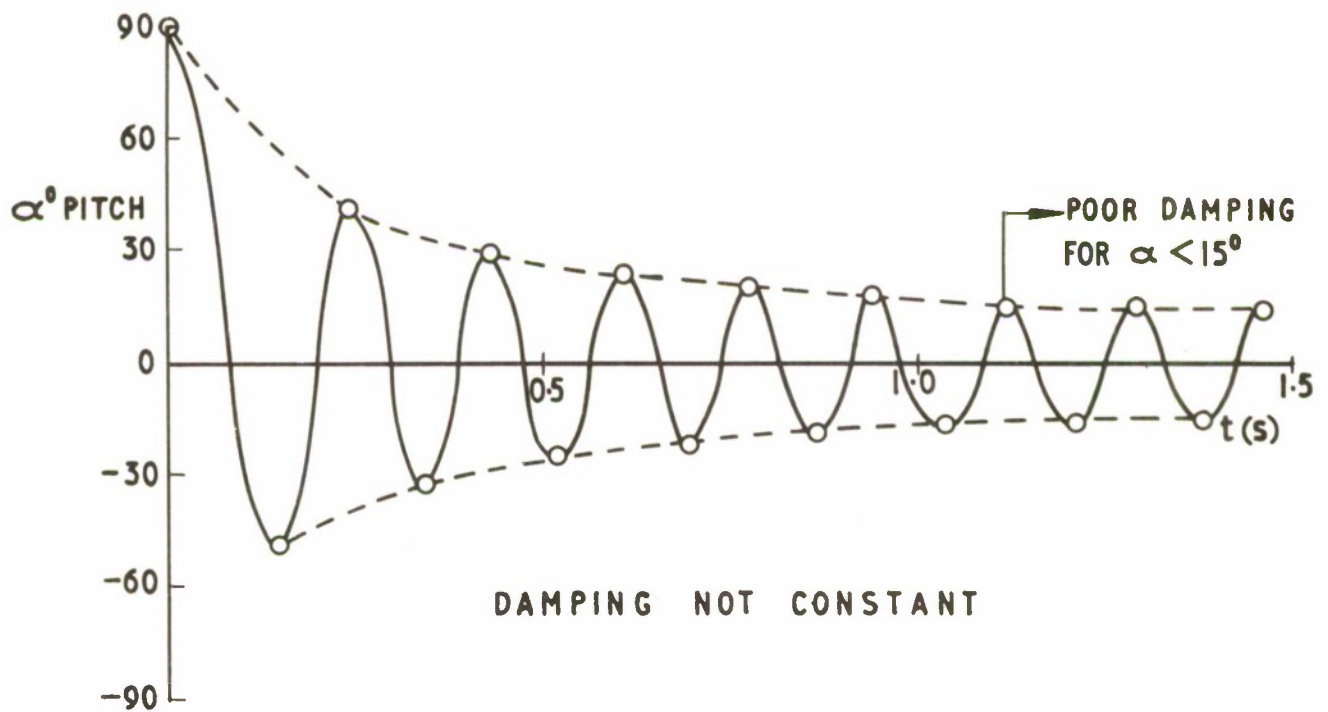
FIN STABILIZED, 1.50 CALIBRE PROBE

FIG. 9 (C) BOMBLET RESPONSE TO AN INITIAL RELEASE
DISTURBANCE IN PITCH (U = 32 m/s)

SYMBOL	CONFIGURATION	λ
X	0·75 CAL. PROBE + STREAMERS*	0·26
O	,, ,, ,, + FIN TAIL	0·13
△	1·50 ,, ,, ,, ,, ,,	0·02

$\alpha < 30°$

$\alpha < 15°$

* THREE CIRCUMFERENTIAL STREAMERS
SOME DATA INTERPOLATED
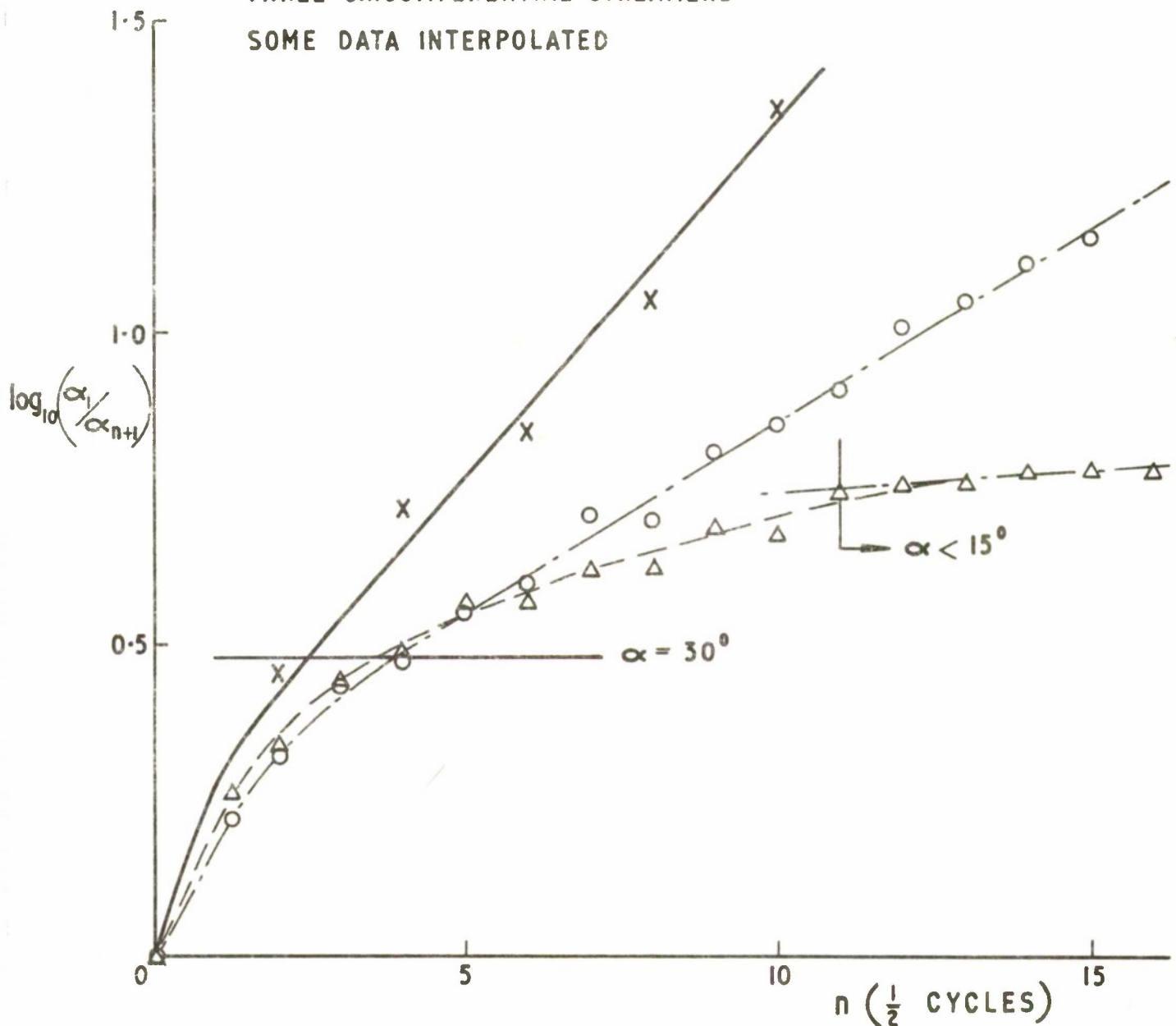
FIG. 10 DELAY OF ANGULAR AMPLITUDE FOR FIN AND STREAMER
STABILIZED BOMBLETS (U=32 m/s)
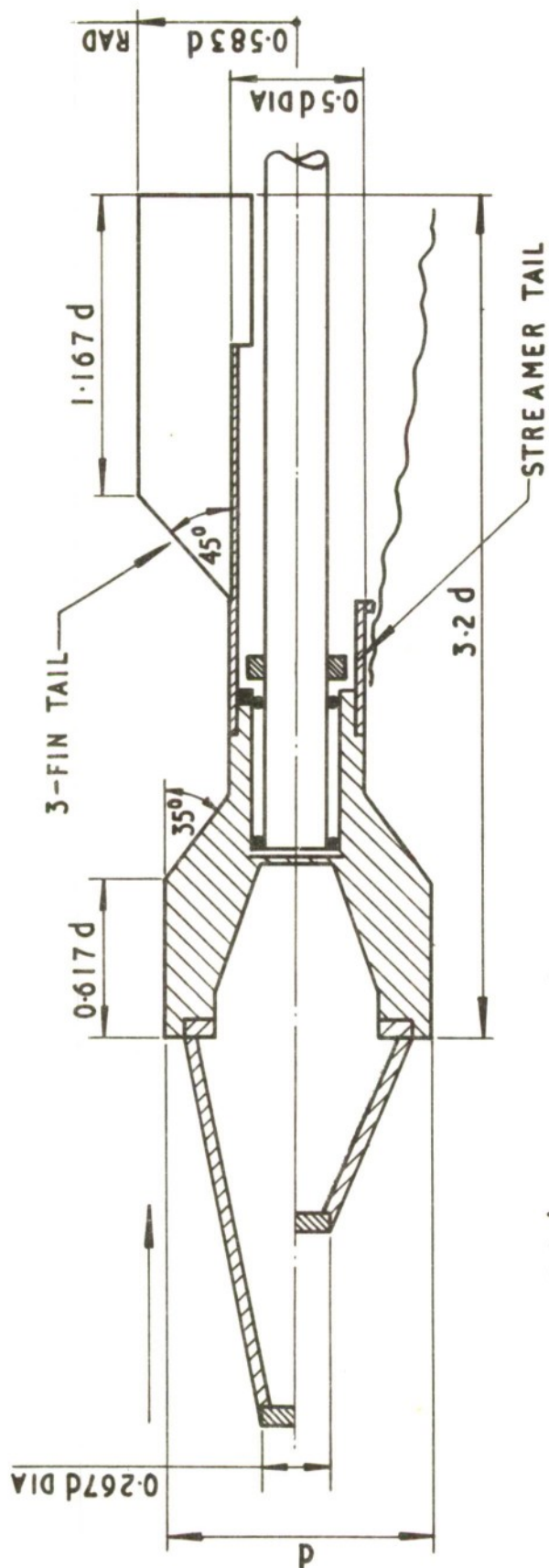
(a) REAR SUPPORT
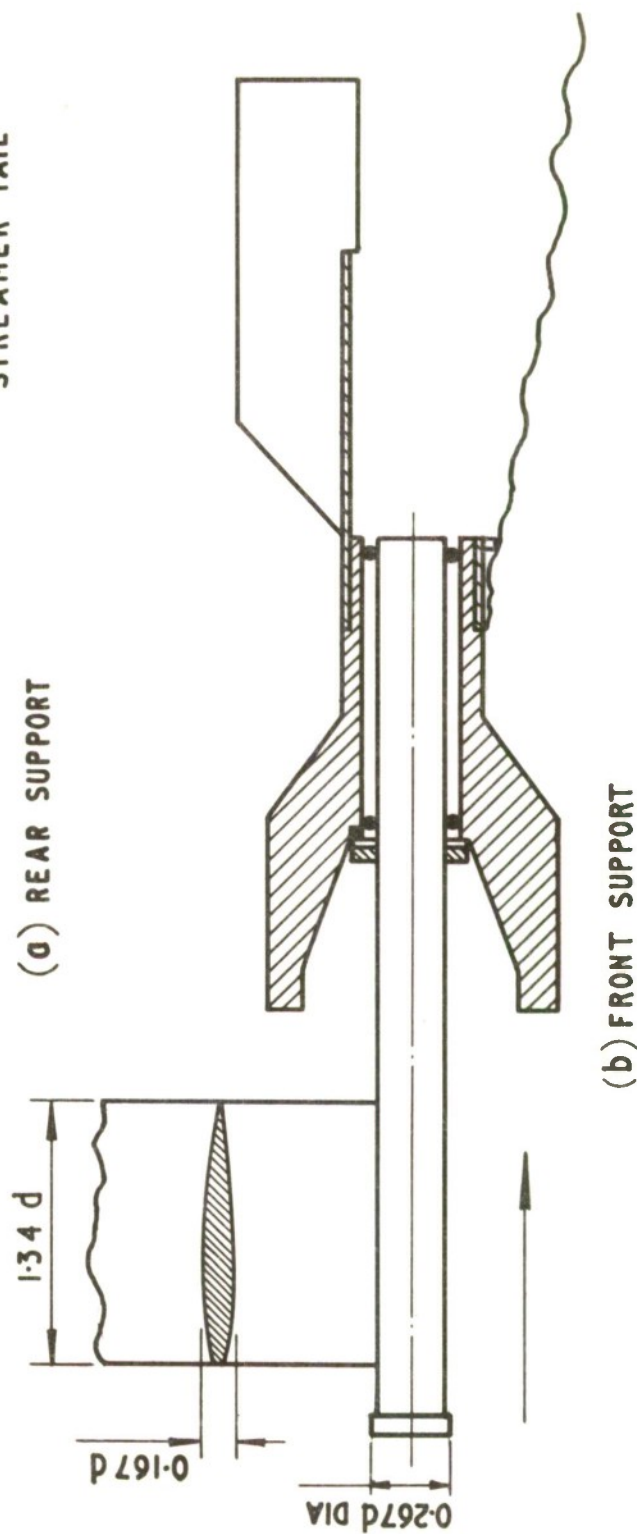
(b) FRONT SUPPORT

FIGS. 11 (a)(b) SPIN DAMPING APPARATUS
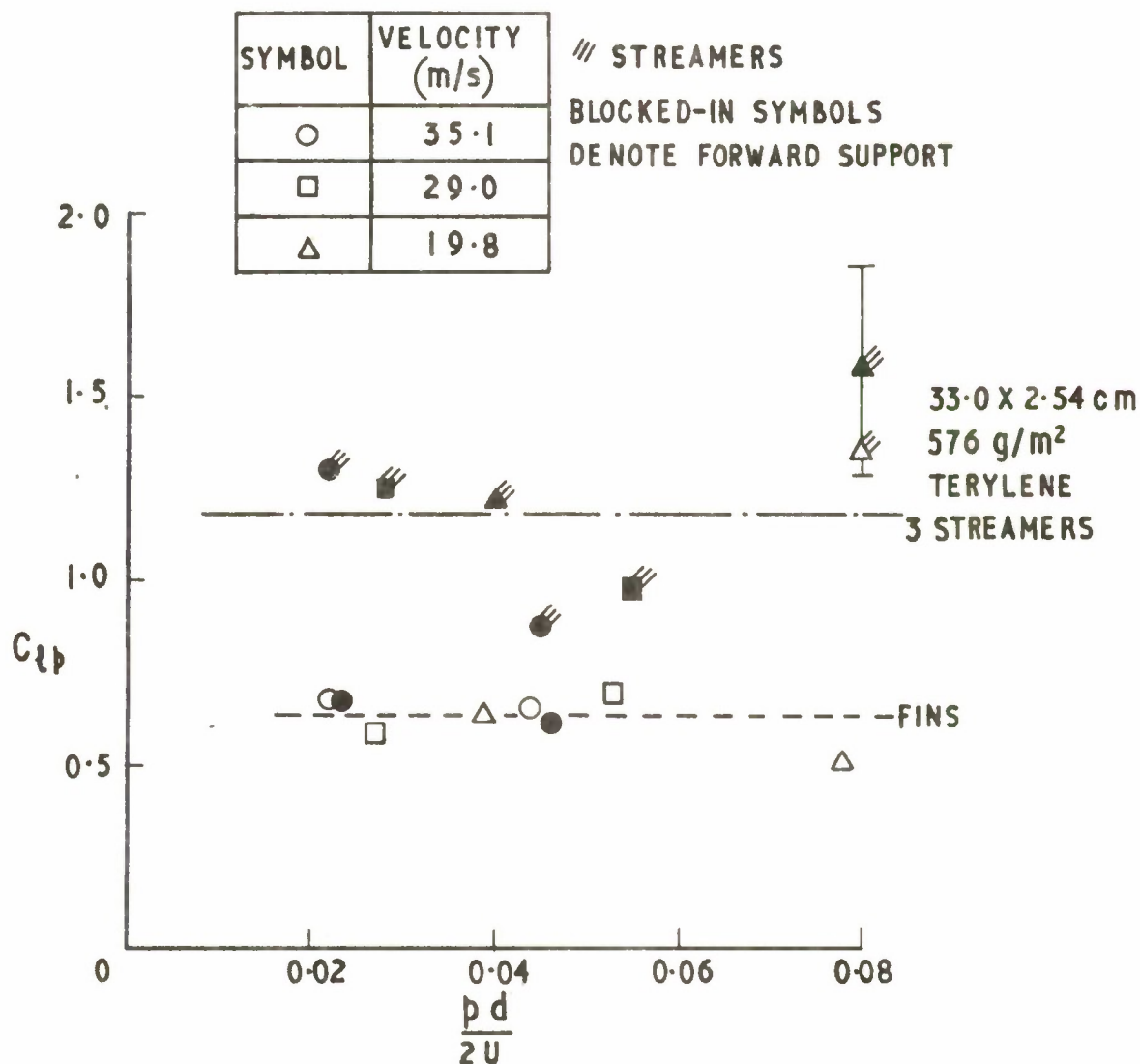
FIG.12 SPIN DAMPING AS A FUNCTION OF SPIN PARAMETER

3 STREAMERS
33·0 X 2·54 cm, 576 g/m² TERYLENE
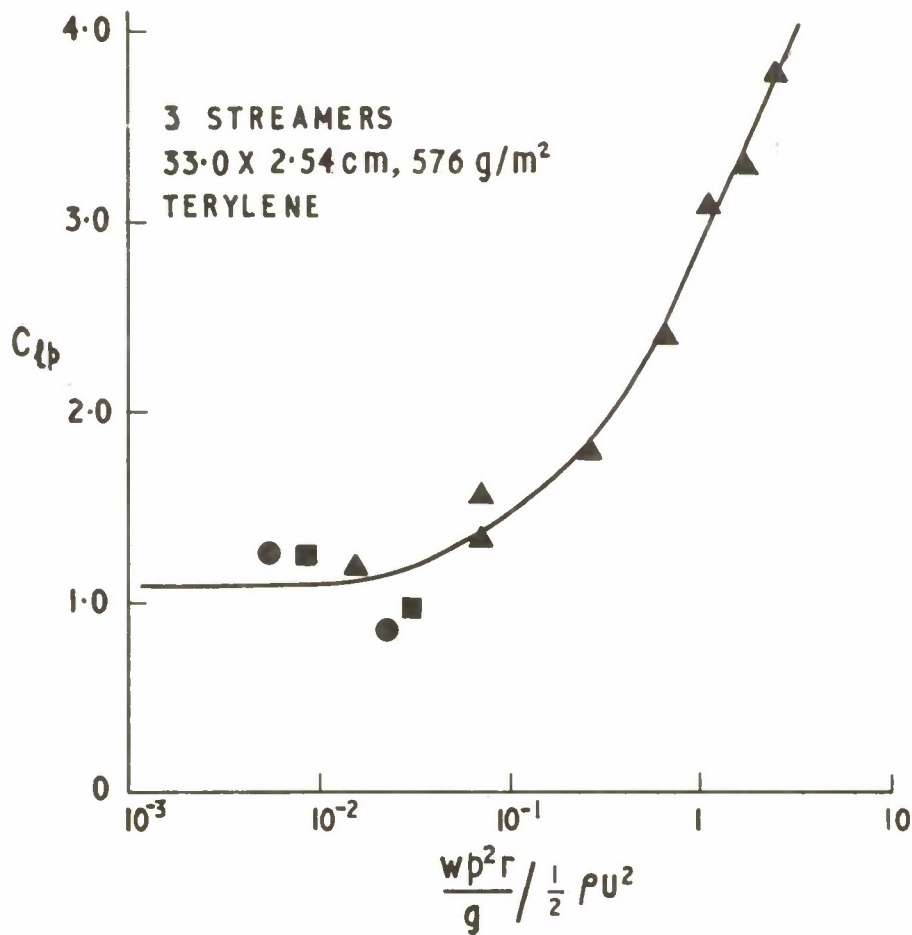
FIG. 13 SPIN DAMPING AS A FUNCTION OF CENTRIFUGAL PARAMETER

3 STREAMERS   33.0 × 2.54 cm, 576 g/m²

$\frac{pd}{2U} = 0.022$

$\frac{pd}{2U} = 0.045$

$U = 35 \, m/s$

C_{lp}
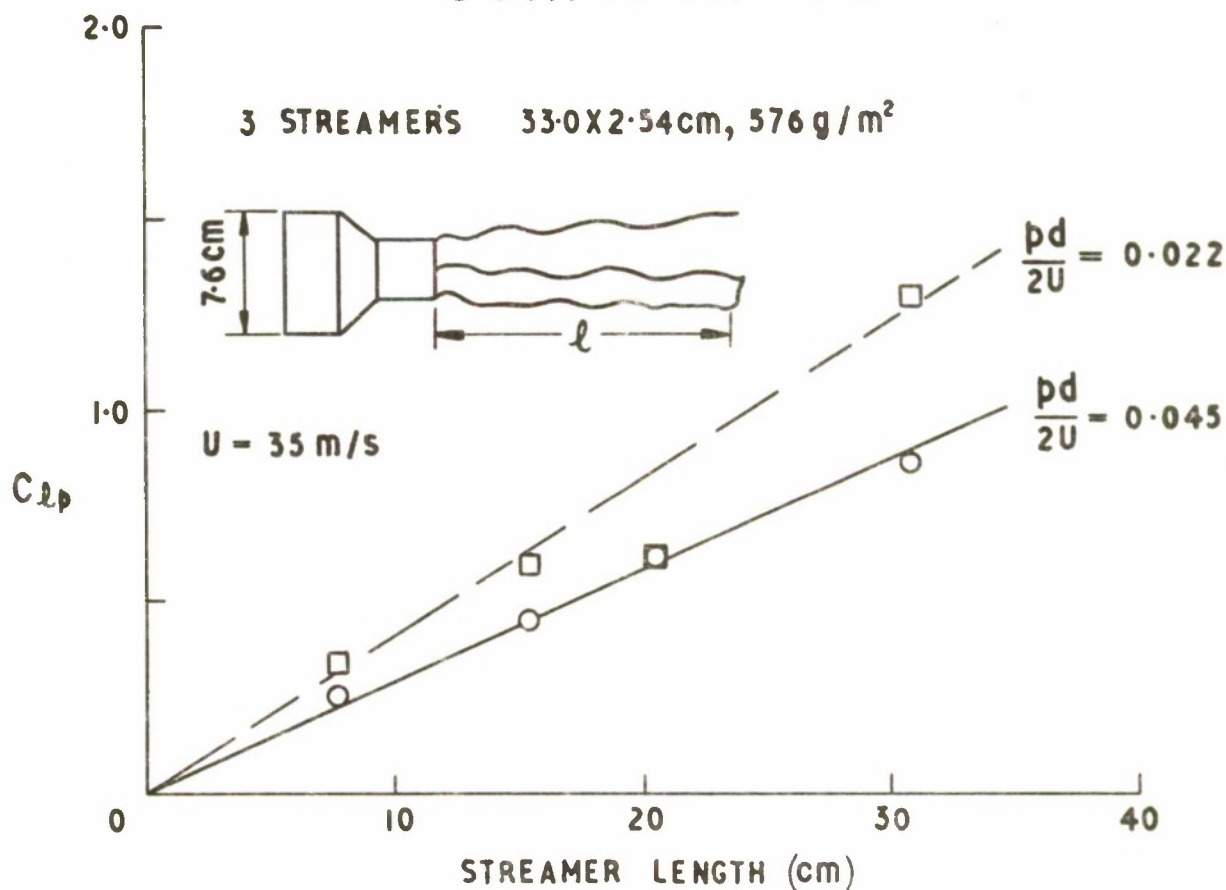
STREAMER LENGTH (cm)

FIG. 14   SPIN DAMPING COEFFICIENT AS A FUNCTION OF STREAMER LENGTH

$\frac{pd}{2U} = 0.022$

$\frac{pd}{2U} = 0.045$

$l = 33.0 \, cm$

C_{lp}

STREAMER WEIGHT/UNIT AREA (g/m²)
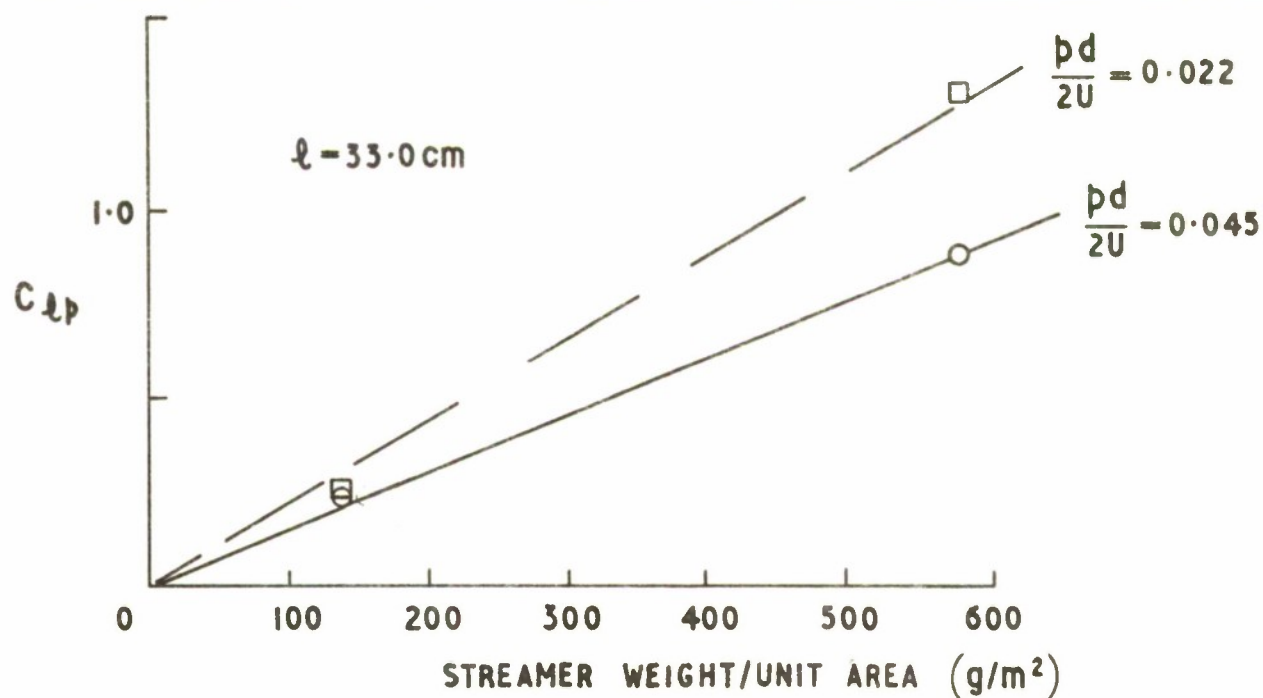
FIG. 15   SPIN DAMPING COEFFICIENT AS A FUNCTION OF STREAMER WEIGHT/ UNIT AREA

ROLL MOTION BEARINGS

YAW MOTION BEARINGS

PITCH MOTION BEARINGS

SECTION
AA

20°

A

A

①

②
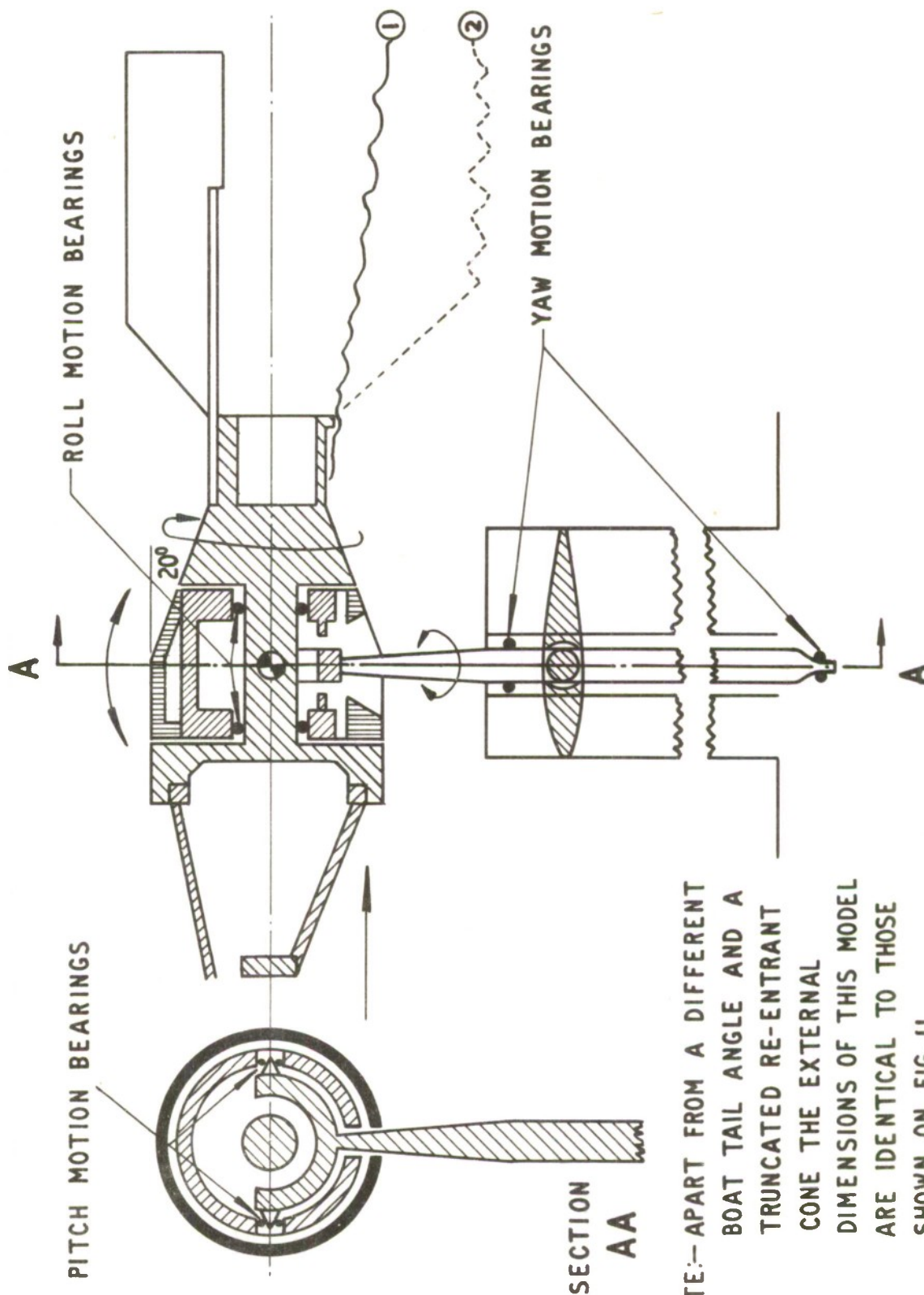
NOTE:- APART FROM A DIFFERENT
BOAT TAIL ANGLE AND A
TRUNCATED RE-ENTRANT
CONE THE EXTERNAL
DIMENSIONS OF THIS MODEL
ARE IDENTICAL TO THOSE
SHOWN ON FIG. 11

FIG. 16 THREE DEGREE—OF—FREEDOM APPARATUS
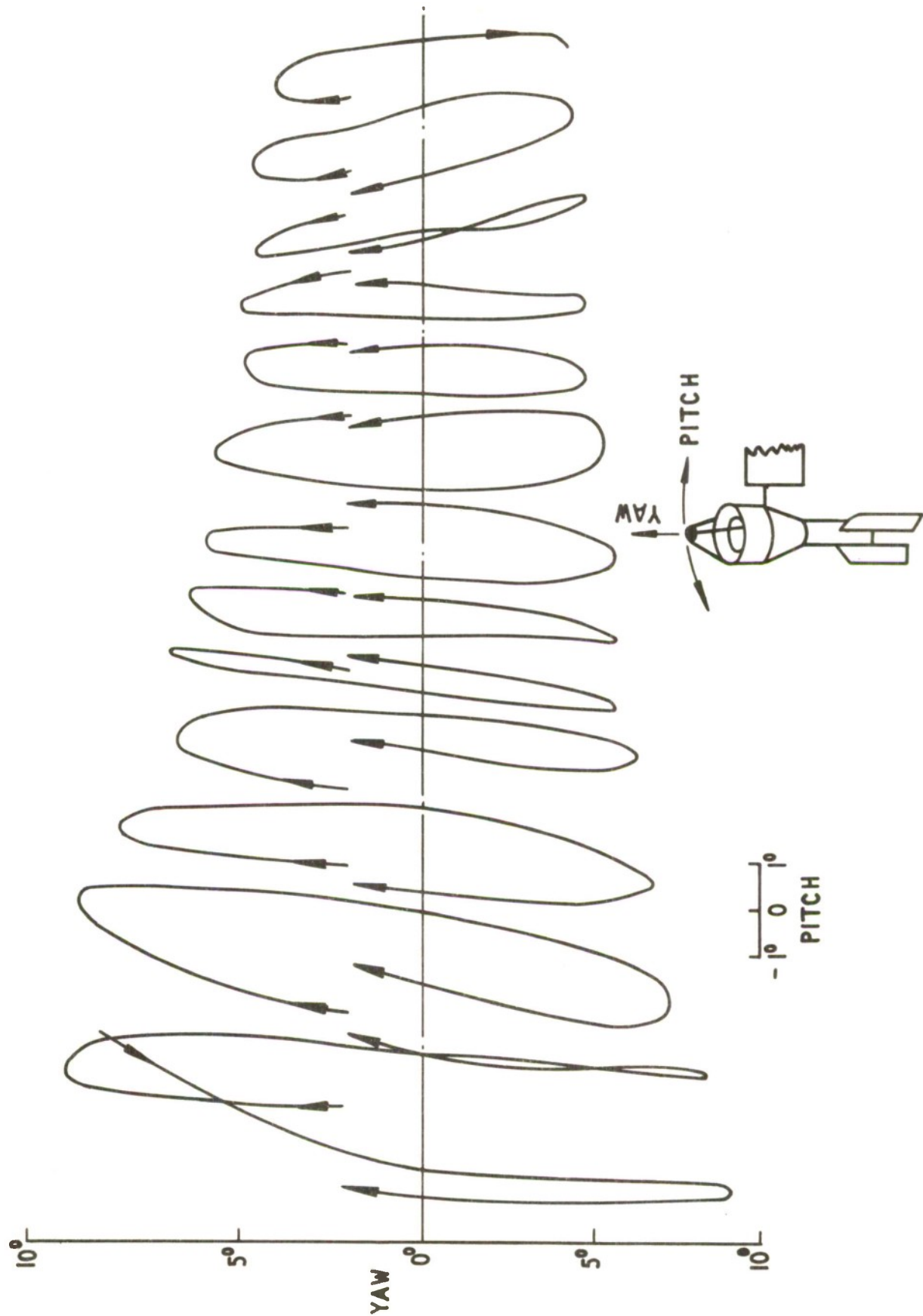
FIG. 17 (a) YAW DAMPING, FIN — STABILIZED MODEL
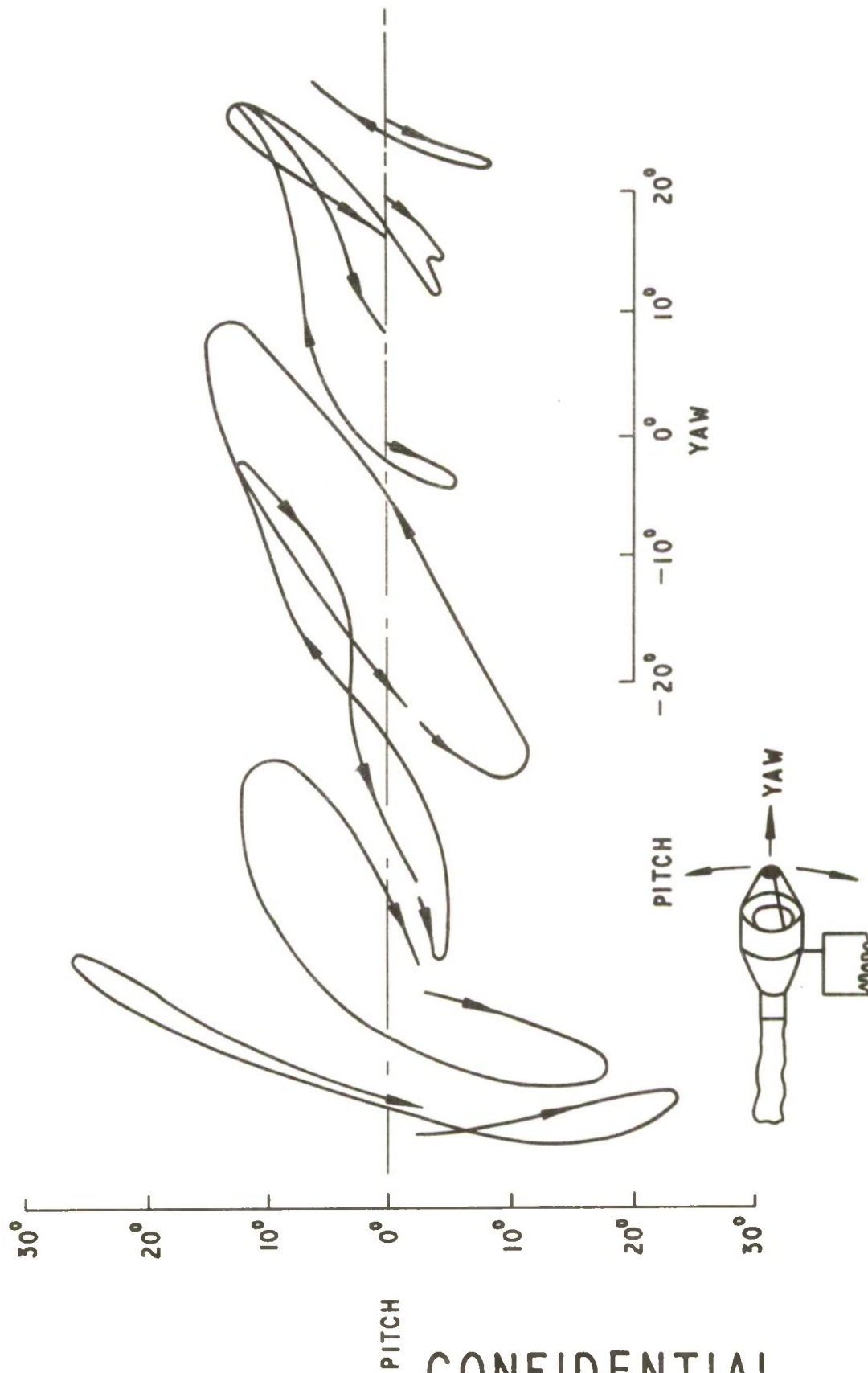
FIG. 17 (b) PITCH DAMPING, STREAMER—STABILIZED MODEL
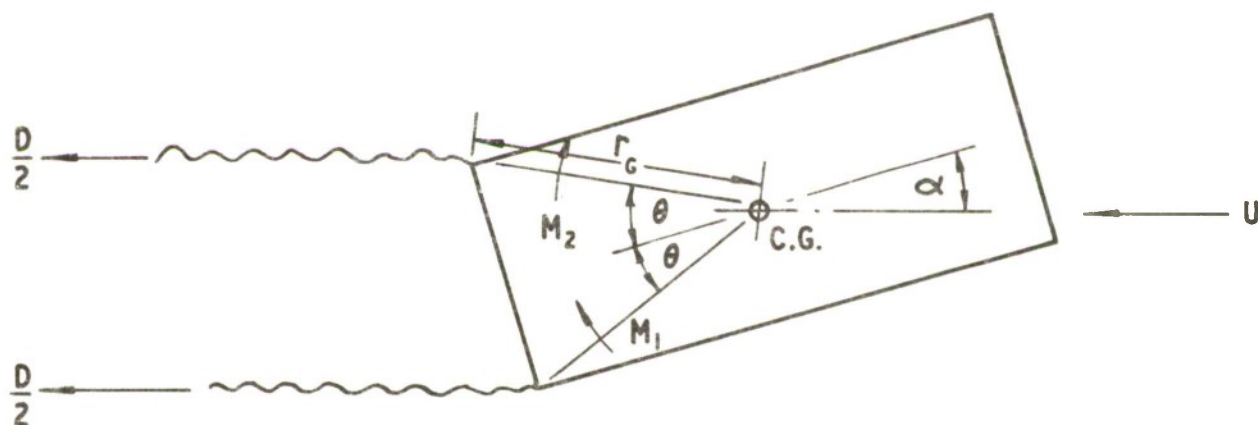
FIG.AI (a) PITCH DAMPING —— STREAMERS
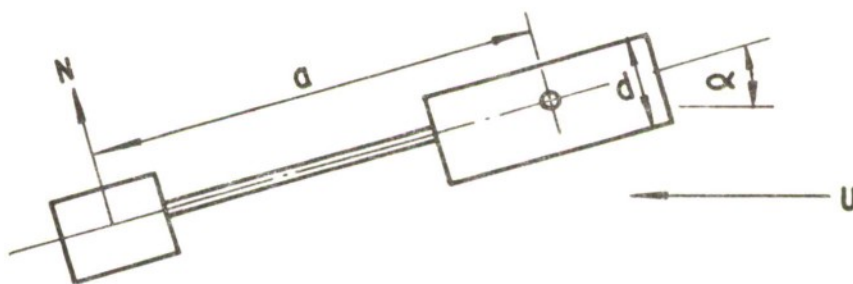
FIG.AI (b) PITCH DAMPING — FINS

FIGS. AI (a)(b) NOMENCLATURE USED IN APPENDICES

$$\frac{wp^2}{g}(y+r)\,ds$$

$$\frac{1}{2}\rho U^2 \frac{\partial c_p}{\partial \theta}\theta\,ds$$

FIG. A2   STREAMER SHAPE
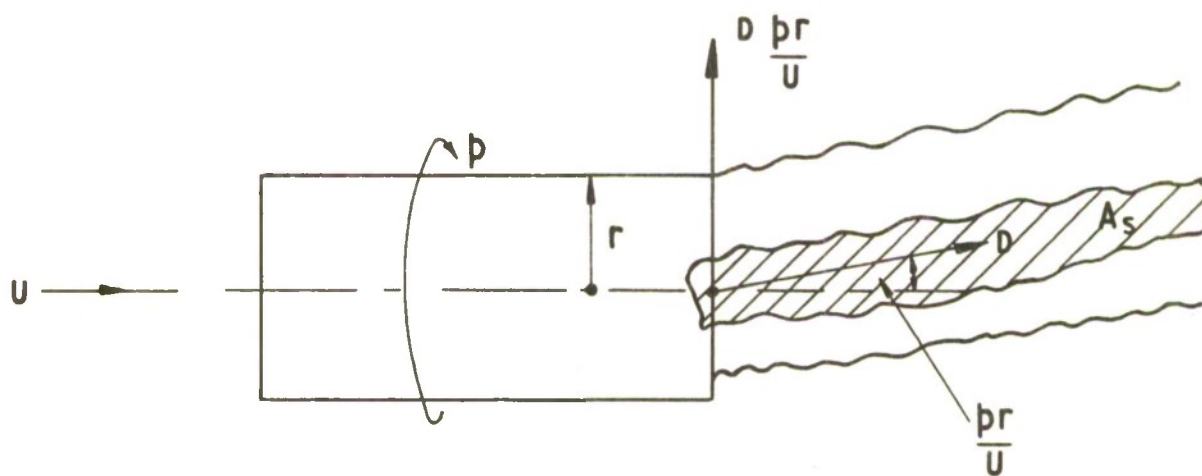
FIG. A3   SPIN DAMPING

FIGS. A2 & A3 NOMENCLATURE USED IN APPENDICES

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623.451.8, FOIL:
623.4.087:
533.665:
533.6.013.4:
533.695.9

Ministry of Defence
Royal Armament Research and Development Establishment
R.A.R.D.E. Memorandum 14/70
March 1970

Subsonic wind tunnel tests on the use of streamers to stabilize the FOIL bomblet.
R. K. Fancett, W. A. Clayden

The aerodynamics of a FOIL bomblet stabilized by streamers was studied in a small subsonic wind tunnel. For this investigation the size and shape of the streamers was based upon an earlier parametric study of the drag of isolated streamers.

The reduction in drag of a streamer operating in the bomblet wake was measured and measurements were also made of the static and dynamic stability and spin damping. These measurements were compared with results /obtained

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obtained for a similar bomblet stabilized with a conventional fin. It is shown that whilst streamers may provide adequate static stability and spin damping, the dynamic stability at small angles of incidence is poor compared with fins though steamers may be as effective as fins in damping out very large angles of incidence.

23 pp. 20 figs. 3 tabs. 9 refs.

24 Maw72

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Record Summary:
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Covering dates 1970
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