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Design Study and Model Trials on a towed near-surface Thermistor-spar

A.R. Packwood

September 1981

Internal Document No. 140

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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1. SPECIFICATION

A specification was received requiring the development of a device for towing a surface following thermistor spar. Sensors on the spar would be used to measure the temperature structure of the upper layers of the ocean. The spar should be 10 m long and sample at 10 or more levels in the surface layers of the ocean. The spar should be roughly surface following and although it would not be deployed in heavy seas, should be able to follow 1 m waves. Towing speeds within the range 0-5 knots are envisaged. The sensors should be deployed beyond the wave and turbulent wakes of the towing ship and yet should be close enough to the ship to permit photography of the sea surface above the spar. It is desirable that the spar should not trail at an angle greater than 20° to the vertical and horizontal accelerations should be minimised. Since the thermistor spar will be towed up, down and across wind in winds of up to 30 knots, the spar motion should be as far as possible decoupled from the heave and roll of the towing ship.

2. THE PROPOSED DEVICE

In order to clear the spar of the ship's wave wake, it would be sensible to tow the spar from as far forward on the ship as possible and in such a manner that it moves itself outward beyond the bow wave into clear water largely uninfluenced by the presence of the ship. An already existing device which accomplishes this is the Neuston net sledge, the operation of which is described in David (1965). The net sledge however could not support a 10 m spar beneath it since it has only a comparitively small reserve buoyancy. However, a more buoyant version of the Neuston net sledge might provide the desired characteristics. The net sledge tows away from the side of the ship by virtue of its having two keels and an offset bridle arrangement which makes the sledge kite away from the towing point. Further, a surface follower linked to the ship can be decoupled from the ship's heave and roll motion if sufficient length of towing cable separates them. The new sledge must be sufficiently buoyant to support the spar suspended beneath it and the associated electronics packages. It should also have sufficient reserve buoyancy to take the vertical accelerations imposed by the wave field and yet not be so large as to interfere with the performance of the spar or be awkward to handle from the ship. To minimise the trail angle of the spar when being towed it may be desirable to add weight to the bottom of the spar. Both spar and any bottom weight should be streamlined to reduce drag and the vibrations caused by vortex shedding.

For ship handling the whole assembly must be extremely robust, not an easy criterion to meet for such a long and slender structure.

3. THE SPAR

Some faired alumimium spar is commercially available which should be suitable for mounting the thermistors. The section of the tube and the size of the thermistor and housing is sketched in fig. 1. It is important that the suspension points, about which the spar will pivot in the horizontal plane, be as close to the spar leading edge as practically possible in order that the thermistors may point into the flow. If the pivot is aft of the quarter chord point the spar will fish-tail i.e. swing violently from side to side. Since the thermistors extend well beyond the leading edge, they will provide a destabilizing moment should the spar take on a yaw angle. To counteract this and provide a correcting moment some lengths of stabilizer should be attached to the trailing edge of the spar. In model tests a stabilizer of approximately three spar chord widths was initially added to half the length of the streamlined spar trailing edge (see fig. 6). Tests indicated that the length and position of the stabilizer was important in damping flexural vibrations of the spar; this is discussed later. Assuming half length and three chord width stabilizer to be sufficient and the entire assembly fabricated in aluminium, the estimated weights <u>in water</u> of the full-scale spar components are:

Spar	30 lb	13 kg
Stabilizer (½ length)	20 lb	9 kg
Thermistor assembly (10 off)	10 lb	5 kg
	60 lb	27 kg
	(93 lb	42 kg in air)

Assuming turbulent flow conditions as a worst case, then friction plus section drag for the spar alone is approximately 30 lb, 13 kg @ 5 kts. Friction drag on the stabilizer might then add 12 lb, 5.4 kg @ 5 kts and the thermistors themselves perhaps another 10 lb, 4.5 kg at the same speed giving a total drag of 52 lb, 23 kg @ 5 kts. These estimates have been arrived at using the drag coefficients given by Hoerner (1958) for the various parts of the spar structure.

4. THE BOTTOM WEIGHT

A standard I.O.S. streamlined weight will be used for this purpose. This is approximately 25 cm diameter and made up of steel discs so that the weight can be varied as desired. The length to diameter ratio of the weight is 5.4, giving a drag coefficient of approximately 0.08 based on cross sectional area. Making some allowance for surface roughness this gives a drag of about 20 lb, 9 kg at 5 kts. The use of a form of wing depressor was considered for the same purpose, this would be lighter and may have less drag. However, the experience of those who have operated such depressors indicates that in the near surface environment they wallow, pitching and rolling at the same time, and do not provide a steady downward force.

The minimum weight required at the bottom of the spar to give the largest allowable trail angle of 20° at 5 kts towing speed is 95 lb, 43 kg. This is given by taking moments about the spar towing point on the sledge as shown in fig. 2. A scaled weight of more than double this was found necessary in the model trials. This is because the Reynolds number in the model test was much lower than would be the case at full-scale thus giving a higher scaled drag. (Drag coefficient usually decreases as Reynolds number increases). It is evident that only full-scale trials will finally resolve the problem of the correct amount of ballast weight.

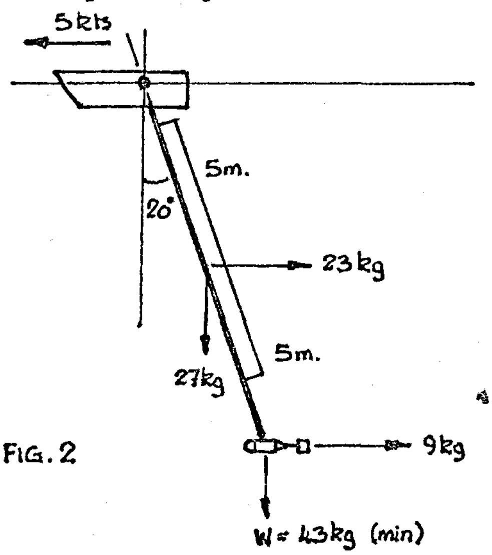

FIG. 2

5. THE SURFACE SLEDGE

The sledge must be capable of supporting the static load of the spar plus bottom weight plus instrument package and have sufficient reserve buoyancy to accelerate these comfortably in 1 m waves without submerging. The more buoyant the surface sledge, the better it will ride the waves it encounters. The peak acceleration experienced in 1 m ocean waves of 4.5s period is about 1 m/s^2. When the mass of the payload, added mass of water in the spar and around the bottom weight and the mass of the sledge itself are taken into account, the dynamic buoyant force required is not inconsiderable. The requirement is for a light and buoyant surface sledge with two keels and offset bridle towing arrangement to carry the spar suspended beneath without interfering with the flow around the spar leading edge. The minimum reserve buoyancy for the sledge based on estimates of the spar weight and minimum ballast weight is 70 kg. But it is felt that the sledge should be capable of payloads up to 200 kg allowing for added ballast weight that may be required and the dynamic loading on spar and ballast weight. Allowing roughly 100 kg for the weight of the sledge itself, remembering it will have to be quite a substantial structure to support a 200 kg point load, then the surface sledge must displace at least 300 kg or 0.3 m^3 of water. This load will have to be met by the buoyancy of the sledge alone because planing lift on the scale of the proposed device will be ineffective at speeds of 5 kts.

For the surface follower to steer away from the ship it must assume an angle of incidence to the flow away from the ship. For this situation to be stable the sledge should be towed on a two strop bridle offset so that the bridle length nearest the ship is shorter than that furthest away, see fig. 3. Let the length of the sledge or the keels be c and their separation w. Then assume the lift and drag forces act at some point A on the centre line of the sledge distance xc from the front of the sledge. If T is the tension in the towing wire which is pulling at an angle θ to the ship's heading, or the incident flow, then by resolving forces it is found that

$$\frac{L}{D} = \tan\theta$$

where L is the side force generated by the keels and D the drag of sledge and spar etc. By taking moments about the bridle intersection point B of fig. 3 we find

$$Lf\cos(\gamma-\alpha) = Df\sin(\gamma-\alpha)$$

$$\therefore \frac{L}{D} = \tan\theta = \tan(\gamma-\alpha)$$

$$\text{or } \theta = \gamma-\alpha$$

where f = distance AB, α is the angle of incidence of the sledge and γ is the angle between the sledge centre-line and the line AB.

The ship wave wake extends out at an angle of $19\frac{1}{2}^\circ$ from the centre line of the ship but the apex of the origin of the wave pattern is usually displaced upstream of the bow by sometimes as much as one ship's length, see Newman (1977). But this pattern does not significantly develop until about half a ship's length aft of the bow. It will be sufficient therefore to get the sledge outboard of the ship's turbulent wake which extends usually about one ship's width either side of the ship creating the wake. The region that the sledge will have to clear is shown hatched in fig. 4. This diagram indicates that θ the tow off angle will have to be at least 30° if towed well forward on a boom off the forecastle. The value of α has to be positive and preferably quite small so that the flow beneath the sledge is not too disturbed. Suppose $\alpha = 5^\circ$ to 10° then γ must be $35^\circ \rightarrow 40^\circ$. It can be shown with reference to fig. 3 that

$$\tan \gamma = \frac{0.5w - l \cos\psi}{l \sin\psi + xc} \qquad (1)$$

where l is the length of the shortest bridle and ψ the angle this bridle makes with the line joining the towing points. This shows that for a sledge of given dimensions w and c, γ can be increased by either reducing l or x. The position of A is variable, in a very low drag configuration the centre of lift and drag would tend toward the quarter chord position, x = 0.25, as for an aerofoil. In higher drag configurations, for instance when the spar and ballast weight are attached to the sledge, the increased drag will move this point back toward the towing point where this added force acts, i.e. toward x = 0.5. In increasing γ there is a limit to the amount by which l can be usefully reduced. Too great a reduction will cause the longer bridle to go slack, any subsequent reduction then has no effect. The maximum amount that l can be reduced by is reached when the line joining A to B passes through the tow point P. When this condition is reached the bridle QB goes slack. But γ can be further increased by reducing x, i.e. by moving the tow points PQ back down the sledge toward A.

For typical sledge dimensions $w = \frac{3}{4}c$ and choosing l = c then a convenient value for k is $\frac{3}{2}l$, this prevents the cable QB going slack. From (1) it is then possible to show that γ will be 31° if x = 0.5. Moving the tow-points aft by 0.1c then increases γ to 32.9°. This is shown diagramatically in fig. 5. As can be seen from fig. 5 having moved the two-points aft, the ratio k/l can be increased, keeping l constant, to a maximum value of 1.61. This is the value at which the longest bridle just goes slack, for which $\gamma = 43.2^{\circ}$. Thus it can be seen that quite small changes in k/l can give large changes in γ. By adjusting the value of x and the bridle length ratio k/l, it is clear that values of γ in the desired range of 35°–40° are practical for such a device.

6. THE MODEL AND EXPERIMENT OBJECTIVES

To establish the towing characteristics of the sledge and spar a $\frac{1}{8}$th scale model was constructed, and tested in the IOS wave/tow tank. The dimensions of the model sledge are given in fig. 6. The buoyancy and framework were fabricated in wood and therefore may be heavier overall than a scaled down foam filled ply or fibre-glass construction. The shape of the sledge was made as simple as possible with the cost of full-scale construction in mind. The design of the sledge is based on the scale of the Neuston net sledge but with sufficient buoyancy to cope with the estimated weight of the various components and vertical accelerations. A model streamlined spar was fabricated from round section aluminium rod, no tube of the correct size being available, with a splitter plate glued to the back of the cylinder then faired with metal putty to a streamlined shape, see fig. 6. A small streamlined steel weight, having removeable sections, was also made. The weights in air and water of the components and their full-scale counterparts are given in Table I.

The variables to be investigated in the model experiments were

(i) bridle configuration and location of towing points

(ii) size of keel area

(iii) size of streamlined bottom weight

(iv) length of stabilizer to be attached to the trailing edge of the spar.

During tests the angle of the towing wire to the direction of motion was measured. The attitude of the bottom weight and spar angle were recorded photographically in one of the tests. The model was towed at a range of speeds, 37 - 110 cm/s corresponding to full-scale towing speeds of 2 - 6 kts; Froude number scaling having been used to determine the scaled velocities. The model was also tested in waves $\frac{1}{8}$ full size. The specification asked that the sledge should be capable of following 1 m high waves. Assuming a typical wavelength of 22 m full scale this gives 0.125 m high waves of wavelength 2.75 m and period 1.3 s. This means that the model scale wave acceleration is $\simeq$ 1.5 times greater than full scale.

7. RESULTS

What follows is a summary of the observations and measurements taken during the model trials.

(i) BRIDLE CONFIGURATION

It was found that bridle lengths of l = 20 cm and k = 30 cm gave the best towing configuration with both bridles taut. If the longer of the two bridles were made still longer by 2 cm it was found to go slack. The towing points were 13.5 cm apart and placed initially 9 cm forward of the spar towing point. When the tow points were moved aft 2 cm, the tow-off angle was increased by $3^\circ - 4^\circ$. This latter configuration is obviously better since high values of θ are required to move the sledge out of the ship's wake. It will be possible to alter this tow-off angle by adjusting the fore/aft position of the tow points on the sledge. Shortening the longest bridle has the effect of reducing θ. The maximum recorded value of θ for the sledge as sketched in fig. 6 with 20 - 30 cm bridle lengths and tow points 7 cm forward of the spar was 38° at 37 cm/s ($\equiv$ 2 kts full-scale) and 35° @ 92 cm/s ($\equiv$ 5 kts).

(ii) SIZE OF KEEL AREA

The larger keels, giving a keel depth of 8.5 cm, cf. 7 cm for the smaller keels, gave a $2^{o} - 3^{o}$ improvement (increase) in tow-off angle over the speed range investigated. The size of keel will have to be selected with due consideration to the interference effects they might have on the thermistor probes near the surface. In this respect outboard keels are better than inboard keels.

(iii) SIZE OF BOTTOM WEIGHT

In the model tests a bottom weight of 237gm in air was found to fulfil the specification and keep the spar trail angle below 20^{o} at towing speeds of up to 92 cm/s (≡ 5 kts full speed). Fig. 7 shows the spar and bottom weight being towed at approximately this speed. The spar shown has stabilizer extended over the full length giving the model spar assembly a weight of 280 gm in air. The bottom weight in this picture weighs 237 gm in air. This size bottom weight corresponds to 267 lb, 121 kg full scale weight in air. This is almost three times that estimated in section 4. The reason is, as explained earlier, because of the difference in the Reynolds numbers for model and full-scale flows. The drag coefficients of the spar and bottom weight are thus much higher for the model than for the full-scale device. Estimates suggest the drag coefficient of the model spar may be 3 or 5 times greater and for the model weight 3 times greater than at full scale Reynolds numbers. It should also be remembered that the model spar is approximately 3.4 times heavier, when scaled, than the estimated full-scale weight because it has a solid section. Thus the effects of the model extra weight and drag almost cancel giving the same trail angle for the spar. This suggests that a bottom weight of approximately 50 kg say may be sufficient in accordance with the earlier calculation of section 4.

(iv) LENGTH OF STABILIZER

The spar was initially modelled with half its length fitted with stabilizer extending 30 mm behind the trailing edge of the spar as in fig. 6. The first trials showed that the spar began to oscillate in the first natural flexural mode of a beam simply supported at both ends. The oscillation was from side to side, perpendicular to the towing path, and only apparent at towing speeds above 40 cm/s. Once started it appeared to be undamped having an amplitude that increased with towing speed to about 3 cm at 92 cm/s. The frequency of the oscillation corresponded approximately to the natural frequency of the spar vibrating in water calculated as 2.3 Hz with no stabilizer and 1.1 Hz with the complete length fitted with stabilizer. Adding more and more lengths of stabilizer so that finally the whole length was fitted with it had the effect of raising the towing velocity at which the oscillation started. The exciting force was not immediately apparent. The oscillation was most certainly not caused by vortex shedding which would have a much higher frequency (17 Hz at 40 cm/s for a circular cylinder) and should largely be surpressed by the fairing. Additional tests indicated that the pendulum mode of the bottom weight swinging on the bottom of the spar had a similar frequency to the observed oscillation with the centre of the weight 13.5 cm below its attachment point. Shortening this distance to 2.5 cm, a practical minimum, completely stopped the oscillation over the entire speed range, 0 - 92 cm/s for the spar with stabilizer over the entire length. However returning to the initial spar configuration, half length fitted with stabilizer, saw the oscillation re-occurring. Why the initiation of the oscillation is speed dependent is still not clear.

It is believed that in the model trials the added stabilizer over the centre section had the effect of both stiffening the flexural mode and also damping the vibration. The full-scale spar, being hollow, will be stiffer than the model spar. Estimates of the full-scale natural frequency give a value of approximately 0.4 Hz if most of the spar has stabilizer fitted. If the bottom weight is attached as near as possible to the end of the spar it will have a natural frequency of 1.2 Hz. It is hoped that these frequencies are sufficiently separated to prevent the oscillation occuring in the full-scale device. The spar remains a very flimsy structure and if vibration or handling difficulties prove to be unacceptable it will be possible to stiffen it using shroud lines as on yacht masts.

(v) TOWING PERFORMANCE

Several test runs were made in the presence of waves, scaled down to approximate the scale of the model. It is evident that when towing at low speed in wave conditions the cable is liable to go slack and snatch causing the spar to pendulum fore and aft. In most circumstances this may be overcome by increasing the towing speed. When towing into waves the bows were observed to submerge on wave crests. A more buoyant sledge with boat shaped bows would ride better. The device obviously works best in calm conditions and its performance definitely deteriorates in waves but no large or potentially damaging instabilities were apparent in the wave tests.

Fig. 8 shows pictures of towing tests without waves at speeds of 38, 57 and 93 cm/s, (approximately 2, 3 and 5 kts full-scale speed). They show the development of a strong bow wave ahead of the square fronted floats which at 93 cm/s almost submerges the starboard float. It is evident that boat shaped floats will be required despite the extra problems and cost involved in manufacture, and some additional buoyancy would be beneficial.

Following these experiments, pointed wedge shaped bows were made up and glued to the front of the sledge. The bows were designed to be made up from plane surfaces, no compound curves. The new bows extended the sledge by ≃ 5 cm. In plan the included angle at the bow was ≃ 46° and in elevation the line of the bow sloped back at 45° as had the earlier flat fronted bows. The new sledge is sketched in fig. 9. In tests this new arrangement towed very much better. The large bow wave that previously had swamped the decks was eliminated. The tow off angle was increased from 35° to 40° because of the reduced drag. This value of θ was constant over the speed range 37 → 92 cm/s (2 → 5 kts full-scale) showing that the lift/drag ratio of the sledge is constant in this regime and is approximately 0.84. In scaled 1 m waves, the nearside pontoon was periodically swamped and in order that the bridles remained taut, a minimum towing speed of 3.5 - 4 kts full-scale was required. However, it was thought that this performance was satisfactory and a great improvement on the slab fronted bows of the first model. It should be remembered that the wave accelerations in the model scale experiments were slightly more severe than might be experienced at sea in the design conditions. The additional buoyancy at the front of the sledge was evidently also contributary to the improved performance.

8. FINAL COMMENTS AND RECOMMENDATIONS

The final scaled up sledge would be 2.4 m long, 1.2 m wide with tow points that can easily be adjusted fore and aft. The bows should be boat shaped to reduce wave drag, a simple shape as in fig. 9 appears adequate. The twin keels should extend approximately 0.6 m below the water line, outboard keels are preferred. Provision should be made for the fixing of the electronics package. The construction should be light but sturdy, capable of taking a point load of approximately 200 kgf (estimated maximum working load) at the spar towing point. Fabrication of the floats and keels may be in moulded ply, fibre-glass sealed and foam filled unless other suitable floats, e.g. small catamaran hulls or sea-plane floats, are more readily available.

The spar fabricated from streamlined aluminium tube should be fitted with a 0.3 m wide stabilizer over ½ → ¾ its length covering the centre section. Provision for further lengths to be fitted if required should be considered. The spar towing point and weight suspension point should be as near the spar leading edge as practical to reduce the tendency of the spar to fish-tail.

The estimated weight of the spar in air is 42 kgf, if it turns out to be much heavier than this, some revisions may be necessary. Provision for the addition of a diamond shroud, to stiffen the spar if handling or operational use of the bare spar proves unacceptable, should also be allowed for. The shroud lines, if fitted, may need to be faired to reduce drag and noise due to vortex shedding.

A standard IOS streamlined variable mass bottom weight of approximately 50 kgf seems sufficient to maintain a spar angle less than 20°. It is very important that the weight be attached to the spar with the very minimum of separation between weight and spar in order to increase the pendulum frequency of the bottom weight and prevent excitation of the flexural mode in the spar. Additional weight may be needed if shroud lines are fitted to the spar.

The offset bridle appears to work satisfactorily with bridle lengths in the ratio 3:2. The tow-off angle for the sledge shown in fig. 9 was $\simeq 40^{\circ}$ in the equivalent full-scale speed range of 2 to 5 kts. This angle may be even larger for the full-scale device because of the Reynolds number scaling effect. However the tow-off can be altered at will by adjusting either the bridle lengths or the tow point positions on the sledge. The tow positions found to be most suitable from the model experiments were 0.56 m ahead of the spar towing position and 1.09 m apart.

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Hoerner, S.F. (1958) Fluid dynamic drag pub. by author.

Newman, J.N. (1977) Marine hydrodynamics, pub. MIT press, pp. 402.

TABLE 1

	(gm)	Full scale equivalent (kg)
Model ballast weight in air - max	314	160
- min	160	82
best combination used in trials (+)	237	120
1st sledge - flat fronted bows with large keels		
weight in air	384	196
upthrust fully immersed in water	667	342
2nd sledge - pointed bows with large keels		
weight in air	444	227
upthrust fully immersed in water	742	380
spar weight in air ½ length splitter (X)	180	92
full length	280	143
¾ length	230	118
(A) weight in water of spar (X) plus ballast weight (+)	284	145
Reserve buoyancy of 1st sledge with load (A)	383	196
Reserve buoyancy of 2nd sledge with load (A)	458	234

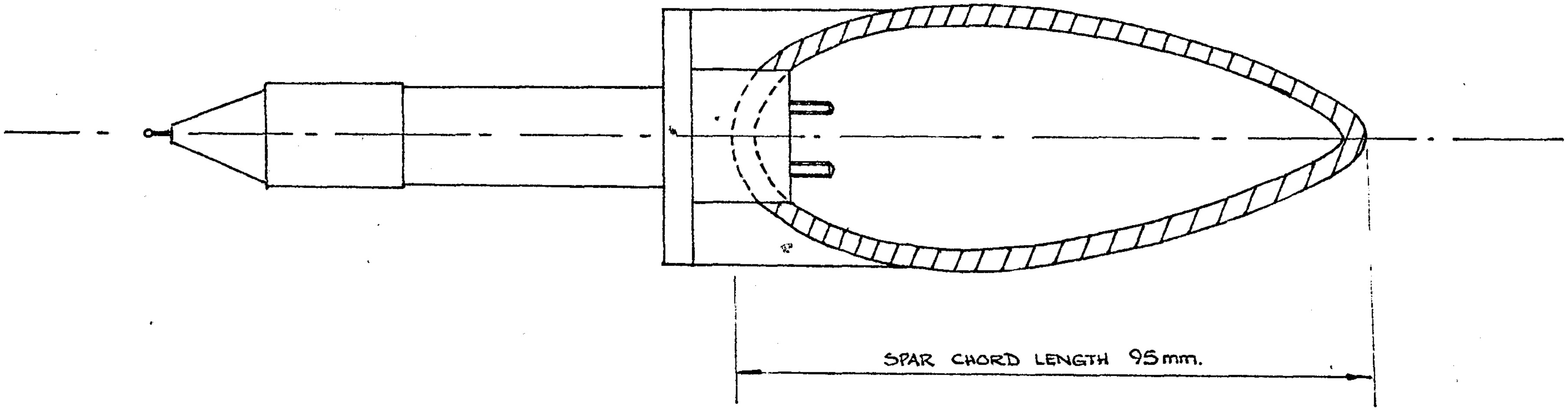


FIG. 1 THERMISTOR AND STREAMLINED SPAR (SECTION)
SCALE 1:1

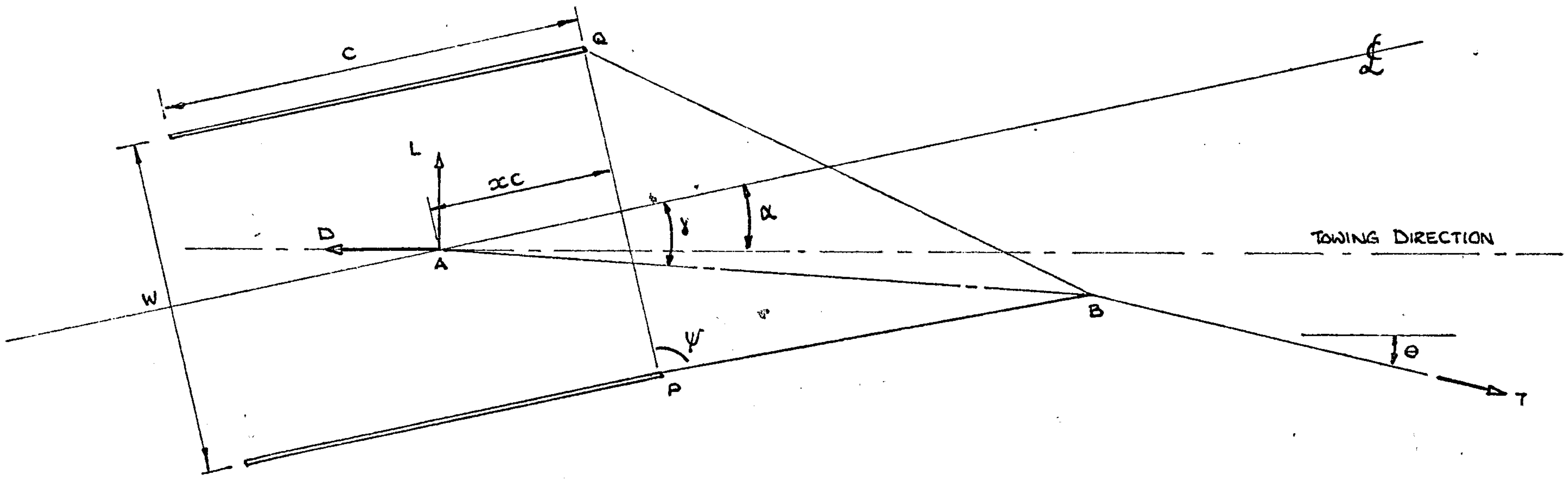


FIG. 3 BRIDLE GEOMETRY

Fig 4. Towing from Discovery

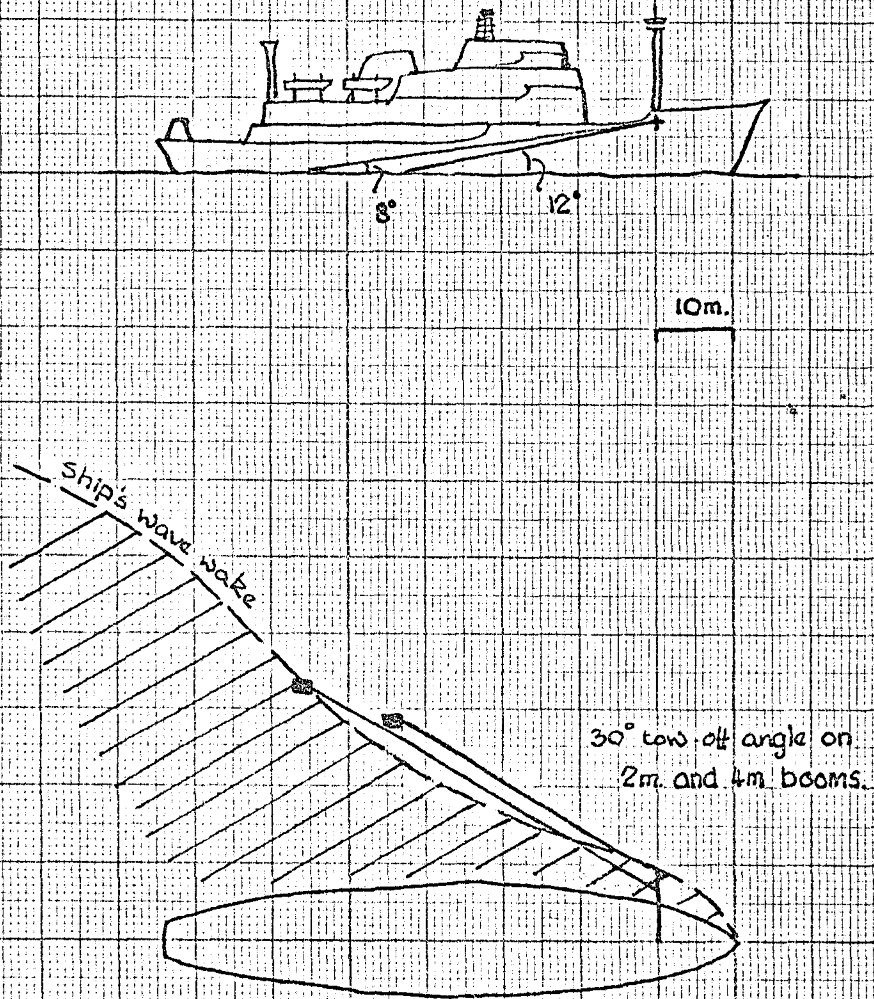
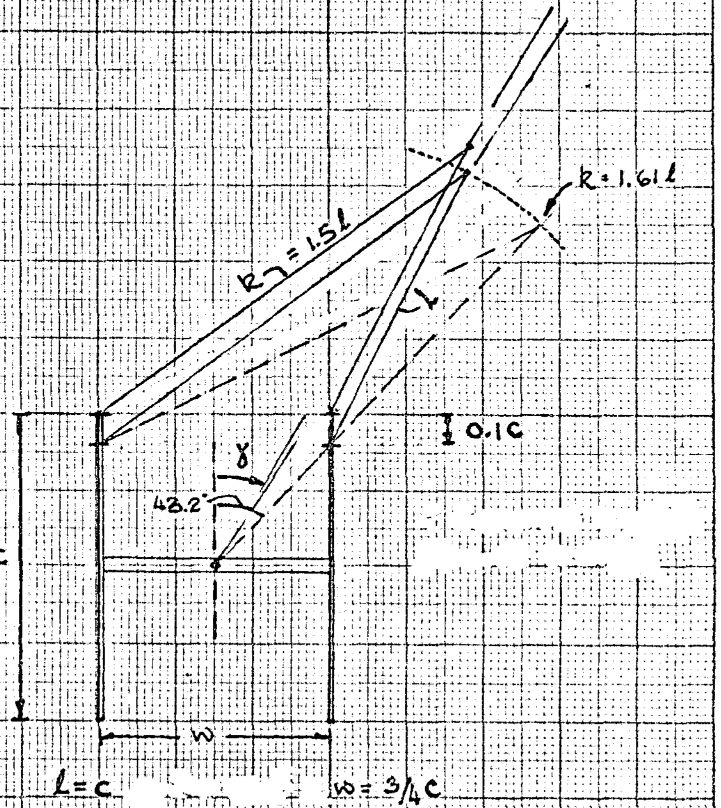
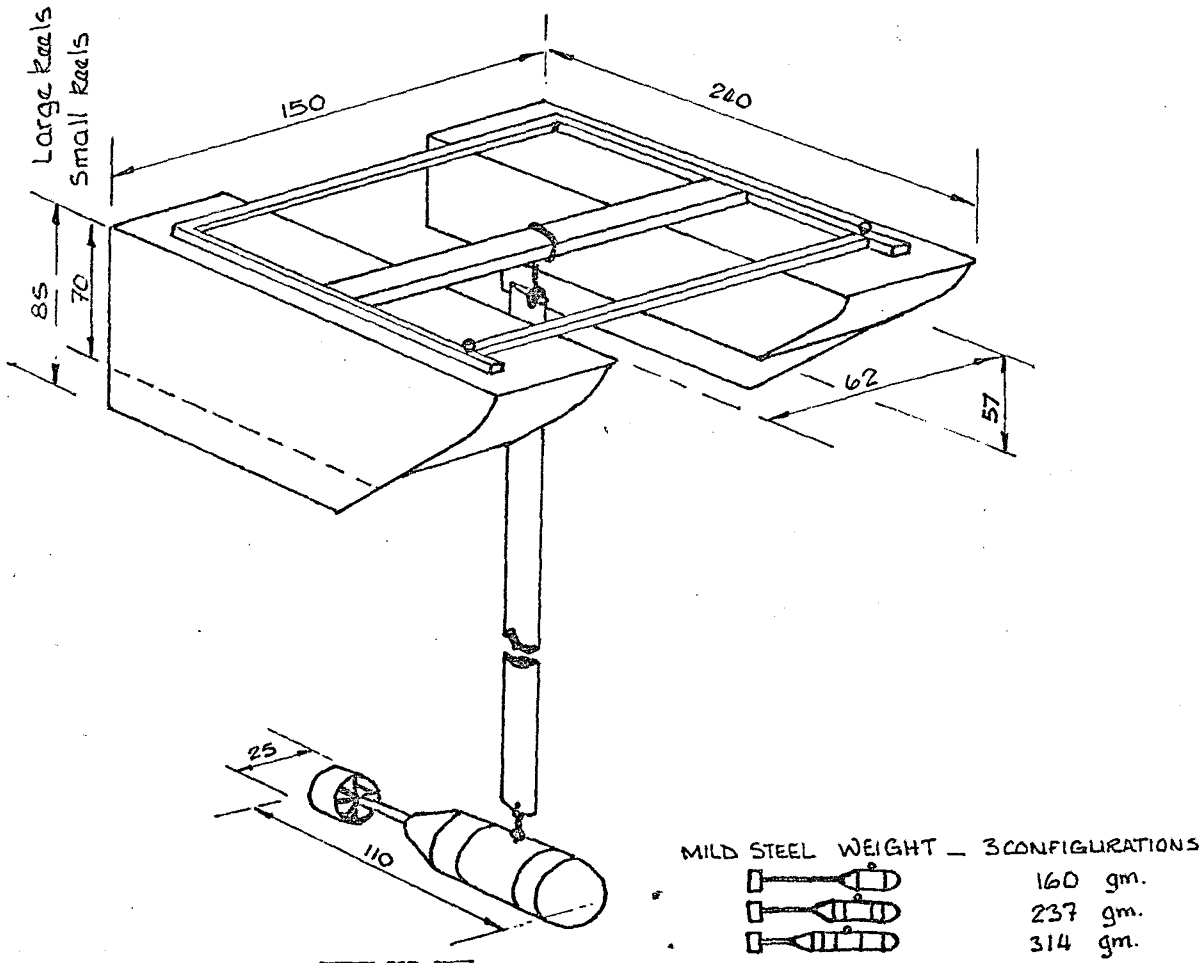
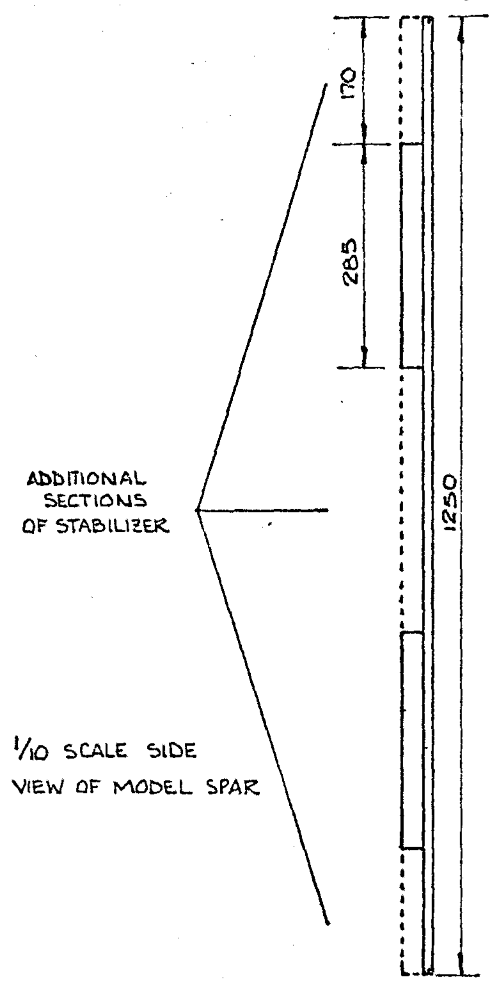


Fig 5 Effect of moving tow-point aft while keeping bridle lengths constant.







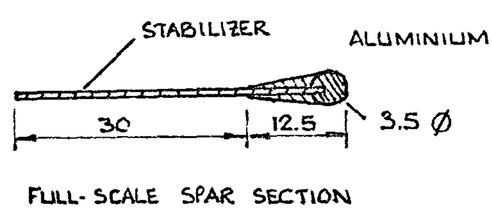


FIG 6 SKETCH AND APPROXIMATE DIMENSIONS OF THE MODEL SLEDGE. DIMENSIONS IN MM.

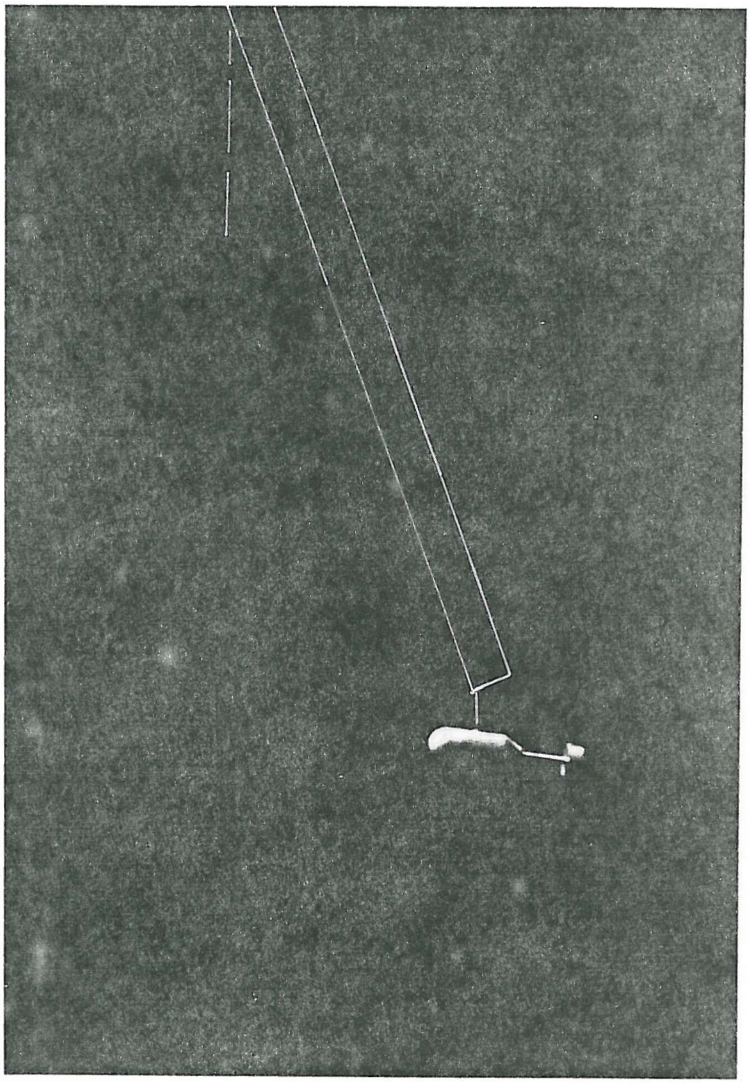
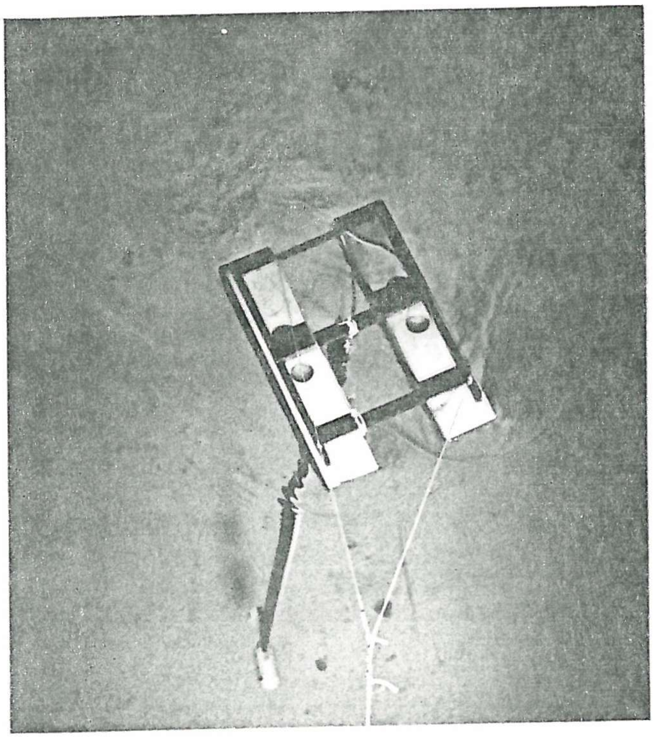
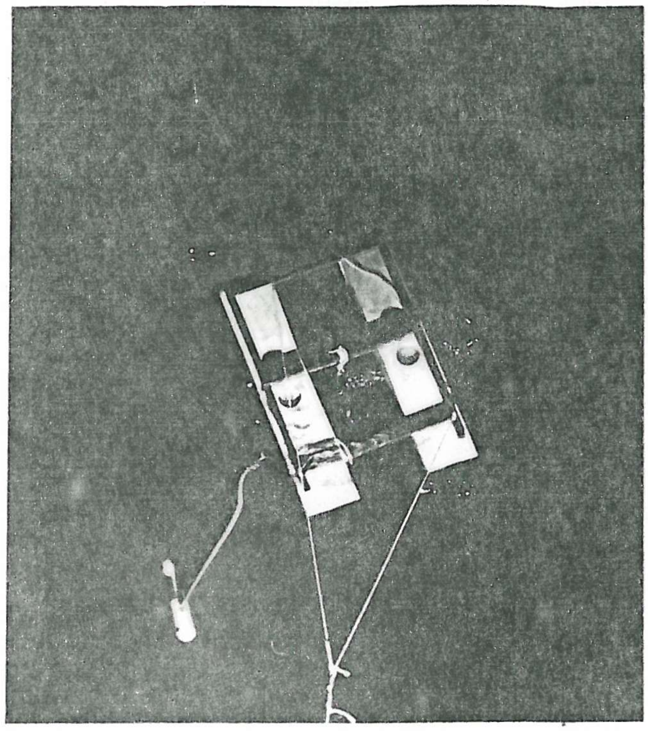


FIG 7 MODEL SPAR AND BOTTOM WEIGHT
TOWING SPEED 93 cm/s SPAR TRAIL ANGLE 20°
≅ 5kts FULL SCALE



(a)



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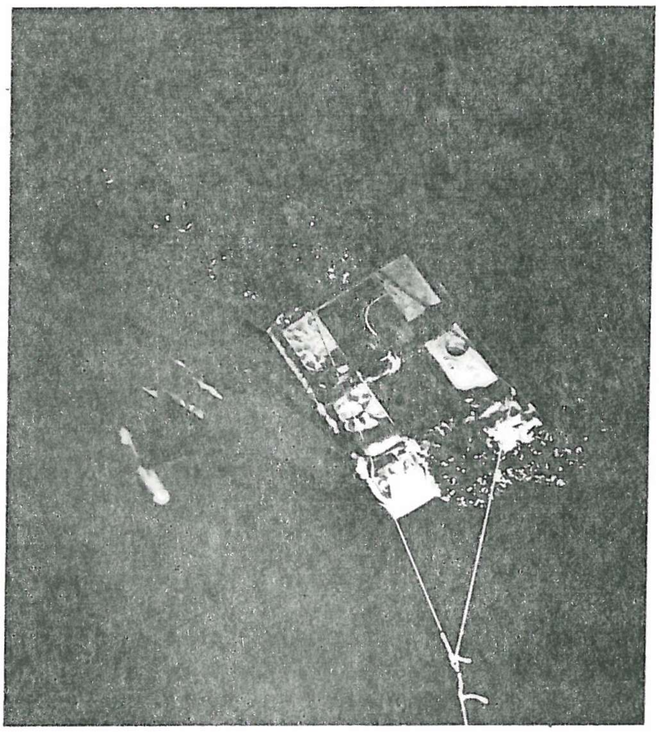

(c)

FIG. 8 MODEL SLEDGE TOWIND CHARACTERISTICS AT SPEEDS OF

(a) 38 cm/s $\hat{=}$ 2 kts (b) 57 cm/s $\simeq$ 3 kts (c) 93 cm/s $\simeq$ 5 kts FULL SCALE

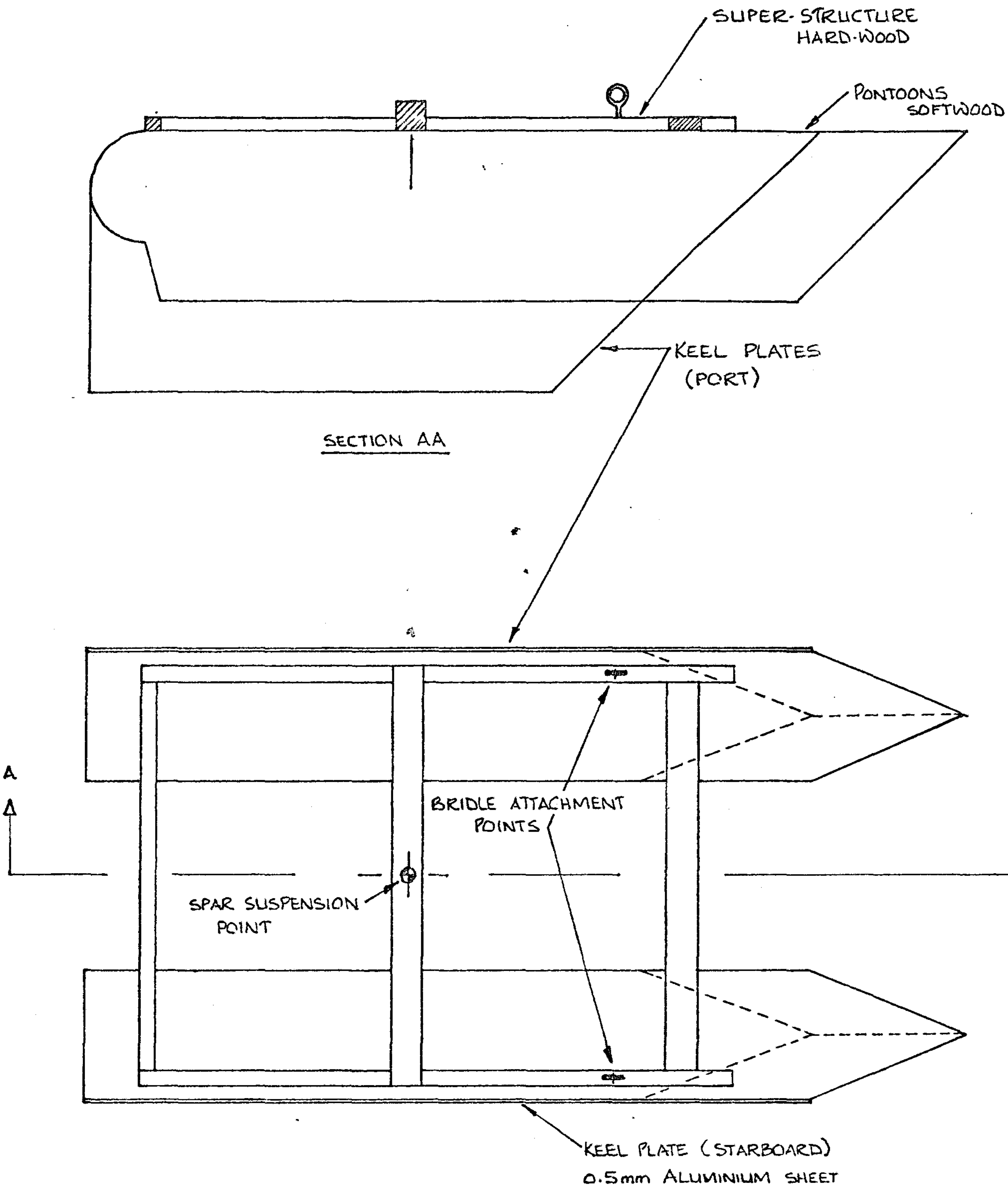

FIG. 9 SKETCH OF MODEL WITH POINTED BOWS
DRAWN 1/2 MODEL SCALE