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Design And Analysis Of A Towed Submersible System

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Abstract:

Hydrodynamic design of a towed submersible system is presented in this paper. The towed system consists of the towed body and the cable towed behind a surface ship. The towed body design described here has the unique feature of having positive buoyancy, which enable the body to stay afloat on the water surface when at rest. This unique feature facilitate retrieval of the towed body in case of an emergency such as cable snapping, since the towed body being positively buoyant will surface on its own thus ensuring the retrieval of the valuable payload.

The geometry of the towed body is determined based on the requirements of payload to be housed. Weight buoyancy budgeting is carried out such that the body is slightly positively buoyant. The optimum value of cable scope and cable tension are determined using Pode's tables. The design of wings is carried out to meet the requirements of negative lift and cable tension to be generated in order to attain the required depth at the specified speed of the towing ship.

Stabilizer fins are designed to provide stability in the pitch and yaw planes. Plan form area and aspect ratio of the stabiliser fins are systematically varied until stable configuration is arrived at.

1.Introduction

Towed submersibles find applications in various fields such as oceanography, geophysics and anti-submarine warfare. A typical towed system comprises of a hydrodynamically designed underwater body housing a payload, towed by a surface ship using an electro-mechanical or electro-opto-mechanical cable. The towed bodies are usually negatively buoyant and sink below the water surface depending on the cable scope while the towing ship is stationary. This paper describes the concept design of a positively buoyant towed submersible system.

The design concept describes a positively buoyant towed body which can be deployed on to the water from the towing platform. The body floats on the water surface while the towing platform is stationary. The towed body is fitted with wings which generate downward lift while being towed through water. This causes the body to dive down underwater. The design of wings is carried out such that they generate sufficient lift in order to get the towed body attain the specified

depth at the given towing speed and cable scope. Depth of the towed body can be varied if there are choices available for varying the cable scope or the ship speed. The design ensures that the body remains at a steady depth under the given tow conditions. The stabilizer fins at the tail contribute towards ensuring the dynamic stability of the body in the pitch and yaw planes. Further the weight buoyancy budgeting of the submersible is to be carefully carried out such that the towed body has slight positive buoyancy. Centre of gravity is to be located below the centre of buoyancy so that criteria for static stability are also satisfied.

Recent developments in the field include the development of a positively buoyant towed antenna system for use on an Unmanned Underwater Vehicle (UUV) for availing the GPS signal and RF communication to the UUV [11].

2. Advantages Of Positively Buoyant Towed Body

The positively buoyant towed body is envisaged to have the following advantages over the conventional negatively buoyant counterparts.

2.1.Deployment And Retrieval

The towed body can be easily deployed and retrieved from the towing ship using a crane facility since the towed body floats on the water surface. This does not call for any specialised handling system.

2.2.Fitment Of Payload

Since the towed body floats on the sea surface, it will ensure the payload to remain upright or nearly upright during all stages of operation including deployment, towing and retrieval.

2.3.Access To The Payload During Towing Operation

During any stage of operation the towed body can be accessed for minor intervention by stopping the towing operation. On rising to the surface, personnel can access the towed body through deployment of a Gemini boat.

2.4.Emergency Retrieval of the Towed Body/ Payload

In case of an emergency such as snapping of the cable, the towed body housing the payload can be easily retrieved since on stopping the ship the body along with payload will surface. This will ensure the safety of the payload.

3.Design Requirements

In the present requirement the towed system has to be designed such that at the specified speed of the towing platform the towed body attains the required depth and remains in stable dynamic equilibrium. The following information is available.

Speed of towing platform	10	knots
Diameter of the tow cable	6.75	mm
Weight of the cable per unit length in sea water	0.024	kg/m
Breaking Strength of cable	8.00	kN
Diameter of payload (ring type transducer)	0.20	m
Height of payload	0.065	m
Weight of payload	4.00	kg

4.Configuration Of The Towed Body

The general configuration of the towed body is evolved based on literature available on the existing towed bodies. Since drag of the towed body is not a major concern for the towed system, a body configuration which provides reasonable hydrodynamic performance is considered. Accordingly a cylindrical middle body, ellipsoidal nose and conical tail body is chosen.

Wing of rectangular plan form is selected for ease of fabrication. The slight reduction in efficiency in choosing such a plan form can be ignored. This can however be accounted for at a later stage if the lift is found to be insufficient. The section of the wings is chosen from the NACA profiles. Symmetric section is preferred since they are easy to fabricate. However option is kept open to go for a highly cambered section, if the angle of attack required at the wing is found to be large to generate the required lift. Since the body floats on the water surface in the stationary condition, it is required to fit the wings in the lower part of the towed body. This will ensure sufficient immersion of the wings in water which is an essential condition for generation of lift.

V-type stabilizer fins are chosen since such a configuration has the advantage that no portion of the tail fin will protrude below the body. The general configuration of the towed body is shown in Fig 5.

The size of payload is a major criteria in finalising the diameter of the body. The envisaged payload has an outer diameter of 200 mm and height 65 mm[9]. Accordingly the following dimensions have been chosen for the towed body.

Length:1935 mm (from nose to tail)

Maximum diameter: 350 mm (at middle section)

5. Design Procedure

The following steps are followed in the design.

- The forces required at the towed body end in order to achieve the specified depth are computed.
- A hydrodynamically suitable body having the required shape and size in order to house the required payload is chosen.
- The wings of the towed body are designed to provide the required downward force.

- Design of the stabilizer fins are carried out taking into account the destabilizing effects of the fins, body and tow cable.

6.Evaluation Of Cable Forces

The towing configuration is as shown in Fig 1. The cable tension (T) required to position the submerged end of the cable is calculated based on the method in Ref [2]. The quantities required for this computation are given below.

The drag per unit length of the cable when towed normal to the stream, R, is computed from the standard equation

$$R=C_R \frac{1}{2}\rho d V^2 \qquad [1]$$

Where,

$C_{R,}$	coefficient of normal drag	1.2 [1]
ρ,	density of water	1025 kg/m^3
d,	diameter of the cable	6.75 mm
V,	speed of the towing platform	10 knots

Cable scope (S) is varied over a range as part of the computation in order to arrive at an optimum value. Cable angle at the water surface (Φ1) is obtained over a range as part of computation.

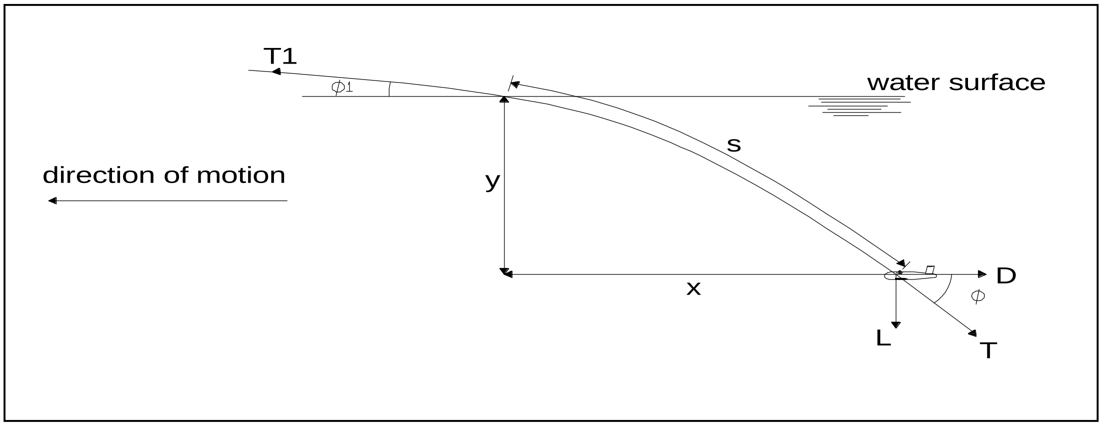

Figure 1:Towing Configuration

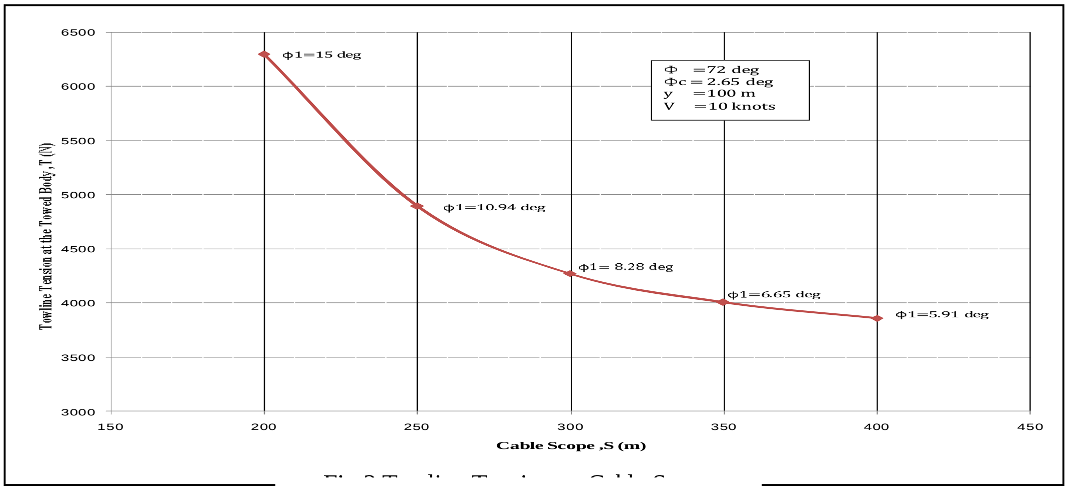

Figure 2:Towline Tension vs Cable Scope

Critical angle of the cable is obtained as

$$\cos\phi_c = -\frac{W}{2R} - \sqrt{\left(\frac{W}{2R}\right)^2 + 1} \qquad [2]$$

Where,

W, weight per unit length of cable in sea water	0.024	kg/m
R, normal drag per unit length of the cable	109.85	N/m

The critical angle Φ_c is calculated as 2.65 deg. The cable angle Φ at the towed body is selected as 72 degrees as being conservative since the design of a body with a downward force to drag ratio of about three is not difficult [1].The cable tension required to position the submerged end of the tow cable at the required depth is then computed using Pode's tables [2]. The cable scope (S) is varied and the required tension (T) at the cable end and the angle Φ_1 is evaluated. The ratio of tangential drag to normal drag of the cable is taken as f=0.02. [1]. Results of the computation are shown in Table 1 and Fig 2.

Cable Scope, S (m)	**Cable Angle at Sea Surface Interface, Φ1 (deg)**	**Tension at the Towed body,T(N)**
200	15.00	6298.46
250	10.94	4905.73
300	8.28	4275.12
350	6.65	3969.88
400	5.91	3862.09

Table 1:Results of Computation for Cable scope vs Cable Angle and Towline Tension

It can be noted from Fig 2 that on doubling the cable scope the required tension reduces considerably. The required depth can be achieved by either increasing the cable scope or by increasing the wing area. However, it is desired to keep both the wing area and cable scope reasonably small. Hence in order to strike a balance between the wing area and cable scope, a value of 350m is selected for the cable scope (S). However, as the design evolves, this could be further refined based on the size of the wing. At a cable scope of 350m, a towline tension of 3969.88 N acting at 72 degrees from horizontal is required to position the towed body at the required depth of 100m while being towed at 10 knots speed.

The downward force Z, is then

$Z = T \sin \Phi = 3775.58$ N

The body is to be given about 10kg positive buoyancy. Hence the net downward force to be generated by the wings is

L= 3873.86 N

7. Design Of Wings

Lift generated by a wing which intersects a cylindrical fuselage of infinite length may be written in the form[3,4]

$$L = a_w \alpha_w q S_w \Omega \qquad [3]$$

where,

a_w Slope of lift curve, is obtained from the relation

$$\frac{1}{a_w} = \frac{1}{a_0} + \frac{1}{\pi A}(1 + \tau) \qquad [4]$$

a_0Slope of the wing section lift curve $dC_L/d\alpha$ [5]

The lift-curve slope (a_w), is a function of planform parameters and the wing-section lift-curve slope (a_0). Planform parameters that must be selected are the taper ratio (**λ**), aspect ratio (A), sweep angle (Λ) and dihedral angle (Γ). Selection of a rectangular planform fixes values of two of these parameters namely, $\lambda=1$ and $\Lambda = 0$. Zero dihedral was selected to avoid complicated fabrication of the wing. However, this might be changed later if stability requirements made it appear desirable.

NACA 0012 is chosen as the fin section, since these are the commonly used control surface sections in ships, submarines and underwater towed bodies[10]. Angle of attack is chosen as 8 degrees and the mounting of the wing on the towed body is made such that angle of attack of 8 degree is achieved. Lift curve slope (a_0) of the NACA 0012 wing section is taken from Ref [5] as $a_0=0.106$ per degree.

The other parameters in equations [3] and [4] are,

AAspect ratio of the wing

τ Correction factor [6]

α_w Angle of attack of the wing section.

q Dynamic pressure = ½ ρV^2

Ω Body interference correction factor

With the wing mounted as shown in fig 5, the effective angle of attack can be maintained at 8 degrees which is slightly less than the angle of stall of the section.

Values of Ω may be obtained from the relation [3,4]

$$\Omega = 1 - \frac{4r^2}{AS_w} \qquad [5]$$

where ,

r Radius of the body at longitudinal position of the wing

S_w Plan form area of the wing

Equation [3] may be written in the form,

$$S_w = \frac{L/q}{a_w\,\alpha_w} + \frac{4r^2}{A} \qquad [6]$$

Using equation [6], the values of $S_w$are calculated for a range of values of aspect ratios. Values of a_w is computed for each selected A using values of τ obtained from Ref [6]. The results of the computations for aspect ratios 3,4 and 5 are tabulated in Table 2. Out of these, the one with the aspect ratio 4 which is most suitable in terms of the span and chord values is selected considering the structural point of view.

L	**(N)**	**3873.86**	**3873.86**	**3873.86**
A	-	3	4	5
τ	-	0.095	0.125	0.145
q	(N)	13561	13561	13561
α_w	(degree)	8	8	8
r	(m)	0.175	0.175	0.175
a_0	(per deg)	0.106	0.106	0.106
S_W	(m^2)	0.616	0.551	0.511
span	(m)	1.359	1.484	1.598
chord	(m)	0.453	0.371	0.319

Table 2: Results of computation for wing parameters for varying aspect ratios

Specifications of the selected wing is given in Table 3.Offset values (1/2 thickness) and section shape of the wing is shown in Table 4 and Fig 3 respectively.

Section NACA 0012	
Planform: Rectangular	
Aspect Ratio	4
Effective Lift Coefficient,C_L	0.518
Dihedral angle, degrees	0
Sweep back angle, degrees	0
Span, m	1.484
Chord,m	0.371

Table3: Specifications of the wing

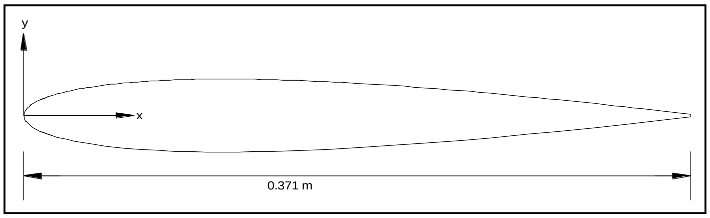

Figure 3: Section shape of the wing

8.Hydrodynamic Stability In Pitch

Hydrodynamic stability is an essential condition for towed body to ensure that the body returns to its steady equilibrium state after the perturbation has died down. Stabilizing fins are to be designed such that the towed body attains stability in the pitch and yaw planes. The forces acting on the towed body when at an angle θ with respect to the stream are shown in Fig 4.

V Velocity of stream

θ Body pitch angle w.r.t. stream velocity

B Buoyancy force acting through centre of buoyancy

X (m)	Y (m)
0.00000	0.00000
0.00186	0.00000
0.00464	0.00703
0.00928	0.00970
0.01855	0.01319
0.02783	0.01558
0.03710	0.01737
0.05565	0.01983
0.07420	0.02128
0.09275	0.02204
0.11130	0.02227
0.14840	0.02153
0.18550	0.01964
0.22260	0.01693
0.25970	0.01359
0.29680	0.00973
0.33390	0.00537
0.35245	0.00299
0.37100	0.00080

Table 4: Offset values of the wing section (NACA 0012)

D_b- Drag on the body

L_w- Lift on the wing

D_w- Drag on the wing

α_w - Angle of attack of the wing

W - weight

L_t - Lift on tail

D_t - Drag on tail

α_t - Angle of attack of tail

ε_t - Flow downwash angle at tail

l_t - Tail lever arm w.r.t. tow point

All quantities are shown directed in the positive sense. The total hydrodynamic moment about the tow point is then written and reduced to coefficient form by dividing by the product of a characteristic force and lever arm. The conventional practice for a towed body is to use the product of the dynamic pressure (q) and maximum cross sectional area of the body (S_b) for the force and the length of the body (l_b) as the lever arm. The resulting equation is differentiated with respect to θ and all quantities evaluated at $\theta_{trim}=0$. For this case, $\theta_{trim}= 0$.

Consequently, considering B and W to act at the tow point, the following equation is obtained [1].

$$C_{m\theta}=2\left(k_2-k_1\right)\frac{V}{S_b\,l_b}-a_t\frac{(l_t\ S_t)}{S_b l_b}\eta_t\left(1-\frac{d\epsilon_t}{d\alpha}\right)\ [7]$$

where,

(k_2-k_1)	Virtual mass coefficients [7]
V	Body volume (m^3)
S_b	Maximum cross sectional area of the body (m^2)
l_b	Length of the body (m)
a_t	Tail lift curve slope
l_t	Distance between tow point and the hydrodynamic centre of tail (m)
S_t	Planform area of tail (m^2)
η_t	Tail efficiency
ε_t	Average downwash angle at the tail plane
α	Angle of attack of the tail plane

The lift-curve slope (a_t) for a vee-tail is given by Ref[12] as

$$a_t = a_{\Gamma=0}\cos^2\ \ [8]$$

Where,$a_{\Gamma=0}$ is the lift curve slope for zero dihedral angle. $a_{\Gamma=0}$ is then evaluated on the basis of aspect ratio, sweep, and section. An approximate formula for $a_{\Gamma=0}$ is used as follows [1].

$a_{\Gamma=0} = 2\pi \frac{A}{A+3}$ [9]

Estimation of the term $\frac{d\epsilon_t}{d\alpha}$ is laborious procedure. Also there is no requirement for minimizing the tail area other than having a compact configuration.

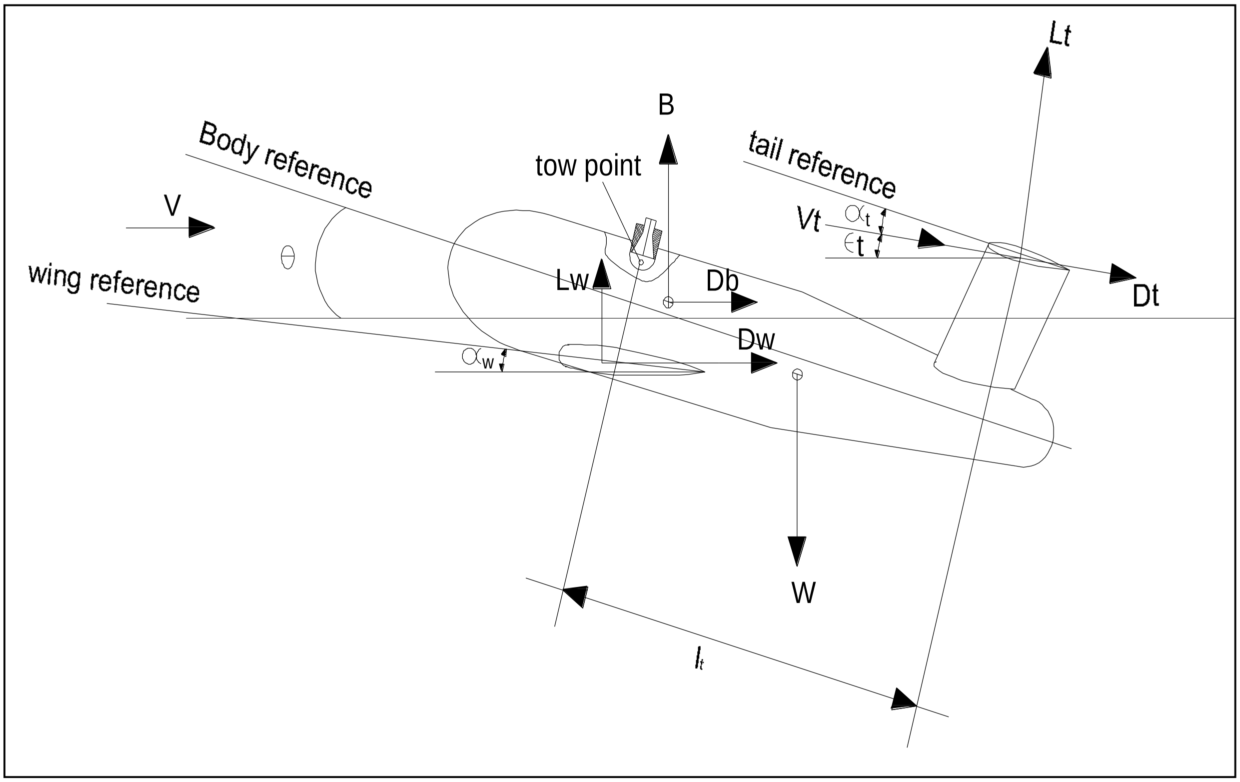

Figure 4: Forces acting on the towed body in level flight at constant velocity

Accordingly, it is decided to make an estimate which
is certain to be conservative.Based on Ref [1], the following relation is used for evaluation of the term $\frac{d\epsilon_t}{d\alpha}$.

$$\frac{d\epsilon_t}{d\alpha} = \frac{2a_w}{\pi A} \qquad [10]$$

The value of a_w is estimated using equation (4).The following values are used for the computation.

(k_2-k_1)	0.8545
V	0.1598 m^3
S_b	0.0961 m^3
l_b	1.935 m
l_t	1.060, m

η_t 0.8 [1]

Substituting these values, $C_{m\theta}$ can be evaluated using equation [7] for various assumed values of aspect ratio A and the corresponding value of τ. The required area of tail fin is thus obtained. Table 5 shows the results of computations carried out for aspect ratios 3, 4 and 5.

Aspect Ratio (A)	**3**	**4**	**5**
τ	0.095	0.125	0.145
Planform area of Tail Fin (S_t), m^2	1.00	0.60	0.45
$C_{m\theta}$	-0.278	-0.365	-0.398

Table 5: Computation of $C_{m\theta}$ for various aspect ratios and plan form area of stabilizer fin

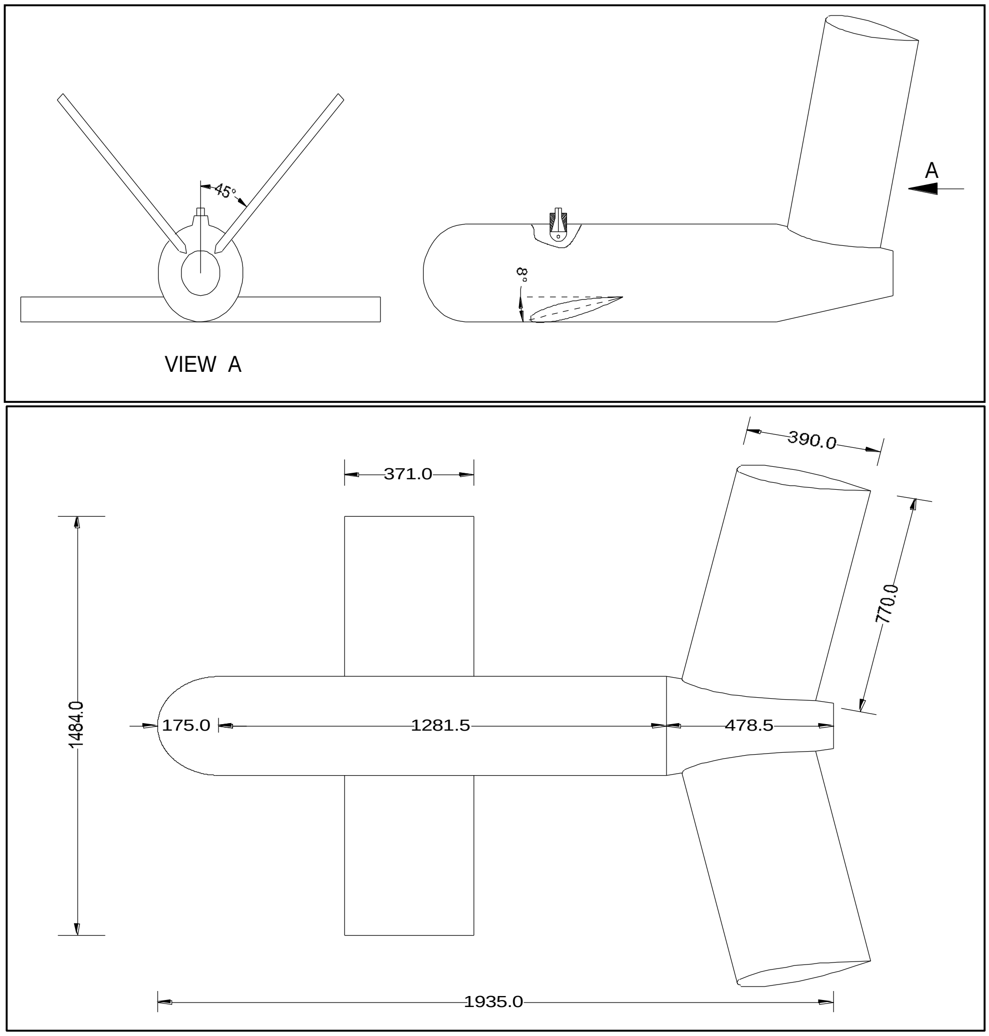

Figure5: General Configuration of the Towed Body

Out of these, the fin with aspect ratio 4 is selected considering the structural aspects as well as compactness of the resulting fin. Specifications of the stabilizer fin are given in Table 6.

Section NACA 0012	
Planform: Rectangular	
Aspect Ratio	4
Planform Area of Tail Fin (S_t), m^2	0.60
Half Span at Vee, m	0.77
Chord, m	0.39
Dihedral angle (Γ), degrees	45
Taper Ratio	1.0

Table 6: Specifications of stabilizer fin

9. Hydrodynamic Stability In Yaw

Since the stabilizer fins are designed based on the criteria of pitch stability, a check is made to ensure that the fins are adequate to provide stability in yaw. The moment equation in yaw is identical to the one for pitch with the angle variable θ replaced by ψ, the yaw angle. For the pitch moment coefficient, equation [7] can be written in the form[1],

$$C_{m\psi} = 2(k_2 - k_1)\frac{V}{S_b l_b} - C_{y\psi}\left(\frac{l_t S_t}{S_b l_b}\right)\eta_t\left(1 - \frac{d\sigma}{d\psi}\right) \quad [10]$$

where σ is the sidewash factor and $C_{y\psi}$ is the slope of the fin side force versus yaw curve. $C_{y\psi}$ may be found from the relation given by Ref [12] as follows.

$$\frac{C_{y\psi}}{C_{L_\alpha}} = K\tan^2\Gamma \qquad [11]$$

K is obtained from figure 2 of reference [12] as 0.726. Sidewash factor is ignored in this analysis. Thus $\frac{d\sigma}{d\psi}$=0.

The following values of parameters are used in the evaluation of $C_{m\psi}$.

(k_2-k_1)	0.8545
V	0.1598 m^3
S_b	0.0961 m^3
l_b	1.935 m
l_t	1.060, m
S_t	0.60
η_t	0.8 [1]
$C_{y\psi}$	1.30

On substituting these values, $C_{m\psi}$ is found to be -2.088 which is sufficient for ensuring static stability in the yaw plane.

10.Location Of Tow Point

As per the design, the longitudinal position of tow point should coincide with the centre of gravity and centre of buoyancy of the towed body. The centre of pressure of the wing section should also coincide with the location of tow point. Hence the location of tow point shall be finalized after structural design of the towed body and considering the location of centre of gravity.

11. Conclusion

Concept design of a positively buoyant underwater towed body is presented. Geometry and dimensions of the towed body have been evolved based on the requirements of the acoustic sensor to be housed inside the towed body. The influence of cable parameters and cable scope on the design of towed body has been addressed. Design of wings and stabilizer fins are carried out such that the towed body is positioned at the design depth at the given towing speed and attains stability in pitch and yaw planes. The structural design of the towed body has not been addressed in this paper. The location of centre of gravity of the towed body obtained after structural design will decide the location of the wings and the tow point.

12.Acknowledgement

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