# TOWED VEHICLES

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## Introduction

As a platform for marine instruments the towed vehicle (often termed a 'towfish' or 'towed body') combines the advantages of a ship-mounted instrument that gathers surface data while under way, and an instrument lowered from a stationary ship to gather data at depth. This article discusses the types of vehicles, the significance of the hydrodynamic drag of the tow cable and methods to reduce it. It also outlines the basic hydrodynamics of towed vehicles and presents the results of a model of the vehicle/cable system, indicating depths and cable tensions for a typical system.

## Types of Towed Vehicles

A towed vehicle system has three main components: the vehicle, the tow cable and a winch. The vehicles fall into two broad categories: those with active depth control and those without.

### Vehicles With Active Depth Control

Depth-controlled towed vehicles (or 'undulators') can move vertically in the water column while being towed horizontally by the ship. The main advantage they have over the lowered instrument is that they can quickly and conveniently measure vertical profiles of ocean properties with high horizontal spatial resolution. The main disadvantage is that it is difficult to reach depths greater than 1000 m while being towed at useful speeds; most available systems are limited to 500 m at best. The reason for the depth limitation is that the hydrodynamic drag of the tow cable must be overcome by a downward force on the vehicle, produced either by weight or a downward hydrodynamic force from hydrofoils or wings. However the cable's strength limits the allowable size of these forces.

The following are the common types of depth-controlled vehicles.

- A vehicle with controllable wings towed with an electromechanical cable that connects it to a controlling computer on board the vessel. The electromechanical cable allows the data to be transmitted to the ship and displayed and processed in real time. This can be an advantage when following a feature such as an ocean front; the ship's course can be adjusted to optimize the data collection. It also has the advantage of enabling fast, real-time response, an important consideration for bottom avoidance when operating in shallow water. As with most towed vehicles, cable drag dominates performance, so cable fairing is commonly used to reduce drag. Examples of this type of towed vehicle are the Batfish (Guildline Instruments, Canada), SeaSoar (Chelsea Instruments, UK) and the Scanfish (MacArtney A/S, Denmark).
- A vehicle with controllable wings that is totally self-contained. It is preprogrammed for maximum and minimum depths and records the data internally. As such a vehicle can be towed on a simple wire rope, it is convenient to use on ships not equipped for research. The lack of real-time control and data can be a disadvantage. An example of this type is the Aquashuttle (Chelsea Instruments, UK).
- A passive vehicle, often with fixed wings, where changes in depth are made by winching the tow cable in and out. This necessitates a high-speed, computer-controlled winch to produce the depth variation, but the vehicle can be simple. A recent development of this type is the Moving Vessel Profiler (Brooke Ocean Technology Ltd, Canada). This system has a winch that spools out the cable fast enough to allow the vehicle to free fall while the ship is under way, and then retrieves it after it has reached its maximum depth, which may be as deep as 800 m. Because the profiler free-falls on a slack cable, the usual cable drag constraints are not as relevant. This allows good depths to be achieved without the complication of cable fairing.

### Vehicles Without Active Depth Control

The vehicle without active depth control produces the depressing force by means of its weight, fixed wings or both. It maintains a constant depth for a given tow-cable length and tow speed. The vehicle can be towed with either an electromechanical cable to provide real-time data to the ship (as used for underwater survey instruments such as the side-scan sonar) or with a wire rope (as often used for plankton recorders).

## Tow Cable Drag

Tow cables are either wire rope or double-armored electromechanical cables. In the latter, two layers of armor provide mechanical strength, and because the layers are wound in opposite directions they are approximately torque balanced, i.e., the cable has little tendency to rotate when loaded. The electrical conductors handle data and power and optical fibers are used for high data rates. Except for systems with short cables used for shallow operations the tow cable is usually the dominant part of a towed vehicle system. Even a modest cable of 8 mm diameter and 500 m length has a mass of about 150 kg and a longitudinal cross-sectional area of $4\,\mathrm{m}^2$. This large cross-sectional area means that the cable drag dominates the performance of the system.

### Drag Caused by Flow Normal to the Cable

The normal drag on a moving body in a fluid is given by

$$D_\mathrm{N} = C_\mathrm{DN}\tfrac{1}{2}\rho u_\mathrm{N}^2 A$$

For a cable, the cross-sectional area $A$ is the product of the cable's diameter ($d$) and length ($l$) (see list of symbols at end of article). This drag is the sum of drag due to the shape of the body (the form or pressure drag) and drag due to surface friction (additionally a shape that produces lift also generates induced drag). The value of the drag coefficient $C_\mathrm{DN}$ depends on the Reynolds number $R_e$ (the ratio of inertial to viscous forces), which is defined as $R_\mathrm{e} = u\,d/v$. For a long smooth cylinder with normal flow at Reynolds numbers less than about $3 \times 10^5$ the flow is laminar and $C_\mathrm{DN} \approx 1.2$. At higher Reynolds numbers, the flow becomes turbulent and $C_\mathrm{DN}$ drops to about 0.35. This change in drag coefficient is due to the large area of separated flow in the wake of the cylinder in laminar flow decreasing when the flow becomes turbulent. For most cables used for towed vehicles, the value of the Reynolds number is less than $10^5$. To exceed this value a 10 mm-diameter cable moving through water requires a normal velocity greater than $10\,\mathrm{m\,s^{-1}}$. For cables with a rough surface, such as the usual stranded cable, $C_\mathrm{DN} \approx 1.5$ when $10^3 < R_\mathrm{e} < 10^5$ (**Figure 1**).

There is a mechanism that increases the drag coefficient of a cable above the value of a rigid cylinder. This is vortex-induced oscillation, commonly referred to as 'strumming'. Vortices shed from the region of flow separation alter the local pressure distribution and the cable experiences a time-varying force at the frequency of the vortex shedding. This frequency, $f$, is a function of the normal flow velocity $u_\mathrm{N}$ and the cable diameter $d$. The Strouhal number $S_\mathrm{n}$ is defined as $S_\mathrm{n} = fd/u_\mathrm{N}$, and $S_\mathrm{n} \approx 0.2$ over the range of Reynolds numbers $10^2 < R_\mathrm{e} < 10^5$. If this frequency is close to a natural frequency of the cable, an amplified oscillation occurs. A tow cable has many natural frequencies and there are many modes excited by vortex shedding; the result is a continuous oscillation of the cable. These vortex-induced oscillations, which can have an amplitude of up to three cable diameters, increase cable fatigue and drag. The increase in drag can be as much as 200%, resulting in drag coefficients as high as 3. Values around 2 are common.

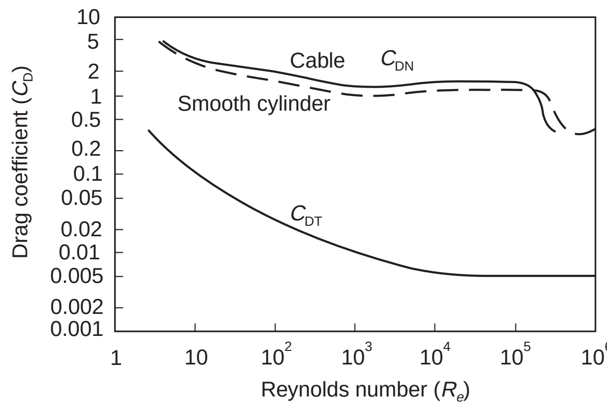


**Figure 1** Normal and tangential drag coefficients for a typical cable.

The values of the drag coefficient for towed cables cited in the literature differ widely because each case has its own set of conditions: cable curvature, tension, Reynolds number and surface roughness vary from case to case. A good starting point for estimating the normal cable drag is $C_\mathrm{DN} \approx 1.5$ for cables that are not strumming and $C_\mathrm{DN} \approx 2$ for strumming cables.

For the towed vehicle to be able to dive, the normal cable drag force must be overcome by downward or depressing forces: the cable weight, the towed vehicle weight and the hydrodynamic forces produced by the vehicle. The normal drag does not contribute directly to cable tension but by influencing the angle of the cable in the water it determines the component of cable weight that contributes to tension.

### Drag Caused by Flow Tangential to the Cable

The tangential drag on a long cylinder is due to surface friction. It is given by:

$$D_\mathrm{T} = C_\mathrm{DT}\tfrac{1}{2}\rho u_\mathrm{T}^2 \pi A$$

For tow cables with Reynolds numbers greater than about $10^3$, a typical value for the tangential drag coefficient ($C_{DT}$) $\approx 0.005$ (**Figure 1**). With a towed vehicle system, the tangential drag contributes significantly to cable tension but has little influence on the depth achieved.

## Reduction of Cable Drag

Normal cable drag can be reduced by an attachment that gives the cable a streamlined or 'fair' shape. Alternatively the attachment can be designed to split the wake, so that the shed vortices cannot become correlated over a significant length of cable and strumming is prevented. These attachments are usually called 'fairing'.

### Rigid Airfoil-shaped Fairing

'Wrap-round' fairing is the most effective method of reducing normal drag. An example is shown in **Figure 2**. A good airfoil shape can have a normal drag coefficient of 0.05, but the practicalities of having a rigid moulded plastic shape that can wrap around a cable, be passed over sheaves and spooled onto a winch often results in a drag coefficient of about 0.2. The greater drag is primarily due to the circular nose of the fairing (to accommodate the cable) and gaps between fairing sections. Because of the large surface area of the fairing, the tangential drag coefficient (based on cable surface area) is about 0.05. This means that, although the normal drag coefficient of a faired cable is only a tenth of a bare cable, the tangential drag coefficient is about ten times greater. A consequence of this is large cable tensions. For a typical system with 500 m of faired cable, at least 50% of the cable tension can be due to the fairing.

Another consequence of the high tangential drag is that this loading must be transferred from the fairing sections to the cable. Every 2–3 m, a 'stop ring' is swaged or clamped to the cable to take the load. If this force accumulates over too great a length the fairing sections will not rotate freely, and in the extreme they can break under the high compressive load.

Another form of rigid fairing is the 'clip-on' fairing (see **Figure 2**). Unlike the 'wrap-round' type this does not totally enclose the cable, but is essentially an after-body attached to the cable with clips. Because of the gap between the cable and the fairing the drag coefficient is higher. Typical values are $C_{DN} \approx 0.4$.

A problem that can occur with rigid fairing is the phenomenon of 'tow-off'. If the fairing sections are not free to align accurately with the flow, they can generate a considerable lift force, which can cause the cable to tow off to the side and decrease the depth it achieves.

Although the rigid airfoil fairing is the most effective method of decreasing drag, it comes at a high cost. Not only is it expensive but it also requires special winches and handling gear. However, if a system is set up well it gives reliable performance.

### Flexible Ribbon and 'Hair' Fairing

Ribbon fairing is made of a flexible material in the form of trailing ribbons (**Figure 2**). Fibers or 'hairs' attached to the cable are also effective. These fairing devices do not usually produce a fair shape, but achieve their effect by splitting the wake. Their main effect is, therefore, to reduce strumming and reduce the normal drag coefficient to the bare cable

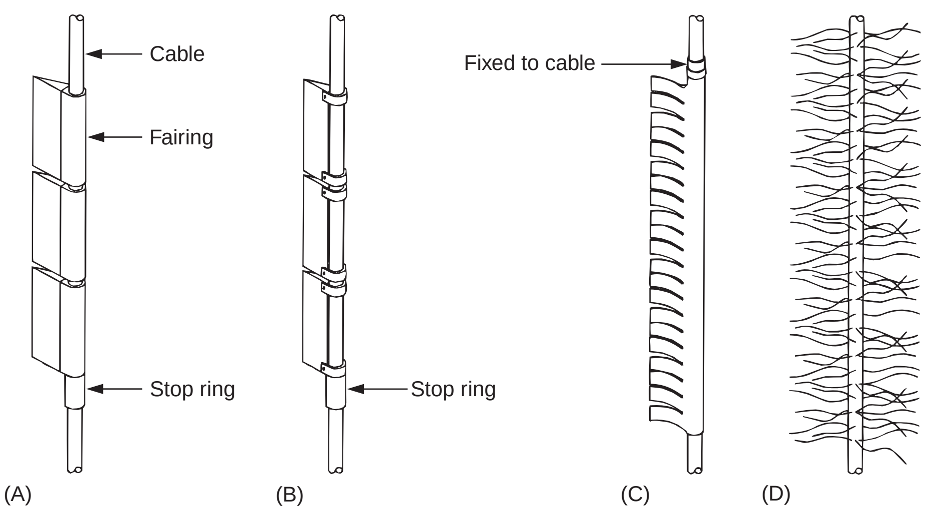


**Figure 2** (A) 'Wrap-round' fairing; (B) 'clip-on' fairing; (C) 'ribbon' fairing; (D) 'hair' fairing.

value of about 1.5. In some cases ribbon fairing can streamline the cable, reducing the normal drag coefficient to about 0.7 (due to the reduction of form drag). Hair fairing reduces strumming but can increase the normal drag coefficient so that $C_{DN} \approx 2$.

These devices increase the surface area over a bare cable so the tangential drag is increased, resulting in greater cable tensions. Flexible fairing does not need special handling gear and can be wound onto a regular winch. However, the fairing deteriorates rather quickly requiring regular repair and replacement.

## Basic Aerodynamics of the Towed Vehicle

### Vehicles that Generate Lift

Most towed vehicles use wings (hydrofoils) to generate the force required to pull the tow cable down. **Figure 3** shows an example of a winged vehicle. As shown in **Figure 4**, a wing moving through a fluid experiences a force perpendicular to the direction of flow (the lift), a force directly opposing the motion (the drag), and a moment tending to rotate the wing (the pitching moment). The pitching moment is usually referenced about a point termed the aerodynamic center, chosen so that the moment coefficient is constant with angle of attack.

The lift force is given by:

$$L = C_L \tfrac{1}{2} \rho u^2 S$$

The drag force is given by:

$$D = C_D \tfrac{1}{2} \rho u^2 S$$

**Figure 3** CSIRO (Australia) modified SeaSoar with a Sea-Bird Electronics Inc. conductivity, temperature and depth (CTD) instrument.

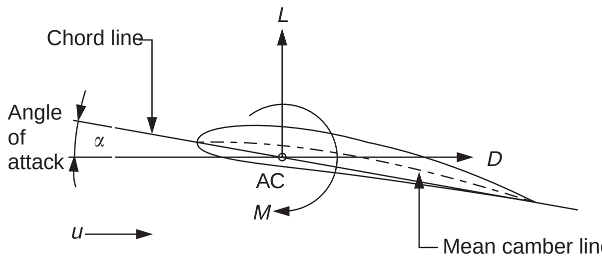


**Figure 4** Forces and moment on an airfoil.

The pitching moment is given by:

$$M = C_M \tfrac{1}{2} \rho u^2 S c$$

The lift coefficient $C_L$ is proportional to the angle of attack. The theoretical relationship for a thin, symmetrical airfoil gives the slope of the curve of lift coefficient against angle of attack

$$dC_L/d\alpha = a_0 = 2\pi/\text{radian} = 0.11/\text{degree}$$

The theoretical aerodynamic center is at the quarter chord point ($c/4$) and $C_M = 0$. If the angle of attack is increased beyond a certain value the flow separates from the low-pressure side of the wing rapidly causing the lift to decrease and the drag to increase. This is termed 'stall' (**Figure 5**).

An asymmetrical or cambered airfoil, where the camber line (the line drawn halfway between the upper and lower surfaces) deviates from the chord line (**Figure 4**), has the same theoretical slope of the lift curve, $2\pi$, but has a nonzero value of the

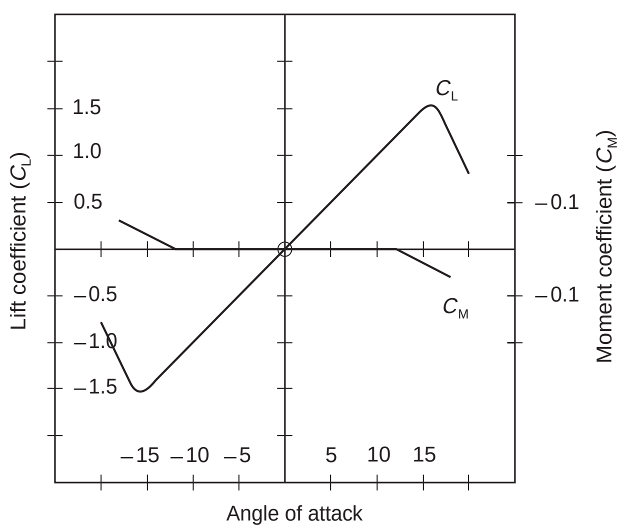


**Figure 5** Typical section characteristics for symmetrical airfoil type NACA0012.

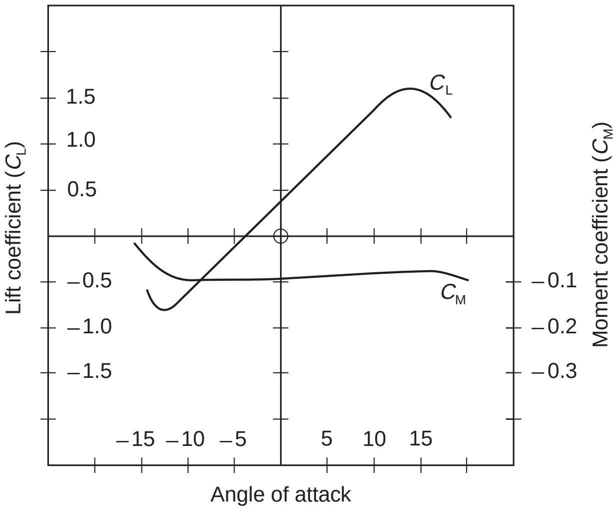


**Figure 6** Typical section characteristics for asymmetrical airfoil type NACA4412.

lift coefficient when $\alpha = 0$. The aerodynamic center is also at the quarter chord point but $C_M \neq 0$ (**Figure 6**).

These properties describe airfoil sections that are two-dimensional. In a real wing, the span is finite and there is spanwise flow. The effect of this is a 'leakage' around the wing tips from the high-pressure side to the low-pressure side. This generates wing-tip vortices, which in turn produce a downward flow around the wing – the downwash. The angle of this local flow relative to the wing subtracts from the angle of attack so that the wing actually experiences a smaller effective angle of attack. Since the lift vector is normal to the local relative flow it becomes inclined behind the vertical and so has a rearward component – the induced drag. This drag can be the dominant drag on a towed vehicle. The induced drag coefficient is given by:

$$C_{Di} = C_L^2/(\pi AR)$$

The reduction in the effective angle of attack of a wing with finite span also reduces the slope of the lift curve, $a$.

$$dC_L/d\alpha = a = a_0/(1 + a_0/\pi AR)$$

The reduced slope of the lift curve means that the wing has a higher angle of attack at stall.

To achieve the necessary mechanical strength, the aspect ratio of wings used on towed vehicles is usually very low. This results in high induced drag and low values of the lift curve slope. It will be shown later that the higher induced drag is not significant. The lower sensitivity to changes in the angle of attack (and the higher angle at stall) can be an advantage: it makes the vehicle more tolerant of flight perturbations such as those experienced when towing in rough seas.

The delta wing (a wing with a triangular planform) is a popular form for vehicles without active depth control. Flow over a delta wing is dominated by large leading-edge vortices and cross-flow that enable the wing to operate at large angles of attack without stalling. A delta wing has a typical lift curve slope of about 0.05/degree (about half that of a conventional wing), but can operate with an angle of attack up to 30° before stalling. Delta wings make robust depressors and are often given large dihedral angles to increase roll stability. The dihedral is the angle of inclination of the wings in relation to the lateral axis.

To control the depth of a towed vehicle, the magnitude and direction of the wing's lift force are usually varied by:

- the use of control surfaces (flaps) on the trailing edge;
- an independent control surface, usually at the tail;
- rotating the entire wing about its aerodynamic center to vary its angle of attack.

The first two methods cause the whole vehicle to adopt an angle of attack and so the body of the vehicle also generates lift. Some towed vehicles, such as the Aquashuttle (Chelsea Instruments, UK), operate without wings, generating all the lift from the body. Others, such as the Scanfish (MacArtney A/S, Denmark) and the V-Fin (Endeco Inc, USA), are effectively flying wings. The third method, used by the Batfish (Guildline Instruments, Canada) and SeaSoar (Chelsea Instruments, UK), maintains the body aligned with the flow, which is an advantage for some types of sensors that need to be aligned to the flow. Both these vehicles use a highly cambered wing section (NACA6412) that has a large moment coefficient ($C_M \approx -0.13$). Thus a large torque is needed to rotate the wing. If a small operating torque is required the wings are typically controlled by an electric servomotor. If large forces are needed a hydraulic system is used. A symmetrical wing section pivoted at the quarter chord point requires only a small torque, but the control system needs to be robust enough to survive rough handling on the ship's deck.

To gain the maximum benefit of any lift force, the vehicle must fly so that the force is directed near to vertical, that is it should fly without a significant roll angle. A towed vehicle often needs to be able to

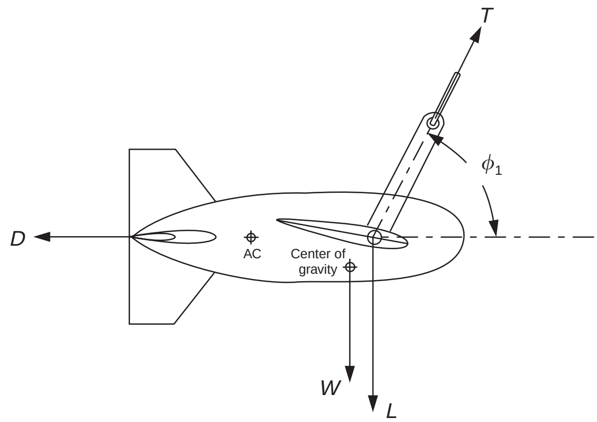


**Figure 7** Basic forces on a towed vehicle.

direct its lift force both down and up, to maximize its depth range. A consequence of this is that dihedral, a common method of providing roll stability, cannot be used. What would be stable for lift in one direction would be unstable in the other. By having the tow cable attachment point above the center of gravity of the vehicle, the vehicle's weight contributes to roll stability (**Figure** 7). But to stabilize the large lift forces needed for good depth performance, additional aerodynamic control by means of ailerons or similar devices is needed. These can be simple systems driven directly with gravity by using a heavy pendulum device or more sophisticated electric servomotor systems. The other basic requirement is for pitch and yaw stability. This is achieved by ensuring that the tow point is ahead of the aerodynamic center (AC) of the vehicle (**Figure** 7). The position of the vehicle's aerodynamic center is controlled by providing a suitably sized tailfin.

### Vehicles That Do Not Generate Lift

These passive towed vehicles use their weight to produce the required downward force. The drag of the cable is overcome by the combined weight of cable and vehicle. Depth is controlled by varying the cable length. The depth is also very dependent on the tow speed. This is because the cable drag is proportional to the square of the tow speed and the depressing force is fixed by the cable and vehicle weight. This contrasts with the vehicle that generates lift; its depth is less speed-dependent because both lift and drag vary with speed in the same manner. A heavy passive vehicle can have good pitch and roll stability if the position of the tow point, center of mass, center of gravity and the aerodynamic center are carefully chosen. The lack of flow separation over lifting surfaces also makes them acoustically quiet. This stability and quietness make them useful vehicles for underwater acoustic work (**Figure** 8).

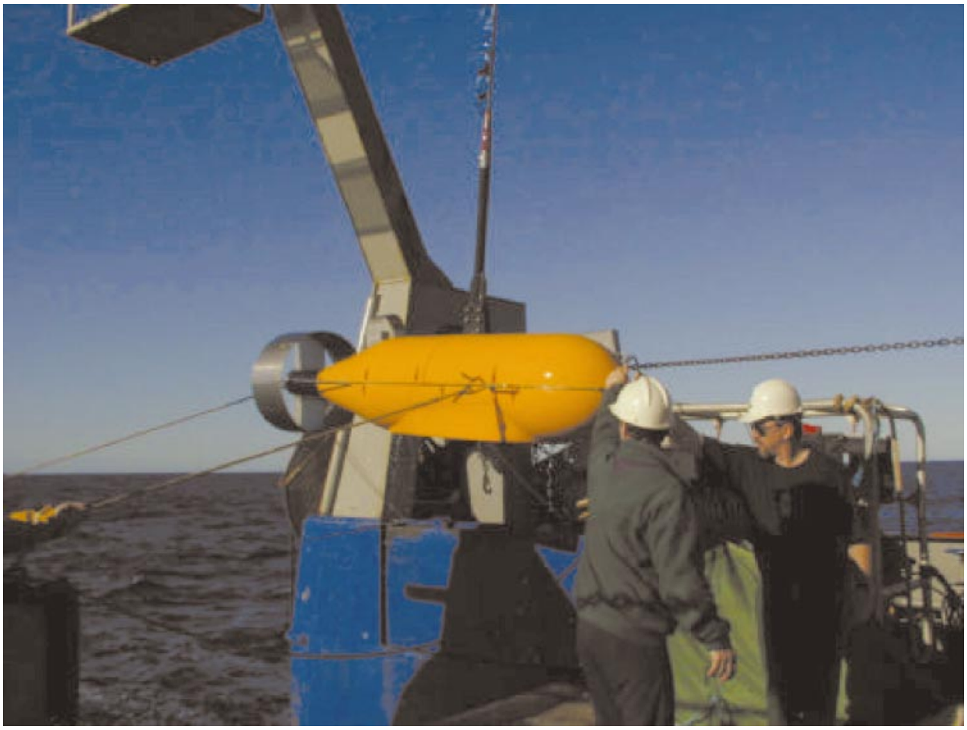

**Figure 8** The CSIRO (Australia) multifrequency towed vehicle used for fish stock measurements. Note the ribbon-faired cable.

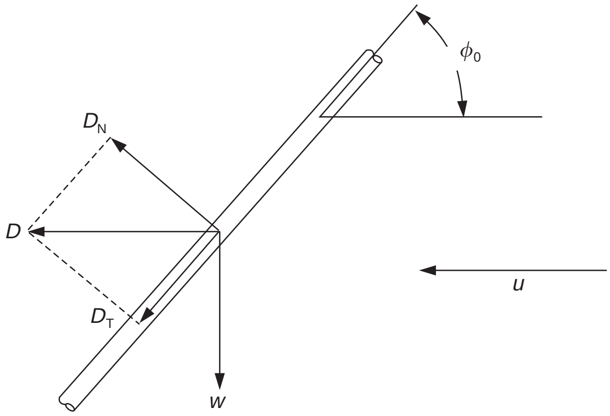


**Figure 9** Forces on the tow cable.

## Performance of the Vehicle/Cable System

When a cable is towed through water, it assumes an equilibrium angle where the drag force ($D$) is balanced by the cable weight ($w$). If the cable properties are uniform, this angle is constant along the cable length

By referring to **Figure 9**

$$\tan \phi_0 = w/D$$

Or expressed in terms of the normal drag coefficient

$$\cos \phi_0 = -1 \pm (1 + 4B^2)^{1/2}/2B$$

where $B = \rho u^2 \mathrm{d}C_{\mathrm{DN}}/(2w)$

The equilibrium depth is ($l \sin \phi_0$). When a vehicle is attached to the end of the cable it perturbs this equilibrium depth by the extent that its weight and lift force either drag the cable deeper when diving, or lift the cable when climbing. This defines the depth range of the vehicle/cable system (**Figure 10**). As shown in **Figure 7** the angle of the cable at the vehicle, $\phi_1$, is determined by the weight ($W$), lift ($L$) and drag ($D$) of the vehicle.

$$\tan \phi_1 = (W + L)/D$$

The cable profile starts at an angle of $\phi_1$ at the vehicle and gradually approaches $\phi_0$ up the cable.

The vehicle drag is the sum of the form drag, the friction drag and the induced drag. With vehicles that generate lift the induced drag is the main component. Even with a poorly streamlined vehicle it dominates, providing perhaps 75% of the drag. The rather poor performance of the typical low aspect ratio wing used on towed vehicles gives the vehicle a lift to drag ratio of about 3. This makes the cable angle $\phi_1 \approx 70°$. Further improvement in the lift to drag ratio does not gain much in cable angle or depth. **Table 1** compares the equilibrium depths for bare and faired cables; **Table 2** compares the performance of bare and faired cable when towing a vehicle with controllable wings. These data were produced by a computer model of the vehicle/cable system.

## Effects of Wave-Induced Ship Motion on the Towed Vehicle

A problem with towing in rough seas is that the wave-induced motion of the towing vessel is propagated down the tow cable to the vehicle. Motion normal to the cable is rapidly damped, but there is surprisingly little attenuation of the tangential motion of the cable. The amplitude of the perturbation of the vehicle is approximately the same as the cable at the ship. This causes changes in the vehicle's pitch angle and depth which can be very significant for towed acoustic systems and vehicles

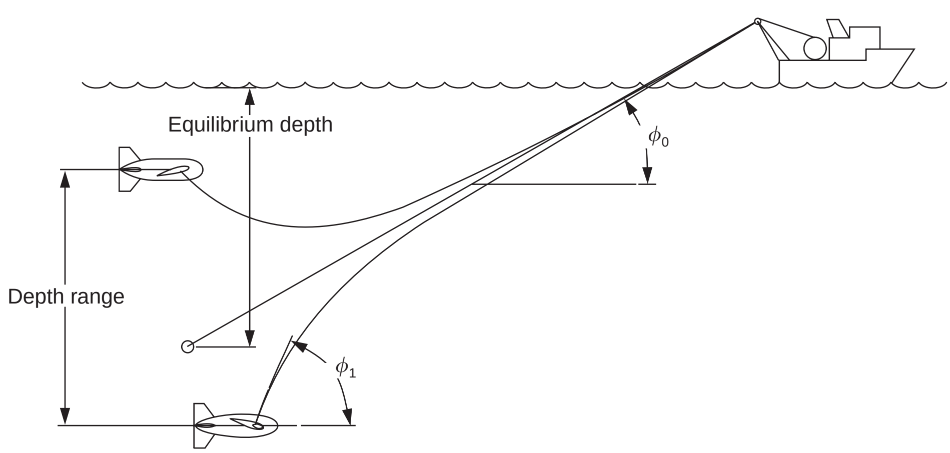


**Figure 10** Towed cable profile.

**Table 1** Comparison of equilibrium depths for 500 m of 8.2 mm diameter cable with a weight of $2.5\,\mathrm{N\,m^{-1}}$ towed at $4\,\mathrm{m\,s^{-1}}$ for faired and bare cable

| | *Equilibrium depth (m)* | *Tension (kN)* | $\phi_0$ *(degrees)* |
|---|---|---|---|
| Faired $C_{DN} = 0.2$ | 142 | 3.6 | 17 |
| Bare $C_{DN} = 2.0$ | 61 | 0.7 | 7 |

such as camera units operating very close to the seafloor.

The following methods are used to minimize the effects of ship motion.

- The vehicle can be tuned to minimize the pitching effect by carefully adjusting the position of the vehicle's aerodynamic center and center of mass in relation to the tow point.
- A constant-tension winch reduces the cable displacement at the ship by spooling cable in and out as the ship surges.
- A device called an accumulator produces an effect similar to the constant-tension winch. The cable runs over a pair of sheaves that are mounted on a sprung or pneumatic arrangement that allows them to take up and pay out cable as needed.
- In the 'two-body system' the instrumented vehicle is passive and near-neutrally buoyant. It is towed behind the depressor or depth-controlled vehicle on a cable that is approximately horizontal. This geometry decouples ship's motion from the second vehicle.
- A system that has a cable angle close to horizontal at the ship is insensitive to ship pitch and heave as these displacements are almost normal to the cable. A system that uses a long cable, a cable without fairing or a high tow speed has this characteristic.

## Flight Control

Tow speeds vary from as low as $1\,\mathrm{m\,s^{-1}}$ for seafloor survey instruments to $10\,\mathrm{m\,s^{-1}}$ for high-speed systems. The fast systems are limited to shallow depths. Speeds of $3$–$5\,\mathrm{m\,s^{-1}}$ are common for oceanographic surveys and depths of up to 1000 m can be achieved. Depth-controlled vehicles operate with vertical velocities up to about $1\,\mathrm{m\,s^{-1}}$.

Depth-controlled vehicles are commonly operated in an undulating mode with maximum and minimum depths set to specific values to give a triangular flight path. The depth is measured by the water pressure at the vehicle and the wings or control surfaces are adjusted to make the vehicle follow the defined path by a servo system. The servo-loop parameters are usually controlled by the shipboard computer; however the actual servo-loop system may reside in the towed vehicle or combine ship- and vehicle-based components. The control algorithm needs to be carefully tuned to achieve smooth flight.

## Sensors

Some of the earliest towed vehicles were used to collect plankton (in fact a trawl net is a form of towed vehicle). These plankton collectors are often separate nets and depressors but can also be single units. An early system, the Hardy Continuous Plankton Recorder, dates from the 1930s. Several commercially available vehicles are a development of this type, for example the Aquashuttle (Chelsea Instruments, UK) and the U-Tow (Valeport Ltd, UK).

Depth-controlled vehicles are commonly equipped with a conductivity, temperature and depth (CTD) instrument. They are also suitable platforms for

**Table 2** Comparison of depths, cable tensions and cable angles ($\phi_2$ cable angle at ship, $\phi_1$ cable angle at vehicle) for the same cable as Table 1 towing a typical vehicle with the following characteristics: weight in water, 1500 N; cross–sectional area, $0.2\,\mathrm{m^2}$; wing area, $0.5\,\mathrm{m^2}$; wing aspect ratio, 1; tow speed, $4\,\mathrm{m\,s^{-1}}$. Positive lift coefficients indicate lift force upwards

| | *Wing $C_L$* | *Depth (m)* | *Tension (kN)* | $\phi_2$ *(degrees)* | $\phi_1$ *(degrees)* |
|---|---|---|---|---|---|
| Faired $C_{DN} = 0.2$ | −1.0 | 360 | 11.2 | 36 | 72 |
| | +0.5 | 0 | 4.3 | 7 | −36 |
| Bare $C_{DN} = 2.0$ | −1.0 | 140 | 6.5 | 8 | 72 |
| | +0.5 | 31 | 1.6 | 7 | −36 |
| | +1.0 | 0 | 3.2 | 6 | −55 |

many other types of sensors, such as fluorometers, radiometers, nutrient analysers and transmissometers. In the case of a CTD it is recommended that the sensors be duplicated. When a CTD is lowered from a stationary ship in the usual manner the calibration of the conductivity sensor is checked by collecting water samples for laboratory analysis. This option is not usually available on a towed instrument so a check of sensor stability can be obtained by using dual sensors. The conductivity cells can also be blocked by marine organisms especially when towing near the surface. Dual cells allow recognition of this problem. **Figure 11** shows the data from a CTD section across an ocean front demonstrating the high spatial resolution realized with a towed system.

Passive towed vehicles are often used for acoustic survey work. Examples are side-scan sonars, towed multibeam systems for seafloor mapping, and vehicles for estimating fish stocks. The towed

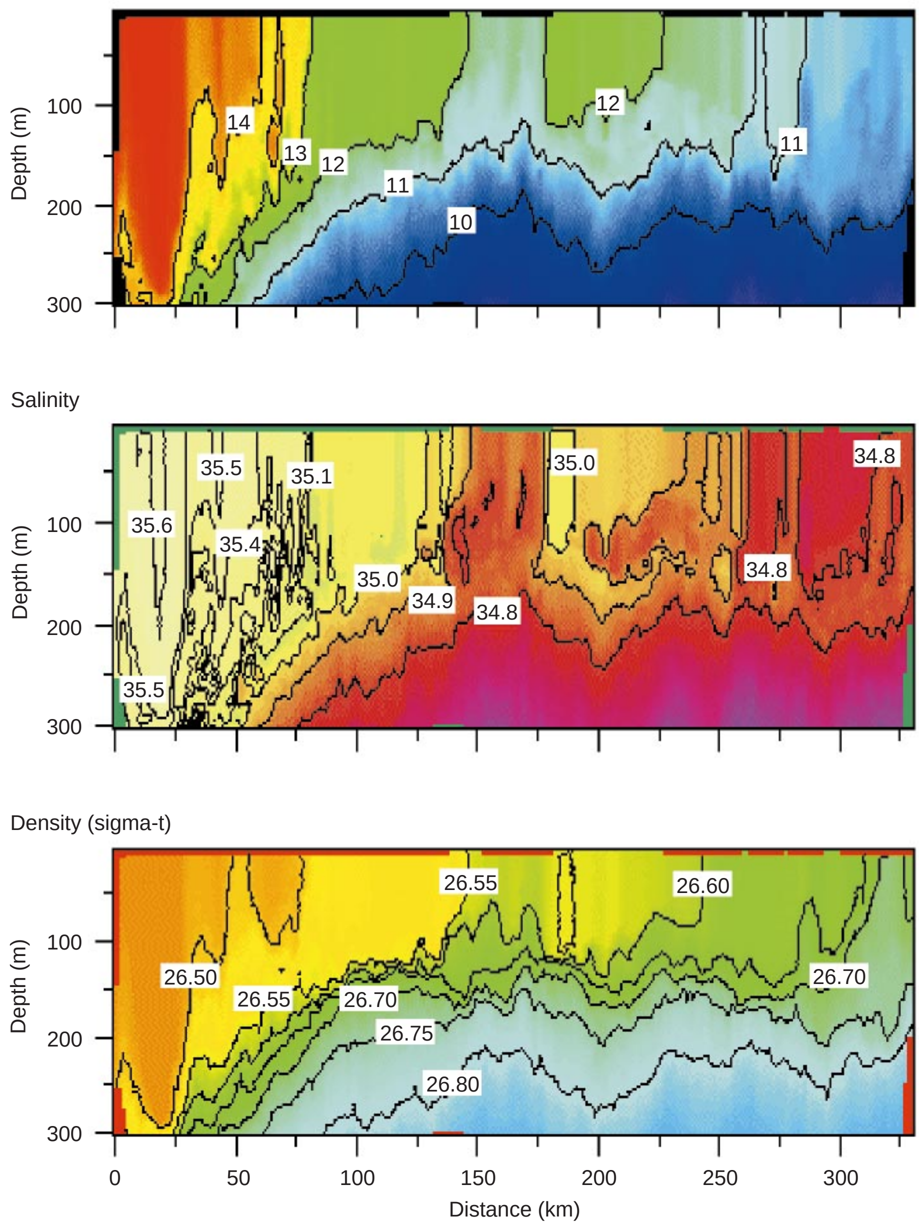


**Figure 11** An example of a conductivity, temperature and depth (CTD) section across the Sub-Tropical Front south of Australia using a SeaSoar towed vehicle equipped with a Seabird CTD instrument. (From Tomczak M and Pender L (1999) *Density compensation in the Sub-Tropical Front in the Indian Ocean South of Australia.* http://www.es.flinders.edu.au/~mattom/STF/fr1098.html.

**Figure 12** A faired cable winch and SeaSoar towed vehicle. This winch holds 5000 m of cable, 400 m faired and 4600 m of bare cable. A combination of faired and bare cable can be a cost-effective method of achieving greater depths.

vehicle offers advantages over hull-mounted transducers by deploying the acoustic transducer away from the high noise environment and bubble layer near the ship and closer to the object of interest. A well-designed system can also be a more stable platform for the acoustic transducers than a ship in rough seas.

## The Winch

Towed-vehicle systems using electromechanical cables usually require a special, purpose-built winch with accurate spooling gear and slip-rings to make the electrical connection to the rotating drum. Cable lengths can vary from 100 m to 5000 m. If a cable with rigid fairing is used special blocks and fairing guiding devices are needed to handle the cable. The faired cable has a large bending radius and can only be wound onto the winch drum in a single layer. As illustrated in **Figure 12**, this type of winch is quite large. If the towed vehicle system uses wire rope for the tow cable, then the winch can be a standard type.

## Symbols used

| | |
|---|---|
| $A$ | Area |
| AC | Aerodynamic center |
| AR | Wing aspect ratio $= b^2/S$ |
| $C_{\mathrm{Di}}$ | Induced drag coefficient |
| $C_{\mathrm{DN}}$ | Normal drag coefficient |
| $C_{\mathrm{DT}}$ | Tangential drag coefficient |
| $C_{\mathrm{L}}$ | Lift coefficient |
| $C_{\mathrm{M}}$ | Moment coefficient |
| $D$ | Drag force |
| $D_{\mathrm{N}}$ | Normal drag force |
| $D_{\mathrm{T}}$ | Tangential drag force |
| $L$ | Lift force |
| $M$ | Pitching moment |
| $R_e$ | Reynolds number $= ud/v$ |
| $S$ | Wing planform area |
| $S_n$ | Strouhal number $= fd/u$ |
| $T$ | Cable tension |
| $W$ | Tow vehicle weight |
| $a$ | Slope of the lift curve for a wing $= \mathrm{d}C_{\mathrm{L}}/\mathrm{d}\alpha$ |
| $a_0$ | Slope of the lift curve for an airfoil section $= \mathrm{d}C_{\mathrm{L}}/\mathrm{d}\alpha$ |
| $b$ | Wing span |
| $c$ | Chord length |
| $cg$ | Center of gravity |
| $d$ | Cable diameter |
| $f$ | Frequency |
| $l$ | Cable length |
| $u$ | Velocity |
| $u_{\mathrm{N}}$ | Normal velocity |
| $u_{\mathrm{T}}$ | Tangential velocity |
| $w$ | Cable weight per unit length |
| $\alpha$ | Angle of attack |
| $\phi$ | Angle of the cable to the horizontal |
| $\phi_0$ | Cable equilibrium angle |
| $\phi_1$ | Cable angle at the towed vehicle |
| $\phi_2$ | Cable angle at the ship |
| $\mu$ | Dynamic viscosity ($\approx 1 \times 10^{-3}\,\mathrm{kg\,m^{-1}\,s}$ for water) |
| $v$ | Kinematic viscosity $= \mu/\rho$ ($\approx 1 \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$ for water) |
| $\rho$ | Density ($\approx 1000\,\mathrm{kg\,m^{-3}}$ for water) |

## See also

**Acoustic Scattering by Marine Organisms. Autonomous Underwater Vehicles (AUVs). CTD. Ships. Sonar Systems.**

## Further Reading

Abbott IH and von Doenhoff AE (1959) *Theory of Wing Sections*. New York: Dover Publications.

Anderson JD (1991) *Fundamentals of Aerodynamics*, 2nd edn. New York: McGraw-Hill.

Wingham PJ (1983) Comparative steady state deep towing performance of bare and faired cable systems. *Ocean Engineering* 10(1): 1–32.