of thrust and centre of pressure affect not only the effectiveness but also the safety of a tug.

The towing point

For tugs towing on a line, the towing hook or towing winch is not necessarily the towing point. The towing point is that point from where the line goes in a straight line from the tug towards the ship. For tugs pushing at a ship's side the contact point or pushing point is of importance. Before discussing the capabilities and limitations of different tug types the towing and pushing point in relation to the location of propulsion and centre of pressure are considered.

The lateral centre of pressure

The lateral centre of pressure is a non stationary point. Its location depends on the underwater hull form including appendages such as rudder and propellers, on the trim of the tug and the angle of attack of the incoming water flow. The influence of rudder and propellers on the location of the centre of pressure seems to be rather high.

Tractor tugs and especially VS tugs have a large skeg aft, resulting in an aft lying location of the centre of pressure.

Incoming water flow exerts a force on the tug. The point of application of this force is the lateral centre of pressure. The direction and magnitude of the force depends on the underwater lateral plane and shape, the angle of attack, the under keel clearance and on the speed squared. Speed, therefore, is a dominant factor.

The exact location of the lateral centre of pressure and the magnitude and direction of the resultant force created by the incoming water flow for different angles of attack and speeds can best be determined in a towing tank. The locations of the centre of pressure mentioned later are merely an indication and are based on observations and information e.g. from Voith.

When water flow towards a tug comes from abeam, caused either by crosswise movement of a tug through the water or by a current at right angles, the centre of pressure generally lies behind midships in a position about 0·3 to 0·4 x LWL from aft. For conventional tugs it is probably more often in the vicinity of 0·3 x LWL from aft and for tractor tugs closer to 0·4 x LWL from aft. Reverse-tractor tugs and ASD-tugs may have a more forward lying centre of pressure, depending on the hull design.

When a tug turns with its bow into the direction of water flow, the centre of pressure moves forward. The smaller the angle between incoming water flow and tug's heading the more forward the centre of pressure lies. For conventional and tractor tugs the centre of pressure does not generally move forward of amidships (0·5 x LWL). Reverse-tractor tugs and ASD-tugs may experience a position of centre of pressure forward of midships with a forward incoming water flow. When a tug is turning with the stern into the water flow the centre of pressure moves aft and with an acute angle of incoming water flow will lie far aft.

Figure 4.3 shows a tug moving ahead, towing on a line, assisting a ship under speed. The resultant force created by incoming water flow is force F, assumed to be centred approximately near amidships. Force F can be resolved into lift force L and drag force D, comparable with the lift and drag forces on rudders or aeroplane wings. Lift force L gives an additional force on the towline and drag force D has to be overcome by the tug's thrust. Towing point T lies a little behind the centre of pressure. The force in the towline in combination with force L creates a counter-clockwise turning moment.

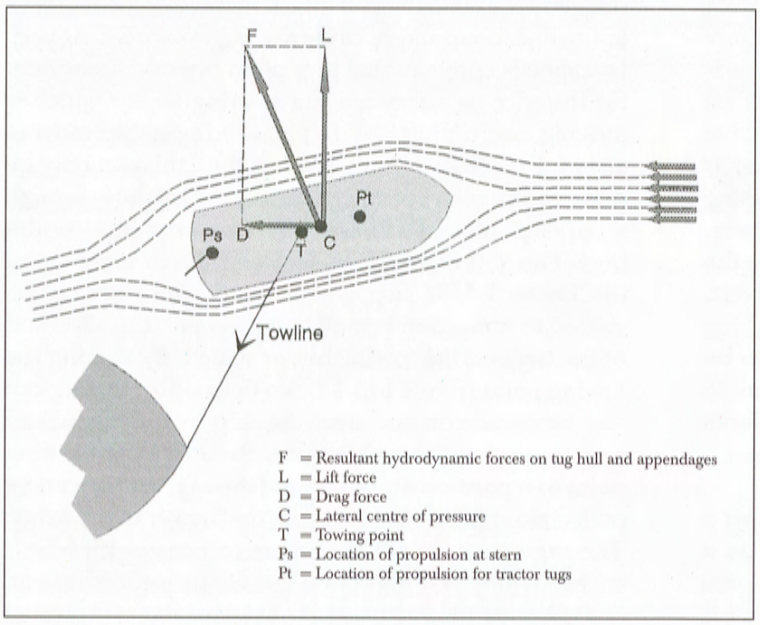

Figure 4.3 Forces created on assisting tug, moving ahead

Consider two locations of propulsion – position Ps for stern driven tugs, a conventional tug for example, and position Pt for tractor tugs. The smaller the distance between T and C the smaller is the turning moment. Thus less steering power, by either rudder deflection or omnidirectional propellers, is needed to counteract that turning moment. Consequently, more engine power is available for towing. If propulsion is located aft at Ps, starboard rudder is needed, giving a little more drag but also an additional force in the towline. If propulsion is located forward (Pt) then sideways steering power is needed, but in the opposite direction. This consequently decreases the towline force.

With increasing speed, force F increases and consequently lift force L. The higher the speed the more steering effort is needed. Therefore, the higher the speed the larger the

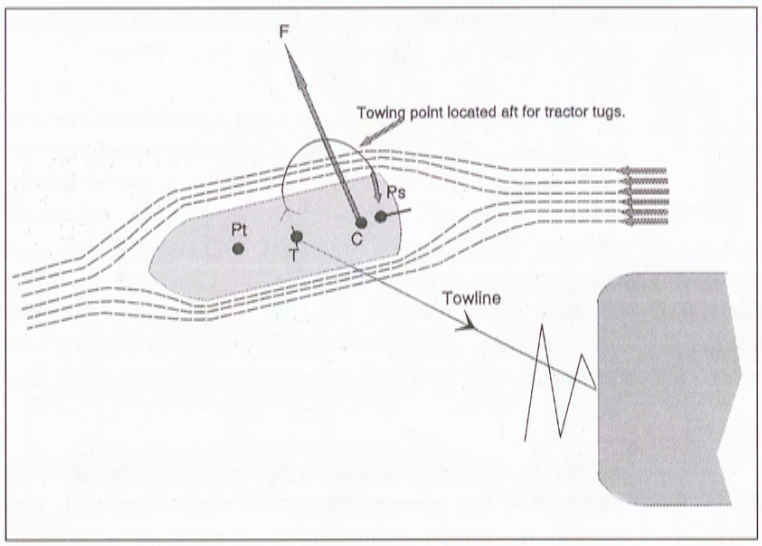

Figure 4.4 Forces created on assisting tug, moving astern

difference in towline forces between a conventional and tractor tug. As a forward tug the tractor tug is more effective if it is possible to operate stern first.

Towline forces also create list. Considering the direction of steering forces it is evident that with the propulsion located in position Ps the sideways steering forces increase the tug's list, while with propulsion located in Pt steering forces counteract the list caused by the towline force. When an ASD-tug is operating like a conventional tug its high steering forces result in larger heeling forces. This is also due to the fact that the centre of pressure of this tug type lies generally somewhat further forward, resulting in a larger turning moment to overcome. The larger heeling moment is more or less compensated for by the large beam of this tug type.

Although the towline position discussed here is the most effective for both conventional and tractor tugs when operating as a forward tug on a line, the towing point on tractor tugs is located further aft for safety reasons and for better performance as stern tug. This is explained later. The consequence of the further aft towing point on a tractor tug is an even less effective tug as forward tug. More sideways steering power is needed to counteract the larger anticlockwise turning moment, resulting in a further decrease in towline force. By giving more engine power in order to achieve the same towline force as a conventional tug would exert, the tug comes more in line with the towline, resulting in higher turning moment and drag force to be overcome. At higher speeds drag force may become so large that a tug is unable to react sufficiently to the force and swings around.

The consequence is that when working forward a conventional tug is more effective when towing on a line than a tractor tug. The better the omnidirectional thrust performance of a tractor tug the more effective it will be. Reducing the underwater resistance of a tractor tug would increase its effectiveness as a forward tug. However, this would have consequences for its effectiveness as stern tug when operating in the indirect mode whereby use is made of the hydrodynamic forces on the tug's hull. Therefore a compromise has often to be found for the location of the towing point and also for the underwater profile of a tug.

In figure 4.4 the tug is moving astern through the water. The centre of pressure lies much further aft e.g. at location C for conventional tugs as well as for tractor tugs. Tractor tugs are considered first. The towing point T is very dangerous, not only because of the large heeling moment caused by the hydrodynamic force on the tug's hull, but also because large crosswise steering forces (at Pt) have to be exerted by the tug in order to compensate for the turning moment created by the incoming water flow, giving additional forces in the towline and additional heeling forces. At higher speeds and/or too large angles of attack of incoming water flow the resulting heeling forces may cause capsizing of the tug. The large vertical distance between the propulsion units and towing point also contributes to the high heeling moment. Therefore although towline forces are high for tractor tugs it is much safer to locate the towing point aft at a small distance abaft C, the centre of pressure for smaller angles of attack. (In VS tractor tugs the towing point lies generally just above the middle of the skeg.) The tug then comes in line with the towline when its engines are stopped and very little steering power is needed to keep the tug in the most effective position when the indirect towing method is applied.

Neither do conventional tugs operate as shown in figure 4.4 because with higher speeds it is almost impossible to steer the tug safely and is therefore very dangerous. If the angle of attack increases, the increase in towline forces might cause the tug to capsize. At very low speeds conventional tugs often operate broadside, for instance as a forward tug steering a ship which is moving astern or as a stern tug steering a ship moving ahead. Especially on single screw tugs, this can only be done with a gob rope or by passing the towline through a fairlead situated aft, as is the case on some combi-tugs. The gob rope system is dealt with in more detail in Chapter 7. Using a gob rope the towing point can be shifted to a position somewhere between the after end of the tug and the towing bitt or winch. By shifting the towing point from T1 to T2 (see figure 4.5), the tug can stay broadside on and steer the ship by moving ahead or astern using the tug's engine. By shifting the towing point to a position at the stern of the tug, the tug can be pulled astern by a vessel without the danger of capsizing. The tug can then use its engine to control the ship's speed. Twin screw tugs often use the propellers instead of a gob rope to keep the tug in the position as indicated in figure 4.5.

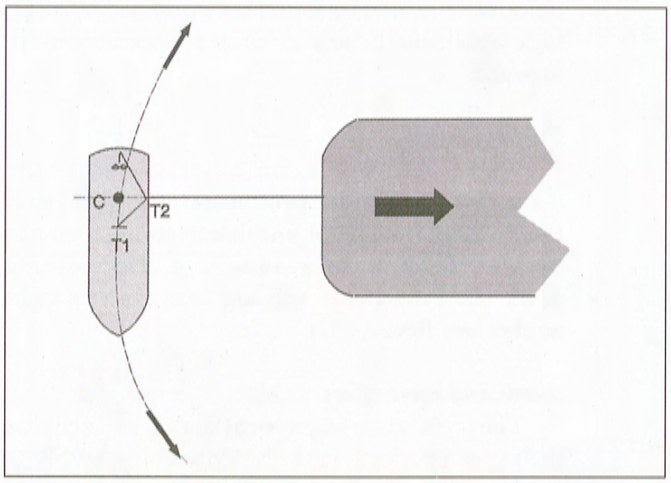

Figure 4.5 Tug working on a gob rope
Ship has a very low speed ahead. Tug can steer the vessel by going ahead or astern on the engine. Conventional twin screw tugs don't always need a gob rope; they can create a couple by the propellers to stay broadside

Direct and indirect towing method

The direct and indirect towing methods are explained in figure 4.8 (overleaf). P is the location of the propulsion, C of the centre of pressure and T is the towing point.

The direct towing method is carried out by an after tug on a line at low ship speeds. The tug pulls in the required direction, either to give steering assistance and/or to control the ship's speed. Tractor tugs assist with their stern directed towards the stern of the assisted ship and ASD/reverse-tractor types of tug assist with their bow towards the stern. Whether tractor tugs or ASD/reverse-tractor tugs are more effective in steering control depends on the relation between the distance P-T and C-T, the tug's engine power and thrust performance in the pulling direction, but also on the tug's underwater plane. The smaller the distance CT in relation to PT the better the tug's performance in the direct towing mode.

The indirect towing method is applied by an after tug at speeds higher than five to six knots. With the indirect towing method, the tug makes use of the hydrodynamic forces created by incoming water flow on the tug's skeg and/or underwater body. The aft lying towing point of the tractor tug, and consequently the small distance between towing point (T) and centre of pressure (C), implies that only a little crosswise steering power of a tug is needed to keep the tug in the most effective position to exert the highest steering forces to the assisted ship.

The ASD-tug/reverse-tractor tug has a larger distance between the towing point (T) and centre of pressure (C). Consequently, more crosswise power is needed to keep the tug in the most effective position, thus decreasing towline force.

In the indirect towing mode tugs can give high initial steering forces to a ship underway at speed, as can be seen in some performance diagrams in section 4.3.2. As soon as a ship starts turning she gets a drift angle and speed of ship's stern, being at the outside of the turn, increases initially, so tug's speed has to increase, resulting in even higher steering forces. The indirect towing method is further dealt with in Chapter 9 – Escorting.

From this brief explanation of direct and indirect towing it is apparent that the locations of the centre of pressure and towing point are very critical. A more forward lying towing point in a tractor tug results in higher towline forces, but the safety of operations and

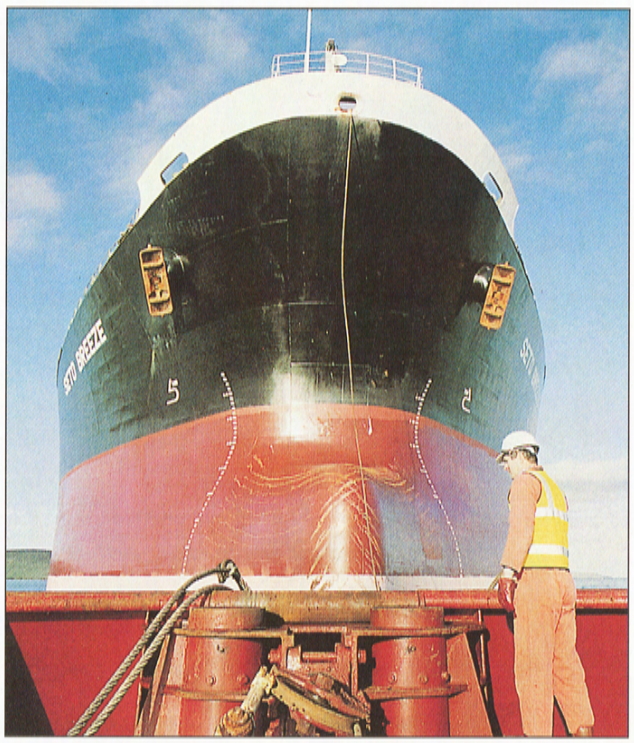

Photo: Shetland Islands Council

Figure 4.6 Swivel fairlead on the after end of a tug's deck for the gob rope

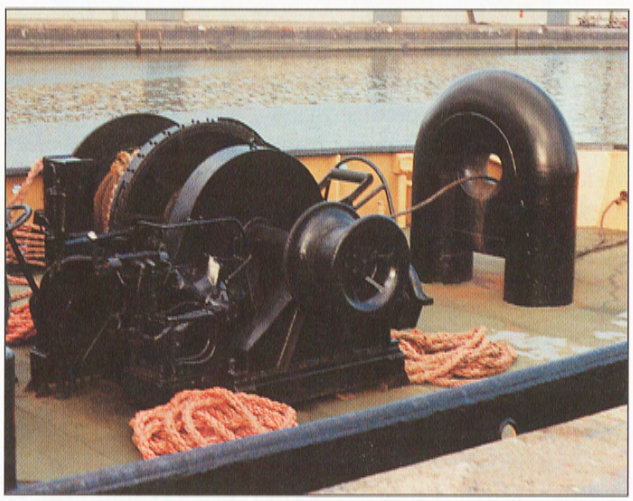

Photo: Author

Figure 4.7 The large fairlead is the aft lying towing point on a VS tractor tug

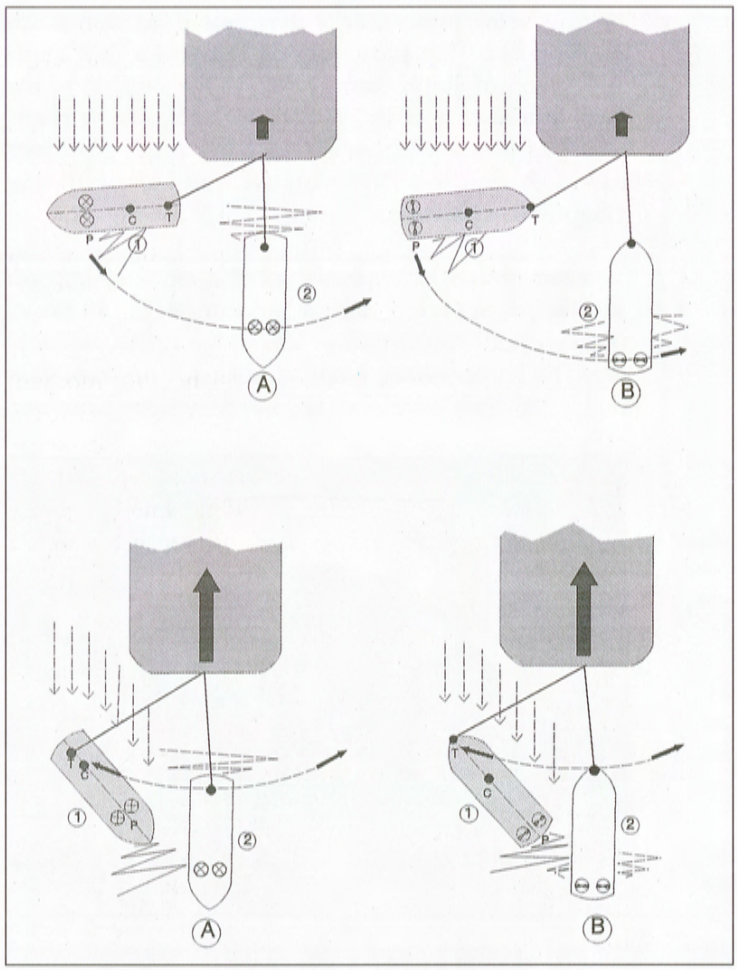

Figure 4.8 Direct and indirect towing methods

Top: Direct Towing Method – A: Tractor tug
B: ASD/Reverse-tractor tug
Position 1: Steering and retarding Position 2: Retarding

Bottom: Indirect Towing Method – A: Tractor tug
B: ASD/Reverse-tractor tug
Position 1: Steering and retarding Position 2: Retarding

as a result performance decreases. A more forward lying centre of pressure in ASD/reverse-tractor tugs does not affect tug safety but increases the tug's performance as a stern tug. To minimise steering effort in keeping a VS tug in line with an escorted vessel when no assistance is required, a second towing point is installed at the after end of some VS tugs, which pins the tug under the towline and reduces the steering effort required. When steering assistance is required then the original towing point more forward is used again, which should be possible without releasing the towline.

In ASD-tugs, specific designs are used to bring the centre of pressure more forward e.g. in the USA ASD-tug *Kinsman Hawk*. This tug is designed with a deep forefoot which results in a more forward position of the centre of pressure and the stern is cut away significantly to provide a clean flow to the azimuth propellers and to push the tug's centre of pressure forward as well. Forward skegs at the bow, or in combination with a bulbous bow, can be found on a number of ASD-tugs, which also brings the centre of pressure more forward.

Pushing point

When pushing at a ship's side, the larger the distance between the propulsion unit(s) (P) and the pushing point (Pu) in relation to the distance between the centre of pressure (C) and the pushing point (Pu), the better the tug can work at right angles (see figure 4.17).

Skegs and their effect

The tug's underwater form should be such that the tug can perform in the best possible way. Skegs can contribute to a tug's performance and tugs are often designed with some sort of skeg.

A pure harbour tug should in general be most effective at ship speeds below six to seven knots, when the assisted ship is slowing down and has to stop its main engine, losing its controllability to a large extent and during turning, berthing and unberthing operations when hardly any use can be made of the ship's own manoeuvring devices, except for bow and stern thrusters (see paragraph 5.1). Such a harbour tug should be able to apply the highest possible towing forces in all the required directions and with a short response time. High pushing forces may be needed with the tug operating at right angles to the ship still having speed. A low underwater resistance is therefore needed.

On the other hand, a tug may have to operate at higher speeds, and escorting of ships may be one of the tug tasks. Then a well designed under water body, which may include a skeg, plays an important role in generating high towing forces in the indirect mode by making use of the hydrodynamic forces working on the tug's hull.

As can be seen a skeg may be effective for one task, but ineffective for other tasks. With regard to skegs it should therefore be well considered what is expected from a tug. There is a large variety of skegs. Mainly the following skegs can be found on tugs, of which some have already been mentioned when discussing tug types:

a) The skeg on tractor tugs. This type of skeg provides better course stability when free-sailing ahead (with skeg aft). It generates additional towing forces when operating as stern tug in the indirect towing mode because it increases the tug's lateral underwater area and brings the centre of pressure more aft, closer to the towing point. The skeg may have a specific form to generate the highest possible lift forces.
b) An aft skeg on tugs not being tractor tugs: A vertical fin attached to the tug's underwater hull in the centreline of the after section at some distance before

Photo: J. M. Voith GmbH, Germany

Figure 4.9 VS tug operating in the indirect towing mode

the propellers, to give the tug a better course stability when free-sailing ahead.

c) A flat vertical skeg, or box keel, in the centreline of several ASD-tugs and reverse-tractor tugs, which extends for some distance before the propellers to the forefoot. It provides better course stability when free-sailing ahead and often, depending on skeg form, particularly astern. It generates additional towing forces when operating as stern tug in the indirect towing mode and when ASD-tugs operate as conventional tugs at a ship having speed.

d) Skeg at the bow of an ASD or reverse-tractor tug. Such a skeg improves the course stability when free-sailing astern (not ahead) and increases a tug's performance when operating as stern tug in the indirect mode and to some extent as bow tug when operating bow-to-bow at a ship having headway.

Combinations of the skegs mentioned can be found as well, for instance of skeg types c and d.

When reading the following paragraphs and the capabilities of the various tug types in the different situations it is good to consider at the same time the possible skegs and their effects.

4.2.3 Stability

Operational stability, one of the basic design requirements, is of great importance for harbour tugs due to the nature of their work. Conventional tugs, when towing on a line as a forward or after tug, can experience very large athwartships towline forces. The same applies to ASD-tugs when towing on a line as a conventional tug. High towline forces can also occur when conventional tugs are operating in the way shown in figure 4.5.

Tractor tugs and ASD/reverse-tractor tugs also experience high athwartships towline forces when indirect towing. At high speeds these forces can be far in excess of a tug's bollard pull. Towline forces can increase even further due to dynamic forces caused, amongst other things, by irregular engine performance and/or tug control, tug movements due to waves, and when towlines are used with too little stretch, such as steel wires.

Tugs with azimuth propellers may heel over appreciably if thrust is suddenly applied athwartships. These tugs tend to be powerful with respect to their size and the deeply immersed point of application of thrust, implying a long heeling lever, results in a large heeling moment. Whether the indirect or direct towing mode is applied this heeling moment counteracts the heeling moment created by towline force. When conventional tugs tow on a line the heeling moment caused by transverse steering thrust enlarges the heeling moment created by towline force, as explained when discussing lateral centre of pressure. The same happens when ASD-tugs operate like conventional tugs while towing on a line. In figure 4.10 heeling forces due to towline force, lateral resistance and steering force are shown for a conventional tug.

All these aspects should be taken into account when tug stability requirements are considered. Means of increasing stability and reducing the heeling effects of external forces on a tug include the following:

High GM and good dynamic stability

Good static and dynamic stability is required because of the high dynamic forces a tug experiences. A tug needs considerable residual dynamic stability when, due to a sudden force, she heels over considerably. The tug's beam has a large influence on its GM (Initial Metacentric Height). Making a tug beamier results in a larger GM and righting moment, assuming all other factors influencing its stability are unchanged. The length/width ratio of harbour tugs is decreasing and many modern tugs have a length/width ratio of between approximately 2·8:1 and 3:1. Several harbour tugs with even lower length/width ratios have also been built, such as the USA tractor tug *Broward* (l.o.a. 30m, bp 53 tons) with a length/width ratio of 2·5:1 or the Canadian reverse-tractor tug *Tiger Sun* (l.o.a. 21·7m, beam 10·7m, bp 70 tons) with a

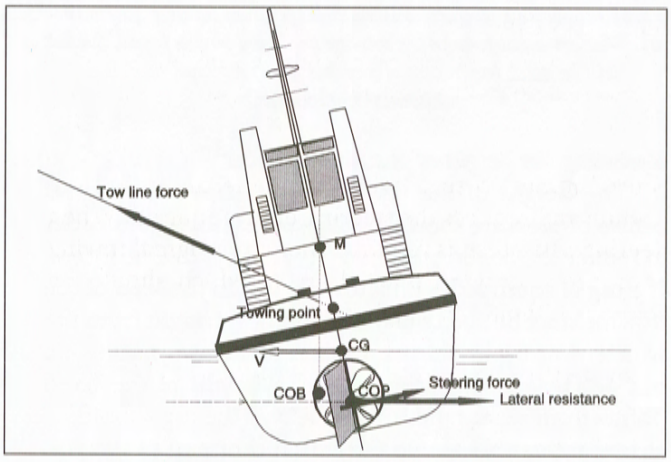

Figure 4.10 Heeling forces working on a conventional tug when towing on a line
M = Initial Metacentre COP = Centre of Pressure
COB = Centre of Bouyancy CG = Centre of Gravity
V = Transverse Speed

Tugs are sometimes designed with sponsons, which create larger righting moments at smaller heeling angles.

Reducing the transverse resistance of the hull

Making the lateral area smaller allows a tug to be pulled more easily through the water instead of rolling over. Low transverse resistance of a tug's hull also increases its capability of working at right angles to a ship's side with a ship underway and reduces its heeling moment. For tugs making use of the underwater body, like conventional tugs towing on a line and tugs using the indirect towing method, this is contradictory to their required performance.

For a good performance these tugs need a high lateral resistance in order to be able to generate high towline forces. A skeg may be added to increase lateral area (which also lowers the centre of pressure) and lateral resistance. The higher towline forces that can be generated and the lower centre of pressure, result in larger heeling angles and consequently in higher stability requirements. A radial hook, as shown in figure 4.11, reduces the heeling angle considerably.

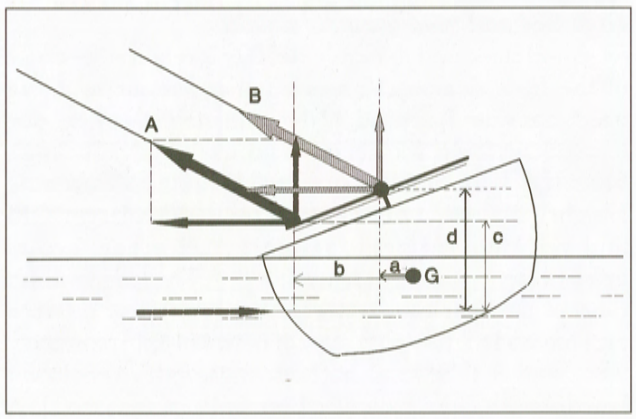

Fig. 4.11 The effect of a radial hook
With a radial hook the heeling leverarm c is shorter than with the towing point in the centre line of the tug (leverarm d). With a radial hook the righting leverarm b is much longer than without (leverarm a). With an equal force in the towline as shown in this figure, the list will be much less in case of a radial hook. A radial hook is a substantial improvement

Reducing the height of the towing point

The height of the towing point above the lateral centre of pressure should be as small as possible in order to reduce the heeling moment created by towline forces. If a tug is equipped with a towing winch the lead of the towline may be such that either it goes straight from the winch towards the ship or it passes first through a towing bitt or fairlead. In either case the height of the fixed points from where the towline leaves the tug should be as low as possible above the lateral centre of resistance. Using a towing arm or radial hook (see figure 4.11) or similar gear, a tug heels until the heeling moment is counteracted by the larger induced righting moment. A radial hook is a substantial improvement for tug safety and performance.

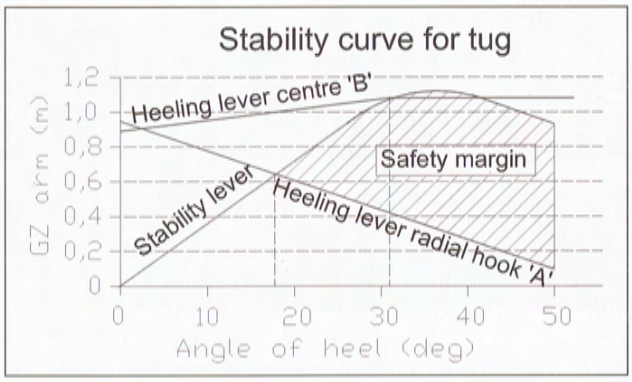

Figure 4.12 The effect of a radial hook on stability
Heeling lever centre 'B' resulting from an athwartships towline force applied to a towing point at the centre line of the tug. The towline force causes a heeling angle of 31°.
Heeling lever radial hook 'A' resulting from the same force but in case of a radial hook. The towline force causes now a heeling angle of 18°.

How a radial hook, or a similar system, increases a tug's safety and consequently safety of operations is also shown in figure 4.12. The situation is for a specific conventional tug and a radial hook with a radius equal to half tug's width. A certain athwartships towline force is applied to the towing point near the centre of the tug. The towline force is such that it almost results in capsizing the tug, because the maximum stability lever is only a little more than heeling lever 'B'. No safety margin is left. With a constant towline force, heeling angle is approximately 31°. In case of a radial hook, the same towline force is applied initially at the same height above the lateral centre of pressure. The heeling lever 'A' resulting from this force decreases fast with increasing heeling angle, and in this specific case maximum heel angle caused by a constant towline force is approximately 18°, with a large safety margin left. The system itself is further discussed in paragraph 7.2.

Reducing the height of the pushing point

The vertical distance between the pushing point and lateral centre of pressure should be as small as possible in order to reduce the heeling moment created by lateral resistance when a tug is pushing at a large angle to a ship's side.

A towline with good shock absorption characteristics

This is required to reduce sudden heeling moments caused by high peak forces in the towline. Towing winches can be equipped with load reducing systems, although these are not suitable for narrow port areas, when such a system would slacken the towline at high loads, for instance, when the tug is close to a dock wall.

Tug freeboard being such that the deck edge is not immersed at too small a heeling angle

According to the former British Department of Transport, Merchant Shipping Notice No. M.1531 of June 1993, this angle should not be less than 10° (see Appendix 2). Openings in superstructures, deckhouses and exposed machinery casings situated on the weather

deck, which provide access to spaces below deck, should be fitted with watertight doors. Such doors should be kept closed during towing operations. Air pipes, vents, exhausts should be designed to be as high up as possible and/or should be fitted with an automatic means of closure.

The International Maritime Organization (IMO) has established recommendations regarding static stability curve requirements. These recommendations apply to ships in international trade over 24 metres in length. In addition, recommendations on weather criteria have been established for ships of 24 metres in length and over. These apply to reserve stability with respect to wind, wind gusts and waves. No specific recommendations for the stability of tugs, which take into account towline forces, are given.

The IMO stability criteria and all related aspects are specified in the 2002 IMO publication "Code on Intact Stability for All Types of Ships Covered by IMO Instruments". The publication consists of the text of Resolution A.749 (18) as amended by resolution MSC. 75(69).

National authorities or classification societies often have their own specific regulations or guidelines. For example, the stability requirements of the United States Coast Guard (USCG) for towing vessels are much the same as the static stability curve requirements of the IMO. In addition, USCG requires that tugs shall either meet the static towline pull criteria or the dynamic towline pull criteria. The static towline pull criteria include a required minimum GM by which no deck-edge immersion will occur due to the heeling effect of deflected propeller thrust at full helm, taking into account the tow hook height above the centre of the propeller shaft. The dynamic towline pull criteria require a certain residual righting energy at the point of equilibrium of the righting and heeling arm curves. The heeling arm curve should be calculated on a given formula which takes into account the deflected propeller thrust and height of towing point.

The American Bureau of Shipping gives recommendations for residual dynamic stability based on a towline pull at 90° of 50% of bollard pull for twin screw tugs with normal propellers and 70% of bollard pull for tugs with azimuth or cycloidal propellers. Heeling arm should be taken from the top of the towing bitt to the centre of buoyancy or for an approximation to half the mean draft.

Other semi-static methods are used, allowing for a constant athwartships towline force acting on the hull, causing it to be dragged bodily through the water. The requirements of the previously mentioned British Shipping Notice are such that the minimum GM of a tug should be sufficient to limit the heel to an angle of deck immersion when being towed transversely through the water at a speed of four knots. This results in the following simple relationship. The GM in the worst anticipated condition should not be less than:

$$\frac{0{\cdot}076K}{f.C_B}$$

Where:

$K = 1{\cdot}524 + 0{\cdot}08L - 0{\cdot}45r$

L = Length of vessel between perpendiculars (in metres)

r = Length of radial arm of towing hook (metres)

f = Freeboard (metres)

C_B = Block coefficient

The effect of a radial towing hook is included in this formula. The same kind of requirement can be seen in Norway where a five knot transverse speed with a tow of 65% of the bollard pull should be possible without deck immersion.

Unfortunately, in a tug's working environment large dynamic forces far in excess of static and semi-static values may be developed and these are almost impossible to estimate accurately. When designing tugs, therefore, stability and in particular reserve stability should be considered very carefully, taking into account all relevant factors including type of tug, required assisting methods, propulsion system and working conditions. It is clear that good stability not only improves a tug's safety but to a large extent a tug's capabilities and performance. With respect to escort tugs, stability requirements are further discussed in paragraph 9.5.1.

4.3 Capabilities and limitations

The capabilities and limitations of different tug types are now considered, based on the two principal methods of tug assistance:

- Tugs towing on a line.
- Tugs operating at a ship's side.

Furthermore, the performance of different tug types and the effect of tug assistance on a ship's behaviour is highlighted. Rudder tugs, more or less comparable to tugs operating at a ship's side but able to assist in steering to port as well as to starboard, are mainly dealt with in Chapter 9, while discussing escorting with normal harbour tugs.

4.3.1 Capabilities and limitations of tug types

Good cooperation between pilot and tug captain is indispensable for smooth, safe shiphandling with tugs. Safety applies both to the ship concerned and to the tug and her crew. Good cooperation is based on a good understanding of the capabilities and limitations of the attended ship and, in particular, of the assisting tugs.

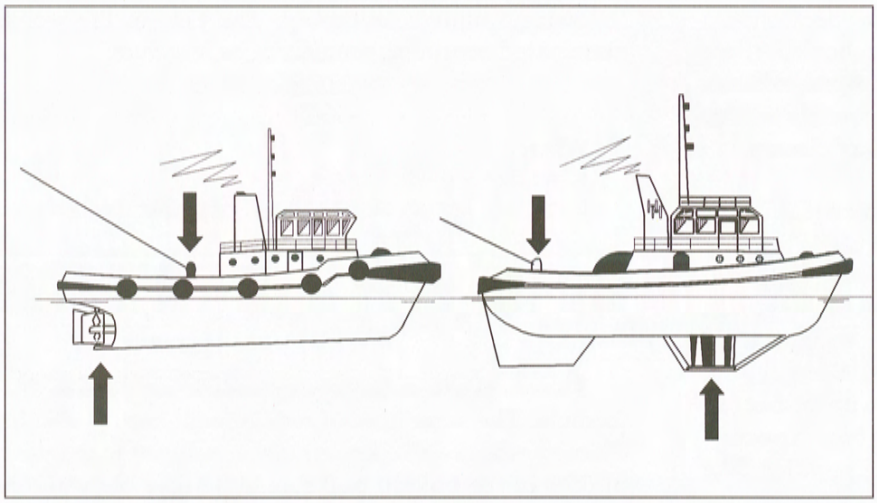

Figure 4.13 Basic difference between tug types
The main difference between types of tug with respect to performance when towing on a line:
Conventional types of tug – towing point located forward of propulsion.
Tractor types of tug – towing point located aft of propulsion

Tugs towing on a line

The capabilities and limitations of tugs towing on a line are closely related to the location of the towing point and the propulsion units, as explained in section 4.2.2. That's why, in Chapter 2, tugs were classified according to these locations. Of course, a tug's manoeuvrability and stability are also factors of major importance when considering capabilities and limitations, but that applies to any situation and to any type of tug.

In figure 4.13 a conventional tug is shown with its propulsion aft and towing point near midships. It could also be an ASD-tug when towing on a line and using the after winch or towing hook in the way conventional tugs do. The other tug shown in figure 4.13 is a VS tractor tug. It may also be a tractor tug with azimuth propellers or even a reverse-tractor tug. As can be seen, the location of the propulsion and the towing point in a tractor tug are opposite to those in a conventional tug. The consequences of this are discussed now.

Forward tugs towing on a line

Forward tugs towing on a line are dealt with first (see figure 4.14A, B). Irrespective of the type of tug, a forward tug towing on a line can give steering assistance or deliver crosswise forces to an assisted ship to starboard as well as to port. However, there is a difference in response times between the performance of tractor and conventional tugs. When required, a tractor tug can move easily and quickly from one side to the other e.g. from starboard bow to port bow to deliver steering assistance or to keep the bow up into the current or wind. This is due to its ability to deliver side thrust from the forward located propulsion units. A conventional tug takes a little longer. In addition, to manoeuvre a tug from one side to the other, captains of conventional tugs often turn their tug at the beginning of the manoeuvre round the towing point on a tight towline. It speeds up the manoeuvre but is not necessary and not advocated, because it results in a short pull in the wrong direction which may adversely affect the manoeuvre, especially for light ships.

A tractor tug (see figure 4.14A) is less effective in giving steering assistance or creating sideways forces on a ship having speed than a conventional tug. As explained in section 4.2.2, a tractor tug lies more in line with the towline and consequently a relatively higher sideways resistance has to be overcome at the expense of effective towline pull.

A conventional tug (see figure 4.14B) can turn the tug around the towing point, has a lower resistance to overcome owing to the smaller angle of attack of the incoming water flow and can make better use of the hydrodynamic forces, all of which contribute to a more effective towline pull.

The effectiveness of a conventional tug increases, depending on the angle (b), and of a tractor tug decreases with increasing ship's speed. The higher a ship's speed the larger the difference in effectiveness between tractor and conventional tugs. The lower the underwater resistance of a tractor tug and the better the omnidirectional thrust performance the higher the effectiveness. With respect to this, it has been experienced that for the same ship's speed an azimuth tractor tug can operate at a larger towing angle (a) than a VS tractor tug and consequently can apply higher sideways and steering forces on a ship, owing to a better thrust performance in directions other than ahead or astern.

With a tractor tug care should be taken that, with increasing speed, angle (a) is not getting too large otherwise the tug cannot overcome sideways resistance any more and will swing around on the towline secured at the aft towing point and will come alongside the vessel. If the towline is on a quick release towing hook or on the winch, the line can be released by the quick release mechanism. It can be concluded that a tractor tug forward is very limited by a ship's speed.

For a conventional tug angle (b) can be very large without any problem. A conventional tug can create large forces in the towline, even with a large towing angle (b), by increasing angle (c). With increasing ship's speed due attention should be given to a tug's heading. When angle (c) between a tug's heading and incoming water flow becomes too large the tug might not be able to come back in line with the assisted ship and, as a

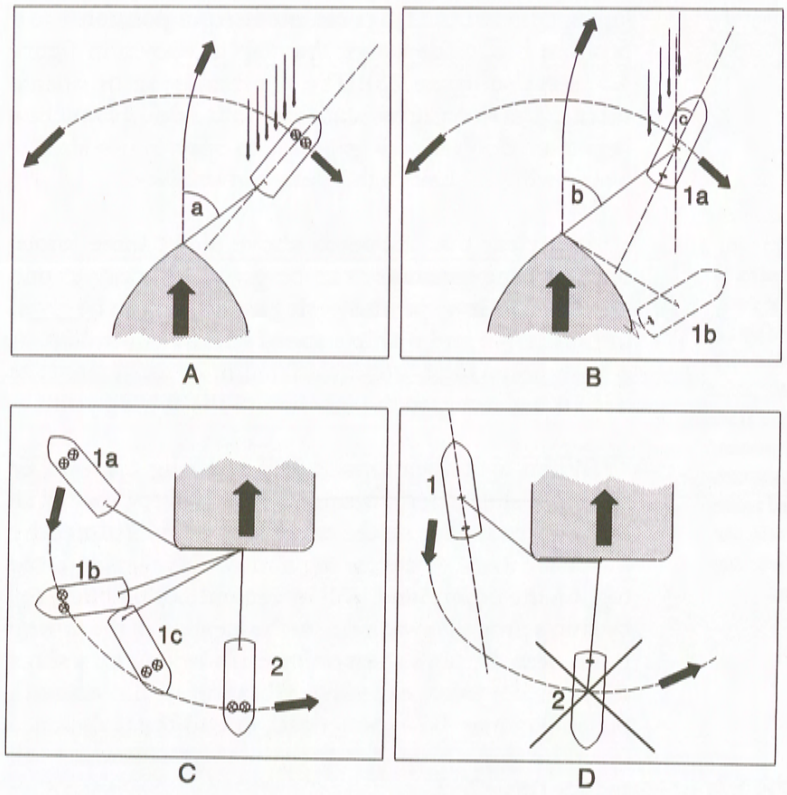

Figure 4.14 Comparison between tractor type tugs and conventional tugs when towing on a line with a ship having headway
A: Tractor type of tug made fast as forward tug B: Conventional tug (or ASD-tug) as forward tug
C: Tractor type of tug as after tug D: Conventional type of tug as after tug

consequence, athwartships towline forces may get too high. This may also be the case with an ASD-tug when operating like a conventional tug. The high athwartships towline forces might overturn the tug if the towline cannot be released in time. This is called girting, which also happens when a ship's speed is too high in relation to the tug's speed or position.

It often happens that quick release hooks cannot be opened in case of emergency, especially when towline forces are very high and the towline, if fastened directly to the towing hook, has a large vertical angle with the plane of the tug deck. Towing winches with quick release systems are safer. Nevertheless, ship's speed should always be carefully controlled when tugs are towing on a line forward and, as far as possible, the pilot should closely observe the behaviour of the tugs.

When a ship's speed is very low a conventional tug can give very effective steering assistance when operating as shown in position 1b (see also the photo of the tug *Smit Siberië* – figure 8.9). A tug's resistance creates high steering forces without increasing ship's speed. The tug itself uses most of its engine power to stay free from a ship's hull and this results in additional towline force.

With a good conventional tug forward on a line, sideways forces on a ship can be exerted by applying rudder whilst at the same time the tug is counteracting the turn as shown in figure 4.15. The effect is greatest at low ship's speed with not too heavy ships. A similar method – rudder hard over towards the berth, engine on dead slow ahead and the forward tug pulling off the berth – can be applied when unberthing with just one tug. Care should be taken not to overtake the tug.

When forward tugs towing on a line give steering assistance, this generally results in a force vector tending to increase ship's speed. There is another important aspect to be aware of when tugs operate on a line – they often have a tendency to keep towlines tight when no assistance is required. This also has an unwanted speed increasing effect on the assisted vessel and should be avoided as much as possible. Pilots therefore often order tugs to keep the towline slack when no assistance is required.

When reverse-tractor tugs, and ASD-tugs operating as reverse-tractor tugs, assist as a forward tug on a line they operate in a similar way to a tractor tug but with the tug's bow directed towards the ship's bow. These tugs have a comparable performance to tractor tugs and the difference in effectiveness depends on the same factors as mentioned earlier when discussing the direct towing method. See also paragraph 6.3.12, section operating bow-to-bow.

Stern tugs towing on a line

For tugs operating as a stern tug on a line the situation is totally different. It depends entirely on the type of tug and ship's speed whether steering assistance can be given to both sides. From the point of view of assistance it is also very important whether a stern tug can control a ship's speed. Whether this is possible or not depends also on the type of tug and ship's speed.

In figure 4.14C a tractor tug is shown again. At lower speeds a tractor tug can give steering assistance by the direct towing method (see position 1a, 1b). Giving steering assistance in position 1b will not increase the ship's speed. On the contrary, in this position braking forces are also applied. A speed increasing force vector is applied in position 1a. In position 1a a tractor tug is less effective than the conventional tug of figure 4.14D (position 1). This situation is comparable to that of forward tugs towing on a line, as previously discussed. If required, a tractor tug can easily change from positions 1 to position 2 for speed control or to a position to give steering assistance to port. Even at higher speeds (e.g. seven knots) a tug can safely swing around from position 1a to position 2 owing to the aft location of the towing point. In some ports position 1a, instead of position 2, is also used as a standby position.

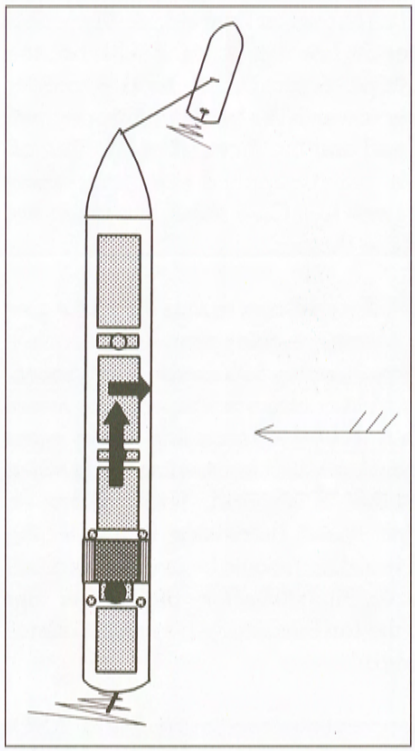

Figure 4.15
When port helm is applied and the tug pulls to starboard to counteract the port swing initiated by the port rudder, the ship drifts less by the wind or even moves a little crosswise to starboard. A similar manoeuvre can be utilised when unberthing with the assistance of one tug forward

At higher speeds the indirect towing method is normally used for steering control (see position 1c). Steering assistance at higher speeds can be given to port as well as to starboard. At the same time the tug is able to control the ship's speed.

ASD-tugs and reverse-tractor type tugs perform in a similar way, but with the tug's bow now directed to the ship's stern. An ASD/reverse-tractor tug will generally be somewhat less effective than a tractor tug when using the indirect towing method for steering assistance. The factors influencing performance and effectiveness of these tugs in comparison to tractor tugs have already been mentioned when discussing the indirect and direct towing methods.

A conventional tug can only give steering assistance to one side; in figure 4.14D this is only to starboard. When giving steering assistance a conventional tug delivers longitudinal forces which may increase a ship's speed. Moving to a position to starboard of the ship's stern, for instance, to give steering assistance to port or to compensate for wind or current forces at that side is impossible at speeds higher than one to two knots.

At speeds over about three knots, it is dangerous to manoeuvre from position 1 to position 2 in order to control the ship's speed. A tug may come broadside on with too high towline forces and may capsize unless the towline is released in time by the quick release mechanism. When a tug is equipped with a gob rope winch, by which the towing point can be transferred to a position at the after end of the tug, the tug can swing around from position 1 to position 2 at somewhat higher speed.

At very low speeds, of not more than about three knots, conventional tugs can move from position 1 to a position broadside astern the ship as shown in figure 4.5 (see also figure 7.5). The tug then lying broadside on can give steering assistance to both sides. Twin screw tugs often don't need a gob rope to operate in a similar way, owing to their higher manoeuvrability.

It is clear that at speeds above about three knots, only steering assistance can be given and only to one side. At very low speeds steering assistance can be given to both sides and a ship's speed can be controlled. A conventional tug is very restricted in its movements as a stern tug owing to the location of the towing point.

When a conventional tug is working close to or behind a ship's stern, a ship should be very careful in using its propeller or the tug might be overturned by propeller wash. A tractor tug and ASD/reverse-tractor tug, on the other hand, will in general not be hindered by ship's propeller wash due to the location of the towing point near the tug's stern or bow. If working on a short towline, however, excessive vibration of the azimuth propellers may be experienced, due to the turbulence from the ship's propeller. Lengthening the towline will reduce this effect.

A tractor tug, approaching a ship sternwards, experiences the influence of a ship's propeller wash on the skeg. Careful steering is then required to keep the tug on a straight course. This is also the case when the tug is secured and has to stay straight behind the vessel, as mentioned while discussing direct and indirect towing methods.

From the above it is clear that prior to securing tugs forward or aft the position of the different tug types in general and of conventional stern tugs in particular should be well considered, taking into account the forces of wind and current to be compensated, bends to be taken, etc.

Each type of tug has several versions with varying capabilities, which should be regarded as well when positioning tugs. A twin screw conventional tug, for instance, will generally perform better than a single screw tug. The same applies to a conventional tug equipped with a radial towing arm. This will increase a tug's capabilities and safety compared to the same tug without such an arrangement. In addition to what has been discussed already, therefore, performance and safety of a conventional tug depend largely on good manoeuvrability and appropriate towing equipment. Also, combi-tugs with their azimuth bow thruster have better capabilities than ordinary conventional tugs, especially when a combi-tug's towing point can be shifted to an alternative position far aft. The capabilities of these tugs were explained in paragraph 2.4.

Tugs operating at a ship's side

Tugs operating at a ship's side while the ship has some speed are shown in figure 4.16. Three types are

shown – a tractor tug (which can be a VS tug or one with azimuth propulsion), an ASD/reverse-tractor tug and a conventional tug.

Pushing mode

Whether one type of tug is more efficient in pushing than another depends on how well a tug can push effectively without increasing ship's speed. The better a tug can work at right angles to the hull of a vessel underway, the more effective it is. It depends largely on the ratio a:b (see figure 4.16A): the relationship between the lever of propulsion (P–Pu) and the lever of hydrodynamic forces (C–Pu). The better a tug can overcome the turning moment resulting from hydrodynamic force by the moment created by sideways thrust of the propulsion, the better a tug can work at right angles to the ship and the more power is available for pushing. In addition, the vertical location of the centre of pressure, stability and freeboard are important factors. Tug fendering should prevent a tug sliding along a ship's hull, otherwise one or two towlines are required.

Owing to its aft lying centre of pressure a conventional tug may find it difficult to come to or remain at right angles when a ship has speed through the water. Conventional tugs generally have a large underwater plane and an important consideration for effective pushing is steering performance, which is less than that of tugs with omnidirectional propulsion systems. Depending on the situation conventional tugs use stern lines to stay at right angles to a ship's hull when the ship gathers speed, as shown in figure 3.2. However, excessive speed impairs safety as the line may part or result in capsizing the tug. Devices increasing the steering performance of conventional tugs, such as high lift rudders and Towmaster systems, increase their pushing capabilities.

The ASD/reverse-tractor tug with its highly efficient steering propellers and the far aft lying propulsion in combination with a generally more forward lying centre of pressure is very effective at pushing. Tug company C.H. Cates & Sons of Vancouver claims that their reverse-tractor tugs can deliver a 90° side push at ship speeds up to eight knots instead of the usual four knots for conventional tugs. Three to four knots is generally the maximum speed for effective pushing by conventional tugs, although it depends on their engine power and propeller/rudder configuration. Tractor tugs are also much more effective than conventional tugs due to their omnidirectional propulsion.

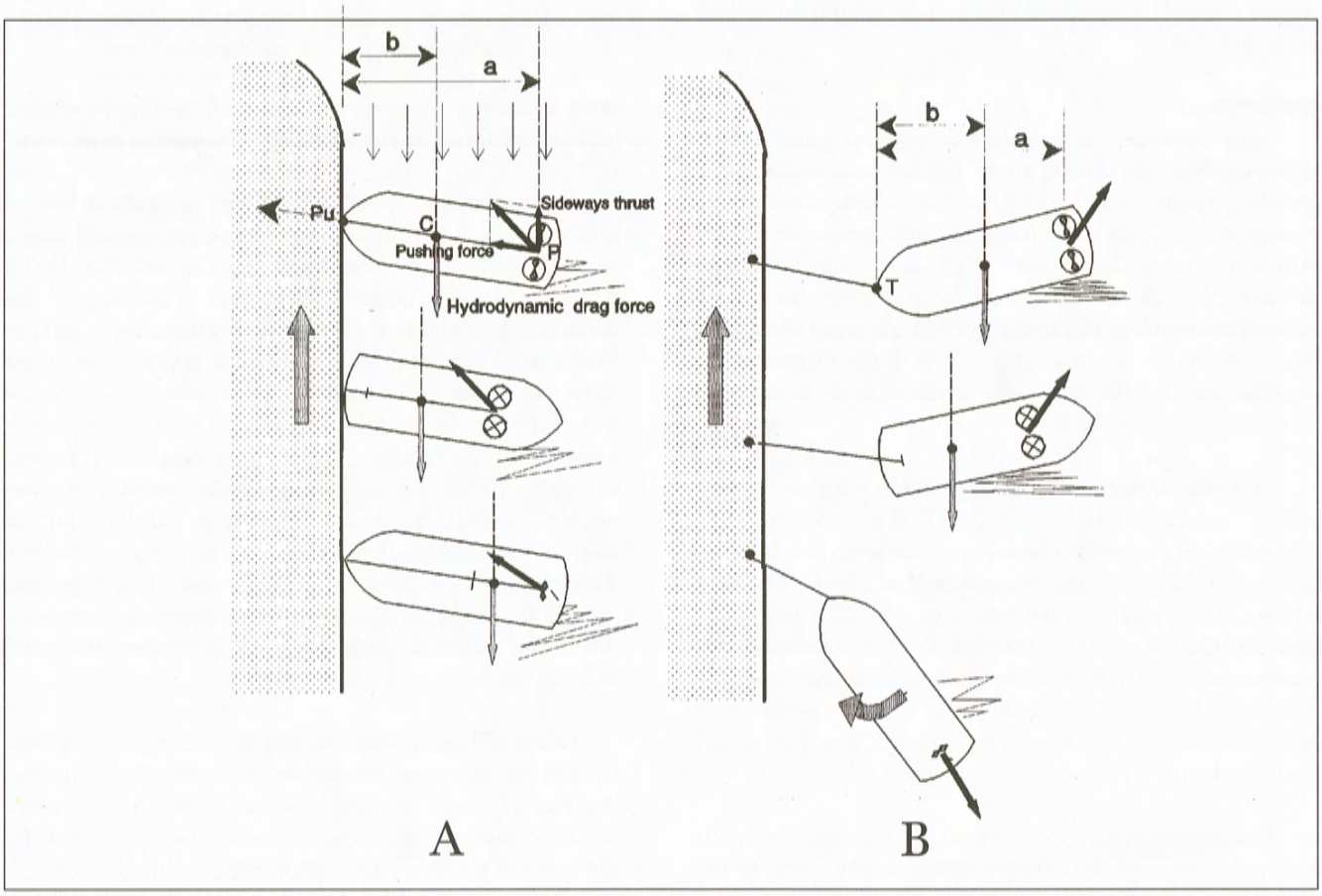

Fig. 4.16 Comparison of performance of tug types when pushing or pulling

Comparison of different tug types when pushing or pulling at a ship's side. The ship has headway. Locations of the lateral centre of pressure are approximated. Apart from the underwater resistance tug performance depends on: a) maximum heel; b) propulsion performance – omnidirectional propulsion systems are very suitable owing to the possibility of applying forces in any required direction; c) ratio a:b (a = distance between propulsion and pushing or towing point, b = distance between lateral centre of pressure and pushing or towing point. The larger the lever a in relation to lever b the less side thrust required to keep position and the more thrust available for effective pushing or pulling

Whether tractor tugs are more or less effective than ASD reverse-tractor tugs depends on the ratio a:b as shown in figure 4.16A, the tug's underwater body, its engine power and thrust performance in the required direction.

There is another aspect which determines a tug's capability for operating at the ship's side, viz. the maximum heeling angle. In this respect the height of the pushing point is important. The heeling moment caused by hydrodynamic forces increases by the speed squared. This is counteracted by sideways steering forces and by a tug's stability. The higher the pushing point the larger the heeling moment and the less it can be compensated for.

Conventional tugs, due to their large underwater plane, experience heeling moments which are more difficult to compensate for by their lower steering forces. Wide beam tractor tugs and ASD/reverse-tractor tugs with their effective and – for tractor tugs – deep set steering power, are in a much better position to compensate for heeling moments. As said, they are capable of remaining at right angles to a ship's hull at much higher speeds than conventional tugs. At high ship speeds, tugs can push at a smaller angle. Lift forces also create pushing forces, which can be rather high (see figure 4.17). This effect can be seen in graphical format in figure 4.20.

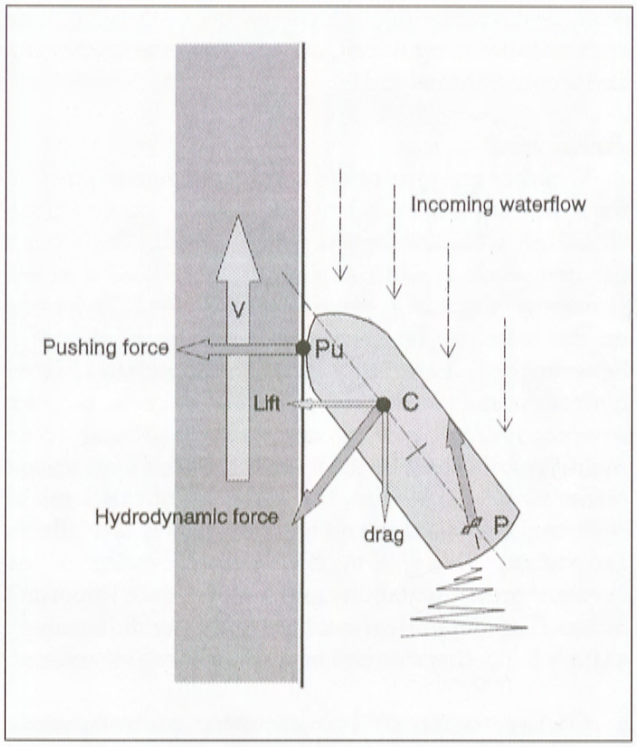

Fig. 4.17 Pushing force created by hydrodynamic force on a tug's hull
A tug keeping position at an angle with the ship's hull may also exert rather high pushing forces caused by the waterflow, depending on the ship's speed and the tug's underwater hull form

Pulling mode

Tugs operating at a ship's side need good astern power, which should be about the same as their ahead power. Tugs with omnidirectional propulsion are therefore very suitable for push-pull work. In figure 4.16B, the same three types of tug are pulling, secured with one line. The ship is underway through the water. The situation does not differ very much from situations when stern tugs are towing on a line in the direct mode, as discussed earlier. Only for conventional tugs is the situation rather different.

The longer tugs can pull effectively with increasing ship speed the better. It is obvious that the conventional tug will swing around. The tug needs a stern line leading forward to be able to pull at right angles. For the situation shown, the paddle-wheel effect of the tug's propeller also adds to the swinging motion. Tugs with twin screws, steering nozzles, a Towmaster system or flanking rudders perform better. The maximum ship's speed with conventional tugs pulling, even using a stern line, can only be low.

Tractor and ASD/reverse-tractor tugs perform much better, because while pulling they can apply forces in the direction of ship's movement. That is a big advantage of omnidirectional propulsion systems engaged in push-pull operations. Whether one of these types is more effective than another depends on the same factors mentioned when discussing the direct towing method, namely the ratio a:b, a tug's underwater size and profile, its engine power and thrust performance in the pulling direction.

An important aspect to take into account is loss of pulling efficiency due to a tug's propeller wash hitting a ship's hull. This force can be as large as its bollard pull, sometimes even larger. The effect is far less if the distance between tug propeller and ship's hull is increased. Tractor tugs therefore push and pull with their stern so as to keep their propellers as far away as possible from a ship's hull. In addition, tractor tugs with azimuth propellers, when pulling, can set their propeller thrusters at an angle, thus diverting the propeller wash. The same applies to ASD/reverse-tractor tugs. Higher pulling effectiveness can also be achieved using a longer towline. This can only be done when only pulling is required, not pulling and pushing, otherwise it lengthens response time. The effect of propeller wash is further discussed in Chapter 6.

When changing from pulling to pushing tug captains should be aware of the dynamic forces in a towline. Particularly with a steep towline angle and in wave conditions these forces may draw the tug quickly in the direction of the ship when its engine is suddenly stopped. When stern thrust is also applied a tug may hit a ship's hull with force (see figure 4.18). See also the note at the end of paragraph 6.3.2 regarding damage to ships caused by tugs.

Stopping assistance

From the foregoing it is also clear that ASD-tugs, reverse-tractor tugs and tractor tugs operating at a ship's side have better performance when braking assistance is required than normal conventional tugs. This is due to omnidirectional propulsion, which provides almost the same bollard pull astern as ahead.

Summary

Many differences in performance, capabilities and limitations of different tug types have been reviewed. For the reader's convenience a brief summary follows of the most important aspects. It is assumed that all tugs discussed are suitable for their tasks and have the required stability, sufficient freeboard, proper towing equipment and manoeuvrability.

Conventional tugs

Conventional tugs can be very effective when towing on a line a ship having speed through the water. They can assist in steering and in compensating wind and current forces, but often also deliver an unwanted force which increases a ship's speed.

As forward tug on a line a conventional tug can assist in steering to both sides but as stern tug it has its limitations. At higher speeds, steering assistance can only be given to one side. Only at very low speeds is steering control to both sides and control of ship's speed possible.

As both a forward and a stern tug, capsizing (girting) is possible as a result of the position of the towing point in combination with induced strong transverse forces. To minimise risk of girting a completely reliable quick release system should be used. A radial towing hook or equivalent system also decreases the risk of capsizing.

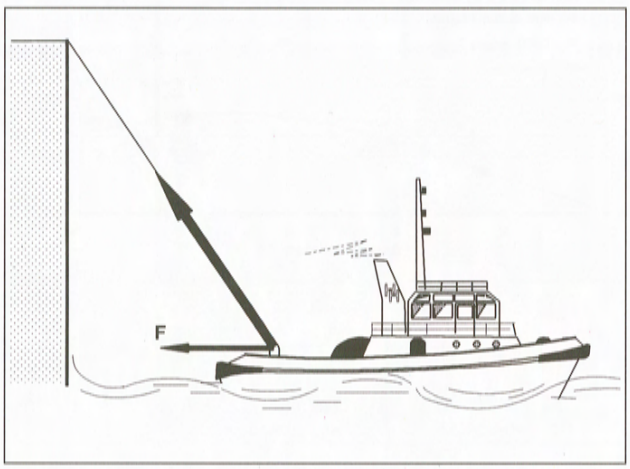

Figure 4.18 Effect of dynamic forces in the tow line
Pulling with a short and steep towline creates high forces in the towline, which are very much enlarged by waves and swell. As soon as tug engines are stopped, the tug will immediately be pulled backwards towards the ship by force F caused by stored energy in the elastic towline. So, when the tug captain is asked to stop pulling he should be aware of this effect and when ordered to change over from pulling to pushing, astern thrust should be applied very carefully

The ability to provide stopping assistance is nil for forward tugs towing on a line and limited to very low speeds for stern tugs towing on a line. Ship's engines should be handled with care when conventional tugs are close to the stern. Due to these limitations as a stern tug, tug positions should be carefully planned in advance.

The pushing effectiveness of conventional tugs decreases quickly with increasing ship's speed; pulling is only possible at zero or low speeds, depending on whether a stern line is used. Ship's speed should be carefully controlled so as to take account of the limited capabilities of a conventional tug operating at a ship's side.

Tractor and reverse-tractor tugs

Tractor and reverse-tractor tugs towing on a line as forward tug are able to render assistance to both sides. As forward tugs only steering assistance can be given, and these tugs may also deliver an unwanted force which increases a ship's speed. As forward tug these tugs are not as effective as conventional tugs for a ship underway at speed.

As stern tug, reverse-tractor and tractor tugs perform very well. They can provide steering assistance to both sides and control a ship's speed even at rather high speeds, although a reverse-tractor tug is generally somewhat less effective than (VS) tractor tugs in providing steering assistance at higher speeds (indirect mode). Risk of capsizing hardly exists during normal port operations and when operating as stern tug, they are hardly affected by a ship's propeller movements.

Tractor and reverse-tractor tugs operating at the side of a ship at speed through the water are effective in pushing and pulling and in applying braking forces. It should be noted that tractor tugs have a relatively large maximum draft, which can be a disadvantage in shallow waters.

ASD-tugs

ASD-tugs are multi-functional and can be effective as a forward tug on a line when operating as conventional tug. As forward tug, ASD-tugs can also operate as a reverse-tractor tug. As stern tug on a line ASD-tugs generally operate as a reverse-tractor tug with the same high performance. When pushing and pulling at the side of a ship at speed, ASD-tugs are very effective, also in applying braking forces.

4.3.2 Effectiveness of tug types

Model testing and full scale trials have been used to determine tug capabilities. Most tests focus on the abilities of one specific tug or tug type. Voith has done, and still does, considerable work regarding VS tractor tugs. Aquamaster has carried out several studies regarding tugs with azimuth propellers. Recent studies and full scale trials that have been undertaken mainly assess specific tugs and tug type escorting capabilities.

Most of these studies and trials, therefore, only involve some specific aspects of ship assisting manoeuvres required during daily tug handling. Of course, several variations in the design of a specific type of tug exist.

Simulation programs provide the possibility of gaining insight into a more extensive range of a tug's ability using, for example, a full mission bridge simulator. When these programs are carried out in close cooperation with pilots and tug captains and are, as far as possible, verified in full scale sea trials, the results give quite high reliability. Simulations are mainly carried out for one specific tug or for a very limited number of tugs of which all details of rudder, propulsion, stability, maximum list, hydrodynamic coefficients and so on are known.

Desktop computer simulation programs exist, based on a steady situation – equilibrium of forces – by which the performance of different tugs and tug types can be determined. With these simulation programs capabilities produced by different variations of tug design can be predicted.

Simulation programs don't normally take into account all factors influencing tug performance, such as ship-tug interaction, flow field around a ship, influence of water depth and confinement on the flow field, and the influence of ship's wake on a tug's braking performance, which are discussed in Chapters 6 and 8. There may, therefore, be some inaccuracy in simulation results, depending on the situation.

Real capabilities and in particular limitations are, of course, experienced during daily shiphandling only, but the results of simulation programs can verify some of what is explained in this book.

Performance diagrams

Performance of a conventional and an ASD-tug when pushing at a ship underway at speed

The graphs in figures 4.19 and 4.20 are based on simulation studies and provide an insight into the capabilities of a conventional tug and an ASD-tug when pushing.

The conventional tug has twin screws and three rudders, length overall of 40m, beam 11m, 5750 BHP (open propellers), 50t bollard pull and draft 17ft. The maximum pushing forces of this tug were determined at various ship's speeds taking into account, amongst other things, maximum heel at deck edge immersion. The graph shows maximum transverse pushing forces and the longitudinal forces exerted at the same time. It also shows the tug's pushing angle. The tug is pushing with a bow line.

As indicated in the graph, the pushing angle becomes smaller as soon as the ship gathers speed. The transverse pushing forces exerted by this tug decrease with ship's speed higher than five knots, but longitudinal forces increase very quickly at speeds above four knots. These longitudinal forces increase ship speed.

When no bow line is used the longitudinal forces but also the transverse forces exerted at speeds higher than five knots are less, so tug performance is less. In waves of approximately six feet high, tug performance drops quickly at speeds higher than three knots.

According to the same study, the effectiveness of conventional tugs with inferior rudder performance decreases quickly at ship speeds of about four knots.

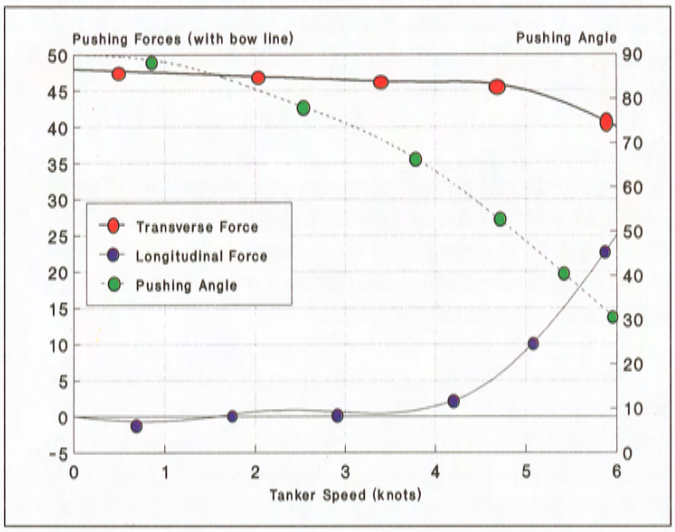

Figure 4.19 Performance and behaviour of a 40m conventional tug

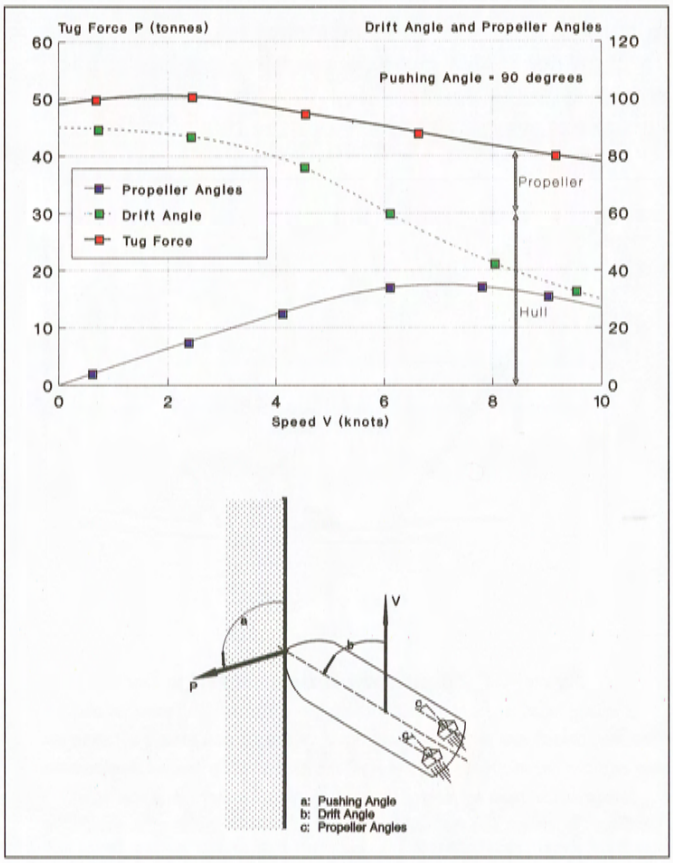

Figure 4.20 Performance and behaviour of a 30m ASD-tug for pushing

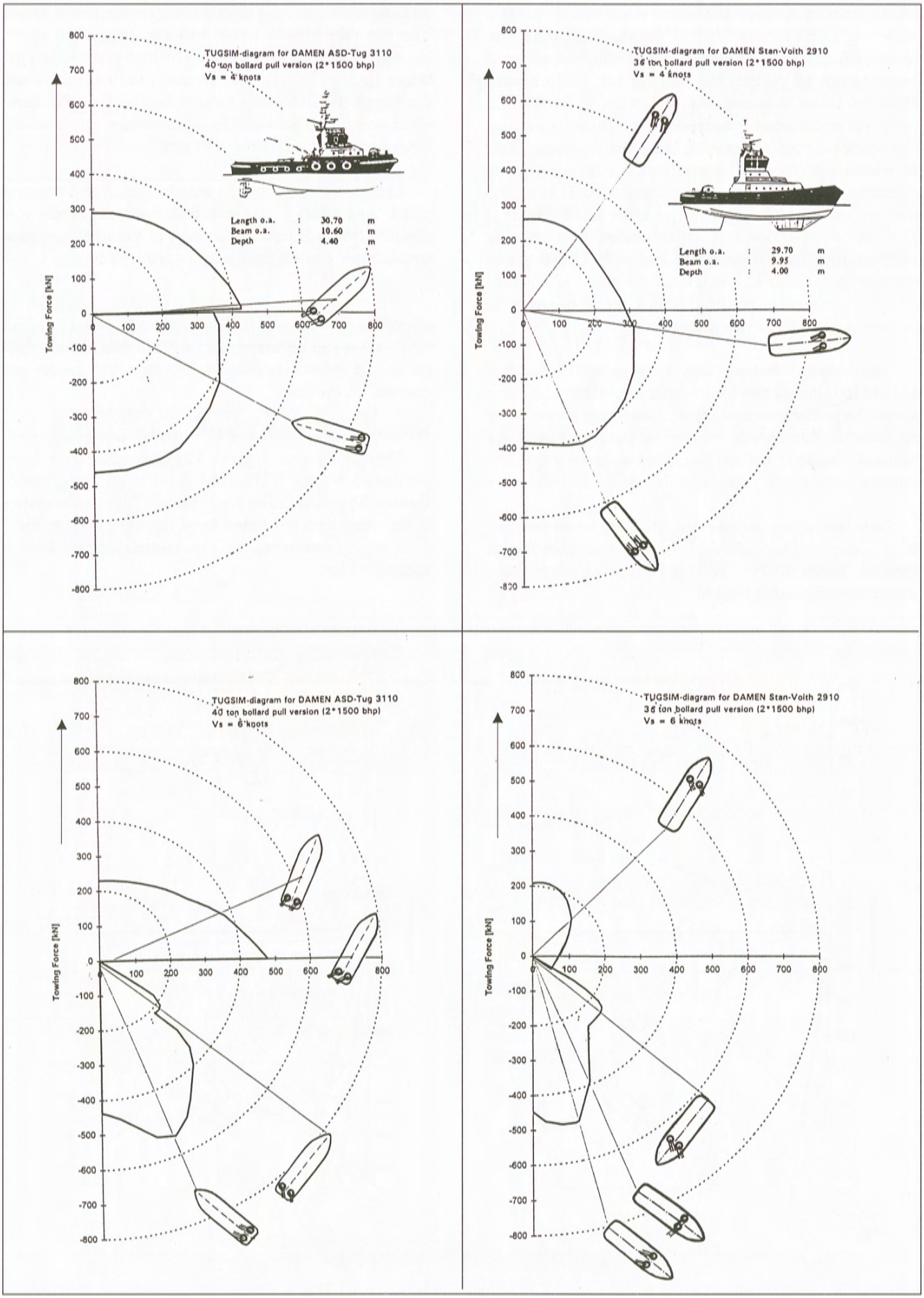

Figure 4.21 Performance graphs for four and six knots speed

In practice a speed of five or even four knots is a rather high limit for conventional tugs to exert transverse forces effectively. The study results may be affected because not all factors influencing tug performance could be taken into account. Naturally, differences in performance exist between various types of conventional tugs. In general, however, the upper limit at which effective sideways pushing forces can be exerted is found to be about three knots. This is also proven by full scale trials in the USA in 1982 with a 1700 HP twin screw tug with nozzles, two steering rudders, four flanking rudders and without the use of auxiliary towlines. The length of the tug was 30m. In addition, effective pulling forces were possible at maximum speeds of less than one knot.

The main conclusion is that at ship speeds higher than around four knots, and for less manoeuvrable tugs three knots, the performance of conventional tugs is very poor. At these higher speeds transverse pushing forces are minimal, but longitudinal forces increase very quickly, thus increasing ship's speed, which is not desirable.

Next the performance of an ASD-tug when pushing is considered. Particulars of the tug are: 31m length overall, beam 10·7m, 3600 BHP, 50t bollard pull, maximum allowable heel 6°.

As can be seen in the graph this tug performs very well. The tug exerts only transverse forces and no speed increasing longitudinal forces. The higher the speed the larger the hydrodynamic forces on the tug's hull and the larger the lift forces created by the hull. At about eight and a half knots, 80% of the transverse pushing force is developed by the lift force.

Tug stability, freeboard and height of the pushing point have a large influence on maximum achievable pushing forces. Limiting factors are maximum engine revolutions, engine torque and excessive heel.

The two graphs show a large difference in pushing effectiveness between ASD and conventional tugs. An ASD-tug is still effective at a much higher speed while no ship's speed increasing longitudinal forces are exerted on the ship.

Performance of an ASD and VS tug while towing on a line

These diagrams (figures 4.21 and 4.22) have been produced by the TUGSIM simulation program of Damen Shipyards, The Netherlands. Tug performance in the diagrams is limited by a tug's maximum list – deck edge immersion, and maximum engine load is accounted for.

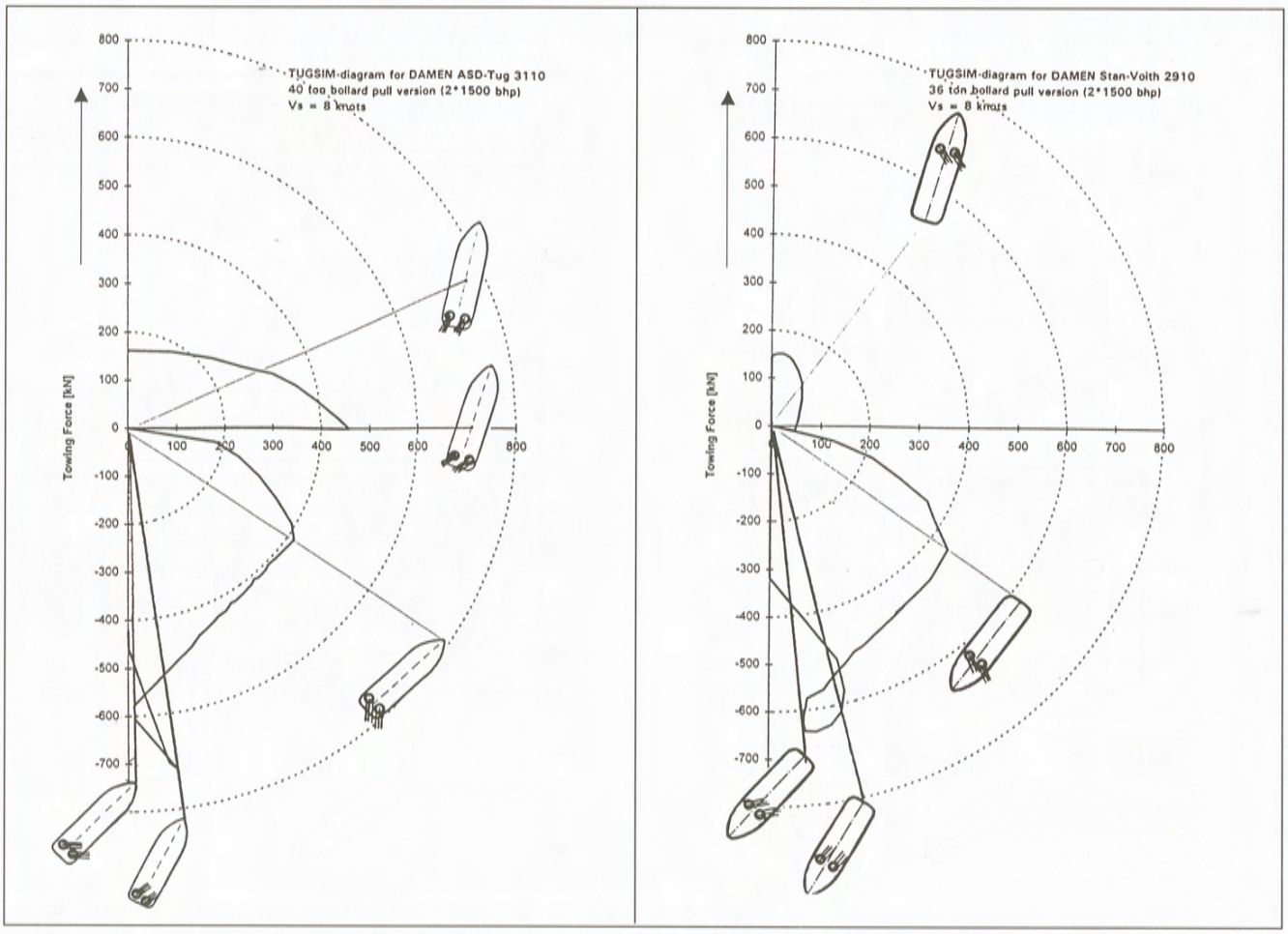

Figure 4.22 Performance graphs for eight knots speed

The TUGSIM program operator actually steers the tug, controlling the rudder and/or thrust angles and thrust magnitude. This prevents theoretical solutions being calculated in which a steady situation exists, but situations in which the tug could never be manoeuvred.

The graphs show an ASD and a VS tug towing on a line at different speeds – four, six and eight knots. Particulars of the tugs are given at the top of the graphs. The main objective of the graphs is to show the maximum steering and braking forces which can be achieved.

The ship is at the centre O of the graph, sailing in the direction indicated by the arrow. The ASD-tug is operating as forward tug up to a towing angle of 90° as conventional tug and as stern tug the ASD-tug operates as a reverse-tractor tug. As stern tugs the ASD and VS tugs operate in the direct or indirect mode, whichever is the most effective.

The following general characteristics can be seen in the graphs. The performance of the VS tug in giving steering assistance as forward tug towing on a line decreases quickly with increasing speed, while up to a speed of about six knots the performance of the ASD-tug in giving steering assistance is decreasing much less at small towing angles and is even increasing at large towing angles. At eight knots the ASD-tug can still produce high steering forces in contrast to the VS tug. Normal conventional tugs often perform in a similar way, but are generally limited more by the tug's stability.

At four knots the tugs operate as stern tugs in the direct mode and are both effective.

At six knots the ASD-tug performs better in the direct mode, while the VS tug starts to perform better in the indirect mode in applying steering forces. The braking performance of both tugs in the direct mode is high.

At eight knots and in the indirect mode high steering forces can be applied by both tugs. The VS tug is somewhat more effective, although it is less powerful than the ASD-tug.

Highest braking forces are achievable at speeds of eight knots by both tugs operating in the direct mode and towing at a small angle (lowest part of the curve). Both tugs perform about the same when taking into account the difference in bollard pull.

Thus the following generalities can be observed. As a forward tug towing on a line the ASD-tug performs better. As a stern tug on a line and at higher speeds the VS tug performs rather better in giving steering assistance and the ASD-tug and VS tug perform about the same in applying braking forces. Another aspect is clearly shown in the graphs: the speed increasing force vector of forward tugs towing on a line. For example, take the ASD-tug of the six knots graph while towing on a line as forward tug. The tug as shown in the indicated position develops a steering force to starboard of 35 tons, but at the same time a force in the direction of ship's movement of about 15 tons. This force increases the ship's speed, which is in most cases not welcome.

On the other hand, all the stern tugs as shown in the graphs when applying steering forces also develop braking forces. This normally has a large positive effect. It keeps the ship's speed low and, in addition, enables the ship to apply additional engine power for steering, without increasing the ship's speed. All this is in line with the capabilities and limitations of tugs as discussed.

Speed control – braking assistance

Tractor, ASD and reverse-tractor tugs perform very well as stern tugs for steering assistance and speed control. This has resulted in competition between the designers of cycloidal propellers (VS) and azimuth propellers (Aquamaster) about which type of tug, VS or ASD, performs best as stern tug at higher speeds. This is mainly due to the discussions with respect to escorting, dealt with in Chapter 9. However, one aspect is briefly discussed here, the braking performance of tugs equipped with azimuth thrusters, because it is important for daily assistance in ports. In this respect some new terms have been introduced by Aquamaster.

It should be noted that when stopping assistance is required by a VS tractor tug or ASD/reverse-tractor tug, for instance at speeds of more than five knots, the braking force that can be applied is higher when the tug is pulling at a small angle with the ship's centre line rather than pulling straight astern, as can be seen in the TUGSIM performance graphs.

When braking assistance is required at high speeds by a conventional tug operating over the bow as stern tug, it may not be possible to reverse fixed pitch propellers due to the high propeller load which has to be overcome by the engine, although the effect of it can be reduced by proper design and tuning of the engine. For the same reason, at a crash stop VS pitch levers should be set in accordance with the ship's speed and azimuth thrusters have to be rotated to astern but can be set, with independently controlled thrusters, at an angle with the tug's centre line to avoid stalling. In the case of azimuth thrusters with controllable pitch propellers, astern pitch should be applied in accordance with ship's speed when a ship having a rather high speed has to be stopped. Because of the low performance of controllable pitch propellers going astern, turning the thrusters like thrusters with fixed pitch propellers is more effective in applying braking assistance.

In the direct assisting method, Aquamaster claims that at speeds of up to eight knots braking forces can reach values up to one and a half times the bollard pull

astern with azimuth thrusters (of ASD/reverse-tractor as well as tractor tugs) rotated 180°, the thrusters thus working in line with the tug's centre line in negative flow. At speeds higher than eight knots braking forces drop off dramatically, regardless of the power applied. Engine load then also increases rapidly to an overload condition. This braking method is called the Reverse Arrest Mode by Aquamaster.

A second way of applying braking force in the direct assisting method is the so-called Transverse Arrest Mode. Large arresting forces can be created by pointing the thrusters outward at an angle of approximately 90°. These forces result from momentum drag and are generated when the propellers accelerate the athwartships component of the wash. The forces increase with speed and exceed the astern bollard pull at speeds higher than eight knots without overloading the engine.

So, below eight knots the Reverse Arrest Mode can be used (thrusters rotated 180° in line with the tug's centre line) and at speeds higher than eight knots the Transverse Arrest Mode (thrusters at an angle of 90° with tug's centre line) can be applied. See figures 9.5 and 9.7 for the different terms used and the achievable braking forces.

Although eight knots is a high speed for tug assistance in port areas, it is good to know how thrusters can be used to deliver high retarding forces. This way of applying braking forces can be utilised by all types of steerable thrusters, but is most efficient when using propellers in nozzles.

4.3.3 Effective tug position

Positioning tugs depends on several factors. Firstly, ship's particulars such as type, size, draft, windage, manoeuvrability have to be considered. Secondly, factors such as the influence of environmental conditions, particulars of the passage or fairway towards the berth, available stopping distance, size of turning circle, berth location, and so on have to be taken into account. Together these factors determine what should be expected from tugs – steering assistance, compensating external forces of wind and current, assistance in stopping the ship or a combination thereof. Ship's berthing side is also an important factor to be taken into account when positioning tugs. And, of course, it is very important to know the number, type and bollard pull of available tugs.

In figure 4.23 different tug positions are given. A ship has headway and has to make a turn to starboard. Tugs have to assist. Whether a particular type of tug is more or less effective in one or more of the positions shown has been discussed already and is summarised in paragraph 4.6. Attention now turns to the effect on a ship when tugs are operating in one of these positions. The location of the pivot point is taken into account.

Forward tug no. 1, towing on a line, is capable of exerting quite high crosswise steering forces on a ship. The effect can be limited because of the transverse forces near a ship's bow to be overcome, as explained when discussing the pivot point. It is clear that for a particular ship these transverse forces are proportional to the draft and underkeel clearance. Also, the more the tug is pulling in line with a ship's heading the more the tug will increase a ship's speed.

Position of tug no. 2 is not so good for the steering assistance required. The tug has to overcome the same transverse forces as tug no. 1, but the lever of crosswise steering forces exerted by the tug is much shorter and the tug's underwater resistance opposes the turn. Also, when a tug is unable to push at right angles to a ship's hull it will increase a ship's speed.

Regarding tug no. 2 it should be kept in mind that this tug might even have an opposite effect. Simulation studies carried out by, amongst others, Dr. Paul Brandner and described in his thesis 'Performance and effectiveness of omni-directional stern drive tugs' (see References) show that a tug pushing at the bow of a loaded tanker on a steady course, with an initial speed of four knots, the engine on Dead Slow Ahead and rudder amidships, has a tendency to turn against the

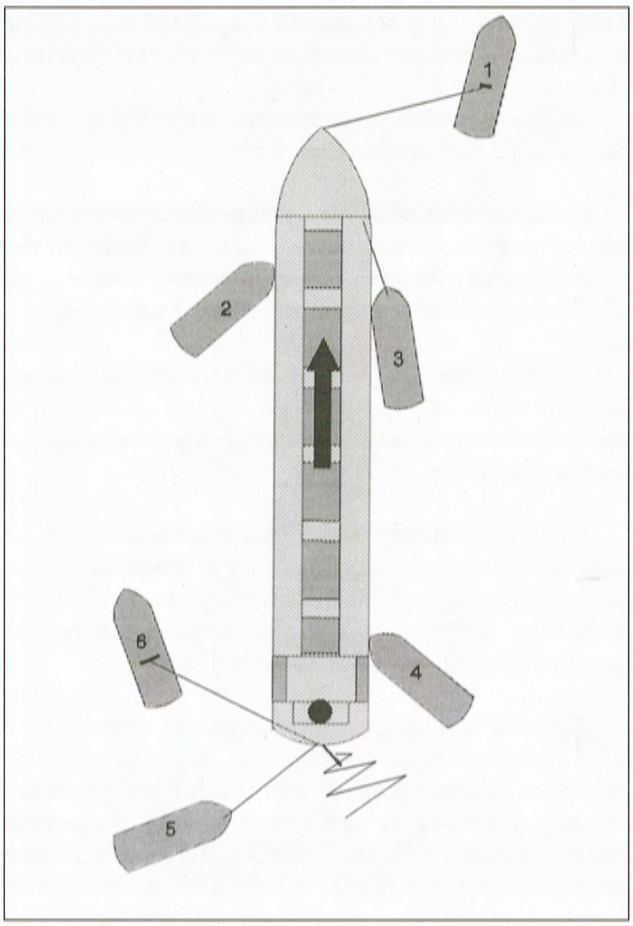

Figure 4.23 Different tug positions

pushing direction of the tug. The tests were carried out with a depth/draft ratio of 1.2. This effect has also been experienced during full scale trials. During these trials a loaded tanker was on a steady course at five knots speed, the rudder amidships, and the engine was stopped. A conventional tug started to push on the port shoulder.After an initial turn to starboard the ship started to turn to port, while speed increased.

It does in no way say that for other ship types or other loading conditions, the same effect might be experienced. The opposing transverse force at the bow differs by ship type, draft, trim and under keel clearance (see above for tug no. 1). In the report mentioned above, test results of other loading conditions are given. If the same tug is pushing at the shoulder of the tanker when in deep water, in ballast condition and trimmed by the stern, the tug does turn the tanker in the required direction and the effect does not differ much from a tug pushing at the quarter (tug no. 4).

Apart from what has just been mentioned, the positions of tugs no. 1 and 2 are not always inadequate. It depends on the situation and circumstances, because the tugs are in a good position to compensate for drift forces caused by wind and/or current from starboard. If required, tug no. 1 can easily compensate for the wind and current forces from port as well. This flexibility in operation is an advantage of the forward tug towing on a line.

Tug no. 3 can assist the starboard turn by going astern. In doing so, an additional starboard turning couple is created by the tug's and ship's engines working in opposite directions. By going astern the tug is slowing down ship's speed, and thus increasing the effect of the ship's engine on the rudder. The tug's underwater resistance contributes to the starboard swing. If tug no. 2 had a bow line, both tugs 2 and 3 are in a good position to take off ship's headway, if required.

Tug no. 4 is in an effective position to assist the starboard turn by pushing, because of the long lever and forward centred lateral resistance, which contribute to the swing. The tug's underwater resistance gives additional turning effect to starboard. When tug no. 4 cannot work at right angles, ship's speed increases, but as a result of the higher rate of turn caused by the pushing tug and consequently the higher drift angle, ship's speed is hardly affected. If the tug has a bowline secured, it could also assist in the starboard swing by going astern, in the same way as tug no. 3. In that case the whole tug has to be pulled crosswise through the water by the ship's stern and hence opposes the turn.

Tug no. 5 is in a very effective position. The longest possible lever for steering forces and the transverse forces centred forward contribute to the swing. Also, the tug does not increase ship's speed. On the contrary, the tug also provides retarding forces while applying steering assistance.

Tug no. 6 is in a similarly effective position to tug no. 5, but has the disadvantage that this tug increases ship's speed. The same would be the case with a rudder tug (not shown in figure 4.23).

The difference in effectiveness between a forward pushing and aft pushing tug can also be seen when a ship gathers speed. For instance, assume that tug no. 3 and no. 4 are of same type and bollard pull and both pushing at right angles. At zero speed the ship, on even keel, moves crosswise. For reasons explained, as soon as ship's speed increases, the effect of tug no. 3 is smaller than that of tug no. 4 and the ship starts turning to starboard. The same applies to tugs of similar capabilities when towing on a line forward and aft.

For swinging, e.g. when the ship is stopped in the turning circle, tugs no. 1 and 5 or 6 are in the best position due to the long lever of exerted tug forces.

The most effective tug positions have now been reviewed. Which positions should be used during passage towards a berth and while mooring/unmooring depends on what is required from the tugs and this depends on the ship, local situation, circumstances and ship's berthing side.

If steering assistance to starboard is required during passage towards a berth then tugs no. 3, 4, 5 and 6 are in a good position. Tug no. 5 can even give steering

Photo: Author

Figure 4.24 Two conventional tugs assisting a tanker having headway in making a starboard turn. The tugs are not in an effective pushing position and are also increasing the ship's speed due to their small pushing angle

assistance to both sides. The same would be the case with a rudder tug. If crosswise drift forces from port have to be compensated for in a narrow fairway, tugs no. 3 and 4 are in a good position and also tugs no. 1 (when this tug shifts to port), 5 and 6. In case stopping assistance is required tugs no. 2 and 3 (with bow lines) and 5 will assist effectively.

If tug assistance is required during mooring/unmooring operations then several combinations are possible, also depending on tug type. For mooring of large ships even four tugs may be used. Often tugs nos. 3 and 4 are used for pushing and 1 and 5/6 for controlling the approach speed towards the berth.

If tug no.1 is a tractor tug, reverse-tractor tug or ASD-tug operating as a reverse-tractor-tug, then tug no.1 together with tug no.5 can easily push as well as control the ship's approach speed towards the berth during mooring

Whether the required tug forces can be delivered effectively, depends on a correct assessment of the required bollard pull and the right choice of the type of tugs with respect to the tugs' positions and assisting methods.

4.3.4 Towing on a line compared with operating at a ship's side

In paragraph 3.2, different assisting methods were discussed. Which assisting method is most appropriate for a particular port depends on the local situation and circumstances. Nevertheless, it is good to have an idea about the advantages and disadvantages of the two basic methods. In paragraph 3.2 the small manoeuvring lane within which tugs towing on a line are able to operate and the limitations of tugs operating at a ship's side due to waves were mentioned. Taking into account the capabilities and limitations of tugs, the following additional comments are given.

Different types of tug can be used for towing on a line, some more effective than others. In a fairway passage towards a berth tugs are normally positioned so that the influence of wind and/or current can be compensated as much as possible and changes in heading can be made in a safe, efficient way. A ship can also berth either side using this system.

Towing on a line, therefore, has the advantage that tugs are normally positioned at the safe side of the ship and are flexible regarding berthing side. Even in the worst case, when wind and/or current are getting too strong, tugs on a line can assist up to the last moment, minimising the risk of severe damage.

When omnidirectional propulsion tugs are used for towing on a line they are able to change over to the push-pull method during berthing without the need to release the towline. This shortens berthing time, because no time is wasted in retrieving towlines or repositioning tugs. In addition, a ship can be kept under better control because towlines stay fastened while tugs either push or pull.

Tugs at a ship's side are positioned according to berthing side, to the forces of wind or current to be compensated for and/or the changes of heading to be made during transit towards a berth. When positioned to compensate for wind and/or current forces this may be the wrong position for berthing. Tugs then have to be shifted before mooring takes place – common practice in some ports. However, this means that a ship has no or little assistance during shifting of the tugs and may start drifting.

When positioned to compensate for wind and/or current forces, risk is involved for both tugs and ship when these forces are underestimated and a ship starts drifting. When it becomes too dangerous for the tugs they may try to get out from between the ship and the leeward or downstream fairway or channel banks, leaving the ship without any assistance.

4.4 Operational limits

Harbour tugs can operate in all conditions of current and wind. However, during fog the situation is different. Fog in confined port areas makes tug assistance very risky. In good visibility a tug captain assesses his position and speed in relation to the speed and heading of the attended ship, and also in relation to the surrounding area, such as buoys, beacons, river banks and quays. Compared to ship movements, tug movements are much faster, making it difficult to manoeuvre from the tug's radar. In addition, tugs often operate close to a ship's side, resulting in a distorted or partly blank radar picture. Furthermore, during fog a tug captain may lose a good view of his towline. Altogether this makes tug assistance during fog much more difficult than when visibility is good. For this reason restrictions on tug assistance under poor visibility conditions exist in a number of ports.

Several ports lie close to open sea and jetties may be situated in open waters. Consequently, tug assistance may also be required in open sea. For harbour tugs, passing towlines in wave conditions can be difficult. Harbour tugs operating at a ship's side have short and often rather steep towlines. When tugs operate on a wave exposed ship's side, dynamic forces in the towline may reach high values and lines are liable to part in deteriorating wave conditions. So, very strong and sometimes double fibre lines of high stretch properties are often used.

However, if circumstances permit, tugs can also change over to towing on a line, allowing them to handle a ship more safely since if towlines are longer they can