Understanding the pivot point

(Study on the sideways motion and rotation of ships)

By Capt. Hugues Cauvier

Introduction

The following text brings forward a new understanding of the pivot point's position shift while handling ships. The proposed method, based on simple physical principles acting in combination, also outlines the limitation of the term "pivot" used to qualify that point. We will start from a basic rule of the thumb, which has been the traditional understanding of the pivot point until recently, and step up to more complex levels giving better explanation of the real-life behaviour of rotating ships.

The current approach highlights the effects that a side force applied on the ship has on the rotation and on the sideways motion of the ship. The author believes that understanding these effects at any stage of manoeuvring is more important than strictly dealing with the pivot point. The text is formatted so the reader can stop his study when he reaches a level that suits his needs or curiosity.

This article will also describe the phenomenon of the *ship generated sideways current* which effects have become obvious during practical trials made to deepen the understanding of the pivot point.

After the theoretical part, you will find a section covering real life shiphandling situations for some of which the traditional concept of the pivot point has no answer.

Definition: The pivot point (or more precisely the "apparent pivot point") is that point along the fore and aft axis of a turning ship, that has no sideways movement, having for reference the surface of the water.

Level 1

The traditional theory: the pivot point is nearly at 1/3 ship's length from the bow when the ship is moving ahead, and between ¼ ship's length from the stern and the rudder post when going astern. The pivot point is considered to be the centre of leverage for forces acting on the ship.

Level 2

The pivot point is generally *at 1/3 ship's length from the bow when the ship is moving ahead, and between ¼ ship's length from the stern and the rudder post when going astern.* But if a powerful and effective lateral force is applied at one end of the vessel, the position of the pivot point will shift at about $1/3^{rd}$ ship's length from the other end of the ship (relative to the applied force).

Example of an Azipod* driven ship moving astern

A ship fitted with Azipod propulsion is backing slowly from a finger pier (fig. 1). According to the traditional theory, when a third of the vessel is out of the corner, knowing the pivot point when going astern is also clear (fig. 2), the ship should not touch if a 90 degrees kick towards the dock side is given in order to swing the bow open towards the river. In real life, it does not happen since the lateral kick pushes the bigger part of the ship sideways (2/3 rd) having for effect a pivot point approximately $1/3^{rd}$ ship's length from the bow (fig. 3)

*An Azipod driven ship was selected for this example since it can produce very effective side thrust without slowing the sternway. A very efficient tug pushing aft on a conventional ship would have a similar effect.

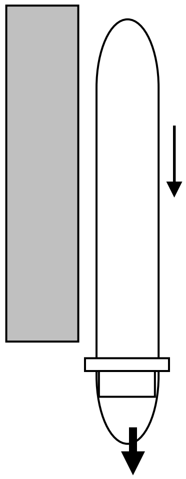


Fig. 1 Azipod driven ship moving astern

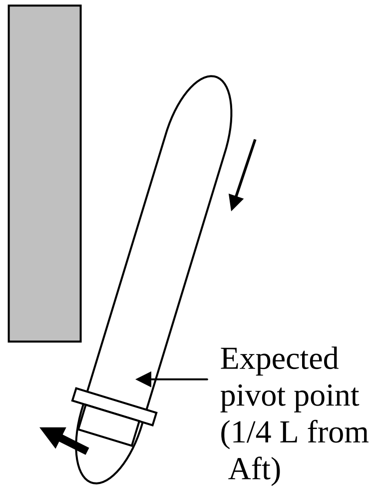


Fig. 2 Expected ship's position after a 90° kick to port (traditional theory)

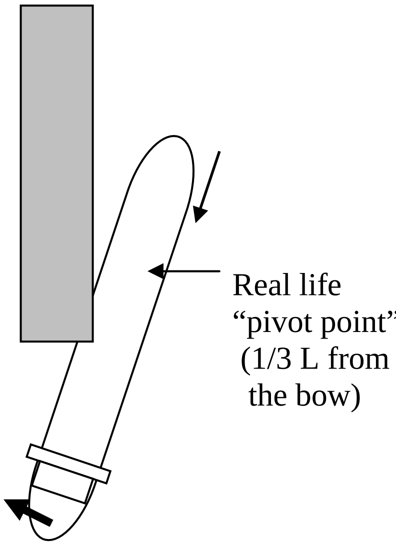


Fig. 3 Actual ship's position after stern lateral kick to port

Level 3

As we have seen in Level 2 the P.P. is not always *at 1/3 ship's length from the bow when the ship is moving ahead, and between ¼ ship's length from the stern and the rudder post when going astern.* If that rule is not always applying, it is simply because it is not a rule.

Here is the major bug in the traditional P.P. theory: imagine that you are pushing laterally on a point very close to the "so called" pivot point, let's say a little bit forward of it. If that point is really a "pivot", the part of the vessel forward of the P.P. should move in the direction of the push, and the part of the ship behind the P.P. should swing in the opposite direction. This would be true if the P.P. was a fixed axis and the ship was rotating around it. It does not happen that way because a ship is a floating object that can also bodily drift sideways when submitted to an effective lateral force. When a force is acting close to the "P.P.", it also pushes this point sideways – together with the ship - so the "pivot point" by this sudden lateral movement is then automatically losing the characteristic that gives it its name.

The position of the apparent pivot point is function of the efficient lateral force(s) applied on the ship. It is not caused by the headway or sternway.

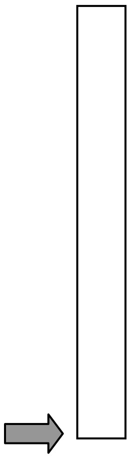
Basic physics principle: sideways motion + rotation

Let's suppose that you have a bar shape body floating on a friction free surface and you apply a lateral force on it at one end (fig 4). The resulting motion can be decomposed in two parts:

First, a moment of rotation about the centre of gravity (fig. 5). Secondly, a sideways bodily motion (fig. 6). These two results when combined will cause a change of position of the body as per fig. 7 after the force has been applied for a period of time.

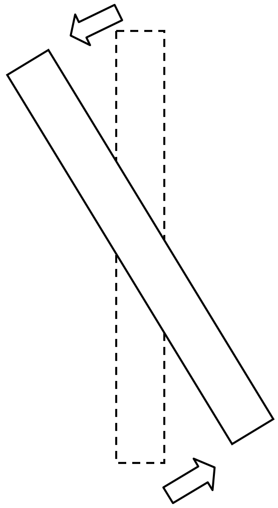
We realize that the part of the bar that has not changed position in space, the "apparent pivot point" (fig. 7), is not located at the centre of gravity but some distance off it, away from the end on which a force is applied.

fig. 4



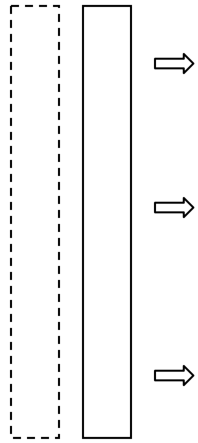
Force acting at one end of a free moving body

fig. 5



rotation

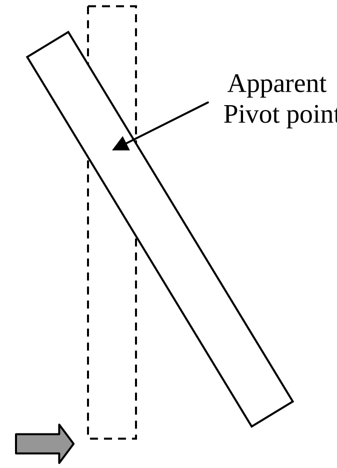
fig. 6



translation

I---------- Resulting motion decomposed ------------I

fig. 7



combined motion of rotation and translation

This basic principle applies to ships. It is the main reason why a ship turning has its P.P. at 1/3 ship's length from the bow, since that ship is submitted to the lateral component of the rudder force. The combined effect of the lateral motion and rotation have for consequence a "P.P." away from the acting lateral force.
That point that has no sideways movement, having for reference the surface of the water is the "Apparent Pivot Point". It has no other importance physically speaking. ~~*The pivot point is considered to be the centre of leverage for forces acting on the ship.*~~ The Apparent Pivot Point is <u>not</u> the centre of leverage of anything.
At port operation speed, the centre of leverage (point of the ship where an effective lateral force causes no rotation) is close to midship. A little more forward if the vessel is trimmed by the head, a little bit more aft if the vessel is trimmed by the stern (a little more means less than 10% ships length). This point is the Center of Lateral Resistance (see level 5.1)

<u>Level 4</u>

From this level on, we will add information that complete the basic principle of Level 3. In depth explanations will be given at Level 5.

- The closer to the centre of the ship (centre of lateral resistance) a force will be acting, the further away at the opposite end of the vessel the apparent pivot point will be. It can even lie outside the ship's physical limits (see level 5.2).
- Little under keel clearance brings the apparent pivot point closer to the centre of the ship (see level 5.3)
- When a ship is turning, but has no longer forces acting on it, the position of the apparent pivot point follows the traditional pattern: approx. 1/3rd ship's length from the bow when the ship is moving ahead, and 1/3rd ship's length from the stern when going astern (see level 5.4).
- A bulkier, wider vessel has an apparent pivot point closer to the bow when moving ahead and turning (see level 5.3)

<u>Level 5</u>

This level explains in detail the rules given in level 3 and 4

5.1 Center of lateral resistance *vs.* apparent pivot point

Let's make a clear distinction between : the *center of lateral resistance* and the *apparent pivot point*.

The center of lateral resistance (COLR):

At a given moment, the COLR of a vessel is that point where, if you apply an "effective" lateral force, no rotation (if the vessel has a steady heading) will occur. Acting on this point, a lateral force has no arm lever, therefore no turning moment, it only pushes the vessel sideways. A force acting ahead of the COLR will rotate the ship in a different direction than the same force acting astern of the COLR would do. The lateral resistance can also be called *hydraulic lift*.

The position of the COLR depends on:
- the centre of gravity
- the centre of the underwater surface area (hull shape and trim)
- the pressure fields around the hull

1) The starting point of the COLR is a point between the centre of gravity of the ship and the centre of underwater surface area, when these two do not coincide.
2) The position of the centre of the underwater surface for one ship is mainly affected by the trim. A trim by the stern moves the COLR point more aft. A trim by the head moves it more forward
3) The pressure field (bow wave, stern sub-pressure) under headway shifts the COLR forward. This is mainly due to the positive pressure built around the bow (in a forward motion) which creates a *more resistant* surface for the hull to lean on when pushed sideways. The same principle applies when going astern. For practical shiphandling purposes, the shift of the COLR due to the speed is rarely more than 10% of the ship's length in the direction of the ship's movement.

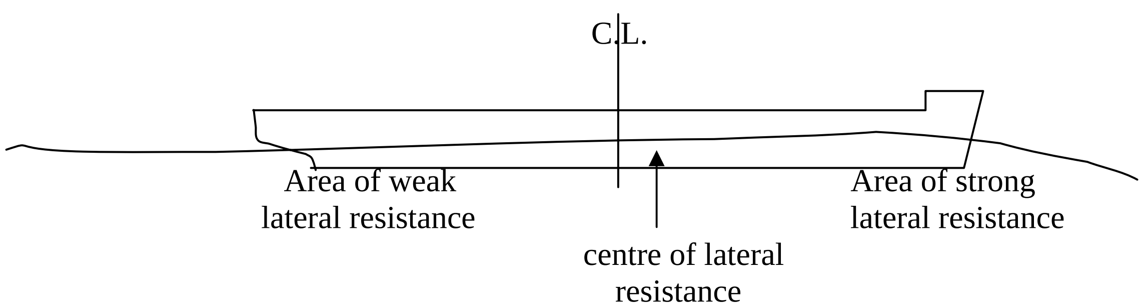


Fig. 8

The COLR is the *leaning point* for arm levers. It is not! the apparent pivot point. Actually these *two points almost never coincide*.

The "*apparent pivot point*" (or the pivot point as the mariners know it) :

the point, along the fore and aft axis of the ship, that has no sideways movement, having for reference the surface of the water.

Position of the apparent pivot point:

The position of the apparent pivot point at a given moment depends on:
- the hull underwater resistance to lateral movement,

- the <u>efficient</u> lateral force(s) applied on the vessel and,
- the inertia of rotation of the vessel

In order to estimate the position of the apparent pivot point we must assess how a lateral force will affect:
- the rotation of the vessel
- the sideways movement of the vessel (see level 3: basic physics principle)

For an easier understanding of the following demonstrations, the shiphandler will imagine his vessel being free to move on a non-friction surface.

5.2 <u>The position of the acting lateral force</u>

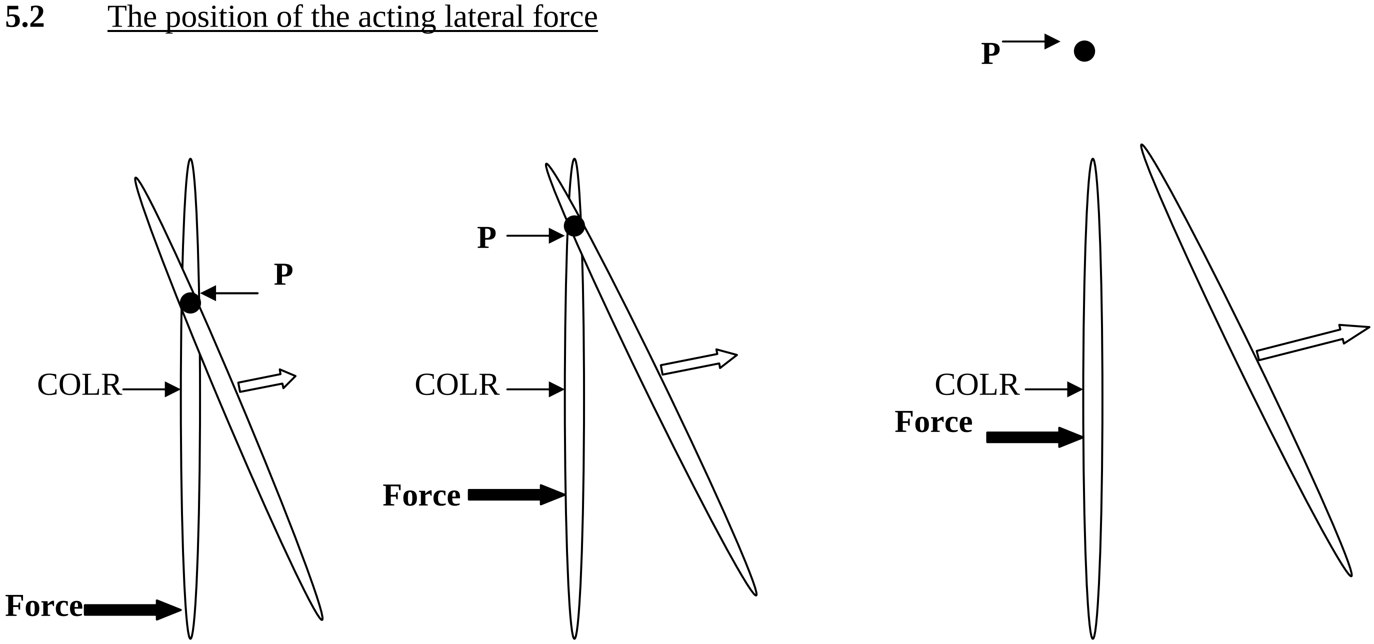


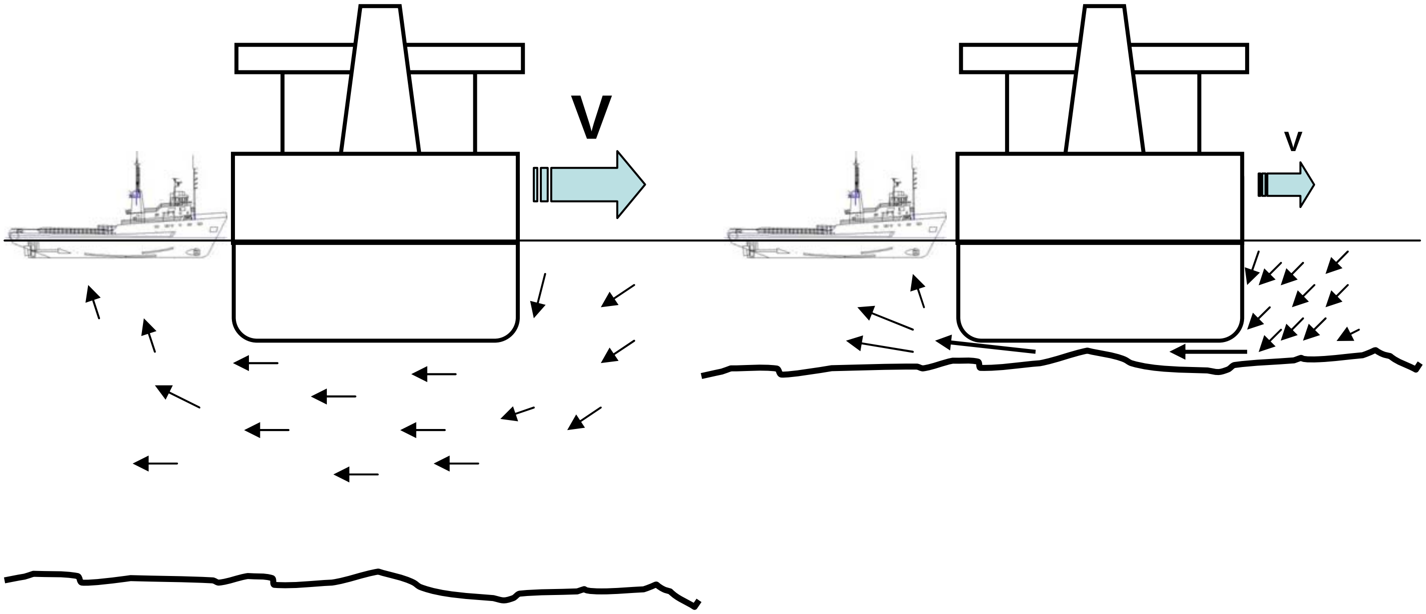
Fig. 9 **Fig. 10** **Fig. 11**

A lateral force acting away (fig. 9) from the COLR will, for the same angle of rotation, push the COLR relatively less sideways than a force acting closer to the COLR. This results in an apparent pivot point further at the opposite end of the vessel (fig.10). The closer to the COLR the force is acting, the further away to the opposite end the apparent pivot point will be, this can even result in a pivot point outside of the vessel physical limits (fig. 112). This principle is very helpful when using tugs.

5.3 <u>Lateral resistance</u>

As we have seen earlier, the "lift" is the *resistance of the water to any lateral movement of the vessel.*
The hydraulic lift varies with:
- The shape of the hull: a more profiled (narrow) hull will induce relatively more lift. Let's compare two ships with the same length, same draft, the first one having twice the beam of the second one. After the ships have developed sideways motion, it is harder to stop the drift of the wider ship (twice heavier) for approximately the same lateral resisting force (L x draught = surface area of the wall of water).

- The under keel clearance: little under keel clearance means more lift (the narrow space under the keel makes it difficult for the water to flow from one side of the ship to the other, so it is harder to push the ship sideways).



A higher lift means a pivot point closer to the COLR

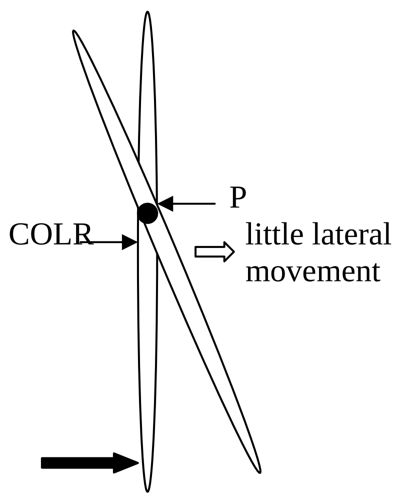


Fig. 13 High lateral resistance

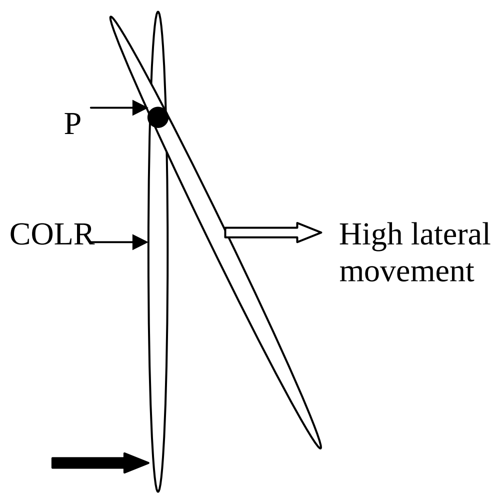


Fig. 14 Low lateral resistance

For the same change of angle, the COLR of a vessel with high lift will drift less sideways than a vessel with low lateral resistance when submitted to a lateral force. This results in an apparent pivot point closer to the COLR for a vessel with high lift than the vessel with low lift.

5.4 Motion of the ship after the lateral force(s) have been applied

The rotation effect

Let’s take again our solid bar free to move on an friction free surface. Let’s push it sideways with with some anti-clockwise rotation. Now stop the force acting on it and watch the resulting movement: The center of gravity is moving to the right and the bar rotates around it. The point that has no speed (having for reference the ice surface) is "P", the apparent pivot point.

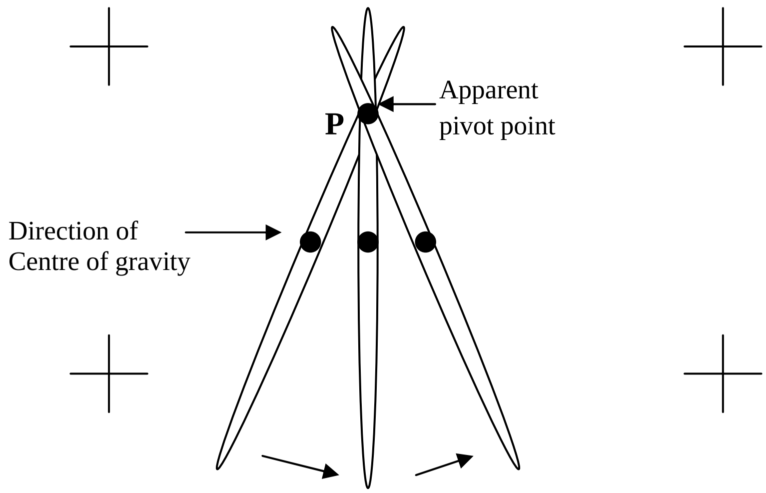


Fig. 15 Body thrown sideways and rotating on a friction free surface

When a ship is being handled at low speed (when the pressure fields on the hull are actually very low), it is mainly due to the above effect that the "apparent pivot point" seems to move astern if the vessel is moving astern and turning, and ahead if the vessel is moving ahead and turning. The other factor affecting it is :
The ship generated sideways current

Level 6

The ship generated sideways current

Let's consider a ship turning, and moving ahead. The "sweeping" movement of the stern creates a vacuum which in turn drags a mass of water towards the quarter shipside. The outer shipside also pushes a mass of

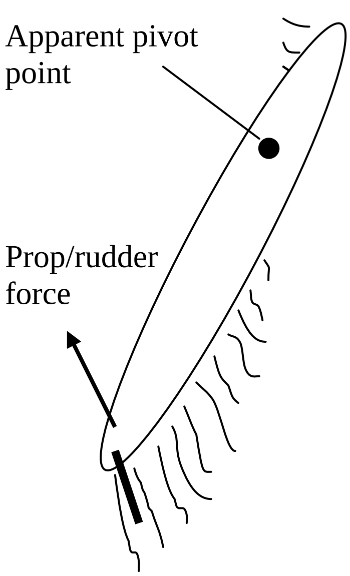


Fig. 15 Ship moving ahead
And turning

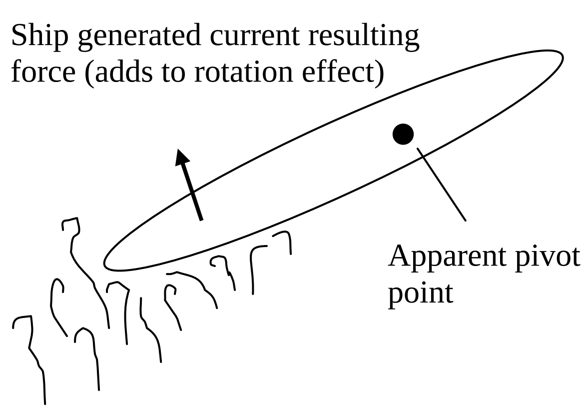


Fig. 16 Ship turning after acting force is stopped

water away. We will call it the *ship generated sideways current* . Let’s now stop the force creating the turning movement.
The ship, with its rotational inertia, keeps on turning, but the rate of turn will reduce due to water friction. The *ship generated sideways current* with its own inertia, will catch the stern and continue to push it sideways, while the forward part of the ship is in undisturbed water. This force, acting more or less sideways on the stern contributes in moving the apparent pivot point more forward.
The ship generated sideways current effect is relatively more important on a deeply laden vessel than on a wide light barge. On the latter, the rotation effect will be more noticeable. The result, however, is the same : an apparent pivot point located forward.

Note: The ship generated sideways current can have surprising effects when an efficient side force (strong tug, for example) is applied, at the shoulder on a ship with headway or at the quarter on a ship with sternway, for long periods. The ship can develop a swing in the opposite direction!

Some real life observations and how they meet theory

Ship generated sideways current and stern seeking to go up-wind with astern movement

1) A ship adrift is pushed sideways in a beam wind.
Its motion creates a *ship generated sideways current.*

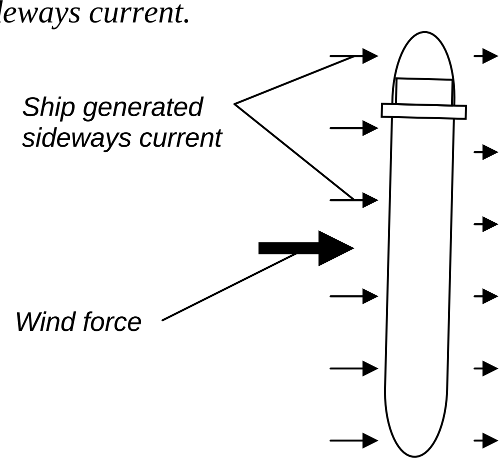


Fig. 17

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2) The vessel is going astern (we neglect here the effect of the transverse thrust), pulling the aft part of the vessel out of the ship generated sideways current. The stern being now in an area of relatively undisturbed water, the rest of the vessel still in the local ship generated current, a turning couple is created, bringing the stern up-wind.

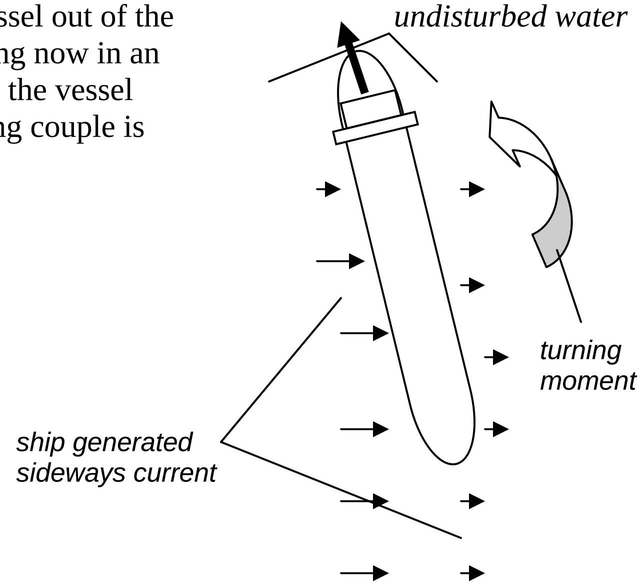

Fig. 18

As the stern is progressively directed into the wind, it gets out of and produces less *ship generated sideways current*. Another force couple is developing: the component of the propeller pull which is directed in the opposite direction of the wind is increasing, causing an arm lever of a length “d” between the propelling force and the centre of windage (fig. 19).

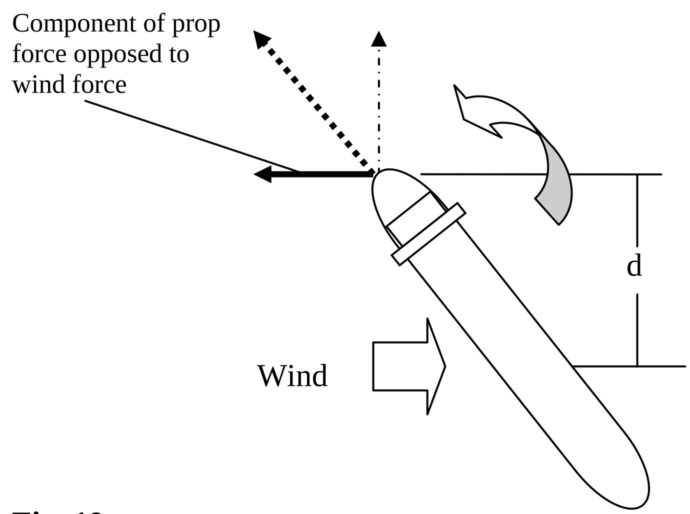

Fig. 19

Donkey-like behaviour of a ship pushed sideways by a forward escort tug *

1) The ship is moving ahead.
The forward escort tug will start pushing in order to direct the bow to port.

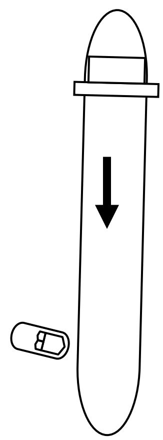

Fig. 20

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* Note: This phenomenon was described in 2001 in the text: *Unpredictable behaviour; example of a reason to reconsider the theory of manoeuvring for navigators* by Capt. Max J. van Hilten of the Maritime Pilots' Institute, Netherlands : **(**http://www.imsf.org/2001AGMPresentations/Genua_paper_1.doc**)**

2) The tug pushing has the following effect on the ship:
- sideways motion of the ship to port,
- rotation of the ship to port, since the force is acting forward of the centre of lateral resistance.

Due to the sideways motion, the ship is displacing a mass of water sideways with her:
- pushing it on port side,
- pulling it on starboard side.

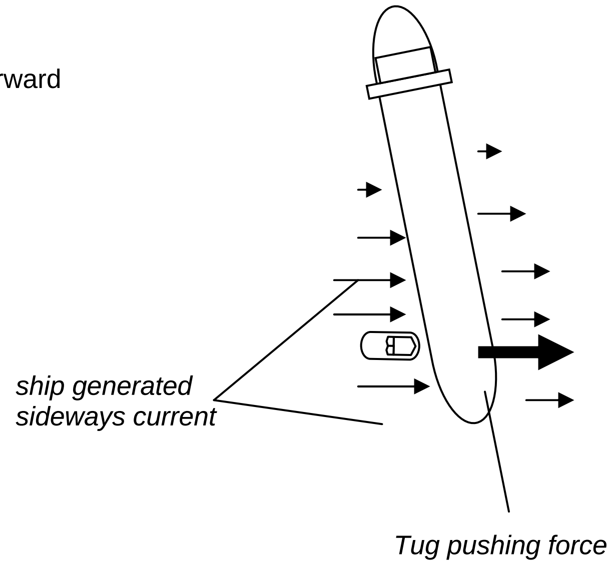

Fig. 21

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3) As the ship moves ahead, the bow will float in an area of relatively undisturbed water. The stern instead will be affected by the *ship generated sideways current* that has started to develop in **2)**, causing a turning moment that will reduce the port swing and can even initiate a starboard swing.

When the ship starts a starboard swing, the stern, due to the rotation, keeps on generating more sideways current than the forward part of the vessel, thus amplifying the turning moment.

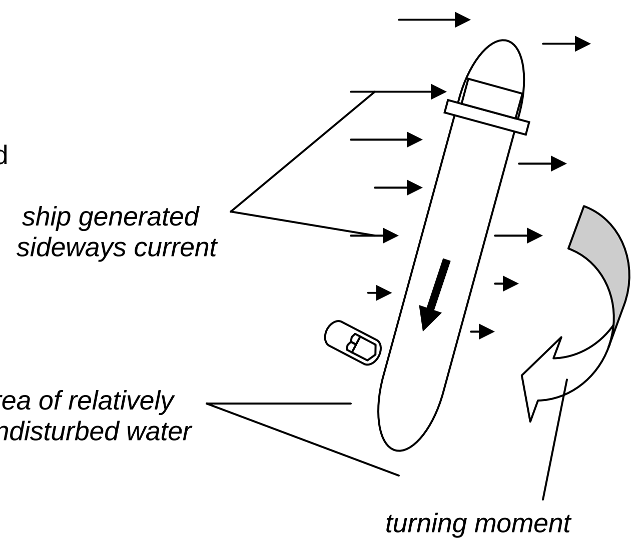


Fig. 22

The similar effect is sometimes observed when leaving a berth with a stream coming from the stern having a tug moored on the quarter and pulling. If the tug is used for a prolonged period to open the stern towards the centre of the river, (with the engines of the ship astern) the forward part of the vessel will be more affected by the ship generated sideways current than the stern. This will cause the bow to go after a while in the same direction as the tug pull.

<u>Kick ahead, hard over while having sternway</u>

What happens after an engine turning astern, causing stern motion, is followed by bold ahead engine movement with rudder hard over. The turbulence around the rudder, caused by the opposite flows of the surrounding water (coming from aft) and the propeller thrust, reduces its efficiency. The ability of a conventional rudder to initiate rotation is then very poor. Most of the propeller thrust kills the sternway, only a little part of it actually pushes the stern sideways.

However, you can, with a powerful twin screw, an azipod or a high efficiency rudder, produce enough efficient lateral force to move the apparent pivot point ahead, as per first basic principle, even with the vessel <u>still having stern way</u>.

<u>Bow thruster efficiency</u>

The poor turning effect of the bow thruster when moving ahead and its good steering properties when moving astern are well known facts. A very interesting article on the efficiency of the bow thruster was published in a Nautical Institute book entitled “Pilotage”. In this article, Captain H. Hensen explains that when the ship starts moving ahead, the high speed stream of water expelled from the thruster bends along the hull (fig. 23). Its high velocity flow creates a low pressure area that “pulls” the bow in a direction opposite to the side we want to thrust it. The result is that the two forces tend to annihilate each other and the net thrust force is very weak.

Ship moving ahead

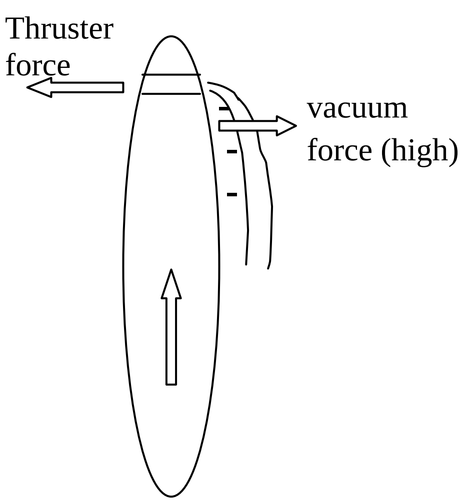


Fig. 23

Ship moving astern

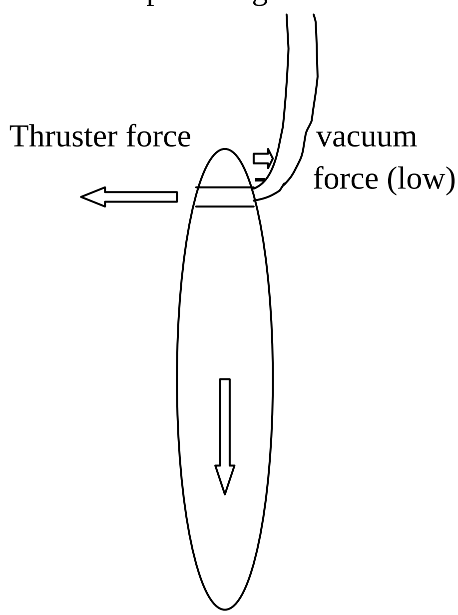


Fig. 24

The bow thruster is simply losing its efficiency as the ship moves forward. The loss of turning effect has therefore little to do with the change of arm lever distance between the thruster and the COLR.

When the vessel is moving astern (fig, 24), the vacuum effect created by the thruster is much less significant since the hull area over which it acts is quite smaller (area between the bow thruster opening and the stem).

<u>Light ship (trimmed by the stern) *vs.* loaded ship (trimmed by the head)</u>

A light ship is usually trimmed by the stern. Its COLR is relatively more aft than a loaded ship. This results in a shorter arm lever from the rudder to the COLR. At first glance this should lead to less steering efficiency. This short arm lever is overcome by the small inertia of rotation* of the light ship (less mass to control, therefore quicker reaction) for approximately the same steering power (same engine, same ruder, with maybe a little less efficiency if they are not completely water covered).

On loaded ships, the larger inertia of rotation (even if the rudder-COLR arm lever is longer) makes the ship

* For those not familiar with “inertia of rotation”, it is the tendency of a body to keep the same rate of turn if no force is applied on it (which also means to keep a steady course if it is initially steady).

slower to react. The following phenomenon can also complicate steering control, especially when some vessels are even keel or trimmed by the head. The more important underwater area ahead combined with over pressure around the bow of these ships bring the COLR well forward of amidships).

Let's take the example of a vessel moving north and initiating a turn to starboard (fig. 25). Once the turn is started, the centre of gravity of the vessel has now a new direction, a bit to the left of the initial course, let's suppose 350°. Because of inertia, the C. of G. wants to keep going that way (350°). Meanwhile the vessel itself has a different orientation, let's say 030°. This means that relative to the new direction of the C. of G. (350°), the COLR, would be some distance d off to the right. That distance corresponds to an arm lever that can be high enough sometimes to accelerate the rate of turn even with the wheel in midship position. Steering such a ship is like trying to keep the arrow of a wind indicator tail in the wind.

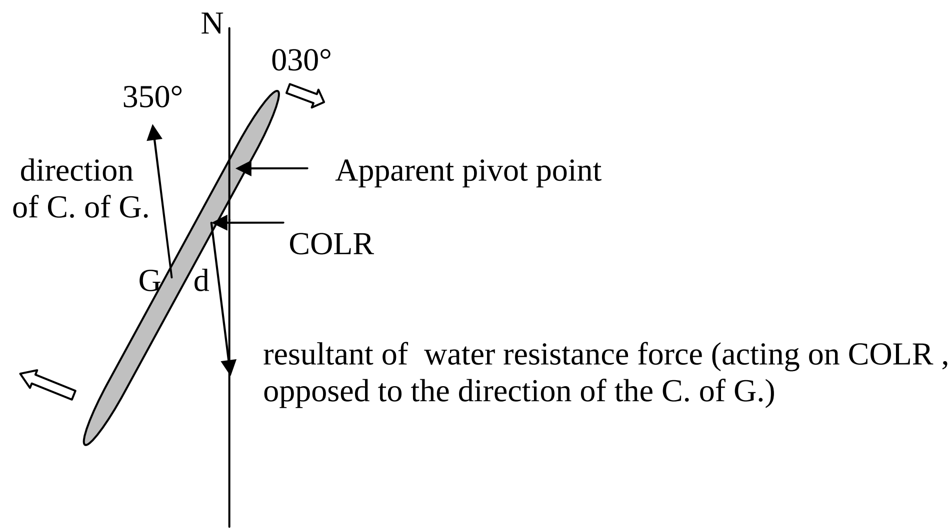


Fig. 25

Here is a familiar "land" example that illustrates this effect :
Push a loaded grocery caddie backwards. As soon as some external forces gives it a slight rotating movement, the rate of turn accelerates and the caddie turns completely around.
This happens because the centre of lateral resistance, is at the level of the rear fixed wheels. These fixed wheels prevent the rear part of the caddie from going in the same direction than the C. of G. of the caddie and cause the turning couple.

<u>Steering a ship going astern with tug alongside</u>
It is possible to steer a ship with a tug, even if positioned at approximately ¼ L from the stern where the traditional pivot point supposedly lies when a ship is moving astern. When the tug is pushing, you do not get a bodily movement as traditional theory suggests but a movement of the stern in the direction of the action of the tug. The arm lever is short. The COLR is lying a little aft of midship since the ship is going astern slowly. The rotation produced is small and the side movement important, the apparent pivot point is consequently somewhere between the bow and 1/3L from the bow.

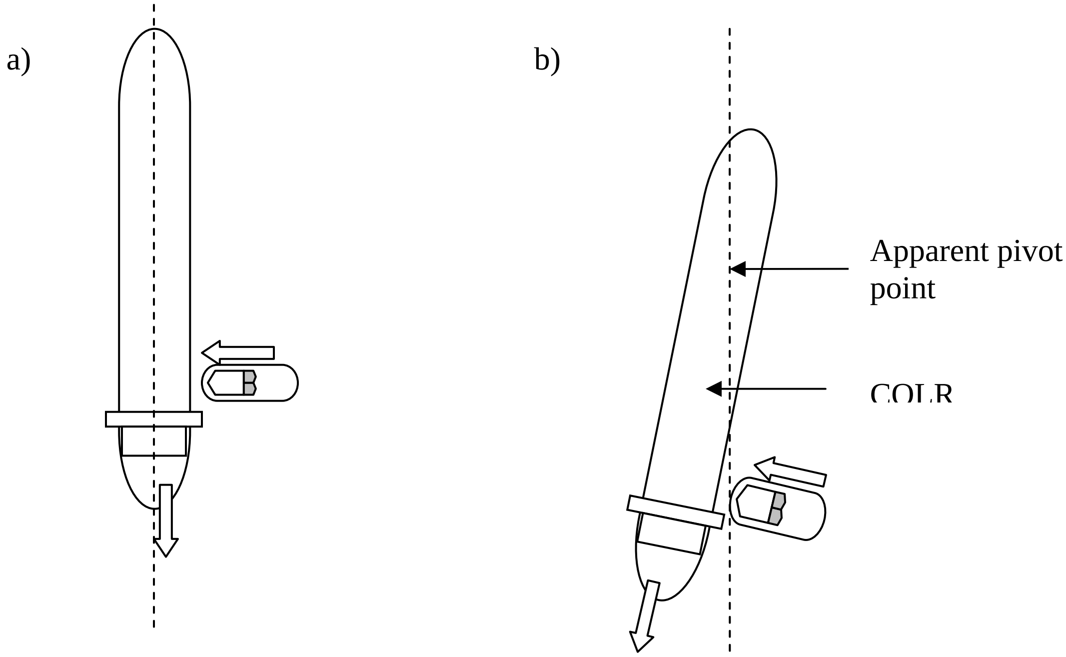
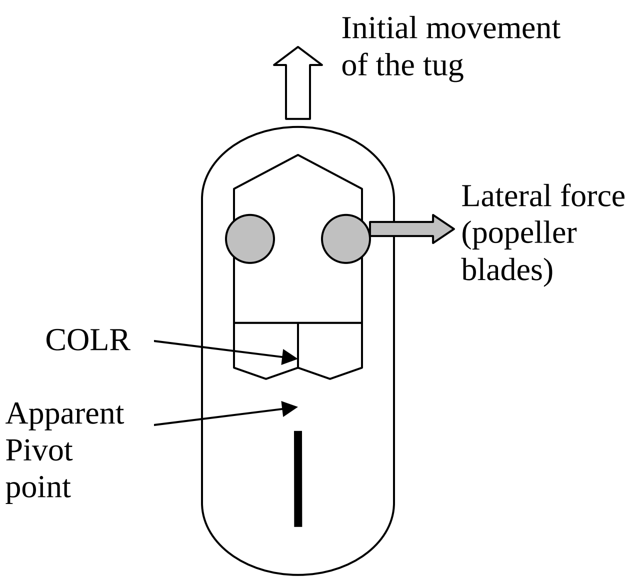


Fig. 26 Tug pushing on the quarter while moving astern

Note : As seen before, if this pushing force is applied long enough for an important *ship generated sideways current* to appear, the rotation of the vessel may stop and even start in the opposite direction!

Voight-Shneider tugs pivot point.

Fig. 27 Voight-shneider tug turning to starboard



Voight-Shneider tugs are an obvious example confirming the present theory. On this type of vessel the propellers, located forward, are also the steering force. When the tug turns, it is because a lateral force is exerted forward of the vessel by the action of the propellers. It is not the stern which is swung out in a direction opposite to the turn, but the bow which is pulled in the direction of the turn with the stern trailing behind like the tail of an arrow. This results in an apparent pivot point located aft of amidship.

Azipods

Azipod driven vessels going astern and turning will best demonstrate the present theory (see level 2). Their high side thrusting capacity will show a pivot point forward of amidship even if the vessel is going astern (especially at low speed). In fact I foresee the greatest usefulness of the present theory for those who handle azipod and Z-drive ships.

Deep draft container vessel *vs.* hovercraft

These two means of transportation seem to have very little in common. There is one thing though, that they do have in common: their respective behaviour when submitted to lateral forces can be explained by the present approach.

The hovercraft: hovercrafts have by definition very little “lift”. They are also usually short vessels. Let’s say

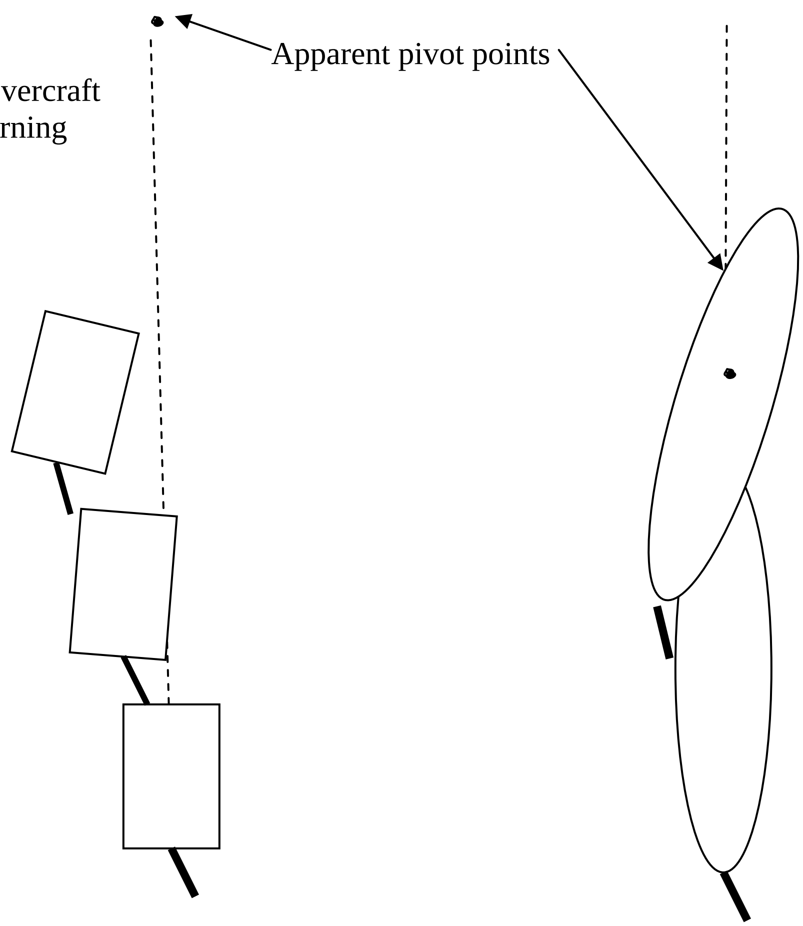


Fig. 28 Hovercraft Turning

Fig. 29 Deep draught container ship turning

that the air cushion vessel alters course progressively from 000° to 030° without overshooting. The steering flap, creating the lateral force, is relatively close to the COLR, this results in an important side movement for a given course alteration. The absence of lift resistance amplifies this relative sideways motion, the apparent pivot point is subsequently very far from the COLR (fig. 28), actually outside the vessel physical limits.

The container ship: in the case of a deep draught container vessel in shallow water, the position of the “apparent pivot point is at the other end of the spectrum when compared to a hovercraft. As we have seen earlier, a profiled ship’s hull has more lift than a bulky one. This results in less sideways movement when turning and an “apparent pivot point” closer to the COLR. In addition, the small clearance under the keel makes it difficult for the water to flow from one side of the ship to the other, because of this effect, when the ship is turning, the sideways drift is again reduced. This causes the apparent pivot point to lie even closer to the COLR (fig 29).

<u>Trivia question</u>

Now a quick one to see if the lesson is well learned.

A vessel is drifting in a current, her fore and aft axis making 90 degrees with the direction of the current . The anchor is let go with sufficient slack. With five shackles in the water, the brake is screwed tight. The anchor dives in the mud, it holds. The ship starts to swing. Where is the pivot point? At the center of gravity? At the hawse pipe? 1/3L from the bow? 1/4L from the stern? Somewhere else?

Answer: The “apparent pivot” point is about 1/3 to ¼ L from the stern as explained in figs. 4 to 7. Let’s not forget that the apparent pivot point is relative to the sea surface surrounding the vessel. If you consider the movement of the ship over the ground, the pivoting point of the ship will of course be initially in the vicinity of the hawse pipe).

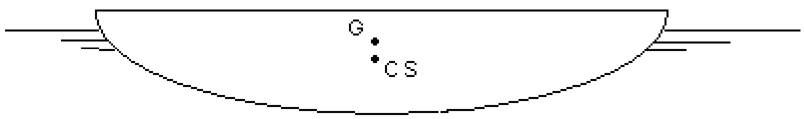
Appendix

Centre of Gravity vs. Centre of Underwater Surface Area

For a body in space where no friction is involved, the arm levers for forces causing rotation have for reference the centre of gravity of the body. For a ship in the water, this is basically true but the real "neutral" point of application for arm levers is also function of the resistance of the underwater surface.

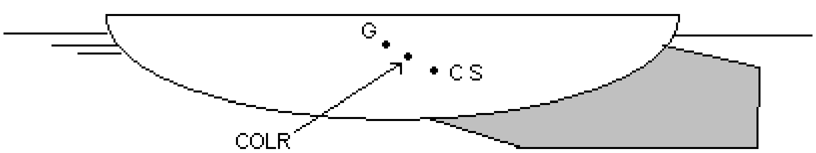
Example: Let's say we have an homogeneous floating object at rest having the following shape (fig. 30). The centre of gravity "G" and the Centre of underwater Surface "CS" are on the same vertical line. It is also the position of the COLR.

Fig. 30



In fig. 31, we have added a large surface stern keel to our floating object. Let's assume this added surface is very light and causes negligible change of position of the centre of gravity. It is quite easy to see that in fig. 30 if we apply a force acting on G, the floating object will move sideways and no rotation will be induced since there is no arm lever. On the other hand, if you apply the same force on G in fig. 31 there will be an unbalance of the water resistance between the areas forward of G and aft of G. The centre of underwater surface area "CS" being more aft in this case, the COLR (neutral point for arm levers) will actually be located between these two points: the centre of inertia G and the centre of water resistance CS.

Fig. 31



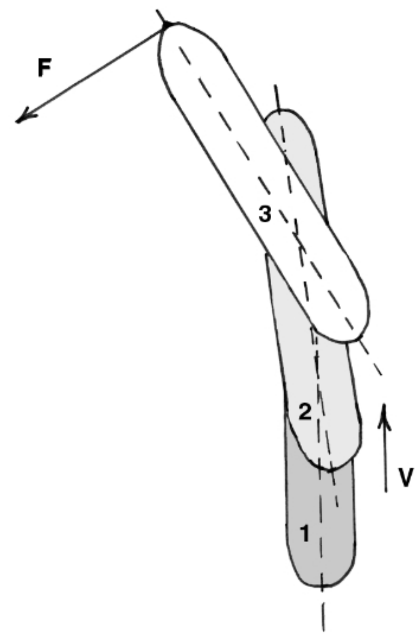
Experiments on small scale models

The following experiments have been performed at the Ilawa shiphandling center in Poland in July 2005. These trials, made on a small scale bulk carrier loaded even keel, were recorded and printed by the centre's high accuracy positioning system.

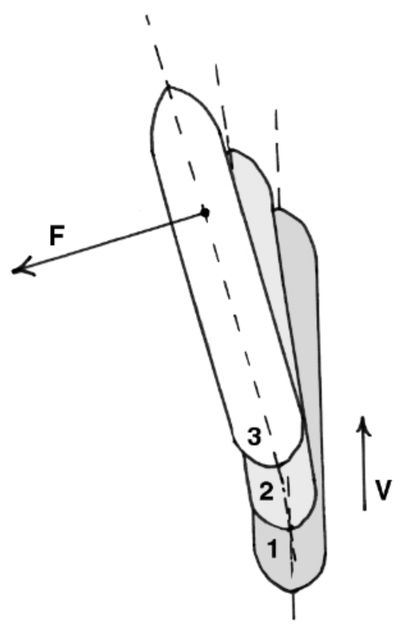
The goal of the experiment was to apply really effective side force on different points of the ship when she was making way through the water. For this we used a hand pulled towing line oriented at 90 degrees from the ship axis. By using a line, the results are not altered by hull/working force hydraulic interactions (as produced by tugs or bow thrusters).

Four tests were made:

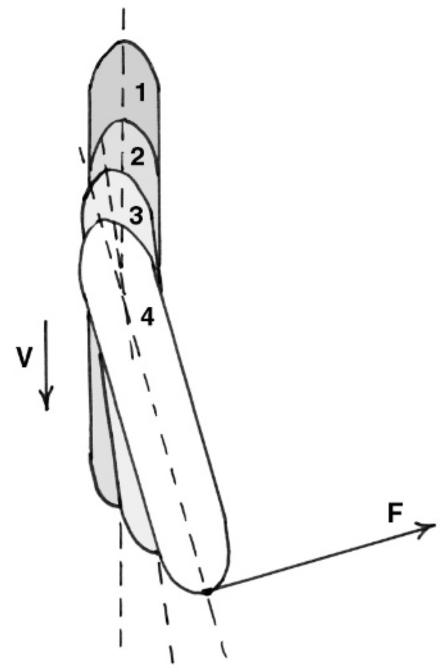
1) ship having headway (+/- 5 kts scale speed) and steady, engine stopped, pulling at the bow



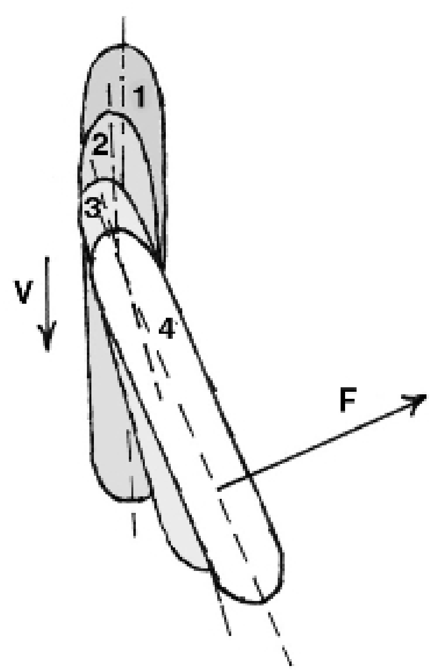
2) ship having headway (+/- 5 kts scale speed) and steady, engine stopped, pulling at about 1/3 L from the bow



3) ship having sternway (+/- 5 kts scale speed) and steady, engine stopped, pulling at the stern



4) ship having sternway (+/- 5 kts scale speed) and steady, engine stopped, pulling at about ¼ L from the stern



The results speak by themselves :

- When the force is applied at the extreme end of the ship (tests 1 and 3), the apparent pivot point is at the opposite end of where the traditional theory expects it to be.
- When the force is applied on the traditional pivot point (tests 2 and 4), the expected result (traditional theory) of a ship only moving bodily sideways since there is no arm lever, does not occur. There is a moment of rotation, therefore an arm lever. The apparent pivot point is also at the opposite end of the one where the force is applied. This demonstrates again clearly the weakness of traditional theory.