TOWLINE FRICTION AND ITS CONSEQUENCES

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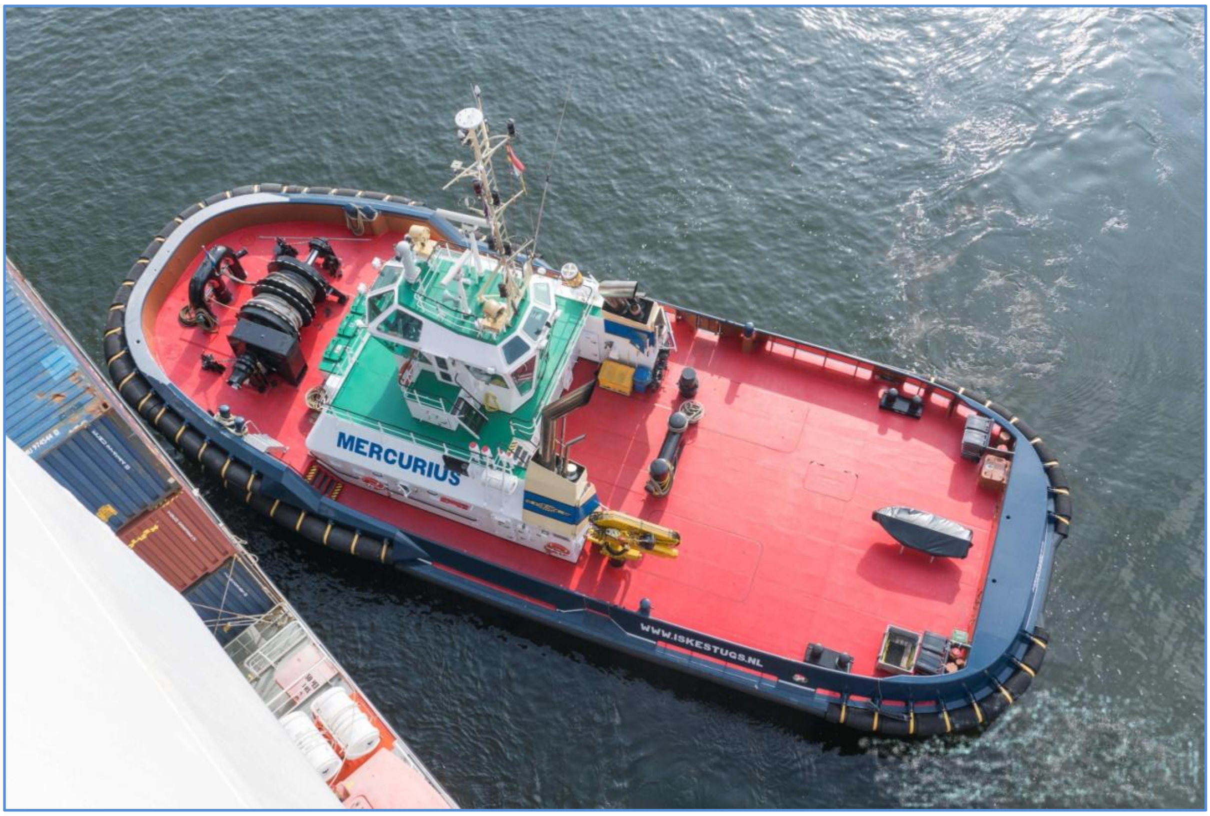
1.0 Introduction

In recent years much attention has been paid to innovative aspects of tug design such as environmentally friendly tugs, underwater hull form, and escort skegs. Several new tug types have also been developed. This focus could create the idea that a tug's deck equipment such as towlines, towing winches, staples and fairleads have reached their optimum design. This is far from being the case. In this article towrope friction will be addressed together with all its consequences. In a subject not often discussed, it will be shown how important this towrope characteristic is and that it requires attention because it may affect the working of a winch and, most importantly, stability.

2.0 Explanation friction and friction coefficient

Friction is introduced when one part of a certain object comes into contact with part of another object and relative movement occurs, for instance the fenders of tug being in contact with the ship's hull, or a towline passing through a fairlead or staple.



Courtesy: Marijn van Hoorn, Rotterdam pilot

Figure 1

Tug pushing with her fenders and sliding along the ship's hull

Friction has three direct negative effects:

a) Friction introduces energy loss; where friction plays a role it costs extra power to move an object.
Example: When a tug is sliding with the bow fenders along a ship's hull, it requires power to move the tug with its rubber fenders along the steel hull. In the case of water lubricated fenders friction is reduced and consequently less power is needed.
Note 1: When friction occurs in the direction of the force/thrust the losses affect the nett thrust. If friction occurs in vertical plane e.g. due to waves, there are no losses on nett thrust.
b) Friction causes heating at the location of friction. This is the reason a towrope under tension gets hot when passing at an angle through a fairlead. Heating can best be experienced when a rope slides through a person's hand. Heating also causes deterioration of the synthetic material. Deterioration increases rapidly above a certain temperature and care should be taken that this temperature is avoided.
c) Friction causes abrasion. The greater the friction the greater the abrasion. This effect assumes a sliding surface, for example where a towrope slides through a fairlead. The rougher the surface of the fairlead, the greater the friction and, consequently, the abrasion.

Sometimes friction is welcome. For example when a ship's rope has to be belayed on bollards, friction is needed to avoid the rope slipping from the bollards; however, this article will focus on a tug's towline.

The degree of friction depends on the type of materials involved, for example, rubber against iron, and whether the surfaces are smooth or not. The amount of friction between two objects is given by the friction coefficient. The friction coefficient (C_f) gives the relation between the friction force (F_f) and the force working perpendicular to the surface of friction (F_n), and has a constant value. This means that if the force F_n doubles, the friction force F_f doubles as well and consequently the friction coefficient C_f does not change.

There is both a *static* and a *dynamic* friction coefficient. The static friction coefficient plays a role if there is no movement between the two surfaces, in the case of a force smaller than the friction force working on one of the objects. The dynamic friction coefficient plays a role when two objects are sliding along each other.

Power is required to pull a rope through a fairlead or around a staple. The amount of power needed is a result of the friction between the rope and the fairlead or staple and the angle the towrope has with the staple or fairlead.

This is the basis of friction; next we will examine the forces at work in a towline and then, the forces working on a tug will be addressed. Thereafter the effect and consequences of friction will be dealt with.

3.0 Forces working on a towing tug

Two different situations will discussed now, one situation for a tug without a towing winch and one for a tug with towing winch.

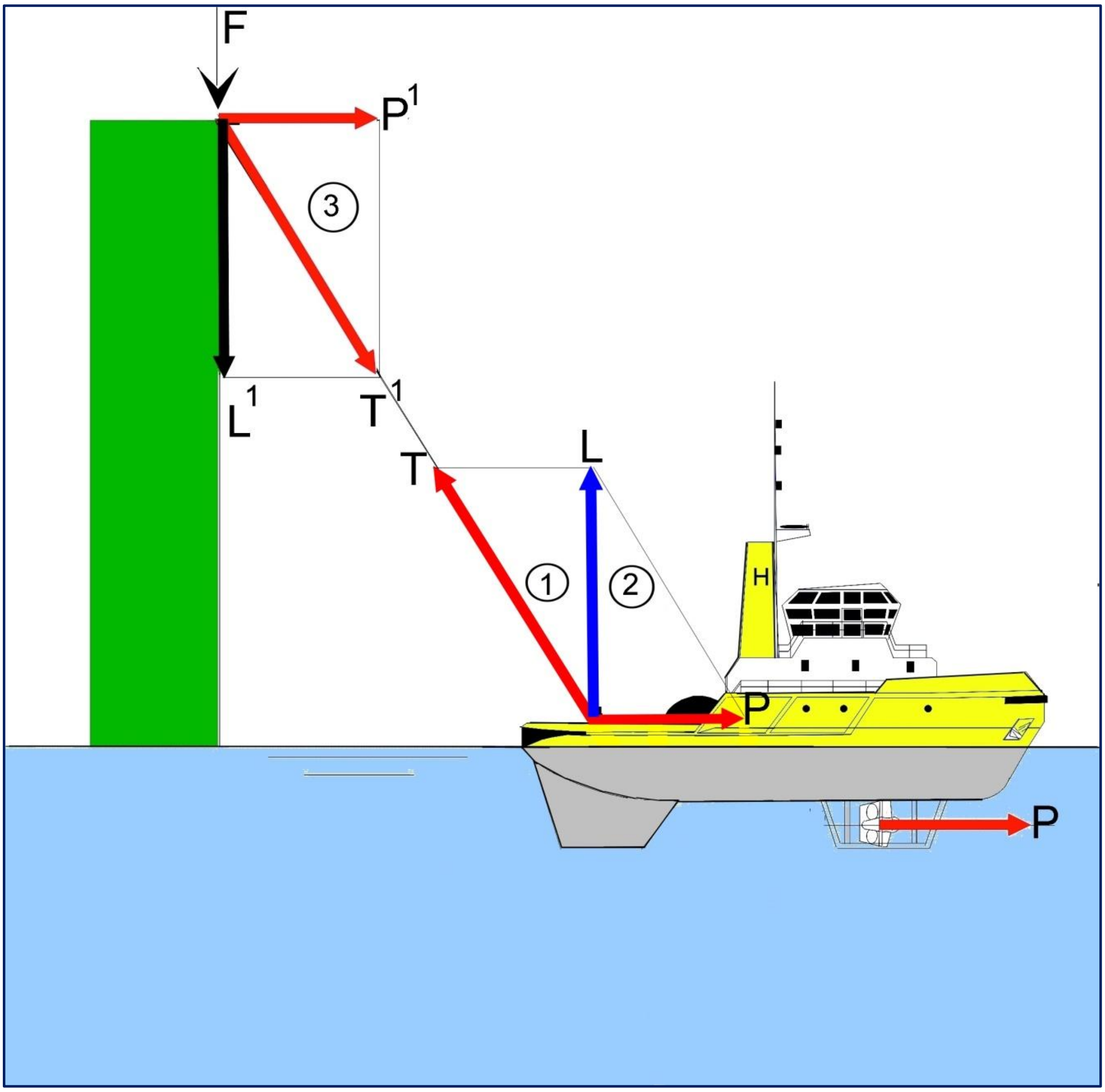


Figure 2
Forces working on a tug with towline on the towing bitt

3.1 Forces working on a tug with towline fastened on the towing bitt or hook

In Figure 2 the various forces caused by a pulling tug are shown. The propulsion force P generates a force T in the towline which is higher than the propulsion force due to the steep towline angle. Assuming a tug's bollard pull of 50 tons, the force in the towline of Figure 2 is then almost 120 tons! This large force T works on the towing bitt, or towing hook, and together with the propulsion force it creates the force L, which tries to lift the tug's stern out of the water, causing the tug to trim by the head.

T^1 is the same force as T and can be split into a horizontal component P^1 and a vertical component L^1. When comparing the triangles 1, 2, and 3 it can be seen that the force P^1 which pulls the ship forward is exactly the same as the propulsion force P. The high towline force of 120 tons also works on the ship's fairlead. The vertical force L^1 is the force that causes the friction in the fairlead F.

It can be concluded that:

- the propulsion force P is the same as the force P^1, which pulls the ship forward;
- the steep angle of the towline causes a very high force in the towline and on the towing bitt;
- the high force in the towline causes high friction and heating in the ship's fairlead which increases the risk of parting.

As said the force P^1 is equal to force P, however, the pulling effect of the tug may be reduced because of the negative effect of the propeller wash hitting the ship's hull especially when the propulsion units are in close proximity to the hull. The negative effect of the propeller wash does not affect the large force in the steep towline, because force P stays the same. This negative effect with the tractor tug shown in Figure 2 will be less in comparison to a conventional or ASD tug towing over the stern in the same position. This is because the propulsion units of the tractor tug shown are at a larger distance from the ship's hull.

Note 2: This negative effect is strongly related to the hull shape and the water depth below the ship's keel. If the tug's propeller wash is going in more or less longitudinal directions along the ship's hull the negative effect is small, in transverse directions the effect is large, especially in shallow water depth.

3.1 Forces working on a tug with towline fastened to the towing winch

The former situation with a rope fastened to a towing hook or to a bitt is now rarely seen on harbour and terminal tugs. In most cases the towing line comes from the towing winch and then passes through a staple or fairlead. Although this is a quite different situation, what has been discussed about the towline forces and the forces working on a tug in case of a steep towline applies equally to a tug with a towing winch.

In Figure 3 the forces in the towline are again shown again with those working on the assisted ship. Now the towline is not fastened to the bitt but passes through the staple and runs towards the towing winch; in this case to the lower part of the drum.

It will first be assumed that the force (T) in the part of the towline that goes from the staple (see note 3 below) to the ship is as large as the force (T_w) in the part that runs from the staple towards the winch although this is not always the case. Because of friction in the staple the force T_w will be smaller than T when the tug is towing at constant power and speed and will be larger than T when the winch starts to haul. This affects the direction of the resultant force F_s and consequently force F_f. Consequently force F_f, which drives the tug forward, can become smaller or larger than shown in Figure 3, depending on whether the tug is towing with constant power and speed or whether the winch is hauling.

Note 3: If the word `staple' is used it also includes a `fairlead'.

We now see that the towline force T_w results in a pulling force on the winch of F_w which is equal to T_w. A force as large as the pulling force F_w on the winch cannot be matched by the tug, instead it would pull the tug backwards because the force is much larger than the propulsion force P. However, the resultant force of the forces working on the staple (T_w and T) is F_s. When splitting up this force in a horizontal and a vertical component it can be seen that the horizontal component F_f pulls the tug forward, and together with the propulsion force will compensate for the large force in the towline pulling the tug backwards.

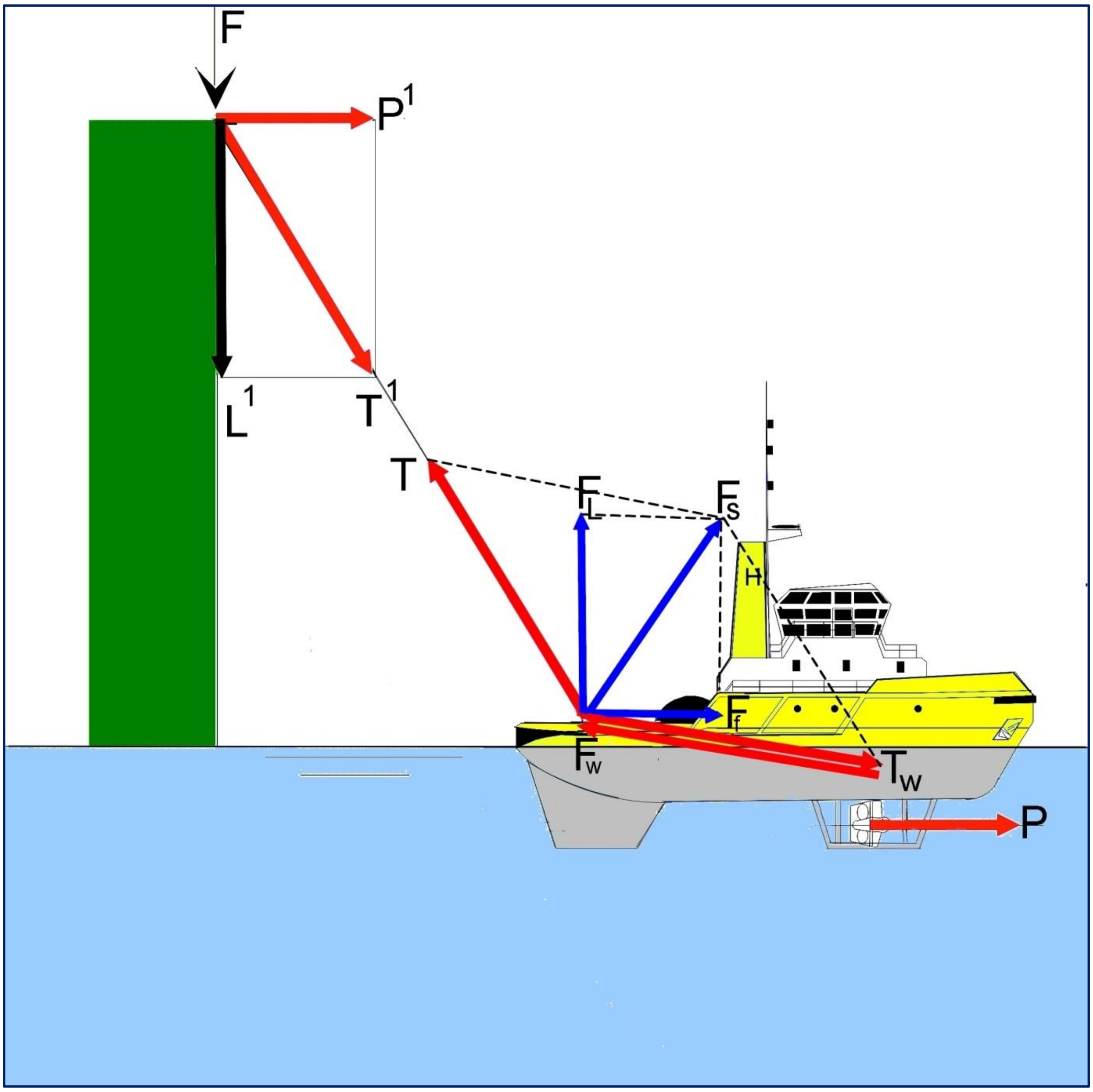


Figure 3
Forces working on a tug with towing winch

4.0 Towline friction coefficients

Before going further it is important to address again some specific aspects of friction in the case of rope over smooth steel.

Some important conclusions of a study mentioned at reference [1] are:

- For a given rope tension, the frictional hold capability of a sheave increases with diameter (of either rope or sheave) due to the reduction of rope pressure on the sheave. Rope pressure per e.g. cm^2 will then be less and this has the consequence that hold capacity of the sheave increases.
- The frictional hold of a sheave decreases as rope wear increases.
- Friction coefficient of a wet nylon and in particular of wet polyester can be about 10 – 20% higher than when dry.

Important for the further explanation are the static friction coefficients, i.e. the rope's resistance to slipping. SamsonRope mentions in their Rope User's Manual [2] a number of static friction coefficients:
Nylon: 0.12 – 0.15; polyester: 0.12- 0.15; Aramid: 0.12 – 0.15; HMPE: 0.05 – 0.07.

As can be seen HMPE ropes have by far the lowest friction coefficients, much lower than nylon and polyester.

For the next discussion the following conditions will be assumed:
- rope over smooth steel;
- a dry rope;
- rope in good condition;
- a friction coefficient of 0.15;
- the towline in contact with the staple or fairlead over an angle of 90 degrees, being about 1.6 radians.

Note 4: it will be assumed that the diameter of the staple or fairlead is in accordance with the requirements of the rope manufacturer. SamsonRope recommends for instance a diameter of 8- 10 times the rope diameter. A diameter that is too small will decrease the lifespan of a rope.

Note 5: For high peak loads the normal friction coefficients are not constant. Practical experience has shown that with extreme high peak loads resistance increases. The reason why is still unknown and further research is needed to clarify this phenomenon. It is anyhow an important item for tugs.

5.0 Friction and its consequences

In this section three situations in which the towing line has a relatively large contact area with the staple or fairlead will be addressed:

1. Operating in the indirect towing mode when the towline has a relatively large angle with the centre line of the tug and consequently a large contact area between towline and staple.
2. Tugs operating in the powered indirect mode which results in an even larger contact area.
3. Conventional tugs and ASD-tugs operating in conventional mode in such a way that the towline has a relatively large angle with the centre line of the tug and thus also a large contact area with the staple.

When discussing Figure 3 it was assumed that force T_W in the part of the towline leading to the winch is equal to force T in the part of the towline leading to the ship. It has already been stated that due to the friction in the staple in a steady towing situation force T_w will be smaller than force T. When the tug increases power or the winch start to haul force T_w will be larger than force T. In the following cases, the average situation will be taking as starting point in which force T_w is equal to T.

This brings us now to the three case studies. Because many tugs are fitted with render-recovery winches or similar systems, focus will be on tugs with such equipment. What could be the effect of friction on such a winch?

For the friction around the staple, following formula known as the Capstan or Eytelwin Friction Equation [3] will be used:

$$T_{load} = T_{hold}\, e^{\mu\phi}$$

T_{load} = applied line tension in Newton
T_{hold} = resulting force at other side in Newton
μ = coefficient of friction between rope and capstan material
ϕ = total rope angle in radians

An easy to use calculator for the above mentioned formula can be found on the website at reference [3].

What is the effect of towrope friction? There are many different shapes of staples, some examples are shown in Figures 5 – 7. Many staples have fairleads of stainless steel or made of some other and even harder material. This will result in a lower friction, but there will also be fairleads that are not totally smooth or not having the required radius for the towline used.

Assume a tug master on a 70 tons bollard pull tug has set the render-recovery system for recovery of the towline at a force of 30 tons. Assume also that the towline has a large angle with the centre line of the tug as in any of the situations 1 - 3 mentioned above.

If the force in the towline is decreasing, at a certain moment the towline force measured will be near 30 tons, and then the winch should start to haul. The towline force is measured by the winch as will be explained later. The holding part at that moment is the part leading to the winch with a measured tension of 30 tons. Due to the friction the calculated force (according to the Eytelwin formula) in the part leading to the ship is 38 tons! But this means that when the winch starts to haul it has to overcome the force of 38 tons plus the friction to be able to recover the towline. The winch would have to pull with a considerably higher force viz. 48 tons, which is much higher than the force of 30 tons set for hauling! The winch will therefore not recover, not before the main towline force has dropped below the 30 tons, viz. at about 23 tons in the towline leading to the ship. This means that when the force in the towline decreases, due to the friction in the staple *the winch starts to recover too late.*

Now consider what will happen when the winch has been set to render, for instance at a towline force of 60 tons? Towline force measured at the winch will then be 60 tons. At the moment the winch starts to render the calculated force in the towline leading to the ship is then about 76 tons. *Due to the friction the winch start to render considerably later* and more force is needed to control the rendering. This results in higher towline load than the winch is set for, increasing the risk of damage to the ship's bitts and fairleads.

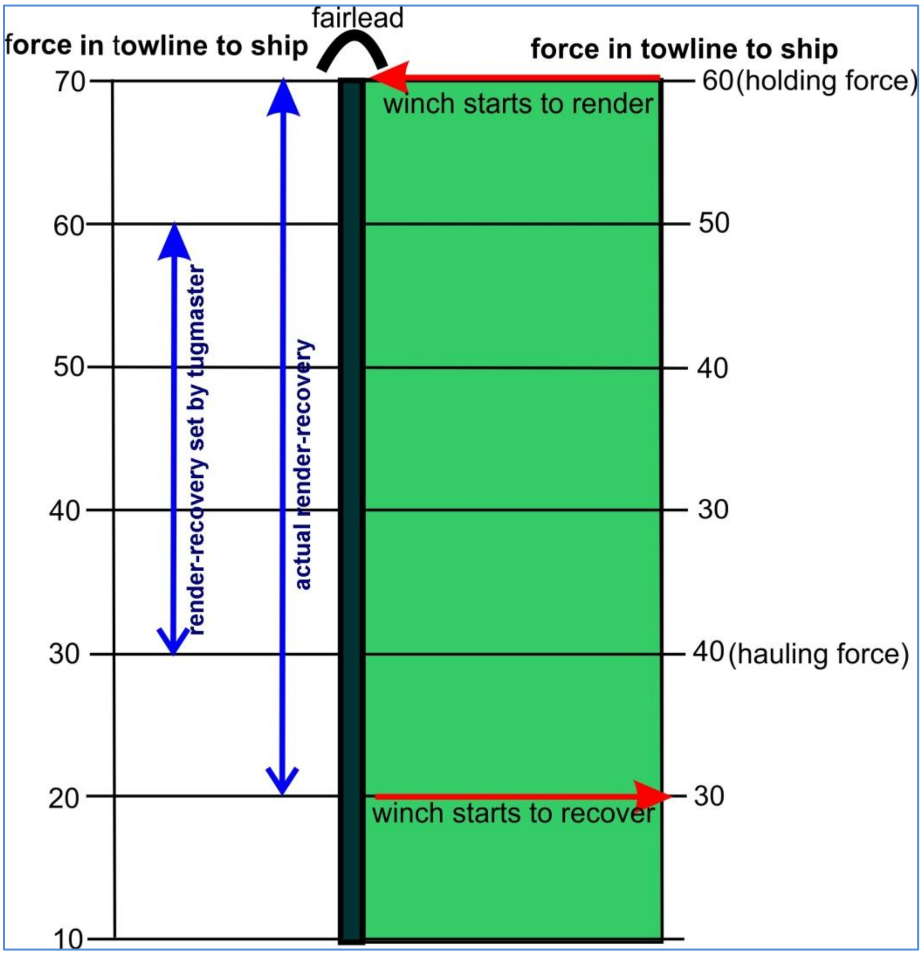


Figure 4
Effect of friction on render-recovery system

Instead of rendering-recovering at 30 and 60 tons, due to the friction in the staple the winch will render and recover too late.

In Figure 4 the effect of friction is shown in a schematic and approximate way. The left blue arrow shows the range of the preset towline forces for rendering and recovery. The right blue arrow shows the actual range due to the effect of friction.

The situation can deviate even more from the expected performance if a wet polyester rope is used, or when the angle is even larger than 90 degrees, or when the surface of the staple or

Courtesy: Daan Markelbach. KOTUG, Rotterdam

Figure 4

ROTOR tug RT Evolution operating powered indirect

fairlead is not smooth. When a tug is operating in the powered indirect mode (see Figure 5) it could result in a contact radius of about 135 degrees, being 2.4 radians. The winch set to recover at 30 tons will then only start to recover at an even lower force in the towline leading to the ship, viz. around 20 tons. If set to render at 60 tons, due to the friction it will actually start to render at a towline force of 86 tons! This means that rendering and recovering will take place at even lower respectively higher forces than calculated earlier. The delay in rendering increases the risk of the towline parting.

Summary of the consequences so far

In case where the towline makes a large angle with the centreline of the tug, or if the tug is operating with a steep towline, because of the friction of the towline in the staple or fairlead, forces at which the winch will render and recover will differ from the render-recovery forces set by the tug master. In particular, rendering may take place at considerably higher forces than those set by the tug master. Variation in the actual render-recovery forces will differ to those set by the tug master depending on the force in the towline, the towing angle and friction.

The consequences of the above are:

- Higher towline loads than set by the render-recovery system.

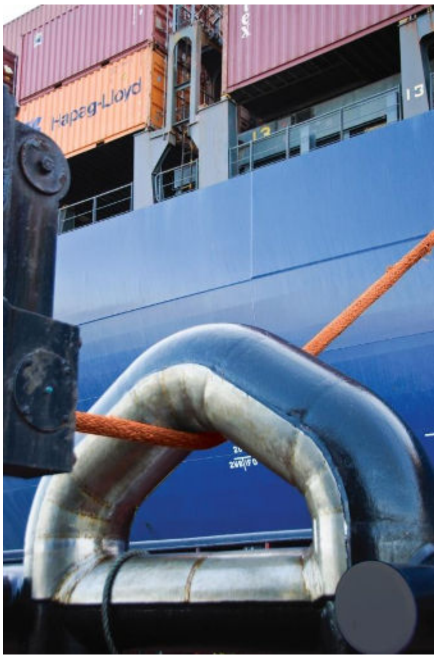
- Increased risk of damage to ship's bitts and fairleads.
- Greater abrasion of the towline.
- Greater heating of the towline.
- Higher risk of parting of towline; and
- a decrease in longevity of the towing line.

Furthermore:

- If the towing line is near right angles to the tug, the higher towline forces experienced before the winch starts to render, causes a larger heeling force on the tug. This can be risky in cases where the tug's stability is not optimum.

Courtesy: Piet Sinke

Figure 5



Courtesy: Brian Gauvin; SamsonRope

Figure 7

Courtesy: Brian Gauvin; SamsonRope

Figure 8

Note 6: There is another important aspect. The part of the towline running from the winch through a fairlead will, due the force variations in the towline, vary in length and constantly move back and forth in the fairlead. As a consequence that part of the towline is continuously *subject to friction and wear which will have a negative effect on the strength of the towline. With towlines made of Dyneema the movement will be less, but still this aspect is important. Another aspect earlier mentioned is that small back and forth movements may lead to a very local heating of the rope fibres and as a result thereof further deterioration of the material.*

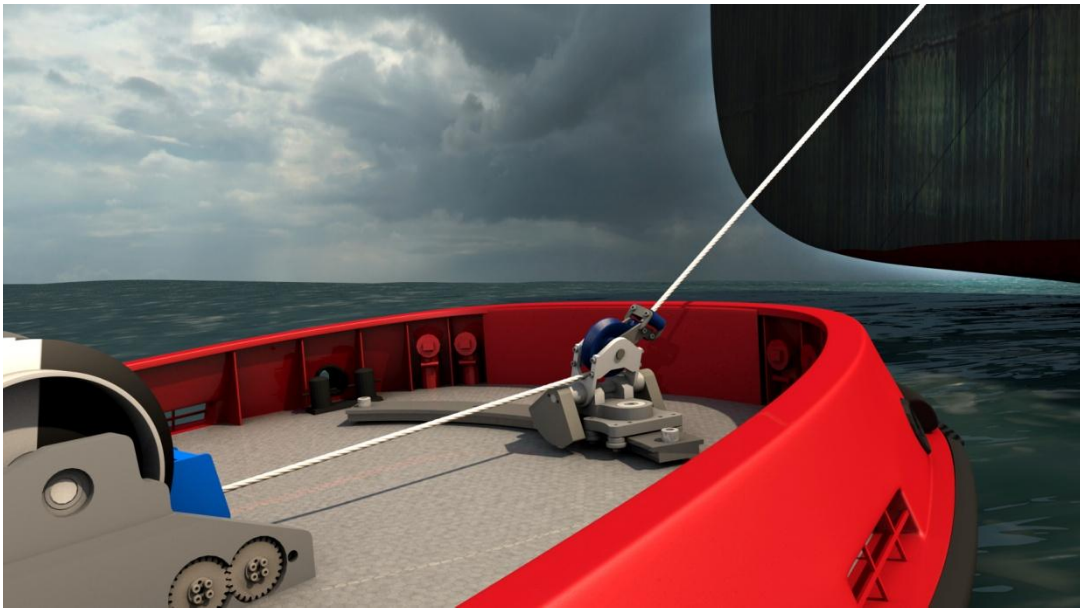


Photo: ROTOR tug, the Netherlands

Figure 9
Azimuth friction free towing point

Alternatives

The situation can be improved by reducing the friction and there are a few options for doing so:

1. The use of ropes with low friction coefficients, such as ropes made of Dyneema. It will be clear that the low friction coefficient only applies when the rope is not covered by some other material.
2. Appropriate roller staples or roller fairleads.
3. An `Azimuth friction free towing point'. See Figure 9.

Option 1 is currently the most realistic option. The render-recovery will take place more in accordance with the settings of the tug master.
Option 2, if realized, would result in hardly any friction left regardless the line type used. A further advantage is that lines with a higher stretch than Dyneema could be used although such lines would be somewhat less easy to handle due to larger diameter and corresponding weight.
Option 3 is an `Azimuth friction free towing point' which is a new system, which has similarities to Option 2. It has a further advantage in that it can travel from port to starboard and back, so decreasing the heeling angle of the tug. Experience should tell whether the system works satisfactorily.

Note 7: A further remark has to be made. When a towline runs through a fairlead, the rope section tends to be a flat ellipsoid instead of a circular original shape. This introduces additional internal forces between the fibres and increasing internal wear. When a towline runs through a right dimensioned sheave, the sheave can have a half circular shape supporting the towline and maintaining an approximate circular original shape. This has a significant impact on the fatigue life.

6.0 Further consequences of using Dyneema towlines

The use of low friction coefficient towlines made of Dyneema is a workable solution to the problems of towline friction. However another issue arises; lines made of Dyneema have only little stretch which is problematic for harbour and terminal tugs working with relatively short towlines. This can result in high peak loads in the towing line if nylon or polyester stretchers are not used. Stretchers would absorb peak loads to certain extent.

The effect on winches with a render-recovery system when Dyneema is used

A closer look should be taken at the working of a render-recovery system focussing on the signalling that causes the winch to operate. It is assumed that towlines made of Dyneema are used without a stretcher.

Note 8: In the past a constant tension winch was regarded as a render-recovery winch. A disadvantage of a constant tension winch is the low pay-out speed which is limited by the maximum rotation speed of the connected motor, particularly when tension in the towline is high [5].
What is discussed here is a real render-recovery winch which is safer because of its larger capabilities with respect to rendering and recovery.

Various systems are used to measure the towline forces in order to activate the render-recovery functions of the winch, these include:

- The towing winch is connected to the deck structure by means of measuring pins which measures the horizontal towing forces.
- The torque of the winch drive and/or brake is measured. Because the torque depends on the force in the towline and the length of the ‘lever’, the length of the towline paid out or retrieved is measured also to approximate which layer the towline is coming from. This can be achieved by counting the number of winch drum revolutions. One should keep in mind that cable layers do vary in distance to the centre due to less optimal (or absent) spooling systems. Sometimes optical systems are used to determine which layer the towline is coming from.
- The use of sensors in the towline which directly measure the force in the towline and enable to record short peak loads within a second (because of minimum inertia influences).
- Use a sheave in the cable 'line' with predefined cable angle (90° or even 180°) and measure the resultant force. In towing this option is rarely used, since the sheave will hinder bulky connections between different towline parts.

Now the following questions arise:

1. When short peak loads higher than those set by the tug master occur, does the system sample quickly and accurately enough to activate the winch?
2. And …. . if so, does the winch immediately start to operate?

Regardless the latest aspect, practically speaking we know that is not the case; there is always some delay to have the whole winch system working.

Periods of peaks in short minimum stretch towlines can be very brief and the forces very high. If the towline force measurements and winch signalling are not attuned to the shortest peak loads, the winch may miss a signal to operate and a high peak load will not be limited by the render-recovery system. This can easily result in damage to the towing winch, parting of the towline and/or damage to ship's bollards and fairleads. This is a complex story, because even if the force sampling system works perfectly including winch activation signalling, there is still the delay factor in the winch due to the inertia of the motor, gear box, drum and cable on the drum.
Further, the mechanical design of a render-recovery winch requires constant switching from render to recovery and vice versa by constant (dis-)engagement of clutch between the motor and the gear/drum and between the drum and the 'earth'. It is absolutely essential that there is a short overlay period to prevent unintended paying out. The (dis-)engagement time and overlay period require valuable seconds!
Short stiff Dyneema cables peak loads may range up from 50 to 150 ton/s, so a delay of 2 sec will correspond to an increase of 100-300 ton (!).
The only winch which does not involve this delay time, is the SafeWinch of Kraaijeveld. Both rendering and recovery is performed instantly without external activations nor overlay period, due to the mechanical ratchet function, saving valuable seconds.

Alternatively, a stretcher can always be used. This has been the case for years particularly with steel wire towlines. However, as tug power has increased resulting in higher towline forces, increasingly heavier stretchers are required which are becoming almost too heavy to handle.
It should be kept in mind that with increasing towline loads, the amount of energy accumulated in a stretcher should be considered carefully since towline parting results in enormous kinetic energy. Therefore, large stretchers should only be used on winches with accurate and instant (automatic) release systems, above a set value.

7.0 Peak loads on tugs without render-recovery winches

In the foregoing attention has been paid to render-recovery winches. Although the consequences of friction and of the use of Dyneema towropes is an important issue, it is not representative for the whole tug world. Many harbour tugs are not equipped with render-recovery winches, and many tugs having such a system don't use it. The use of such a system in confined port areas includes risks when a render-recovery would start to render in places with only little room.

In case a tug has no render-recovery system or where render-recovery systems are not used, forces in the towline can become uncontrollably high, particularly with Dyneema. In the majority of conventional winches no load measuring is performed, so there is no information at all available to the tug master to evaluate his manoeuvring. Also steep towing lines upward cause high peak loads, many tug master are not aware of.
Furthermore, shaving in the fairlead will then be high causing much abrasion (unless the earlier mentioned systems are used to prevent or minimize shaving), so further decreasing longevity of the towline and risk of damage to winch and parting of the towline increases. A well experienced and attentive tug master may mitigate these risks. However, he needs some kind of feedback from the actual load to make the right decisions. If no loads are (accurately) measured, he can not perform a proper evaluation.

However, these tugs use often various systems to limit peak loads in the towline. Sometimes a Dyneema rope is used with a pennant of e.g. polyester. What also can be seen is a polyester main line made of e.g. polyester with a grommet of Dyneema.

9.0 Conclusions and recommendations

Towline friction has consequences for the longevity of the towline and the working of render-recovery systems. It plays a role when operating with steep towlines or when the towline has a large angle with the centre line of the tug. This is in particularly the case when operating in the indirect mode as can be the case with active escorting, or operating in the powered indirect mode.

The problems could be solved by the use of proper roller staples or fairleads, or a system like the `Azimuth friction free towing point', or by the use of towlines with low friction such as ropes made of Dyneema.

However, another problem is introduced with the use of towlines made of Dyneema resulting in high, and often very short peak loads due to the limited length of the rope and the lack of stretch. Therefore, harbour and terminal tugs equipped with a render-recovery system using ropes made of Dyneema require an extremely fast sample system for measurement of the towlines forces. Also, an equally fast winch activating signalling system is required, all of which being tuned to the short peak periods that may happen in the towline. Even if this works perfectly then there is still the (large) inertia of the winch and the required time for (dis)engagement and overlay of both clutches. This causes the winch not being instantaneously operational when towline forces reach their maximum. This delay may cause the winch to get damaged, the rope to part and/or damage to the ship's deck equipment; a far from optimum system. A stretcher would be a solution to certain extent; it would absorb the largest peak forces in the towline without delay. Or alternatively to dimension the stretcher in direct relation to the winch inertia, to select (just) enough elasticity in the towline to enable the winch to start to rotate. This is something to further explore!

If stretchers are not used because of handling problems, then for the safety of tugs and ship handling in ports, port approaches and at offshore terminals, a further study is required to optimize or redesign a proper towline force control system. Successfully achieving this means we will have tugs available with a reliable deck equipment that is able to limit high peak forces in the towline thereby preventing damage to the winch, parting of the towline and extreme heeling forces.

One practical alternative is to run the towline through a rotatable or linear movable sheave (swivel fairlead) which is connected to a spring system, and from there to the fairlead, preferably an appropriate roller fairlead. Short peaks will then result in the rapid movement of this light sheave and thereby allow valuable time for the winch to operate regardless of control system and inertia delays.

Another option might be a winch drum integrated with a spring system which will absorb peak loads to certain extent.

The company STUbitec has launched a project where a dedicated winch for van escort tug has been developed. The winch is mounted on two shock absorbers which will permit a certain longitudinal movement; this in order to avoid towrope failure during snatch loads [4].

Overview

TUGS WITH RENDER-RECOVERY WINCHES	**TUGS WITHOUT RENDER-RECOVERY WINCHES OR NOT USING THEM**
Because of friction problems, recommended are: Roller staples; roller fairleads; Dyneema ropes Render-recovery signal problems + winch inertia High peak loads System needed to limit high peak loads	Normal synthetic ropes with stretch can be used or combination of Dyneema rope and rope with stretch. (suggestion for overload release system to prevent elastic energy release)

[1] Friction hold of various sheave configurations on synthetic ropes. Department of the Navy. Navy Civil Engineering Laboratory. 1983.
[2] ROPE USER'S MANUAL
http://www.samsonrope.com/Documents/Rope_Users_Manual_WEB.pdf
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[5] TUG STABILITY. A Practical Guide to Safe Operations. Henk Hensen and Markus van der Laan. The ABR Company. 2016.