Proper Use of Fiber Ropes on Capstans and Bitts

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Abstract

Ropes are commonly tensioned by capstans on merchant and navy ships as well as on shore. Here the term capstan means any cylinder around which a rope is wrapped, including warping heads, bitts and bollards. Improper use of ropes on capstans can cause injuries and fatalities.

When a rope is wrapped around a capstan, it is held by friction. The ratio of effective tension to back tension is a function of the number of turns on the capstan and of the friction coefficient between the rope and the capstan. If insufficient turns are applied, the rope cannot be held by back tension. If too many turns are applied, then the rope cannot be released by relaxing back tension.

This paper discusses the capstan formula, which relates friction coefficient and number of turns to the ratio of effective tension to back tension. The formula is not new or original. But it is not widely known and has not published before in a form accessible and usable by merchant and navy personnel, advisors and consultants.

The capstan formula can help understand the loss of tension which occurs when a rope passes around a cylinder. It can be used to calculate the friction coefficient of a rope against a surface, and with that information, it can then be used to calculate the loss of tension in other similar circumstances.

Introduction

This paper discusses the science behind the art of restraining a rope on a capstan. Here the term capstan means any rotating or stationary cylinder around which a rope or other flexible tension member is wrapped in order to apply or retain tension in the rope. The term capstan specifically means a vertical-axis revolving drum. Capstan is commonly also used for a horizontal-axis revolving drum, usually attached to a winch, but the correct term for this is a warping head (and it is sometimes called by several politically incorrect terms).

In this paper, the term capstan includes bitts and bollards, used to restrain the rope. Bitts are a pair of cylinders mounted on the deck of a vessel. A bollard is a single cylinder mounted on a pier, dock, or quay. In the broadest sense of this paper, capstan means any cylinder, such as a shaft, mast, spar or post, around which a rope is wrapped and tensioned.

The Capstan Formula

When tension is applied to a rope which is wrapped around a capstan, the rope is restrained by friction on the capstan. A mathematical formula is helpful to understand the manner in which the friction coefficient and the number of wraps influence this rope restraint.

The increase (or decrease) of tension in a rope which is wrapped around a capstan can be calculated by the capstan formula :

$$\frac{T_{high}}{T_{low}} = e^{2\pi n \mu} = 2.718^{6.28 n \mu}$$

where

T_{high}	=	Tension on high tension side
T_{low}	=	Tension on low tension side
n	=	Number of wraps
μ	=	Friction coefficient.
e	=	2.718

The derivation of this formula is given in Appendix 1.

Fig. 1 shows a capstan and defines the senses of T_{high} and T_{low} with respect to the direction of rotation.

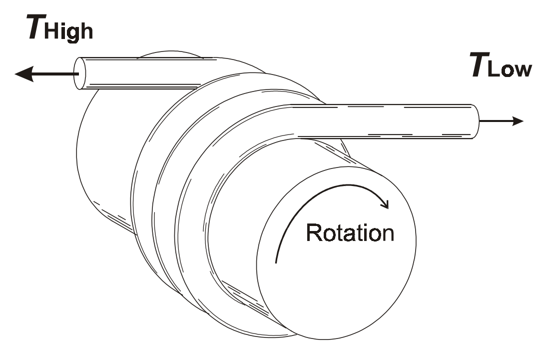


Fig. 1 Tension in Rope Around Capstan

When a rotation capstan is used to draw in a line, the back tension applied on the rope end toward which the capstan is turning is less than the effective tension produced on t\he opposite end of the rope. T_{high} is the tension in the rope being drawn toward the capstan. T_{low} is the back tension, that tension applied by the handler pulling on the free end of the rope.

On a stationary capstan, such as a bitt or bollard, effective tension tends to pull rope from the capstan. T_{high} is that effective tension pulling on the rope. Back tension T_{low} is applied on the opposite end to restrain the rope.

When the value of T_{low} is great enough, the rope will not slip around the capstan. In this stationary case, the static friction coefficient should be used in the above formula.

When the rope slips on the capstan, T_{high} is the effective tension tending to pull rope from the drum, and T_{low} is the back tension at the opposite end of the rope. In this case, the sliding friction coefficient should be used, which is less than the static coefficient. Thus once the rope begins to slip, a higher force will be needed to restrain it again.

Applying the Formula To Ropes on Capstans

Typical friction coefficients for fiber ropes on typical capstans (including warping head, bitt or bollard) range from 0.10 to 0.30. Friction coefficient data are discussed later in this paper.

Table 1 presents the ratio of T_{high} to T_{low} for increasing numbers of rope wraps and several friction coefficients.

For a low friction coefficient, 0.10, T_{high}/T_{low} essentially doubles for each successive wrap of rope. At an intermediate friction coefficient, 0.20, the ratio increases by a factor of about 3.5 for each wrap. At a high friction coefficient, 0.30, the ratio increases by a factor of more than 6 for each wrap.

Note that the ratio of T_{high}/T_{low} is not proportional to the number of turns. For example, for a friction coefficient of 0.20, the difference between one turn and three turns is over 12, the difference between one and four turns is 43, and the difference between one and five turns is more than 150..

When tending a rope on a capstan or warping drum, the objective is to apply enough back tension that the rope doesn't slip, but that it is still possible to release the rope if it becomes overloaded. For this purpose only a few turns should be applied, as discussed later.

Table 1 Reduction of Tension In Rope Around Capstan

	Friction coefficient				
	0.1	0.15	0.2	0.25	0.3
Wraps	Tension Ratio, T_{high}/T_{low}				
1	1.9	2.8	3.5	4.8	6.6
2	3.5	6.6	12.3	23	43
3	6.6	16.9	43	111	286
4	12.3	43	152	535	1,880
5	23	111	535	2,574	12,380
6	43	286	1,880	12,380	81,519
7	81	732	6,604	59,543	

When securing a rope on bitts or a bollard, the purpose is to apply sufficient wraps so that the rope will not slip, no matter how much tension is applied. The weight of the free end of the rope usually applies sufficient back tension. For high friction coefficient ropes, only a few turns may be sufficient, but many turns are usually applied for security.

Synthetic Rope Properties

The friction coefficient of a synthetic fiber rope depends on its material, construction, and condition, as well as on the material and condition of the capstan. Thus an exact value usually cannot be given, even for a particular rope.

A typical friction coefficient for conventional new nylon, polyester, and polypropylene ropes on typical capstans is 0.25. As the rope becomes worn and soiled, this value may increase.

High-modulus fiber ropes are now becoming common as ship-board mooring lines. The principal material in such ropes is high-modulus polypropylene (HMPE) (e.g. Spectra, Dyneema) or aramid (e.g. Kevlar, Twaron). Such ropes are sometimes jacketed with other fibers. The friction coefficient of unjacketed HMPE rope is probably less than the above value for conventional fiber ropes, possibly as low as 0.10.

Another material property of concern is melt temperature. The melt temperature of HMPE is 135° C (275° F) and that of polypropylene is 170°C (338° F). The heat produced by surging on the capstan can melt the surface of these ropes.

Melting creates three problems: As the rope melts, its friction coefficient decreases, allowing the rope to slip in an uncontrollable manner. As the melted rope surface solidifies after slipping, it adheres to the capstan, increasing the friction coefficient and making the rope more difficult to control. And melting damages the rope and reduces its strength.

The melt temperatures of nylon and polyester are greater than 220° C (425° F). Thus the risks of melting are less with these materials.

Past Guidance on Tending Rope On A Capstan

Little meaningful guidance on the proper tending of rope on a capstan is given in common seamanship references. The primary purpose of this paper is to rectify that situation.

The following advice is given in the British Admiralty Manual of Seamanship.[1]

"To bring a rope to a warping drum take three turns of the rope round the drum. Three turns are usually sufficient when hawsers are hove in, but for heavy loading it may be necessary to take an extra one or two turns, giving due regard to the size and strength of the rope and equipment involved. ... To hold the rope stationary while the drum is heaving in, ease the pull on the hauling part sufficient to allow the turns to slip or surge round the drum ... do not let riding turns to develop on a warping drum, because if this happens control of the rope is lost unless the rope is stopped."

The following advice is given by House.[2]
"A minimum number of turns should be used when heaving man-made fibre ropes about winch barrels, warping heads or capstans. Friction generated heat should be avoided, and to this end no more than three turns should be used on drums. ... Never surge on man made fiber rope. Should it be required to ease the weight {tension} off the rope, walk back the barrel or drum as when coming back on a stopper."

The following advice is given by OCIMF.[3]
"Do not apply too many turns; generally 4 turns should be taken with synthetic lines – if too many are applied then the line cannot be released in a controlled manner. ... Do not surge synthetic lines on the drum; in addition to damagind the rope, as it melts it may stick to the drum or bitt and jump, with a risk of injuring to people nearby. Always walk a winch back to ease the weight [tension] off the rope."

There is apparent disagreement among these references. The Manual of Seamanship endorses relaxing tension on the hauling (back tensioned) part of the rope to temporarily prevent the warping drum from pulling on the rope. This practice is known as surging, and the other references (correctly) caution against this practice.

Analysis of Tending Rope On a Capstan

Sufficient turns should be taken on the capstan so that the rope will not slip when normal back tension is applied. A person can normally hold a rope under about 0.13 kN (30 lb) tension for an extended period of time and about 0.18 kN (40 lb) tension for a short time.[4]

Referring to Table 1, exerting 0.13 kN back tension to a rope having a friction coefficient of 0.25 with four turns on a capstan can produce a tension of 70 kN (16,000 lb). This is about 20% of the break strength of a typical conventional synthetic fiber rope used on ship's capstans. If the back tension is increased to 0.18 kN, the produced tension is 95 kN (21,000 lb). If the effective rope tension increases much above this value, the rope will surge on the capstan.

If an additional turn were taken, then 0.18 kN of back tension could produce a tension of more than 460 kN (100,000 lb). This tension is typical of the new break strength of some conventional synthetic ropes used as ship mooring lines, and it could potentially break the rope.

These calculations demonstrate how proper tending of a synthetic rope on a capstan can prevent overloading and how improper tending can potentially break the rope.

Proper Tending of Rope on a Capstan

The friction coefficient is usually not know, and thus it is not possible to calculate the proper number of turns. The number of turns must be found by "trial" and by experience.

Enough turns should be taken around the capstan to allow the rope to be drawn in at a moderate effective tension while applying moderate back tension. When the rope begins to surge (slip) around the capstan under moderate tension, an additional turn should be applied But when a very high effective tension is experienced, the rope should be allowed to surge in order to prevent it from breaking.

Surging of the rope should be used to prevent overload. If too many turns are applied, then this overload-prevention surging action cannot take place. It is especially bad practice to allow the tensioned rope to wrap over a lower turn, as this in effect locks the rope on the capstan.

The use of surging should be kept to a minimum. It should not be routinely used to maintain or relieve tension, as this can damage the rope. Capstan rotation should be stopped to maintain tension. And the capstan should be reversed to relieve tension, or if it is desired to completely relieve tension, then back tension should be quickly released, but not so suddenly that the rope surges in an uncontrolled manner.

An operator should be at the controls of the capstan and a line handler should be tending the rope at the capstan. Don't leave the capstan unattended and rely on surging of the rope alone to stop applying or to relieve tension. Don't secure the rope on the capstan such that a line handler is not needed.

More turns should be taken on a smooth-surfaced capstan than on a rough-surfaced capstan. More turns should be taken with a new rope than with a well-worn rope.

Illustrations of Good and Bad Practices

Fig. 2 shows good practice, with a rope wrapped four times around a capstan. The proper number of turns will depend on the condition of the rope and of the capstan. To few turns will make it difficult to restrain the rope. But too many turns will prevent the rope from surging at high tension and thus might break the rope.

Fig 2 Rope on Capstan

Fig. 3 shows bad practice, with the back-tensioned rope wrapped over itself. This significantly increases the ratio between back tension and effective tension and makes the rope uncontrollable.

Fig 3 Bad Practice, Overwrapping

Fig. 4 shows good practice. Back tension is applied to the side, out of the potential path of a recoiling rope.

Fig. 4 Good Practice, To Side and Away from Rope Path

Fig. 5 shows bad practice. The rope is gripped too close to the capstan drum. If the rope surges, the handler's hands will be drawn into the drum and crushed. Also, if the rope recoils, it might strike the handler.

Other Considerations and Cautions

Capstan drums should not be painted. Paint on a smooth drum may increase the friction coefficient: Paint on a rough drum may decrease the friction coefficient. In either case, the friction coefficient will then change as the paint wears away. The paint will rapidly wear away if the rope is surged on the drum. The paint will thus make it more difficult to control the rope on the revolving capstan.

Figure 5 Bad Practice, Too Close and In Rope Path

Other precautions should be taken when working with ropes on a capstan or in other situations. Don't stand in the potential recoil path of a tensioned rope, unless this is absolutely necessary to accomplish an important task, and in that case don't stay there longer than necessary. Don't stand in the bight (loop) of rope. Don't step on a tensioned rope, even to determine its tension, as the increased tension might cause it to break.

Inspect ropes for evidence of fatigue, abrasion, and damage before and after use.[5] If damage is localized, cut it out and resplice the rope.   Retire ropes which have lost significant strength. Make sure that replacement ropes are of at least the same strength and quality.

References

[1] *Admiralty Manual of Seamanship*, BR 67, Ministry of Defense, London, HMSO, 1993

[2] House, D.J., *Seamanship Techniques*, Heinemann, 1987

[3] "Effective Mooring", Oil Companies International Marine Forum (OCIMF), Witherby & Co., Ltd., London, 1989

[4] Clem, Bill, "Evaluation of Grip Strength and Endurance with Regard to Rope Handling", MTS '91 Conference Proceedings, MTS, Washington, 1991, pps 1019 - 1021.

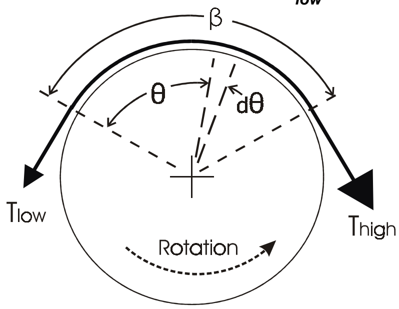
[5] "Fiber Rope Inspection and Retirement Criteria", Cordage Institute, Wayne, PA, in press.

Appendix 1

Derivation of the Capstan Formula [6] [7]

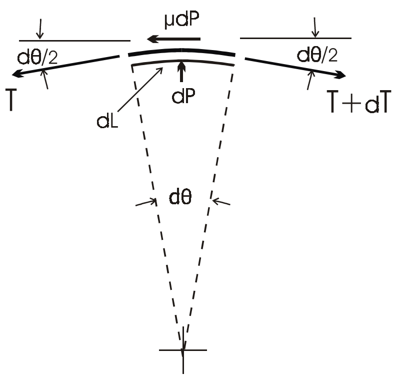
Figure A-1 shows a rope wrapped partially around the circumference of a capstan.

The angle of warp is β. The capstan is turning counter clockwise, such that the tension of the rope at the right side is T_{high}, and the tension at the left side is T_{low}.



Consider a small increment of rope length dL. This increment of rope contacts a small arch $d\theta$ on the circumference of the capstan.

Figure A-2 shows the forces acting on that segment of rope. The normal force (force perpendicular to capstan surface) on the length of rope dL is dP.



The tension in the segment of rope is T, and the change in tension over the length of the segment is dT. This change in tension is due to friction against the surface of the capstan. The friction coefficient is μ, and thus the force due to friction is μdP

From the equilibrium of forces perpendicular to the surface

$$dP = 2T\cos\frac{d\theta}{2}$$

Since dθ is a small angle, we can substitute

$$dP = T\,\theta$$

The frictional force μ dN acts on the length dL in the direction opposing motion. From the equilibrium of forces acting on dL parallel to the capstan surface.

$$(T + dT)\cos\frac{d\theta}{2} - T\cos\frac{d\theta}{2} - \mu\,dP = 0$$

Again since dθ is very small

$$\cos\frac{d\theta}{2} = 1$$

and thus

$$dT = \mu\,dP$$

This equation can be rearranged and integrated around the circumference of the capstan from $\beta = 0$ to $2n$ where n is the number of warps.

$$\int_{T_{low}}^{T_{high}} \frac{dT}{T} = \int_{0}^{2\pi n} \mu\,d\theta$$

This gives

$$\ln\frac{T_{high}}{T_{low}} = \eta\,\theta$$

The friction coefficient is then

$$\frac{T_{high}}{T_{low}} = e^{\mu\theta}$$

where

T_{high}	=	Tension on high tension side
T_{low}	=	Tension on low tension side
θ	=	Angle of wraps in radians
μ	=	Friction coefficient
e	=	2.718

The angle used in this formula is expressed in radians. To convert from degrees to radians, multiply by 0.0175 (π/180˚). One complete wrap is 6.28 (2π) radians, or 360˚.

$$\frac{T_{high}}{T_{low}} = e^{2\pi n\mu} = e^{6.28 n\mu}$$

where

n = number of wraps around capstan

References:

[6] Flather, John J. PhB, A Treatise on the Transmission of Power by Means of Fibrous Ropes, John Wiley & Sons, New York, 1907

[7] Samset, Ivar, Winch and Cable Systems, Norwegian Forestry Research Institute, Martinus Nijhoff / Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1985

Appendix 2

Using the Capstan Formula to Determine Friction Coefficient

The capstan formula, derived in Appendix A, is commonly used to determine the friction coefficient of fibers, ropes, and other flexible materials.

Yarn on Material Surface Friction Coefficient

The friction coefficient of fiber and yarn on particular materials is of concern in weaving, sewing, and other textile operations.[8] [9] For this purpose, the formula is used in the form :

$$\mu = \frac{\ln \frac{T_{high}}{T_{low}}}{2\pi n}$$

The fiber or yarn is drawn across a cylinder of the particular material, with a known wrap angle. while the tensions on both sides of the cylinder are measured.

Rope on Capstan Friction Coefficient

The above formula can also be used to determine the friction coefficient of rope on a capstan.

Static friction coefficient can be determined by wrapping the rope around a stationary capstan, attaching a weight to one end of the hanging rope end and increasing the tension on the other end of the rope until it slips on the capstan.

Dynamic friction coefficient can be determined by then decreasing the applied tension until the rope stops slipping. Alternatively, static friction coefficient can be determined by wrapping the rope around a cylinder which can be rotated.

Care must be taken when measuring friction coefficient on a capstan. The coefficient depends on the roughness of the capstan surface. If the same capstan is used for successive tests, the surface tends to become polished and depressions in the surface tend to clog with particles abraded from the rope, and thus its friction characteristics change. Successive tests can also increase the capstan surface temperature.

This method was used by Brown to measure the friction coefficient of a number of different ropes on capstans with several different metal surfaces.[10] However, the tests were not conducted in a controlled and reproducible manner, the published report is hard to understand, and the results are inconsistent, confusing and hard to interpret. Similar tests should be conducted in a more controlled manner using contemporary synthetic ropes.

Yarn–on-Yarn Friction Coefficient

The friction coefficient of a yarn rubbing against itself is of interest in textile science, especially in analyzing synthetic rope performance.

The following variant of the capstan formula is used to determine the friction coefficient friction between yarns of the same material.

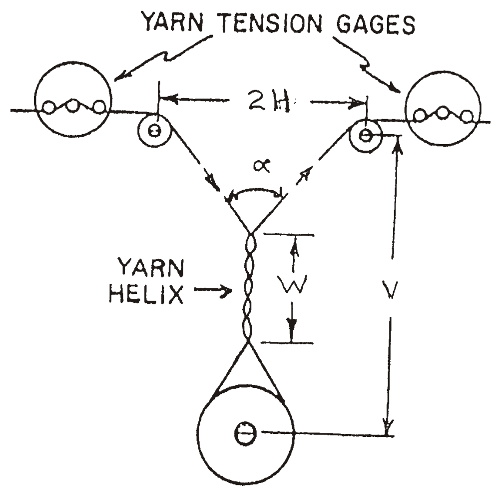
$$\mu = \frac{\ln \frac{T_{high}}{T_{low}}}{2\pi n \alpha}$$

where

α = angle between yarns

The derivation of this equation can be found in Goksoy.[11]

Fig. A-2 shows the arrangement used in determining yarn-on-yarn friction in ASTM Test Method D 3412.[12]



References:

[8] Morton, W.P., and J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute, Manchester, UK, 1962, 1975, 1993

[9] ASTM "Standard Test Method for Coefficient of Friction, Yarn to Solid Material", D 3108, American Society for Testing Materials, West Conshohocken, PA

[10] Brown, W.E., Friction Coefficients of Synthetic Ropes, Report TP 544, Naval Underseas Center, San Diego, CA, 1997, Defense Documentation Center ADA036718

[11] Goksoy, Mustofa, "A Study of Yarn -on-Yarn Abrasion", PhD Thesis, University of Manchester Institute of Science and Technology, Manchester, UK, 1986

[12] ASTM "Standard Test Method for Coefficient of Friction, Yarn to Yarn" D 3412, American Society for Testing Materials, West Conshohocken, PA