The MIT Marine Industry Collegium
Opportunity Brief #42

Design Consideration for the Uses of Ropes and Cables in the Marine Environment

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DESIGN CONSIDERATIONS FOR THE USE OF ROPES AND CABLES IN THE MARINE ENVIRONMENT

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1.0 INTRODUCTION AND BUSINESS PERSPECTIVE

Tow jobs range from aiding disabled pleasure boats to hauling giant semi-submersibles across the ocean, from carefully pulling a barge full of toxic wastes to yanking a ship off a shoal. In addition, the armed forces are interested in towing ships which are damaged or have lost power. A disabled ship might have to be towed for long distances under attack or in bad weather, increasing the demand for a reliable towline. More information about rope dynamics is needed to reduce the likelihood of towed vessels being lost at sea or running aground. Professors Jerome Milgram and Michael Triantafyllou and graduate student James Burgess mentioned recent research in towing dynamics at the September 20, 1985 Marine Industry Collegium meeting.

Mooring systems have always played an important role in offshore engineering because they are one of the most economic means of positioning marine structures in the ocean. As offshore structures move into deeper and more hostile environments, a demand has arisen for mooring system designs capable of working in water from 1000 to 3000 ft deep.

This move into deeper water challenges mooring system designers. At greater depths, increased initial tension in the mooring lines is needed to avoid excessive platform movement and consequent damage to marine risers (the conduit that transfers fluids from the well head to the producing platform). Greater initial tensions, in turn, reduce the amount of wave-induced dynamic tension that the mooring line can accommodate. However, as the length of the line increases, so does the wave-induced dynamic tension.

Engineers currently do not have the tools to study dynamic loads in cables, so they design cables for static load conditions even though the dynamic load can be two or three times more than the static load. Because of the necessarily large initial tension in the mooring lines, designers must be provided with a good understanding of the dynamic behavior of mooring systems and the ability to accurately predict their dynamic tension. Dynamics of mooring lines were covered at the Collegium meeting by Professor Michael Triantafyllou and Dr. Antoine Bliek.

Professors Stanley Backer and John Mandell discussed their work in how rope deteriorates. Environmental forces such as sunlight and seawater can eventually harm the outer surface of ropes, while internal abrasions can insidiously chew up the rope from within. Sometimes a rope reveals its first sign of internal damage when it snaps. Foundering helplessly at the other end of the broken line could be a barge or a ship already crippled by engine trouble. Frayed ropes have sent moored ocean research instruments tumbling to the sea bottom with their months of unique data irrevocably lost. More ominously, a breaking synthetic fiber rope releases tremendous energy that can maim or kill sailors and dockside workers.

At the Collegium meeting, research results on both the dynamics of ropes and cables and the pathology of ropes in marine environments were reviewed and tentative future research programs were considered.

2.0 DYNAMICS OF A TOWING CABLE

James J. Burgess, a doctoral candidate in the MIT Department of Ocean Engineering, is developing methods to determine the extremal statistics for the motions of a tug and towed vessel and the loads within the towing hawser. This information will provide a design tool for towing systems and will supply planners with input to help insure that the tows arrive on schedule and intact. It will also lay the groundwork to optimize towing speed, heading and hawser length in given sea states, and to help design a "smart" towing winch which could predict the occurence of high cable loads and respond accordingly.

The towing hawser is a simple cable structure subjected to continuous dynamic loading. However, the current design practice for towing systems is based on a simple static analysis of the force which can be supplied by a given tug. This practice overlooks the dynamic loads and motions generated by the presence of even mild sea conditions, despite the knowledge that towlines are often subjected to dynamic loads from heavy seas.

Along with its failure to accurately predict hawser loads, the static analysis has three additional deficienies:

1. It does not allow designers to consider the seakeeping properties of the tug and tow, and possibly modify their design.

2. Without knowing the effect of the sea state, it is impossible to plan routes or schedule tows to avoid threatening sea conditions.

3. It does not help the tug captain adjust control variables--forward speed, hawser length, and heading--to minimize either the motion of the tow or loads in the hawser.

While seakeeping, towlines and cable dynamics have been investigated for years, Burgess says that dynamics of towing cables have not been studied thoroughly. "The dynamics of a towing hawser are generally neglected because they are difficult to analyze." In studying the towing hawser, "we want to eliminate the assumption that the dynamics of the towing hawser are negligable. If any cable is excited slowly, it will not be terribly inaccurate to assume a force displacement relationship for the cable. However, in a seaway there might be excitation of approximately the natural frequency of the cable, which may lead to large dynamic tensions. Also, during the towing the cable frequently will 'snap', or suddenly come up taut and straight. In our analysis we want to accurately predict the dynamic tension asssociated with this sort of severe loading," he says.

"To study the hawser we introduce a number of simplifications in the towing system," says Burgess. "We assume that the dynamics of the cable have little effect on the rapid motion of the tug and towed vessel, since the tug and tow will have substantially greater mass than the cable. We assume that the cable is under high enough quasi-static stress so that the ratio of cable weight to horizontal tension is small. The cable should suffer the most damage during such times of high quasi-static stress, as when the tug is hauling the tow at a high speed or in heavy seas. We also assume that the towing hawser is a single horizontal homogeneous steel cable with negligible bending stiffness." Even though the ends are exposed and parts emerge and submerge during towing, the hawser is assumed to be completely immersed in water.

Because the cable is immersed in water, a nonlinear drag term is included in the equations of motion. The nonlinear term eliminates the possibility of a closed form solution for the cable motions and forces the analysis to be carried out through time domain simulation. "The prediction of towing loads and motions for the towing system using time domain techniques, which include a nonlinear model for the hawser dynamics, will be the major contributions of this research," says Burgess. "It will translate current seakeeping knowledge to the time domain and it will establish the groundwork for the development of such things as the 'smart' towing winch."

Normally designers would choose a linear frequency domain analysis if they wanted to run large numbers of simulations to cover a given design environment. "That way they can make judgments on the design system without spending a fortune on the time domain simulation," says Burgess. "If they find a particular circumstance that looks dangerous, then they can simulate that case to check for tensions or motions far in excess of what the linear theory would predict."

With spectral methods the cable motions are expanded into a set of orthogonal functions such as the natural modes. This form is more attractive for improving the efficiency of the time domain simulation because it may only be necessary to expand the motions into a set of a few functions to obtain solutions with sufficient engineering accuracy.

In implementing the spectral method, two sets of functions are used: the natural mode and a set of sinusoids. Using the natural mode is awkward for time domain simulation because of the complicated nature of the natural mode, the nonlinear drag force term, and the large number of natural modes necessary to recover elastic phenomena. Therefore the simulations are reformulated using simple sinusoids, which prove to be an easily implemented set of functions.

Burgess's simulations show close agreement with simple linear solutions and lead to the same fundamental conclusion established in simulations with forced end motion. The presence of a nonlinear drag term forces the hawser to respond to end displacements through stretch. Dynamic tensions caused in both the transient and steady state response are significantly greater than those predicted by a linear model which neglects the nonlinear drag.

To determine the extremal statistics, a 5-degree-of-freedom seakeeping program developed at MIT calculates the wave forces, the added mass coefficients and damping coefficients for a vessel on a seaway. The hydrodymamic coefficients are determined using this existing program with an additional surge model. Burgess has a 12-degree-of-freedom seakeeping program that uses that earlier program to calculate wave force vectors on a tug and a tow vessel coupled by a towline that acted as a simple linear spring with a simple force displacement relationship. "In reality, displacement of force in a cable is a highly nonlinear function. But if the motions are small enough, the linear approximation for the tow line stiffness may be close enough for engineering purposes," says Burgess.

Extremal statistics for the vessel motions and hawser loads will then be derived using frequency domain methods. "It is necessary to develop a nonlinear model of the towing system. This model will involve the inclusion of nonlinear viscous damping in the roll motions of the tug and tow, and the nonlinear characteristics of the hawser," says Burgess.

The modeling of the hawser will be carried out in steps. First, the hawser will be considered as a linear spring with viscous damping that arises from the cable being submerged in water. Second, the geometric nonlinearities due to the changing catenary shape will be considered along with the viscous damping, to provide a model with both nonlinear spring and damping characteristics. Finally, the presence of transverse and axial waves must be considered along the cable, with the axial waves becoming important as the hawser comes up tight or snaps.

3.0 DYNAMICS OF MOORING ROPES

Between 1981 and 1984, MIT Sea Grant researchers embarked on a study to provide fundamental understanding of dynamic behavior of cable systems in the marine environment. The major contribution of this study was to identify the range of parameters where substantial dynamic tension amplification was possible, which could result in direct failure or failure by fatigue. In 1983, the offshore industry joined MIT Sea Grant in funding a joint study to investigate the design implications of dynamic tension amplification. Six companies joined the first phase of the project, in which computer codes were prepared to look at the linear and nonlinear cable dynamics for the range of cable parameters where the linear analysis predicted substantial dynamic tension amplification.

The researchers are now ready to embark on the second phase of the project, a fatigue study for cables to assist the practicing engineer to choose proper values for cable parameters. In particular, the group wants to investigate the effect of three nonlinearities on the fatigue life of a cable: fluid drag, geometric (large amplitude) nonlinearity, and cable-bottom interaction. The effect of the nonlinear fluid drag is to smooth out the pronounced peaks of the linear theory while dramatically increasing the dynamic tension for all frequencies. Geometric nonlinearity introduces a substantial nonlinear component in the tension which for large amplitudes can double the dynamic tension predicted by linear theory. The cable-bottom interaction can introduce impact phenomena, or by modifiying the lower boundary condition can cause a shift in the natural frequencies of the cable.

A computer code will be prepared to provide quantitative predictions of the fatigue life of mooring lines. The program will accept as input the characteristics of the mooring lines and the storm statistics of the area of interest.

Professor Michael Triantafyllou and Dr. Antoine Bliek of the MIT Department of Ocean Engineering propose to develop a complete computer package that will investigate the fatigue properties of cables once the storm statistics are defined. The program will be used to assess the impact of having natural frequencies in the wave range, as well as the effect of the elastic stiffness, while it will be a self-contained package for the practicing engineer.

The research consists of a first phase in which the necessary developments for modeling the drag force, cable-bottom interaction and snap loading were made. The second phase, which is currently in progress, concentrates on developing the fatigue package, and investigating the effect of the elastic stiffness and of having natural frequencies directly in the wave frequency range.

During the first phase the nonlinear dynamics of mooring lines were investigated by Professor Triantafyllou, Dr. Bliek, and graduate student Hyunkyoung Shin. The principal mechanisms of nonlinear behavior: drag, tension-displacement relation, and cable-bottom interaction, were investigated with numerical codes based on recently developed theories of cable behavior. Methods to simplify the numerical analysis and principal trends were uncovered. "At this point we have a complete research tool; the computer program, and a number of theoretical developments that explain the effect of fluid drag, the effect of cable-bottom interaction and the effect of suddenly applied loads," says Professor Triantafyllou.

It is possible to replicate the results of the nonlinear code by using a frequency domain approach and the equivalent, linearized drag term, an important step for fatigue studies when very long simulations are required for each possible storm in an area. The frequency domain approach can provide answers with minimal effort and with well known probability estimates. The disadvantage of the frequency domain approach is offset when proper linearization and knowledge of the system have been established.

A number of important questions can be addressed with such a program: what is the effect of the recently discovered hybrid modes (and the accompanying tension amplification) on the fatigue life of cables? What is the parametric dependence of the fatigue life on the elastic stiffness to catenary stiffness ratio?

For deep water lines (more than 1500 ft) the hybrid modes are a definite possiblity for such systems as semisubmersibles and guyed towers, while the first few natural frequencies lie within the wave frequency range. This research will provide an easy-to-use tool to investigate their effect on the fatigue life of the mooring line.

The second year effort will use a frequency domain program. The researchers will develop a long term simulation package to determine the fatigue life of mooring lines over their life span, given the storm statistics of the area. There are three steps in this effort:

1. Develop the first phase theories on nonlinear drag, cable-bottom interaction and snap forces for irregular excitation, so that a complete frequency domain model can be constructed. Considerable effort will be spent on testing the performance of the frequency domain program (in particular regarding the dynamic tension) against the nonlinear code.

2. Develop a computer code which will incorporate the cable program and which will admit the storm characteristics of a specific area over the life span of the cable; the life period of the system; and the fatigue characteristics of the line.

3. Investigate the effect of the recently developed theory of tension amplification on the fatigue life of cables.

Damping affects the value of the dynamic tension so that the long term effect of the tension amplification on the fatigue life should be assessed through correct modeling of the drag forces. Also, for a cable lying partly on the ground, the bottom-cable interaction alters the boundary condition at the bottom and introduces loss of energy per cycle.

4.0 DETERIORATION OF SYNTHETIC FIBER ROPE DURING MARINE USAGE

Today's ships no longer have webs of manilla hemp ropes to raise and lower sails, stabilize the masts and serve as ladders for sailors to scramble around the rigging. However, ropes continue to be vital for anchoring boats and mooring lines, moving objects around a ship, making slings to handle cargo, and towing everything from sailboats in trouble to disabled tankers.

Modern marine ropes are made of synthetic fibers such as polyester, nylon, polyproplene, and in special cases aramid (Kevlar). Compared to natural fibers, the synthetics are stronger, more durable and more resistant to sunlight and biological degradation. However, they are not impervious to damage. Professor Stanley Backer in the MIT Department of Mechanical Engineering has been involved in a long-term project on how and why ropes deteriorate. The eventual goal is to predict when seemingly stout ropes are no longer safe for their intended purpose.

Part of Professor Backer's project involves dissecting ropes and examining them under a scanning electron microscope to check how they have deteriorated over years of use. That painstaking task requires dissecting the rope to separate out the fibers and measure their mechanical and chemical properties. The researchers study any loss in strength or changes in chemical structure or properties within various parts of the rope, and see how the fibers break. In some cases they can measure the molecular weight, which is related to changes within the fiber caused by photochemical degradation.

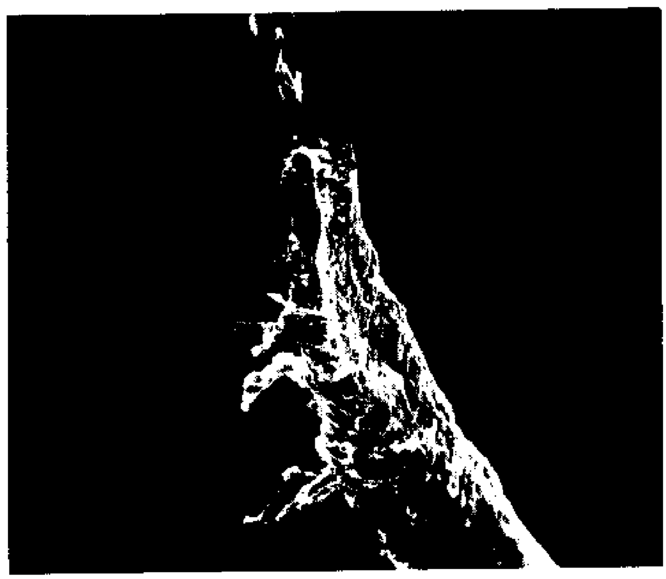
As expected, the outside surfaces of well-used ropes show photochemical degradation as well as abrasions from being dragged over rough surfaces and wound around winches. (See Figure 1.) Sunlight affects the fibers only on the surface, and cannot penetrate more than one or two yarns deep. "We had to verify the extent of sunlight degradation and abrasion degradation, and then try to evaluate how much tensile fatigue degradation occurred in the rope itself," says Professor Backer.

"We are carefully charting the strength of elongation of fibers throughout the vertical cross section, so we know what happens to the fiber on the outside and also what happens as that same fiber winds its way to the inside," states Professor Backer. "Even though the inside fiber may be identical to the outside fiber, it is protected and receives entirely different kinds of forces and photochemical exposure."

Since Professor Backer had expected to find very little deterioration in the protected inside fibers, he was surprised to uncover a considerable amount of damage. When he started to construct models, he realized that the damage was caused by high pressure and lateral motion, and the resulting friction. This type of internal friction can lead to abrasions, which can eventually degrade a rope that displays no outward signs of weakness.

Damage to ropes usually accumulates over many years. Some accelerated tests are being done in the laboratory to subject the rope to cyclic loading, but

Figure 1. This damaged fiber comes from the surface of a rope where it was exposed to weather and abrasion.



Professor Backer notes, "The results of the accelerated tests are different from the results from the long-term experiments." In the tensile cycling machine the residual amount of stretch diminishes as the machine pulls a rope fiber toward its breaking limit. (See Figures 2 and 3.) Fibers from ropes showing abrasions after having been in the ocean for eight years also have less residual stretch. But the fibers in the old ropes that aren't abraided have a greater residual stretch than new fibers. In a laboratory test the fiber slowly stretches out, reaches its ultimate elongation, then breaks. In practice, the fiber is loaded cyclically while being in water, and depending on the load applied it may shrink and get shorter. Such a shrunken fiber then displays greater residual elongation.

"Ropes have single fibers twisted into yarns, then twisted into rope yarns, which are twisted into plied yarns. The plied yarns are twisted into strands, which are twisted into ropes. The geometry of all those helixes around helixes is very complicated," says Professor Backer. He has to build the geometry of the rope into a mathematical model, and predict how the rope will resist being stretched. The mathematical model deals with the classic three-stranded rope and the more recent double-braided rope, and is being extended to the eight-plaited rope.

The mathematical model should be useful in predicting trends, Professor Backer thinks, such as what would happen if larger fibers or yarns are used or if the twist is increased. It might tell how much untwisting will take place with a three-stranded rope or how much twisting torque will develop when the rope is pulled. One great disadvantage of the three-stranded rope is that it tends to untwist when a weight is hung on it. Once the weight is released, such as when an anchor hits bottom and the rope goes momentarily slack, the rope snarls up on itself. This process changes the rope geometry and builds in stresses which could subsequently lead to a rupture of the rope.

Professor Backer expects that the model will be useful in anticipating changes in design and checking the subsequent effects on the rope properties. If the properties of a rope are altered to achieve greater durability, the rope might end up being stiffer. Using a much stiffer rope to tie a ship to a dock could well build up very high forces in the mooring hardware. Instead of the rope breaking under tension, the hardware might fly loose, bringing unhappy visions of a 200-lb piece of metal snapped through the air like a slingshot stone.

With the model Professor Backer and colleagues can determine the lateral compression within different parts of the rope and can calculate the relative movement between different strands in the rope. In laboratory tests fibers are rubbed against each other with different pressures to see how much they abrade. "If we could calculate the pressures and the relative motion within a rope, and if we know from laboratory tests how fast the fiber wears out under those conditions, we should be able to predict how fast the rope will wear out. We should be able to predict how changes of design will affect the internal abrasion resistance," says Professor Backer. "At the present time we cannot really test that internal abrasion characteristic very easily."

Figure 2. Fractography of fibers on the surface of a rope which was exposed to the elements for several years. About 3 million filaments of this size (1/1000 in. diameter) are required to make up a 3-in. diameter rope.

Figure 3. This previously undamaged fiber was fractured in a laboratory test. (Fiber is 1/1000 in. diameter.)

The model has certain limitations because of built-in assumptions, such that the fibers are linear and elastic. "We assume that if a rope is unloaded it would just reverse what happens during loading, but we know that is not true. The model assumes that the new rope has no residual stresses or strains in it from the manufacturing, although we know that the manufacturing process introduces many stresses and strains. We have to gradually eliminate those assumptions we used as a basis for the predictions, and see how the changes affect the results," says Professor Backer.

"Our prime objective is to find out why rope deteriorates, then to model the rope so we know what factors dominate its properties. Eventually we will combine the deterioration information and the mechanical structures information based on the models to predict what a worn rope will do. If we can predict how a worn rope will behave, or how long before it wears out, then presumably the Navy or a maritime organization could judge how long to use a rope in a particular application before entering the danger zone," says Professor Backer. "The modeling then allows us to go back and predict how long the system will go before it collapses."

5.0 FATIGUE OF MARINE ROPES

Because of widespread critical uses for marine ropes such as ship towing and single point oil tanker moorings, marine rope technology has been increasingly examined in recent years. John F. Mandell of the MIT Department of Material Science and Engineering is analyzing rope fatigue data from testing programs, in an attempt to correlate them with recent results on the small scale fiber and yarn elements of which the ropes are composed. "Our program is intended to complement Professor Stan Backer's work as a study of fundamental deterioration mechanisms of the fibers in the yarns that make up ropes, under the fatigue and environmental conditions which they experience in service," he says.

Most marine ropes are made up of individual synthetic fibers about 30 microns in diameter, which are themselves composed of a microfiber structure. The individual fibers are usually used as lightly twisted textile singles yarns containing 100 to 300 fibers. A number of singles are twisted together to form rope yarns, which are then combined into plied yarns. The plied yarns may be braided to form a cover and core structure of double braided rope, or further combined to form large strands. The strands then may be twisted together for three stranded rope or combined into an eight strand plaited rope. Each of these constructuions is commonly used with several chemically different synthetic fibers.

The tensile fatigue behavior of nylon and polyester single fibers and yarns derives from a simple process of accumulating creep strain, with failure occuring at a strain similar to the static strain to failure. Research on fibers and yarns at room temperature and relatively high stresses has shown:

1. The cumulative strain to failure is independent of load history, whether static stress-strain, creep rupture, cyclic fatigue at various frequencies, or cyclic fatigue followed by a residual stress-strain test.

2. The cyclic fatigue lifetime at various frequencies can be predicted from the creep rupture behavior using a linear damage law integrated over the total test time. Thus, the creep rupture curve is the only significant material property influencing fatigue lifetime.

3. The residual strength is nearly equal to the original strength over most of the cyclic lifetime, at leat to 75% or 80% of the mean lifetime at a particular load condition.

4. As a specimen is subjected to increasing cycles, the stress-strain curve becomes stiffer (steeper) and the hysteresis energy decreases.

5. The hysteresis energy at the same percentage of the strength is about an order of magnitude higher for nylon than for polyester. Hysteresis energy decreases gradually with increasing frequency.

6. Fiber finish has no effect on untwisted yarns, as there are no significant fiber-fiber interactions.

7. Moisture reversibly reduces the initial modulus of nylon by more than a factor of two, while reducing the strength by 10% to 15%. Salt water and solutions of severe stress cracking agents for bulk nylon have the same effect as distilled water. Polyester is almost unaffected by water.

Nylon and polyester fiber and yarns display relatively simple and predictable fatigue behavior at frequencies and conditions relevant to marine rope use. The highly oriented internal structure of rope fibers reduces environmental sensitivity and dictates a fixed cumulative extension at failure regardless of load history. Additional effects which may complicate this picture in a rope environement include fiber shrinkage with long term water exposure, transverse loading, internal and external abrasion, recovery periods betwen loadings, hysteretic heating, and photochemical degradation at the surface of the rope.

Fatigue data for wet nylon and polyester ropes up to 120 mm in diameter show two dominent failure modes. At high loads above 30% to 40% of the new strength for nylon or 60% to 70% for polyester, most failures occur near the splice according to the cumulative time under load, which can be predicted from the creep rupture behavior of the individual fibers and yarns. At lower loads, down to 5% of the breaking strength (and high cycles) failure usually occurs at the eye/bollard contact area due to external abrasion. A cumulative cycles model based on abrasive wear agrees with data trends for failures at this position. Limited polyester data at high cycles with improved eye protection shows a shift in failure position to the splice, apparently due to internal abrasion. The abrasion model also correlates with the trend of these results. In both failure modes (room temperature and wet), polyester outperforms nylon. Tests on dry ropes often involve significant hysteretic heating which can dominate the failure process.

Properties of ropes change continually as cycling progresses. The load-extension curve becomes steeper and the systeresis energy absorbed per cycle decreases. Both of these changes occur at a decreasing rate as cycling progresses. For creep rupture dominated failure, the residual strength remains close to the new strength until very close to failure, while the total strain accumulates to reach a value close to the new breaking strain at failure. External abrasion dominated failures can occur at lower average cumulative strains at high cycles, and the residual strength should decrease more steadily as the cross-section is worn away.

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