Experimental Study for Small Diameter Flexible Lines

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***Abstract* - For a class of flexible lines structures such as fibers, strands, cords, composites, biological structures, etc. a number of mechanical properties are difficult to evaluate. Often, experimental measurements are required, especially for developing new products. The problem is complicated for very flexible lines made of more than one material when no direct correlation among properties can be precisely established, especially from small displacement theory and at very low loads. The solution is farther complicated by the anisotropic (usually transversely isotropic) nature of the line structure and its viscoelastic behavior.**

This paper presents novel procedures and apparatus for studying bending stiffness, fatigue, and wear and friction characteristics of small diameter flexible lines. Detailed experimental results are presented for lines made of various braided or solid cores embedded in a polymeric jacket. The evaluation of experimental results is based on certain classical analytical solutions. Time dependent and environmental effects are easily incorporated in the experiment. This research provides background for the development of an analytical model for predicting mechanical properties for flexible lines.

I. INTRODUCTION

Flexible line structures such as small strands, cords and composites have extensive application in area of fishing lines and biological structures. We are focusing on structures having the diameter in a range of 1mm or less, made of various polymers reinforced with continuous fibers. While tensile tests are quite simple and well established, a number of mechanical properties like bending stiffness, friction coefficient, or fatigue life in bending are difficult to evaluate. Often, experimental measurements such bending stiffness or fatigue under bending are required, especially for developing new products. The problem is complicated for very flexible lines made of more than one material when no direct correlation among properties can be precisely established, especially from small displacement theory and at very low loads. The solution is farther complicated by the anisotropic (usually transversely isotropic) nature of the line structure and its viscoelastic behavior.

This paper presents a novel procedures and apparatus for studying bending stiffness, fatigue, and wear and friction characteristics of small diameter flexible lines, such as fishing lines. Detailed experimental results are presented for lines made of various braided or solid nylon cores embedded in a polymeric jacket and for lines made of braided Spectra fibers stiffened with a viscoelastic polymeric material. The evaluation of experimental results is based on certain classical analytical solutions. This paper shows how time dependent and environmental effects could be incorporated in the experiment and how one can correlate simple tests to determine mechanical properties of flexible lines.

The purpose of this study was to provide data and knowledge for developing more competitive fishing lines with improved friction, bending and fatigue characteristics. In the process of developing fishing lines there is a competing challenge between the lifetime characteristics (abrasion resistance and the durability) and the feel of the users (in this particular case the fisher-man/women) in terms of slickness, flexibility and hardness. Our focus was to determine slickness, flexibility, hardness, and fatigue characteristics and provide manufactures with information for improving the desired characteristics.

The results of this research provide background for the development of an analytical model for predicting mechanical properties for flexible lines, [1]. The initial purpose of the research was to develop simple apparatus for testing fly lines, which can be used in house for further development.

II. ANATOMY OF A FLY LINE

Fly lines can be typically grouped into:

- floating lines
- sinking tip lines
- full sinking lines.

The lines are comprised of two parts: the core material and the coating material. By modifying these two components the line characteristics are modified to meet certain fishing applications. In the process of fishing castability, shootability and durability are matters of significance. The purpose of our study was to develop mechanical tests that will assist manufactures to alter line characteristics to meet specific fishing needs.

The core of a line determines its tensile strength, stretch and stiffness. A typical fly line has tensile strength in the range of 20 to 40 lb, the stronger lines are for fishing in heavy saltwater. The stretch (or longitudinal stiffness) determine the ability to control the line; too much stretch creates a mushy line, too little stretch adds to line memory. Most lines have a core of braided nylon, or single strange of monofilament. Stiffness is determined by application. For example, tropical heat demands a line with a stiffer core then a line to be used in cold waters.

The core of line is coated with a PVC (PolyVinil Chloride) material, "the versatile plastic". Depending on how it is formulated, it may be a rubbery flexible material or a rigid high impact product. The end performance and the processing characteristics are determined by a series of additives used in the formulation of the compounded product. In addition, in the process of flylines fabrication fillers and colorants are also added. For example, for manufacturing floating lines in one instance small (about 20mm diameter) glass hallow spheres are added to make the PVC compound lighter, in other instance "air cell" is added. The density determines whether the line will float or sink. The speed of sinking (speed rate in inch/second) is also an important characteristic for fly lines. In some lines powdered tungsten is used to make lines to sink. Hydrophobic agents are used in some lines to repel water and increase flotation. Al these additives have an influence on mechanical properties of lines. Typical mix proportions are about 5 to 6% glass microspheres and about 1.2% of color pigment.

Most common fly lines have variable cross-section: the tip, the body and the running line. The total length of a fly line is about 30 to 35 yards. Most weight is concentrated in the body section. The body weight is what carries the cast. The gradual change in line's mass (weight) effects how casting energy is transferred to the fly and how powerful the line is delivered.

We also studied the development of Spectra fiber lines. Spectra fiber is composed of polyethylene, a very slick plastic. Our effort was in stiffening the Spectra braided fiber lines. We have achieved this by impregnating the braid with a polymer and producing a smooth round line with a very small friction coefficient, which is gentler on rod guides, on reel and on lines themselves.

III. FRICTION TEST

Our major interest was to measure the relative friction coefficient among lines for developing purpose. In particular, we were interested to measure the friction between the rod guides and the line. In the process we have invented an apparatus which simulate the friction between the line and the rod guides during casting the line. The focus was to study the surface roughness for line casting process. A smooth line will cast easier, faster and further. However, measuring the coefficient of friction for fly lines was a challenging problem. We have invented an apparatus to do this.

The line friction apparatus developed at Cornell is shown in Fig. 1. It consists of a bicycle wheel about 25 inch diameter on which are mounted 36 guides. The line is attached at one end to a load cell and the other end is loaded with dead weight, F_1=100 grams. By rotating the wheel, for example counterclockwise, the rings move with respect to the line thus inducing friction force as each ring is passing the line. At any given time, ten rings are in contact with the line. By measuring the change in force during the rotation of the wheel, we record, with a precise load cell, the "friction force" F_2 between the line and the rings. The friction coefficient is calculated from the following equation, $f = 2/\pi\ (\ln F_1/F_2)$, with F_1 and F_2 as defined in [2].

Fig. 1. The apparatus for studying the friction coefficient

The duration of the test (the recorded data) for each line was over a period of 10 seconds. The average speed of "guides/rings passing over the line" was about 8.5 ft/s. The friction force F_2 has been recorded at ½ second, thus the F_2 data is an average of 20 data points. Results from testing 16 different fly lines are given in Table 1.

TABLE 1

RECORDED F_2 AND FRICTION COEFFICIENT f

Specimen	F_2	f
1	67.43	0.25
2	75.99	0.18
3	82.69	0.12
4	86.75	0.09
5	87.58	0.08
6	81.61	0.13
7	82.37	0.12
8	76.55	0.17
9	83.94	0.11
10	72.61	0.20
11	63.46	0.29
12	73.94	0.19
13	53.35	0.40
14	64.38	0.28
15	79.08	0.15
16	77.63	0.16
17	63.55	0.29

A graphical representation of the variation of friction coefficient with time during the testing is shown in Fig. 2.

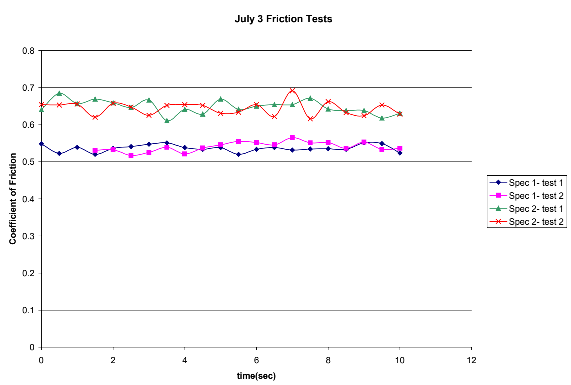

Fig. 2. Variation of friction coefficient with time of test

The friction coefficient is influenced by dry and wet conditions. With the system we invented we could study the dry and wet friction. The lines are first soaked in room temperature tap water for approximately one minute. The wet test was conducted in a similar manner to the dry test. After the line is attached to the apparatus, the water is turned on via a valve immediately before the wheel apparatus begins to spin. Water is continually applied to the line at room temperature via a pump and tubing apparatus. The water is pumped using a thermally protected utility pump, and dispersed to the line at 6 points spaced one inch apart. The dripping continues for the duration of the test. The friction coefficient was quite high. Average f for dry line was significantly higher, about 3 times higher than the friction coefficient for wet lines. A comparison of the variation of friction coefficient f with the testing time is shown in Fig. 3.

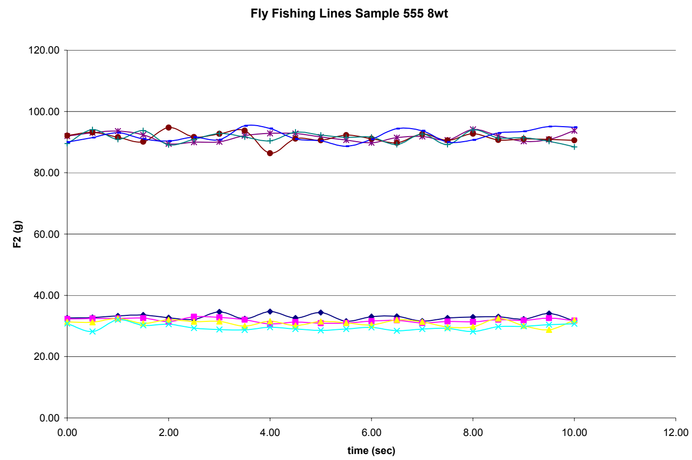

Figure 3. Friction wet (bottom) versus friction dry (top)

A comparison of friction coefficient for dry and wet lines is given in Table 2.

TABLE 2

DRY FRICTION VERSUS WET FRICTION

Specimens	Dry friction	Wet friction
1	0.33	0.06
2	0.31	0.04
1	0.19	0.09
1	0.21	0.10

IV. BENDING STIFFNESS MEASUREMENTS

The model for the bending stiffness tester is shown in Figure 4. It consists of a system in which a sample specimen consisting of “n” parallel circular coils (rings) is subjected to bending deformations. The force applied is in the range of a few grams. For each force increment of about 1 g we measure precise the change of diameter in 0.001” units. Then, from equation of ring displacement subjected to a force W along the diameter we compute the bending stiffness EI.

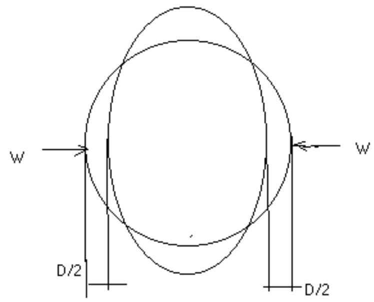

Fig. 4. Mathematical Model for Bending Stiffness

The bending stiffness is calculated from the following equation given [3].

$$EI = 0.1481\ W R^3/(N\ D)$$

where W is the applied force, R is the radius of coil, N is the number of coils, and D is the change in coil diameter due to the force W.

Results of bending stiffness for three specimens are given in Table A1, Appendix. The results are the average of 5 measurements for each sample. It was convenient to increase the displacements in 0.05-in. increments and record the change in force, via a precise calibrated load cell. We found that measuring bending stiffness for very flexible lines, such as fishing lines is quite a difficult task. The bending stiffness apparatus has been successfully used to fatigue lines and to measure the stiffness degradation after a number of cycles.

A bending stiffness tester was developed, as shown in Fig 5. The tester has been used to measure the bending stiffness of lines in order to assist the process of developing new advanced lines.

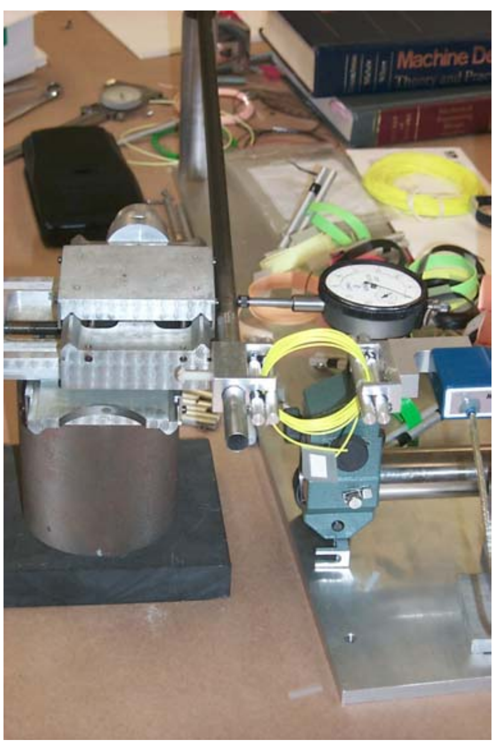

Fig. 5. Bending stiffness apparatus

The results of bending stiffness studies for a number of are of qualitative nature, but they clearly reflect the change in stiffness of various lines in the development process. Results of development lines are shown in Fig. 6.

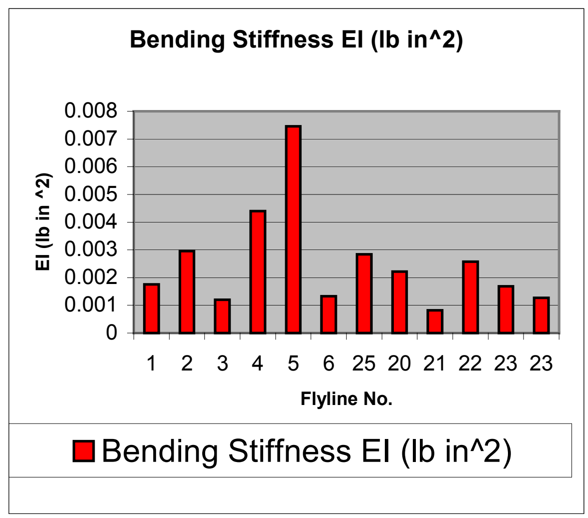

Fig. 6. Bending stiffness results for developing lines

V. CONCLUSION

The apparatus invented for studying friction coefficient and the bending stiffness of fishing lines proved to be a very versatile system in the process of developing better lines. Results from friction test provide the manufacturers with a simple method for calibrating their mixes according to the purpose of the line. The procedure could be extended to a host of flexible lines including fibers for the study of fiber coating in synthetic rope technology.

ACKNOWLEDGMENTS

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[2]. J. L. Meriam and L. G. Kraige, "Engineering Mechanics- Static" 5th Edition, (2002)

[3]. Raymond J. Roark, et al, "Roark's Formulas for Stress and Strain" Seventh Edition edited by Warren C. Young, (2001)

APPENDIX

THE MATHEMATICAL MODEL OF FRICTION WHEEL

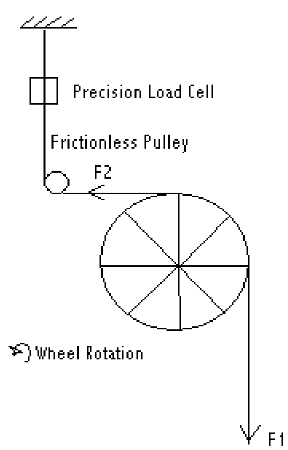

Figure A1. Setup for studying friction coefficient

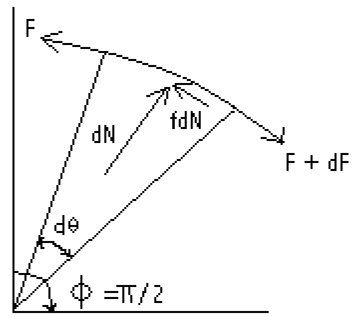

Figure A2. Free body diagram of forces acting on line

Consider the forces the forces in Fig A2 and impose the equilibrium conditions of forces as in [2].

Summing these forces in the radial direction, we obtain:

$$(F+dF)\sin(d\theta/2) + F\sin(d\theta/2) - dN = 0$$

or $$dN = Fdf$$

Summing in the tangential direction:

$$(Ft+dF)\cos(d\theta/2) - F\cos(d\theta/2) - fdN = 0$$

or $$dF = fdN$$

Substituting the value of dN from the above,

$dF = fFd\theta$, $dF/F = f\,d\theta$

$$\int dF/F = f \int d\theta \qquad \ln F_1/F_2 = f\,\phi$$

and $$F_1/F_2 = e^{f\theta}$$

where f is the friction coefficient and ϕ is the wrap angle. For a wrap–angle of $\pi/2$ the friction coefficient is calculated from the following equation:

$$f = 2/\pi\ (\ln F_1/F_2)$$

with F_1 and F_2 defined above.

TABLE A1

DETAILED RESULTS OF BENDING STIFFNESS TESTS

Specimen	Number of Coils	Delta d1 [in]	R1 [V]	Delta d2 [in]	R2 [V]	mV	W = Force [grams]	D = (change of coil diameter) [in]	E I [lbs x in^3]	Average EI
1	10	0.05	2.482	0.1	2.477	5	2.404	0.05	1.59E-03	1.65E-03
1	10	0.1	2.479	0.15	2.472	7	3.365	0.05	2.22E-03	
1	10	0.15	2.472	0.2	2.467	5	2.404	0.05	1.59E-03	
1	10	0.2	2.467	0.25	2.462	5	2.404	0.05	1.59E-03	
1	10	0.25	2.462	0.3	2.458	4	1.923	0.05	1.27E-03	
2	10	0.05	2.484	0.1	2.478	6	2.885	0.05	1.90E-03	1.40E-03
2	10	0.1	2.478	0.15	2.473	5	2.404	0.05	1.59E-03	
2	10	0.15	2.473	0.2	2.469	4	1.923	0.05	1.27E-03	
2	10	0.2	2.469	0.25	2.466	3	1.442	0.05	9.52E-04	
2	10	0.25	2.466	0.3	2.462	4	1.923	0.05	1.27E-03	
3	10	0.05	2.476	0.1	2.467	9	4.327	0.05	2.86E-03	2.41E-03
3	10	0.1	2.467	0.15	2.458	9	4.327	0.05	2.86E-03	
3	10	0.15	2.458	0.2	2.452	6	2.885	0.05	1.90E-03	
3	10	0.2	2.452	0.25	2.444	8	3.846	0.05	2.54E-03	
3	10	0.25	2.444	0.3	2.438	6	2.885	0.05	1.90E-03	