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A measurement system for testing wire rope in support of research on wire rope and cables was developed at NRL. The system is used to measure rope variables (tensile load, torque, elongation, and rotation) for different test specimen end restraints, either clamped or swiveled. The measurement system was applied to an experimental investigation. The objective of this study was to determine the constitutive constants of a 3/4-in. diameter wire rope. This work was done to supplement an analytical investigation of coupled extensional-torsional oscillations in wire rope.

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CONTENTS

TESTING WIRE ROPE:
MEASUREMENT SYSTEM AND EXPERIMENTAL STUDY

INTRODUCTION

Wire rope is elastic, flexible, and capable of transmitting force. Because of this, it has many ocean applications. Some of these include ocean salvage and construction operations, deep-sea moors, and marine vehicles. There is currently a lack of data available on the mechanical properties and behavior of wire rope [1]. This knowledge is required by the ocean engineer who must select a wire rope from the wide variety available.

The Naval Research Laboratory (NRL) began a wire rope research program to alleviate the lack of data available to the ocean engineer. The objective of this program is to determine experimentally the mechanical properties and behavior of wire rope under simulated field conditions. In the marine environment wire rope is usually subjected to static and dynamic forces. The rope's response to these forces is unique when compared to other structural members. For instance, a tensile load produces not only extension in the rope but also rotation, or a torque if rotation is prevented. This torsional behavior is often responsible for the failure of wire rope (see Fig. 1).

Fig. 1 — Hockling failure of wire rope

The wire rope research program began several years ago. Since then, a number of studies have been made [2-6]. One study [4] germane to the program resulted in the development of methods for measuring the mechanical properties and behavoir of wire rope by laboratory testing. Associated with this study was the development of test specimen preparation techniques and a measurement system. The system is capable of accurately measuring rope variables: axial load, torque, and elongation. The system was limited, however, to tests of rope specimens with clamped ends: the clamped end specifies zero end rotation. Recently, the measurement system was further developed to include tests of rope specimens with a swiveled end, the swiveled end specifying zero

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Note: Manuscript submitted May 8, 1974.

torque in the rope. Each of the end restraints (either clamped or swiveled) represents a practical boundary condition of many wire rope applications.

This report presents details of the current measurement system capability, together with test procedures and the results of an experimental investigation. The experimental investigation was conducted in support of analytical work on the coupled extensional-torsional oscillations in wire rope [7].

THE MEASUREMENT SYSTEM

A schematic of the complete measurement system is shown in Fig. 2. The system has three major parts: a force transducer,* a displacement transducer, and an angular displacement indicator. The measurement principles and the characteristics of each part are discussed in the following paragraphs.

Force Transducer

During a test, the force transducer is mounted in the test machine in series with the test specimen as shown in Fig. 2. The transducer is used to measure, simultaneously, axial load and torque reactions of the test specimen. Two sets of four strain gages are cemented to the transducer for this purpose. Each set is used in a four-arm Wheatstone bridge circuit, one for measuring torque, the other for axial load. The techniques for properly positioning the strain gages on the transducer and their judicious placement in Wheatstone bridge circuits are described in Ref. 8. The basic principle upon which a resistance strain gage operates is that when the gage is strained by an external force, its resistance changes in direct proportion to the force.

The force transducer was constructed from high-strength maraging steel. It was designed for maximum combined working loads of 50,000 lb tension and 500 ft-lb of torque. In terms of test specimen size, it has sufficient strength to load most 7/8-in. diameter specimens to rupture. A mechanical calibration of the force transducer revealed that it is capable of measuring axial load and torque within a 1% accuracy [4]. To eliminate the necessity of performing the mechanical calibration more than once, calibration resistors were used.

Displacement Transducer

The displacement transducer (commercially known as an electro-optical tracking system) is used to measure test specimen elongation. The system is illustrated in Fig. 2. It consists of two optical heads and their associated control units, two targets, and a differential amplifier. The lens on each optical head must be focused on a black-to-white discontinuity. Targets are attached to the test specimen to create this discontinuity. Since the targets are illuminated from behind (see Fig. 2), their upper edges create the discontinuity required. A photomultiplier tube (PMT) within the optical head converts the

*Here a transducer is defined as a sensing device that develops a voltage proportional to the variable measured.

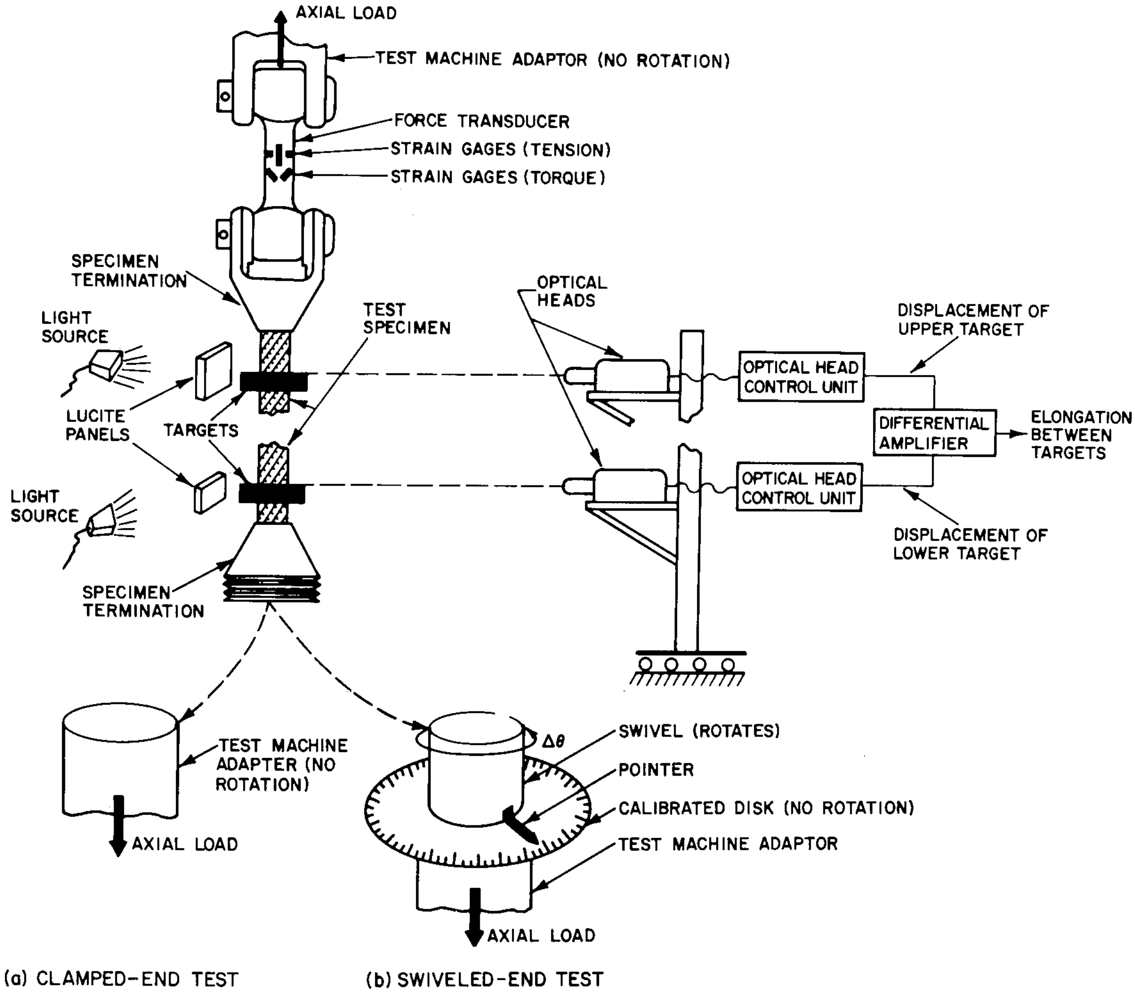


Fig. 2 — Schematic of the measurement system (a) Clamped-end test (b) Swiveled-end test

black and white target image into an electron image. When the target moves upward, the PMT sees fewer electrons. When the target moves down, the PMT sees more electrons. For either case, there is a corresponding change in the output voltage from the optical head control unit that is directly proportional to target displacement. The differential amplifier subtracts the voltage signals from the control units and therefore represents the elongation of the test specimen.

The two optical heads are mounted on a stable platform that can be freely positioned at almost any distance from the targets. The distance determines the size of the optical head's field of view (FOV) (see Fig. 3). The size of the FOV increases with distance from the targets which in turn determines the accuracy of the transducer and minimum target dimensions. For testing specimens, a FOV equal to about 125% of the estimated target displacement is used. Accuracy of the transducer is 0.1% of the FOV.

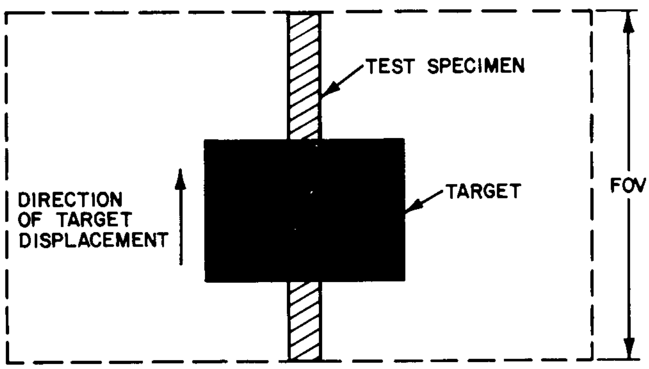


Fig. 3 — Schematic of the optical head's field of view

The targets are physically attached to the test specimen as shown in Fig. 2. Two types have been used: a flat one, Fig. 4a, and a cylindrical one, Fig. 4b. The flat target can be used only for clamped-end tests since it will rotate out of the optical head's FOV during a swiveled-end test. To circumvent this problem a cylindrical target was designed. This target consists of a clip and two half cylinders. The clip is first rigidly attached to a single wire of the test specimen by a spot weld, Fig. 5. Next, the cylindrical halves of the target are soldered to the clip. The gage length over which elongation is measured in the distance between target spot welds.

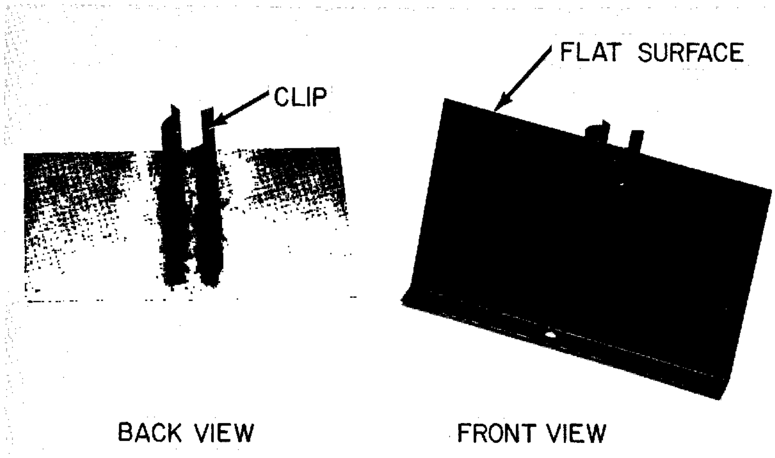
Calibration of the displacement transducer is generally required before every test. Mechanical or optical methods can be used to accomplish this. The choice depends on estimated target displacements. Optical calibration of the transducer is much faster and less cumbersome than mechanical calibration. However, the optical method is limited to about 1-in. target displacement. An optical calibrator is shown in Fig. 6a in front of the optical head. It has a mirror which can be manually moved to give known apparent target displacements. Mechanical calibration is used for estimated target displacements greater than 1-in. Prior to testing, the transducer is attached to the test specimen as shown in Fig. 6b. Calibration is performed by displacing the calibrator's targets in known amounts. (These targets are situated parallel to and flush with the specimen targets.) After the calibration, the apparatus is removed from the test specimen.

The displacement transducer permits elongation measurements to be made up to and including specimen rupture since the targets are expendable. In addition, the transducer has a dynamic response of 30 μs, making it ideal for dynamic test applications.

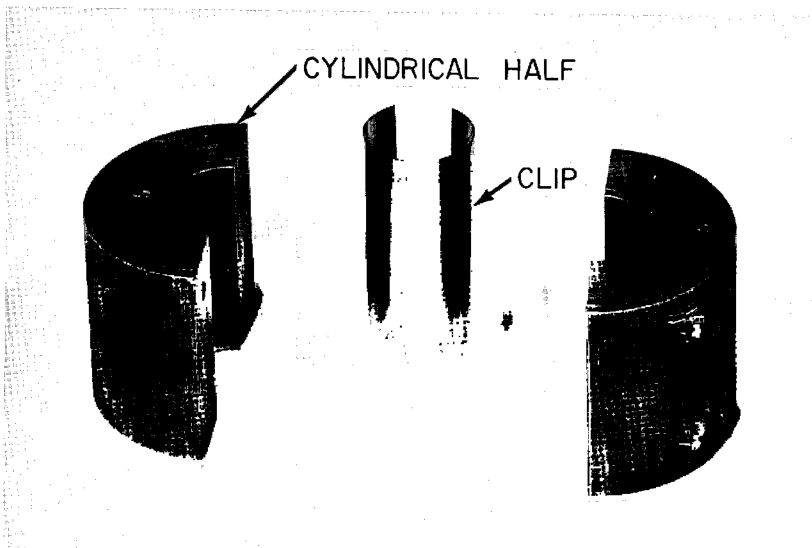
Angular Displacement Indicator

As its name implies, the angular displacement indicator is used to measure test specimen end rotation during a swiveled-end test, Fig. 2. This device consists of a disk calibrated in degrees, a swivel and pointer, and a torque arm (Fig. 7). The disk is physically attached to a nonrotating part of the test machine. The swivel has a pointer attached and is free to rotate under load. The torque arm is used during some tests to rotate the swivel manually to adjust torque in the rope.

The angular displacement indicator requires manual data readings and is therefore not applicable to dynamic or static-rupture tests.



(a) Flat targets for clamped-end tests only



(b) Cylindrical targets for swiveled-end and clamped-end tests

Fig. 4 — Electro-optical target design

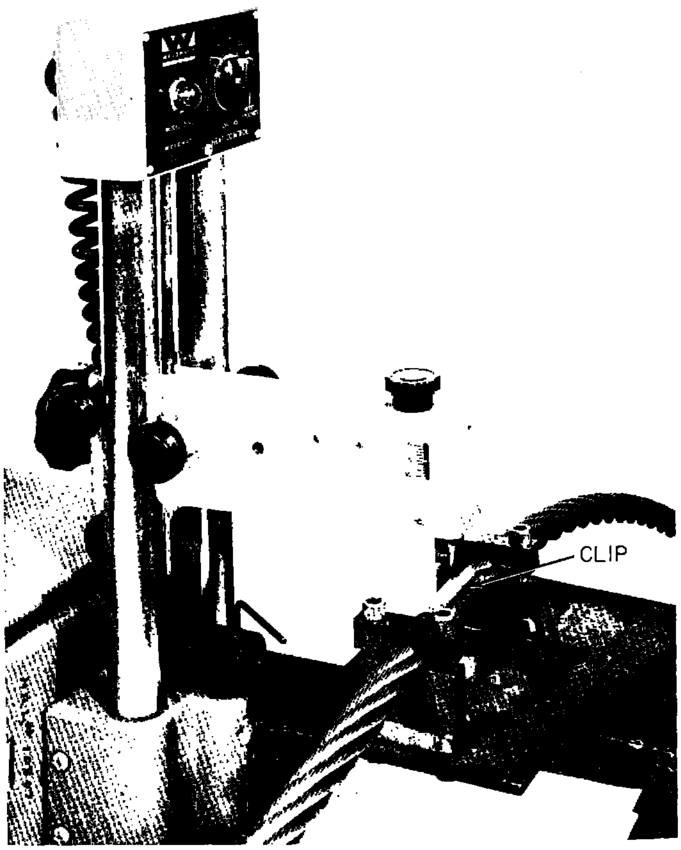
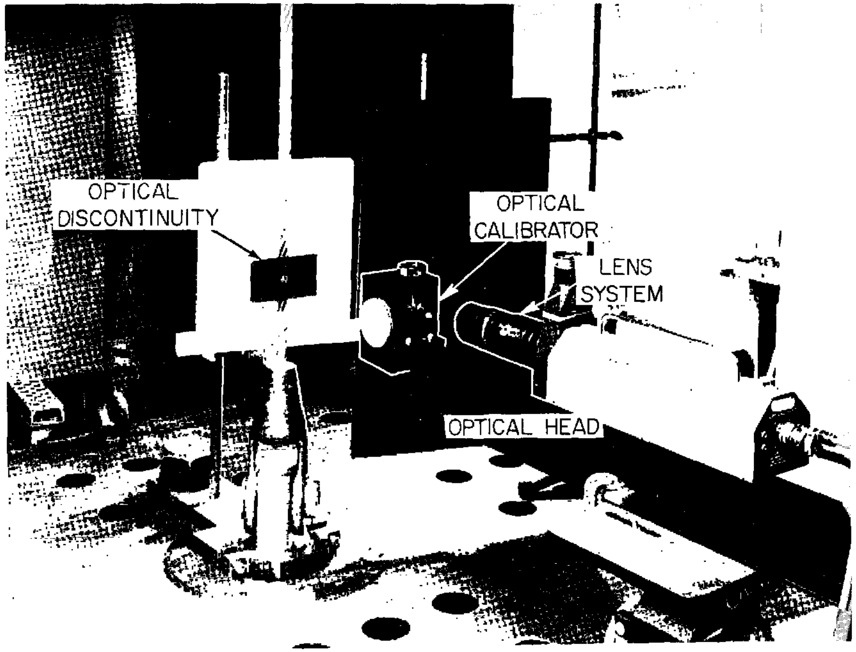
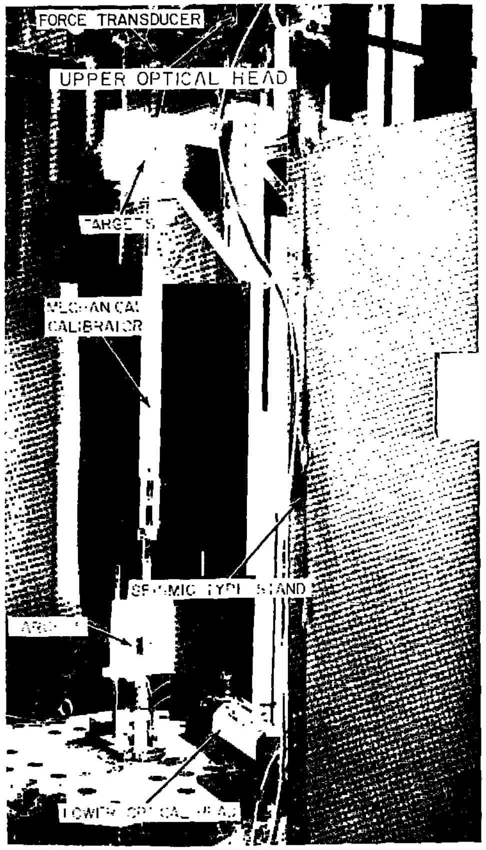


Fig. 5 — Spot-welding machine for attaching electro-optical targets to a single wire of the rope



(a) Optical calibrator



(b) Mechanical calibrator

Fig. 6 — Calibration of the displacement transducer

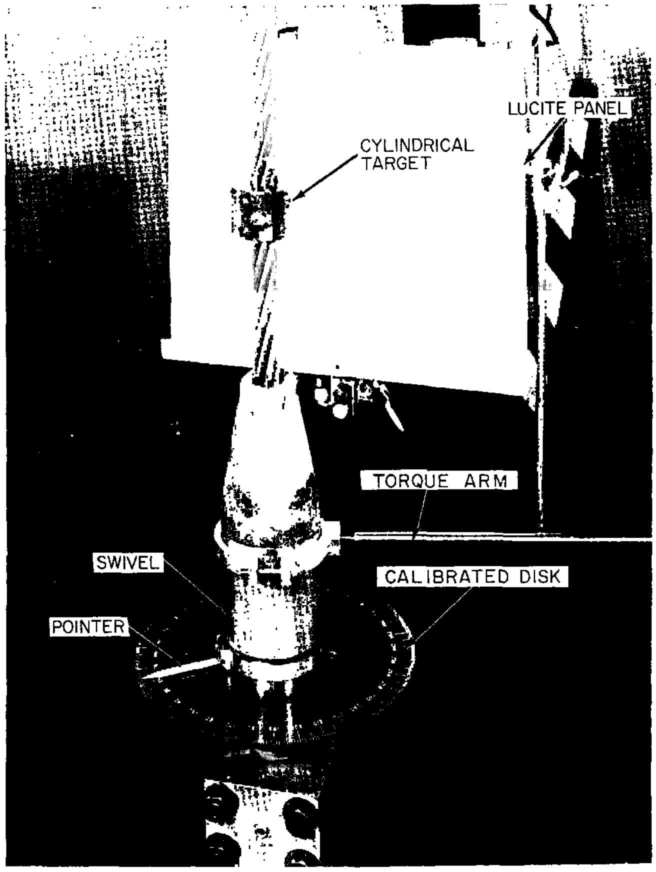


Fig. 7 — Angular displacement indicator

Associated Instrumentation

A certain amount of associated instrumentation and other equipment is required to support the measurement system. These include XY recorders (for recording data), an oscilloscope, and digital voltmeters (Fig. 8). In addition, of course, a tensile testing machine is required.

EXPERIMENTAL DETERMINATION OF CONSTITUTIVE CONSTANTS

Recently Samras, Skop, and Milburn [7] developed a mathematical model for determining the critical frequencies of wire rope moored to the ocean floor. In their analysis, a sinusoidal forcing function representing wave action was applied to the rope and located at the ocean surface. Furthermore, they considered constitutive equations relating rope tension and torque to extensional and rotational rope deformations. (The classical engineering approach considers extensional deformation only.) In the coupled constitutive equations, four constants appear which must be determined experimentally.

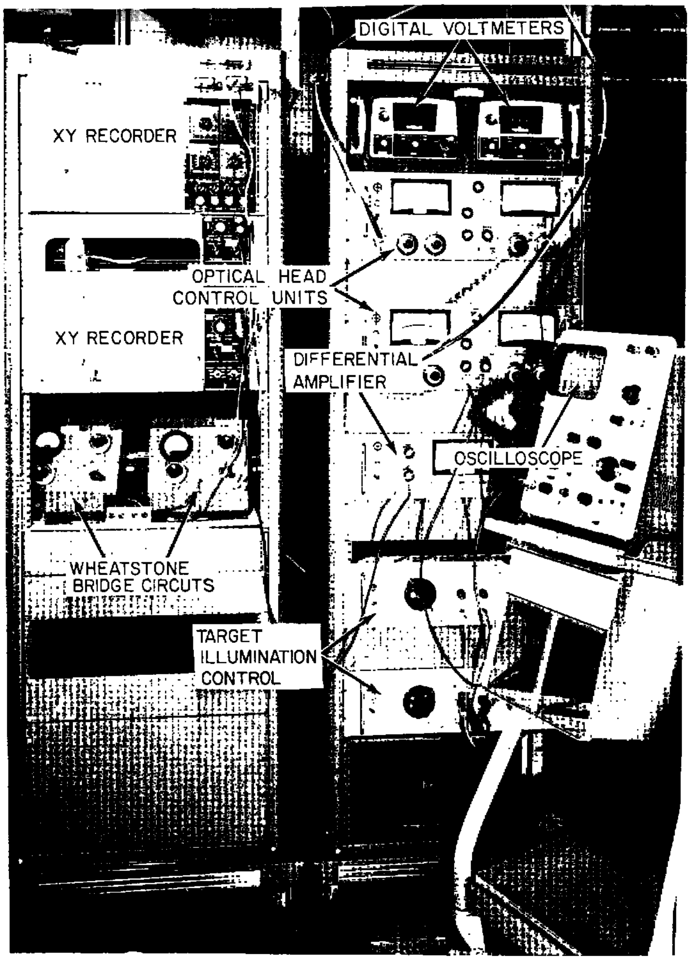


Fig. 8 — Some associated instrumentation

In this section of the report, use of the measurement system (Fig. 2) is demonstrated by describing the experimental measurement of constitutive constants for a 3/4-in. diameter wire rope. Results of this measurement were used to supplement the analytical work of Samras, et al. [7].

Constitutive Equations

Based on previous wire rope studies [4,9], Samras, et al. postulated constitutive equations as

$$T = A_1 \epsilon + A_2 \tau \tag{1a}$$

and

$$C = A_3\epsilon + A_4\tau \quad (1b)$$

Here T is rope tension; C is rope torque; ϵ is longitudinal strain; τ is rotational strain; and A_1, A_2, A_3, A_4 are the constitutive constants. These constants depend on the type of rope (material, construction, etc.). The longitudinal and torsional rope strains are defined mathematically as

$$\epsilon = \delta/L_e \quad (2a)$$

and

$$\tau = \Delta\theta/L_r \quad (2b)$$

where δ is rope elongation, $\Delta\theta$ is rotational deformation, and L_e and L_r are rope the lengths over which deformations δ and $\Delta\theta$ are measured, respectively.

If Eqs. (2) are substituted into Eqs. (1), the constitutive equations become

$$T = A_1\ (\delta/L_e) + A_2\ (\Delta\theta/L_r) \quad (3a)$$

and

$$C = A_3\ (\delta/L_e) + A_4\ (\Delta\theta/L_r)\ . \quad (3b)$$

Experimental Procedures

Constants A_1, A_2, A_3, and A_4 appearing in Eqs. (3) were determined experimentally for a 3/4-in. diameter wire rope. A cross-sectional view of this rope is shown in Fig. 9. Two tensile tests (clamped-end and swiveled-end) were conducted for this purpose.

For the clamped-end test, $\Delta\theta$ in. Eqs. (3) is zero since rotation was prevented. As a result, Eqs. (3) can be written as

$$A_1 = L_e\ (T/\delta) \quad (4a)$$

and

$$A_3 = L_e\ (C/\delta)\ . \quad (4b)$$

Rearranging Eqs. (3) gives expressions for A_2 and A_4 which can be evaluated once A_1 and A_3 are known from Eqs. (4):

$$A_2 = L_r\ (T/\Delta\theta) - A_1\,(L_r/L_e)\ (\delta/\Delta\theta) \quad (5a)$$

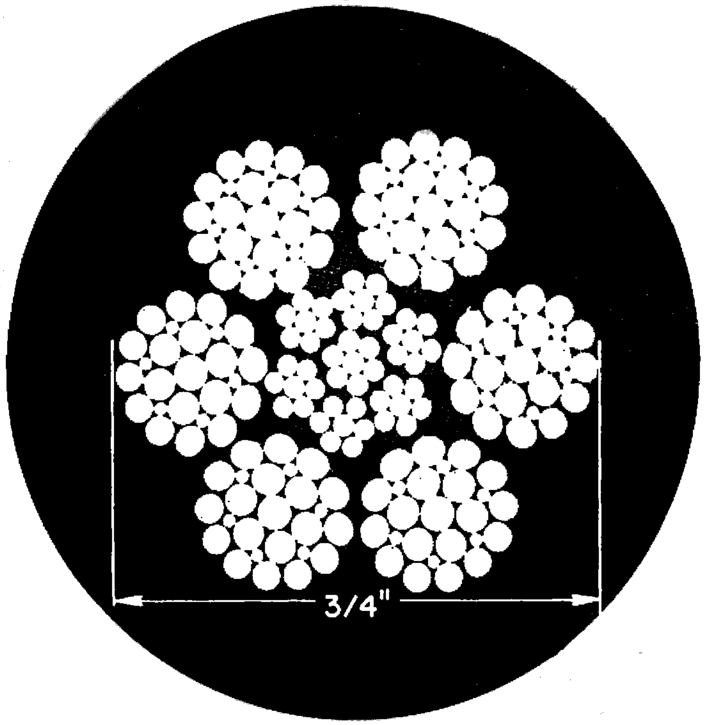


Fig. 9 — Cross-sectional view of the 3/4-in. diameter, stainless steel wire rope of 6 × 19 (7 × 7 IWRC) construction with filler wire [10]

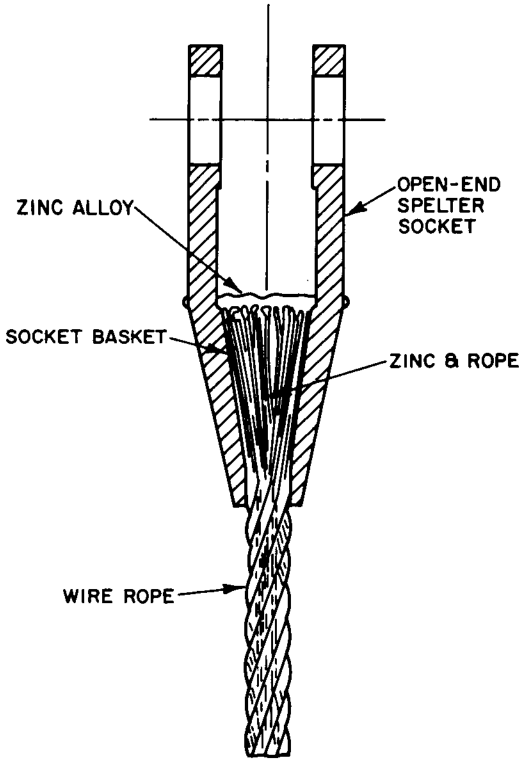
and

$$A_4 = L_r\ (C/\Delta\theta) - A_3\ (L_r/L_e)\ (\delta/\Delta\theta)\ . \qquad (5b)$$

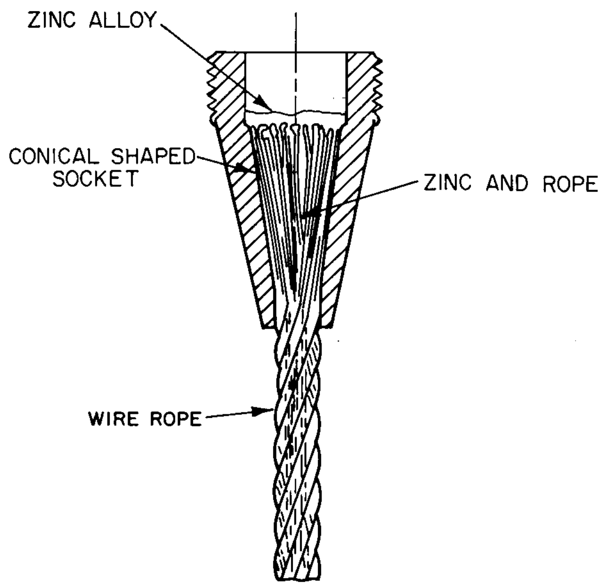
A testing machine that permitted us to test a long rope specimen was used for the tensile tests. The machine has a single screw drive that applies load to the test specimen at a constant rate of machine crosshead displacement. A rate of 0.15 in./min was used for each test.

A test specimen was prepared from a sample of 3/4-in. diameter rope, Fig. 9. In preparing the test specimen, techniques described in Ref. 4 were followed. Commerical zinc-pour sockets [10] were used to terminate the test specimen. At one end an open-end spelter socket (Fig. 10a) was used, at the other a conical socket (Fig. 10b). An alignment fixture was used to hold the specimen and socket in nearly perfect axial alignment prior to pouring the molten zinc (Fig. 11). The molten zinc was poured into the socket basket (Fig. 10), filling it completely before solidifying.

After terminating the test specimen, targets were attached to a single wire of the specimen by means of a spot weld. Next, the specimen was mounted in the test machine shown in Fig. 12. Gage length for elongation L_e is the distance between the target spot welds. Rotation gage length L_r is the distance between socket ends (see Fig. 12). For the specimen tested, L_e = 71.0 in., L_r = 82.4 in.



(a) Open-end spelter socket



(b) Conical socket

Fig. 10 — Cross-sectional view of test specimen terminations

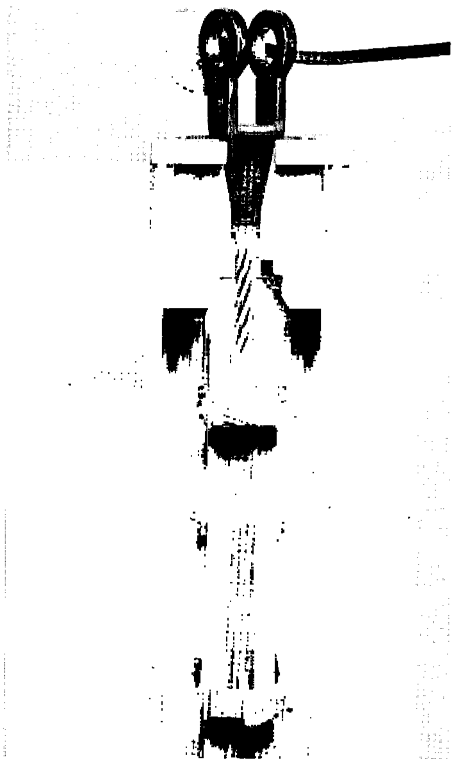


Fig. 11 — Alignment fixture for terminating ropes

The first test performed on the test specimen was the clamped-end test. For this test, the lower specimen socket shown in Fig. 10b was attached to a test machine adaptor which prevented it from rotating (see Fig. 4). The test specimen was then load cycled between 0 and 30,000 lb (this is about 50% of the specimen's break strength). Load-cycling of the specimen was done to remove the constructional stretch [4,11] in this new rope. Axial load T, torque C, and elongation δ were accurately measured by the transducers described earlier. Two XY recorders were used to plot continuously both axial load and torque vs specimen elongation. These data were used to calculate constants A_1 and A_3.

The other test performed on the specimen was the swiveled-end test. For this test, the lower specimen socket, shown in Fig. 10b, was attached to the angular displacement indicator as shown in Fig. 4. The angular displacement indicator has a swivel that permits the end of the specimen to rotate. The test specimen was load cycled within the same elongation interval that was obtained from the clamped-end test. Axial load, torque, elongation, and rotation $\Delta\theta$ were accurately measured. The data were recorded manually for both a zero and a 300 in.-lb constant torque manually applied to the test specimen. After this test, both axial load and elongation vs rotation data were plotted. These data were used to calculate constants A_2 and A_4.

Fig. 12 — Swiveled-end test in NRL's three million pound capacity testing machine

Results

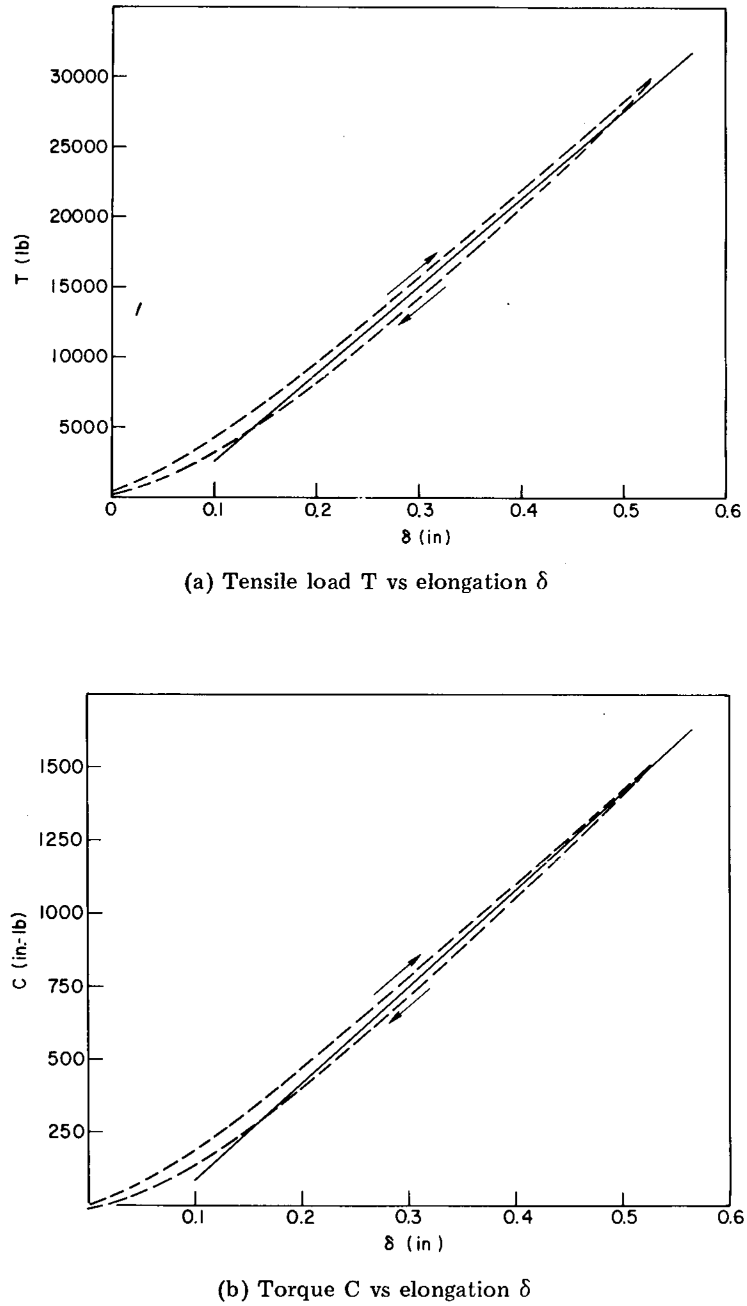
Results of the foregoing tests are given in Table 1. They include the gage lengths L_e and L_r, slopes of the plotted data, and calculated values of the constants A_1, A_2, A_3, and A_4.

Table 1
Test Data and Constitutive Constants for the 3/4-In. Diameter Wire Rope

Test Data		Constitutive Constants
Gage Length	Slopes of Curves*	
L_e = 71.0 in. L_r = 82.4 in.	$T/\delta = 6.26 \times 10^4$ lb/in. (Fig. 13a) $C/\delta = 3.32 \times 10^3$ lb (Fig. 13b) $T/\Delta\theta = -5.56 \times 10^2$ lb/rad (Fig. 14a) $\delta/\Delta\theta = -4.34 \times 10^{-3}$ ft/rad (Fig. 14b)	$A_1 = 4.44 \times 10^6$ lb $A_2 = 1.86 \times 10^4$ ft-lb/rad $A_3 = 1.97 \times 10^4$ ft-lb $A_4 = 9.92 \times 10^1$ ft^2-lb/rad

*Positive or negative quantities are the result of the sign convention used for loads and deformations in Ref. 7.

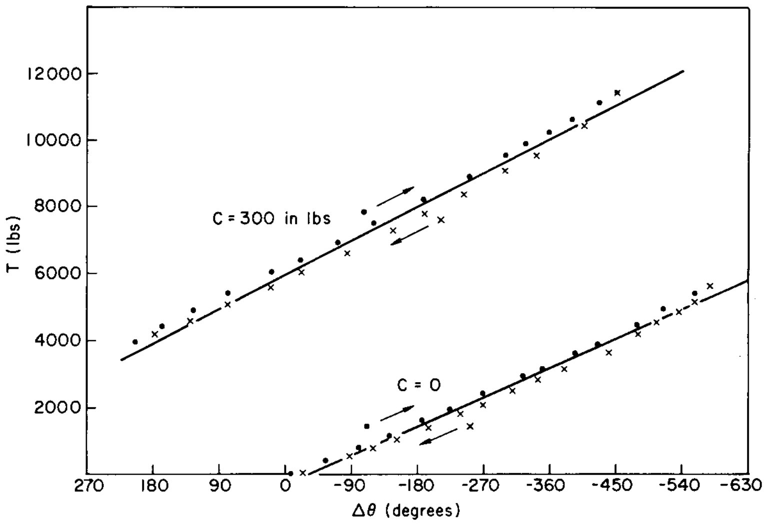
Results of the clamped-end and swiveled-end tests are shown in Figs. 13 and 14, respectively. An average slope for each data set was defined and calculated (Table 1). Constants A_1 and A_3 were determined from Eqs. (4); A_2 and A_4 from Eqs. (5).



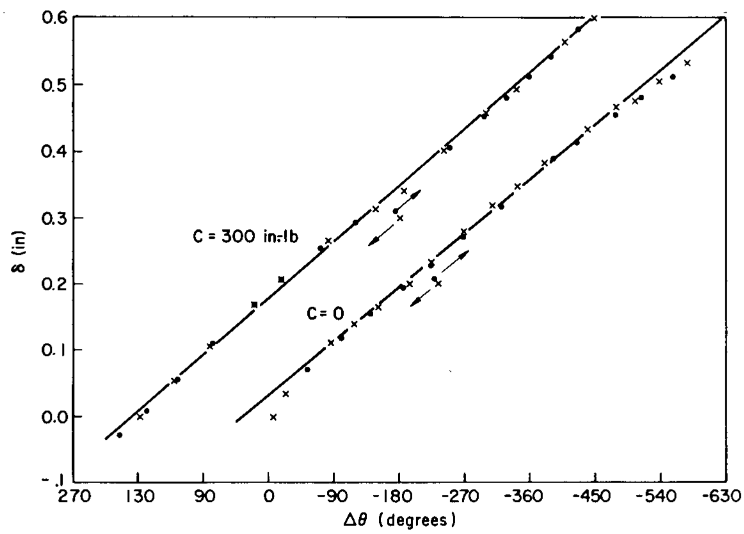
(a) Tensile load T vs elongation δ

(b) Torque C vs elongation δ

Fig. 13 — Data from the clamped-end rope test



(a) Tensile load T vs end rotation $\Delta\theta$



(b) Elongation δ vs end rotation $\Delta\theta$

Fig. 14 — Data from the swiveled-end rope test

CONCLUDING REMARKS

A measurement system was developed at NRL for testing wire rope in support of research on wire rope and cables. The system is used to measure the rope variables tensile load, torque, elongation, and rotation. It can be used to perform tests on ropes with clamped or swiveled end restraint conditions. The principles of operation and characteristics of each part of the measurement system were discussed. Salient characteristics of the system can be summarized as follows:

1. The measurement system can be used to measure rope variables to an accuracy of 1%.

2. The force and displacement transducers can be used for static or dynamic testing conditions. At present, use of the angular displacement indicator is limited to static testing only.

3. The transducers can be used to measure rope variables during test specimen rupture tests; the angular displacement indicator cannot.

4. In general, gage lengths used for elongation measurements are limited by the size of the test machine, not by the displacement transducer.

Recent applications of the measurement system to some NRL rope tests are documented by Milburn and Rendler [4]; Milburn [6]; Cullen and Milburn [5]; and Samras, et al. [7].

This report has also described the test procedures and results of an experimental study. The study objective was to determine the constitutive constants for a 3/4-in. diameter rope. The work was done to supplement the analytical investigation of coupled extensional-torsional oscillations in wire rope performance by Samras, et al. [7]. That investigation demonstrated the importance of considering both extensional and torsional properties in predicting the dynamic response of wire rope.

At present, the measurement system is being used to investigate the extensional and torsional properties of electromechanical cables and torque-balanced wire rope.

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