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Laboratory Evaluations of Hoist Rope Diameter-Monitoring System

By G. L. Anderson and T. M. Ruff

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	m/min	meter per minute
F	farad	mm	millimeter
Hz	hertz	mm/s	millimeter per second
kHz	kilohertz	s	second
m	meter	Ω	ohm

U.S. Customary Units

ft	foot	in	inch
ft/min	foot per minute	in/s	inch per second

LABORATORY EVALUATIONS OF HOIST ROPE DIAMETER-MONITORING SYSTEM

By G. L. Anderson[1] and T. M. Ruff[2]

ABSTRACT

The U.S. Bureau of Mines (USBM) has conducted research to improve the nondestructive testing (NDT) of wire hoist ropes. Losses in the diameter of a wire hoist rope are used as one criterion for judging when a rope should be replaced. Losses are determined by periodically measuring the rope diameter and comparing this measurement with the original measured diameter; when the diameter reaches a specified minimum at any point along its length, the rope must be retired. Generally, these measurements are made at randomly selected locations along the length of the rope, using a hand caliper.

To provide more accurate measurements and to allow measurements to be taken continuously along the length of a hoist rope, an optical diameter-monitoring system was built for the USBM under contract. Continuous measurements are preferable because, when combined with continuous electromagnetic NDT results, they can indicate whether losses in metallic cross-sectional area originate from external wear or internal wear and corrosion. Tests of the system showed that the instrument met specifications when measuring wire rope at low rope speeds but was inaccurate at speeds over about 30 m/min (100 ft/min). This report describes the prototype system, presents the results of the test program, and describes the capabilities of the system.

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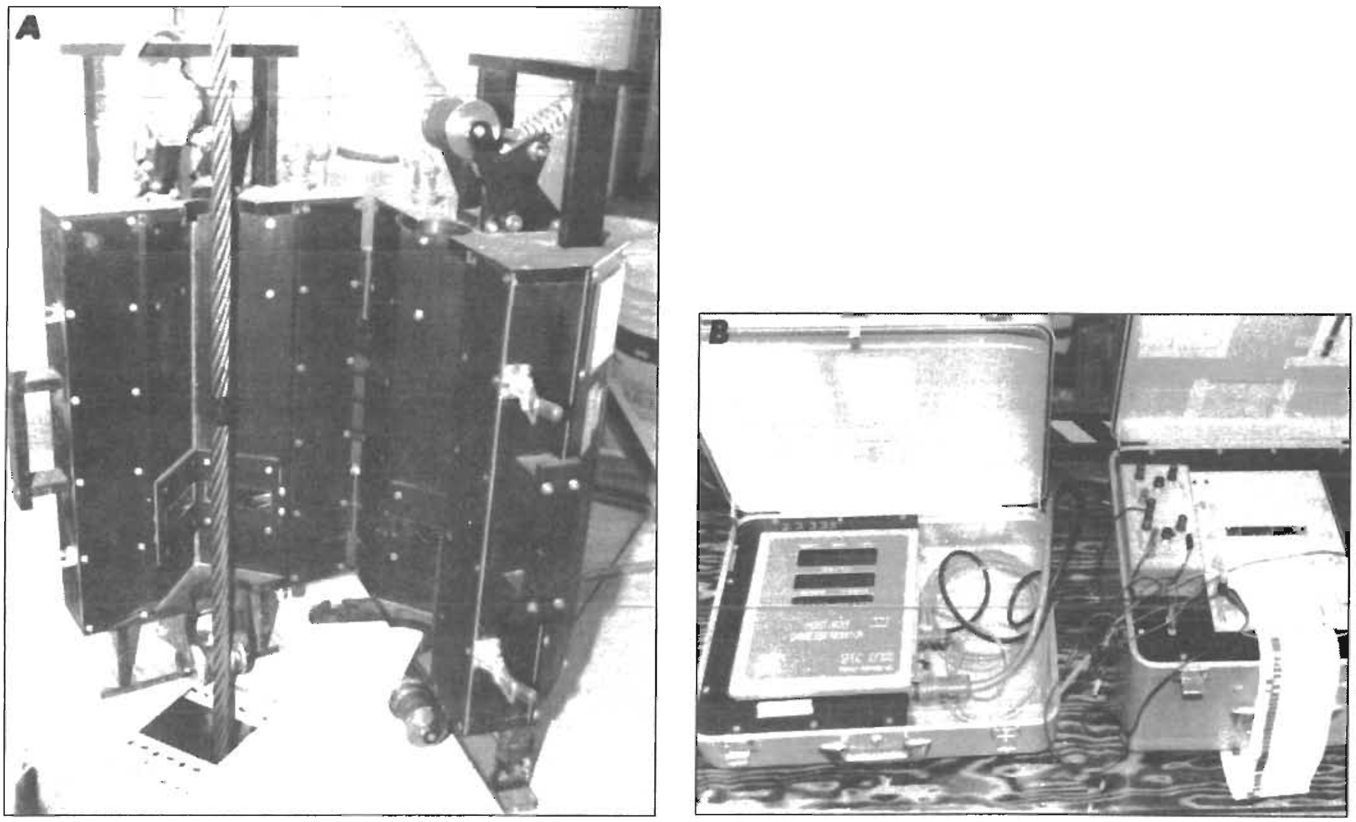
INTRODUCTION

Wire ropes are used in underground mines to hoist workers, materials, and ore. Damaged or worn ropes may fail, resulting in injuries to workers, as well as losses in production. As part of its mission to enhance the safety of mine workers, the U.S. Bureau of Mines (USBM) is studying ways to improve the nondestructive testing (NDT) of wire hoist ropes so that damaged or worn ropes can be more easily identified and can be replaced before they fail. One method of determining the condition of a wire rope is to periodically measure the rope's diameter. A loss of diameter indicates external wear, elongation, or internal metal or core loss. Unfortunately, when the diameter is measured with a hand caliper, it can practically be measured only a limited number of points along the rope's length. Such measurements are not always taken where the rope has deteriorated, and losses of diameter over short lengths of rope can be easily missed. For these reasons, a method of measuring diameter over the full length of a rope is needed.

Instruments that use the principle of optical profiling are well established as quality control devices in the manufacture of wire products. However, using this principle to measure the diameter of a mine hoist rope at a mine site was a unique opportunity. A prototype instrument called the hoist rope diameter-monitoring system was obtained by the USBM. The system uses available optical caliper technology but requires special packaging of the measuring head to make it rugged enough to withstand the moist and dirty conditions found at mine sites.

The system measures and records two diameter axes in the same plane along the total rope length as the rope passes through the measuring head at test speeds of 30 to 152 m/min (100 to 500 ft/min). The system, shown in figure 1, was designed and built for the USBM by Target Systems, Inc., of Salt Lake City, UT, under contract. The instrument was evaluated at the USBM's Spokane Research Center.

Figure 1



Hoist rope diameter-monitoring system. A, Optical measuring head; B, display and control module and strip chart recorder.

DIAMETER-MONITORING SYSTEM

The hoist rope diameter-monitoring system (figure 1) is composed of three modules: a measuring head, a display and control module, and a strip chart recorder. The specifications provided by the manufacturer are as follows:

Measuring principle: Collimated light shadowgraph.
Light source: Tungsten halogen lamp.
Optical detector: Solid-state linear diode array.
Resolution: 0.0025 mm (0.0001 in).
Digital scanning rate: 1 kHz.
Measurement range: 0-7.6 cm (0-3 in).
RS 232 serial communication channel.

Features are the instrument's ability to

Detect a diameter change of 0.025 mm (0.001 in).
Measure two orthogonal axes in the same plane.
Measure rope speeds to 300 m/min (1,000 ft/min).
Maintain two analog output channels that print to a two-channel strip chart recorder.

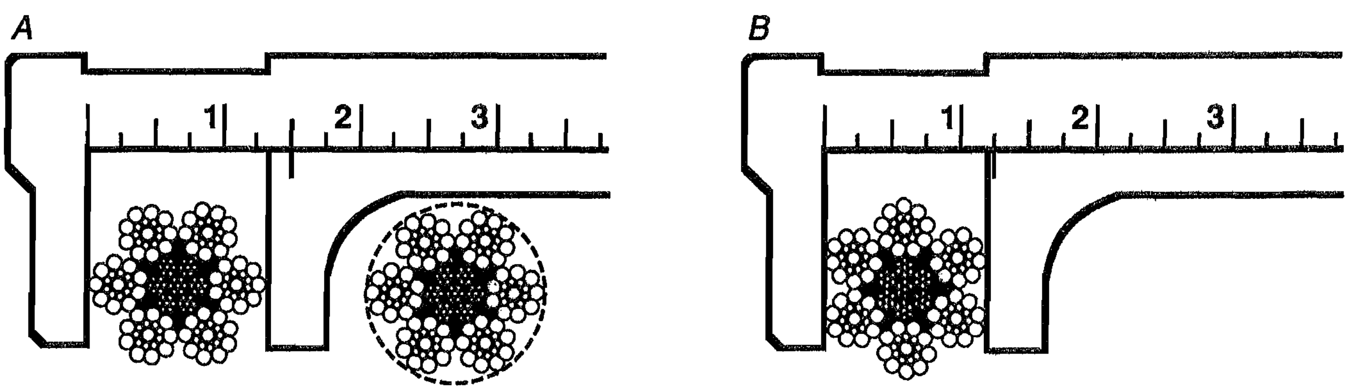
The measuring head contains collimated light sources and photo diode detectors that measure diameters in two orthogonal axes (referred to as X- and Y-axes), guide rollers to center the rope in the head, and a length meter incorporated into one of the guide rollers. The signal from the roller is converted to a square wave, which is drawn on the edge of the chart paper. The period of the wave provides a measure of the length of rope that has passed through the measurement head. The length meter, for this evaluation, was set so one period of the square wave indicated a rope length of 1.91 m (6.25 ft).

The display and control module microprocessor communicates with the measuring head and outputs information to the analog and/or RS 232 interfaces. The RS 232 serial channel can be used to communicate with the microprocessor or it can be used to transmit digital data to an outside digital recording instrument. Signal output to the recorder is through analog channels A and B, and the length meter signal is sent to the marker pen on the recorder. The configuration of the two analog output channels can be changed with switches within the display and control module. Diameter readings can be configured to deviate from a previously designated set point or from an absolute diameter. Within either of these configurations, the analog A and B output can be as follows:

Analog channel A		Analog channel B
Average	and	Diameter X
Diameter X	and	Diameter X
Diameter X	and	Diameter Y
Average	and	Diameter Y

For a round wire rope, some of the above choices are repetitive; however, the instrument design has the capability for the two axes to be different, as would be the case if the instrument measured a rectangular bar. For USBM applications, the orthogonal X- and Y-axes provide measurements for maximum diameter, minimum diameter, or average diameter (X + Y)/2. As the rope moves through the optical head, output varies between maximum and minimum diameters. These two readings correspond to a correct way and an incorrect way to position calipers when measuring wire rope diameters (figure 2). For most wire rope uses, the desired measurement is maximum rope diameter, as shown in figure 2A.

Figure 2



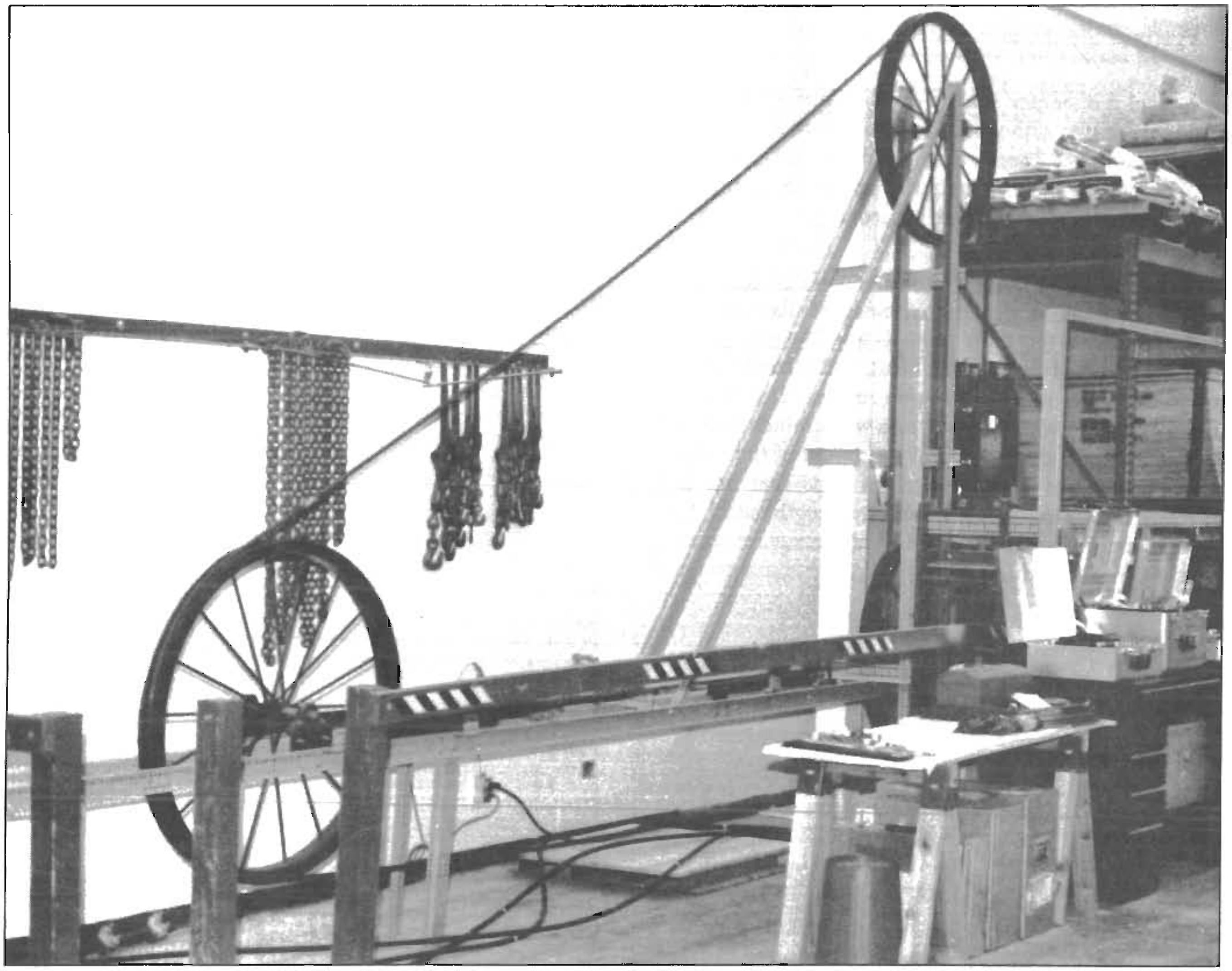
Caliper position for measurement of wire rope diameter. A, Correct position; B, incorrect position.

TEST PROCEDURE

A 17.4-m (57-ft) long rope was joined at the ends to form a loop and mounted on three 107-cm (42-in) diam sheaves of a test fixture. This test fixture, shown in figure 3, can test various diameters, lengths, and constructions of ropes at speeds from 24 to 122 m/min (80 to 400 ft/min). The optical measuring head of the test instrument was positioned on the vertical section of rope in the same position as it would be for vertical hoists in a mine. The diameter measurements were recorded on a strip chart. The rope used for the test was a 6×19 Seale, fiber-cored rope with right regular lay construction and a strand lay of 13.23 cm (5.21 in). This configuration resulted in a strand-to-strand distance of 2.21 cm (0.87 in).

For work reported here, control module switches were set to provide X and Y or average and X diameters, and deviation was measured from a set point of 1.9 cm (0.75 in), which is the nominal diameter of the test rope. Caliper measurements were made by hand at 1.5-m (5-ft) increments along the test rope; these measurements are presented in tables 1 and 2.

Figure 3



Wire rope test fixture and rope loop.

Table 1.—Caliper measurements of maximum, minimum, and average diameters of test rope with nominal diameter of 1.9 cm (0.75 in)

Distance from end, m	Maximum, cm	Minimum, cm	Average,[1] cm	Distance from end, ft	Maximum, in	Minimum, in	Average,[1] in
1.52	1.943	1.783	1.864	5	0.765	0.702	0.734
3.05	1.935	1.773	1.854	10	0.762	0.698	0.730
4.57	1.951	1.786	1.869	15	0.768	0.703	0.736
6.10	1.958	1.778	1.869	20	0.771	0.700	0.736
7.62	1.938	1.781	1.859	25	0.763	0.701	0.732
9.14	1.941	1.773	1.857	30	0.764	0.698	0.731
10.67	1.935	1.758	1.847	35	0.762	0.692	0.727
12.19	1.943	1.770	1.857	40	0.765	0.697	0.731
13.72	1.951	1.783	1.867	45	0.768	0.702	0.735
15.24	1.953	1.763	1.859	50	0.769	0.694	0.732
16.76	1.941	1.775	1.859	55	0.764	0.699	0.732
Average	1.944	1.775	1.860	Average	0.766	0.699	0.732

[1](Maximum + minimum)/2.

Table 2.—Caliper measurements, ranges of averaged data

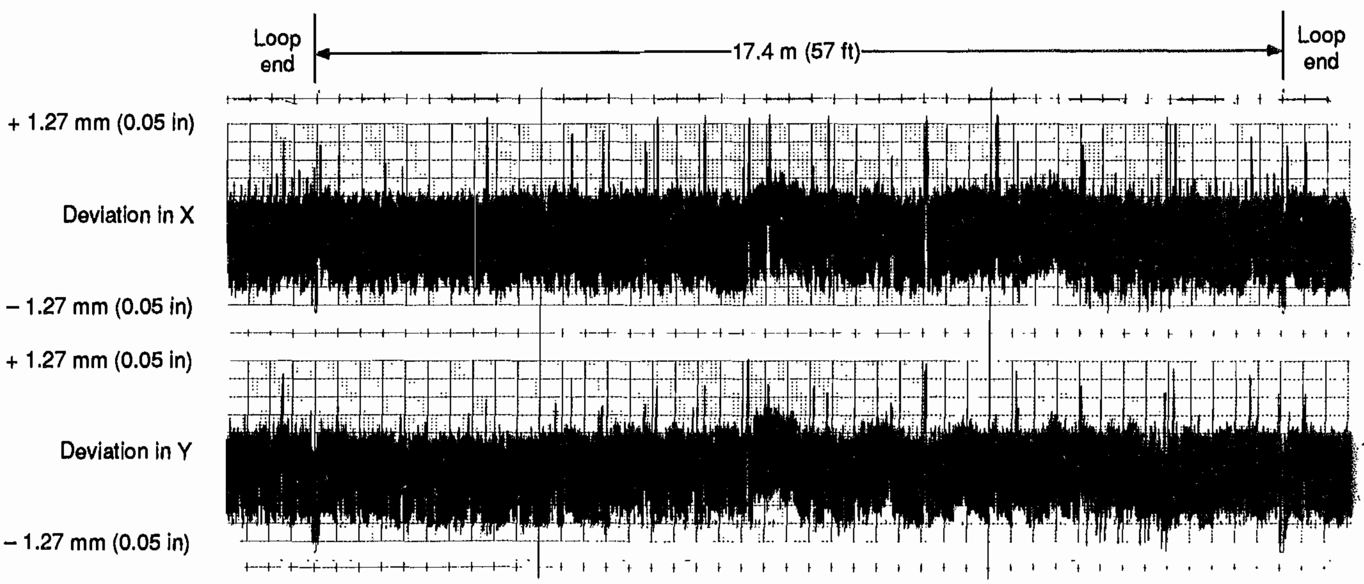
	Difference, cm	Difference, in
Maximum minus minimum	1.944 - 1.775 = 0.169	0.766 - 0.699 = 0.067
Maximum minus nominal	1.944 - 1.900 = 0.044	0.766 - 0.750 = 0.016
Minimum minus nominal	1.775 - 1.900 = -0.125	0.699 - 0.750 = 0.051
Average minus nominal	1.860 - 1.900 = -0.040	0.732 - 0.750 = 0.018

RESULTS

DEVIATION OF DIAMETER FROM SET POINT

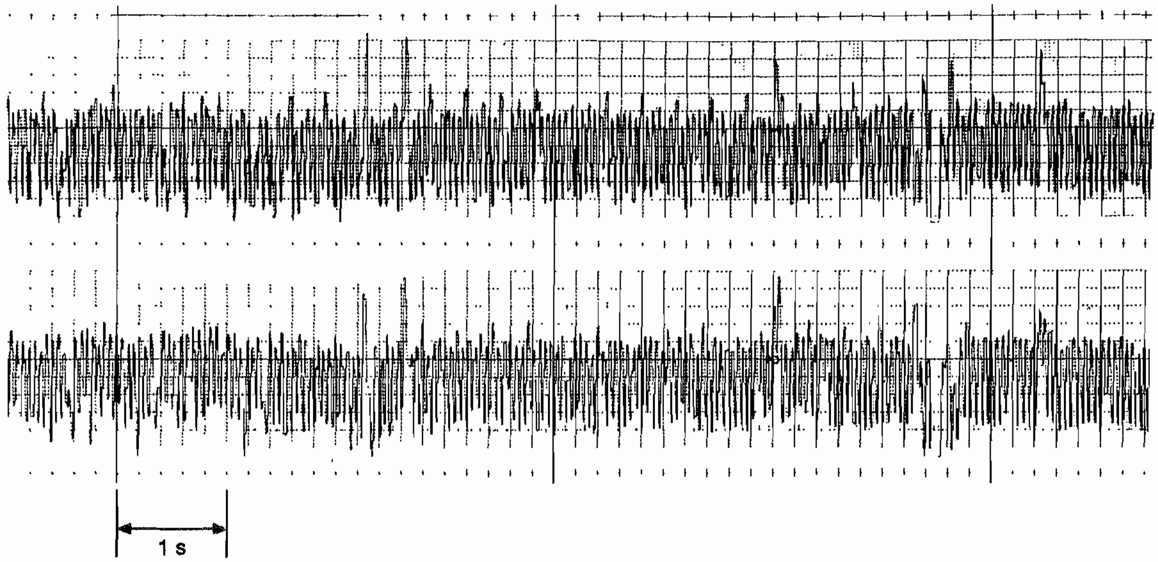
Results from the tests run at a rope speed of 24 m/min (80 ft/min) are displayed in figures 4, 5, and 6. Deviation was calculated as measured diameter minus 1.9 cm (0.75 in). The strip chart recorder was run at speeds of 5, 25, and 125 mm/s (0.2, 1, and 4.9 in/s). The traces are not a single straight line because the instrument also records the inherently uneven exterior of a wire rope.

Figure 4



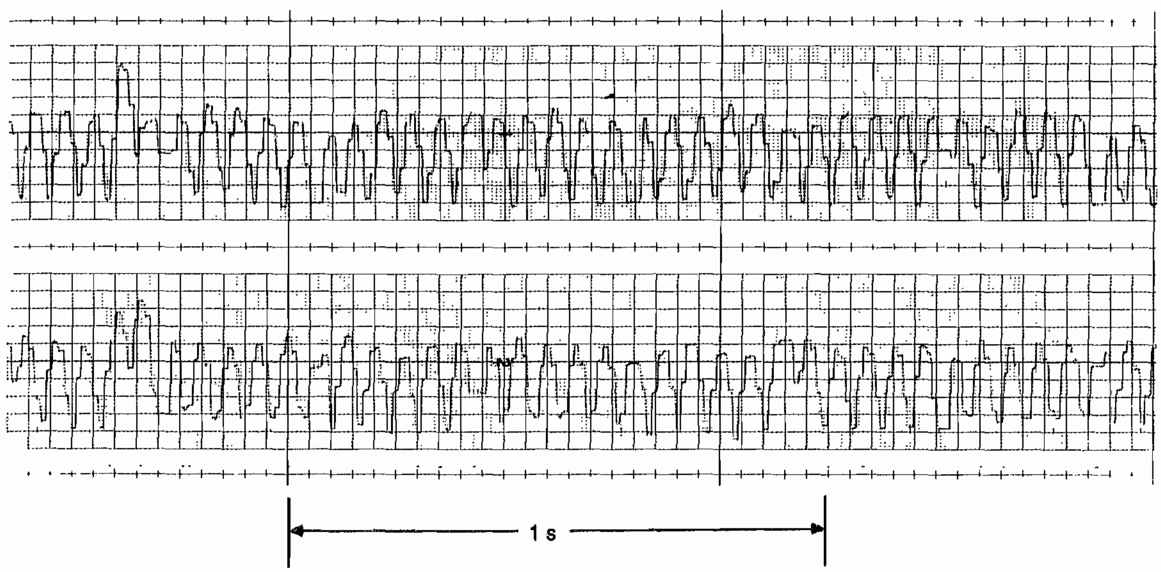
Trace showing diameter deviation from set point of 1.9 cm (0.75 in). Chart speed is 5 mm/s (0.2 in/s).

Figure 5



Trace of diameter deviation expanded at chart speed of 25 mm/s (1 in/s).

Figure 6



Trace of diameter deviation at chart speed of 125 mm/s (4.9 in/s).

The pattern in figure 4 reflects the peaks and valleys in the rope profile created by the strands. The peaks show the maximum diameter to be about 1.94 cm (0.765 in) [1.9 + 0.038 cm (0.750 + 0.015 in)] and the minimum diameter to be about 1.8 cm (0.708 in) [1.9 – 0.107 cm (0.750 – 0.042 in)]. The reference line for diameter on each strip chart channel is located at the center of each chart grid. The chart diameter scale was calibrated so that the smallest chart division was 0.051 mm (0.002 in). This provides a deviation range of +1.27 to –1.27 mm (+0.050 to –0.050 in) from the nominal rope diameter of 1.9 cm (0.75 in). At a chart speed of 5 mm/s (0.2 in/s), 5 mm on the chart represents 40.6 cm (16 in) of rope length (table 3).

The microprocessor takes measurements at a rate of 1,000 scans per second and then averages groups of 10 scans; therefore, analog output to the recorder strip chart is composed of an average of 10 scans of output 100 times

Table 3.—Optical scans versus rope speed

Strand pattern frequency,[1] Hz	Rope speed, m/min	Rope travel, cm/s	Rope travel in 10 scans, cm	Strand pattern frequency,[1] Hz	Rope speed, ft/min	Rope travel, in/s	Rope travel in 10 scans, in
18	24	41	0.406	18	80	16	0.160
23	30	51	0.508	23	100	20	0.200
45	60	102	1.016	45	200	40	0.400
92	120	203	2.032	92	400	80	0.800
230	300	508	5.080	230	1,000	200	2.000

[1]Strand pattern frequency = rope travel ÷ pattern repeat length.

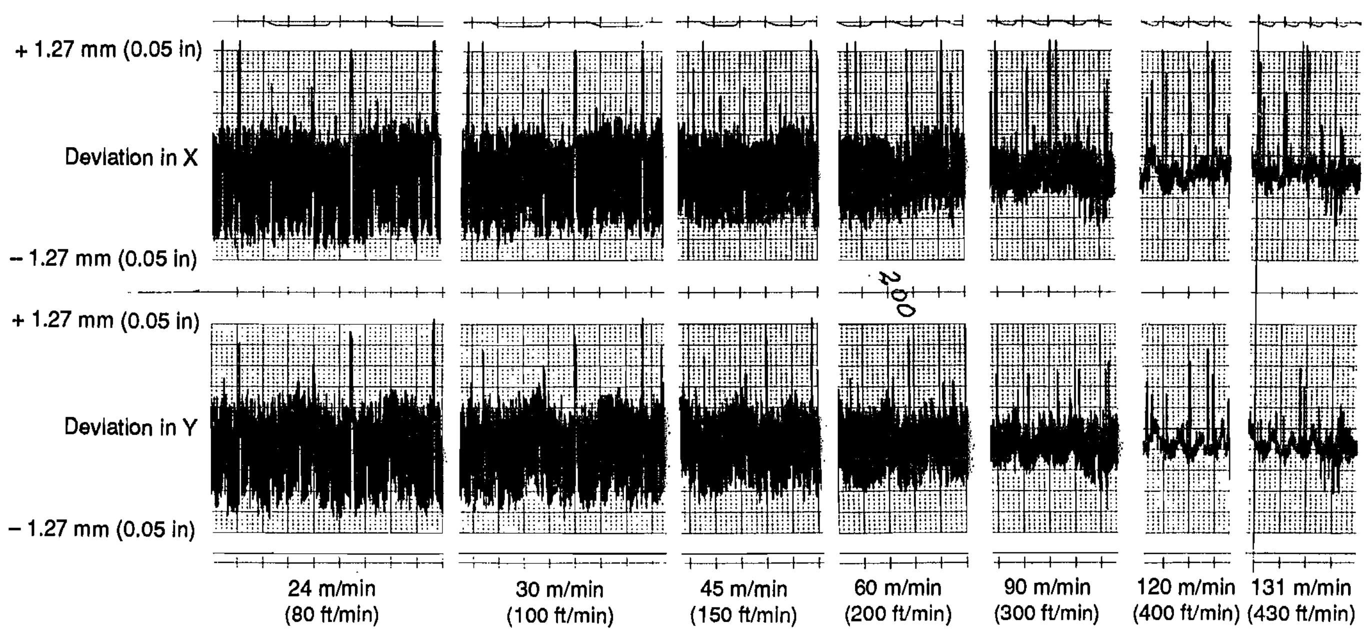
a second. The rope travel per scan for various rope speeds is given in table 3. Field tests of hoist ropes are performed in a general range of 122 m/min (400 ft/min). For a rope speed of 24 m/min (80 ft/min), there is one scan for each 0.41 cm (0.16 in) of rope; thus, a maximum-minimum rope strand pattern of 2.21 cm (0.87 in) would be covered by about 5.5 scans. This is a strand pattern frequency of about 18 Hz. These individual averaged scans are shown in figure 5, which is expanded by using a chart speed of 25 mm/s (1 in/s), and in figure 6, with a chart speed of 125 mm/s (4.9 in/s).

EFFECT OF ROPE SPEED

The frequencies at which each strand pattern passed the measuring head varied from 18 to 92 Hz for rope speeds between 24 to 122 m/min (80 to 400 ft/min) (see table 3). The attenuation of the signal with increasing rope speed can be seen in figure 7 and indicates that the digital sampling rate of 100 Hz is not enough for the instrument to measure the full maximum-minimum diameters of the test rope at all rope speeds. The attenuation of the signal can be attributed to the fact that the sampling frequency does not meet the Nyquist rate, which requires that the sampling frequency be twice the highest frequency contained in the signal for accurate reconstruction of the sampled signal. The attenuation can also be attributed to the 10-scan averaging function of the diameter monitor.

By inspecting figure 7 and the frequency column in table 3, one can see that attenuation of the signal for rope speeds faster than 30 m/min (100 ft/min) can be expected for the 1.9-cm (0.75-in) diam rope. When attenuation occurs, the trace attenuates toward a line that is an average diameter (X + Y)/2.

Figure 7



Attenuation of lay pattern with increased rope speed.

Wire ropes with larger diameters also have longer lay lengths. Lay length can be estimated as approximately seven times the rope diameter for a round strand rope. Using this logic, it is estimated that 3.81-cm (1-1/2-in) diam ropes could be tested to about 61 m/min (200 ft/min) and 5.1-cm (2-in) diam ropes could be tested to about 91 m/min (300 ft/min) before signal attenuation would affect measurement.

ELIMINATION OF LAY-INDUCED CYCLES

Average diameter was investigated as a usable measure of diameter obtainable from the diameter-monitoring system. Deviation of the average diameter is shown in the top chart of figure 8. It is difficult to define an average centerline of an oscillating trace that represents the outer surface of a wire rope. Therefore, a filter (figure 9) was added to the circuit to provide a straight-line representation of wire rope diameter. This is a rudimentary low-pass filter that eliminates frequencies above a chosen band width. The results are shown in figure 10. The 1.9-cm (0.75-in) diam rope was passed through the instrument several times using various filter configurations. The filter eliminated cyclic variations and accurately passed the noncyclic signal representing the average diameter of the wire rope.

In the filtered average trace, several different values of resistance (R) and capacitance (C) were tried to filter the higher frequency oscillations. These cutoff frequency changes are indicated in figure 10 by the numbers 1, 2, 3, and 4, which correspond to 10, 4, 1, and 0.25 Hz, respectively. The cutoff frequency for the filter can be calculated by

$$F_c = 1/2\pi RC,$$

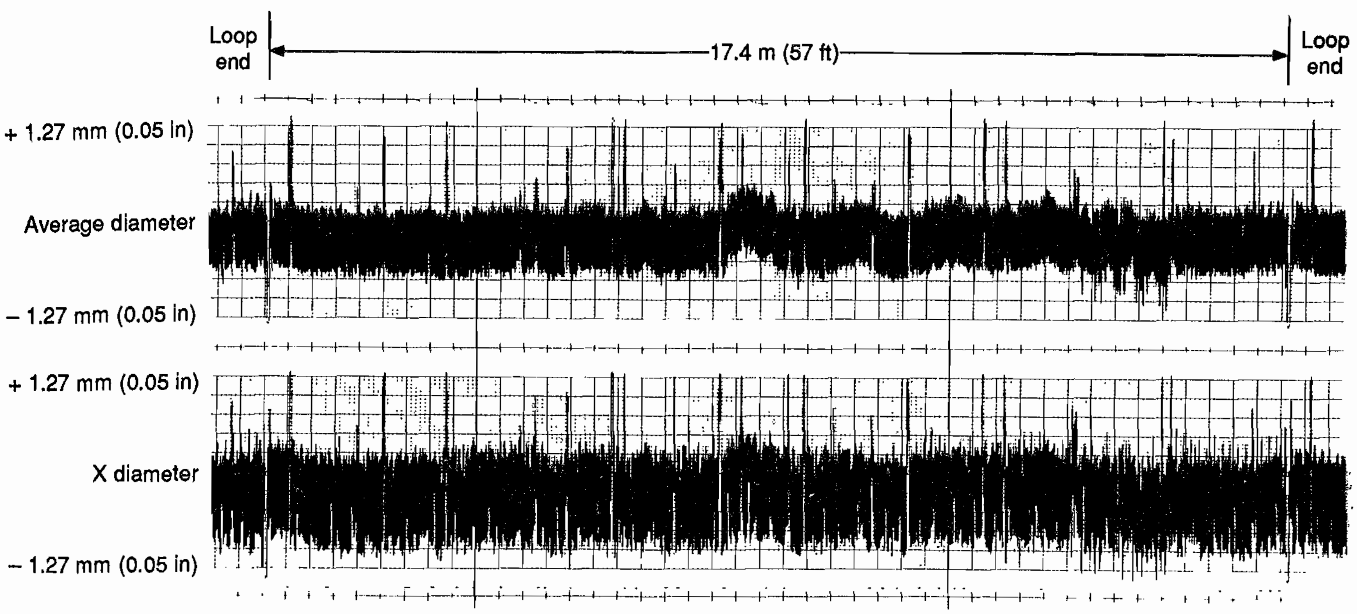
where F_c = cutoff frequency, Hz,

R = resistance, Ω,

and C = capacitance, F.

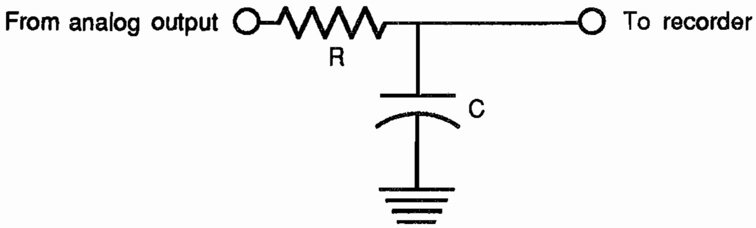
Even though the filter used in these tests appeared adequate, a higher order filter could be used to improve the filtering characteristics. Some users may choose to record the analog output on two recorder channels, one unfiltered and the other filtered to whatever degree desired.

Figure 8



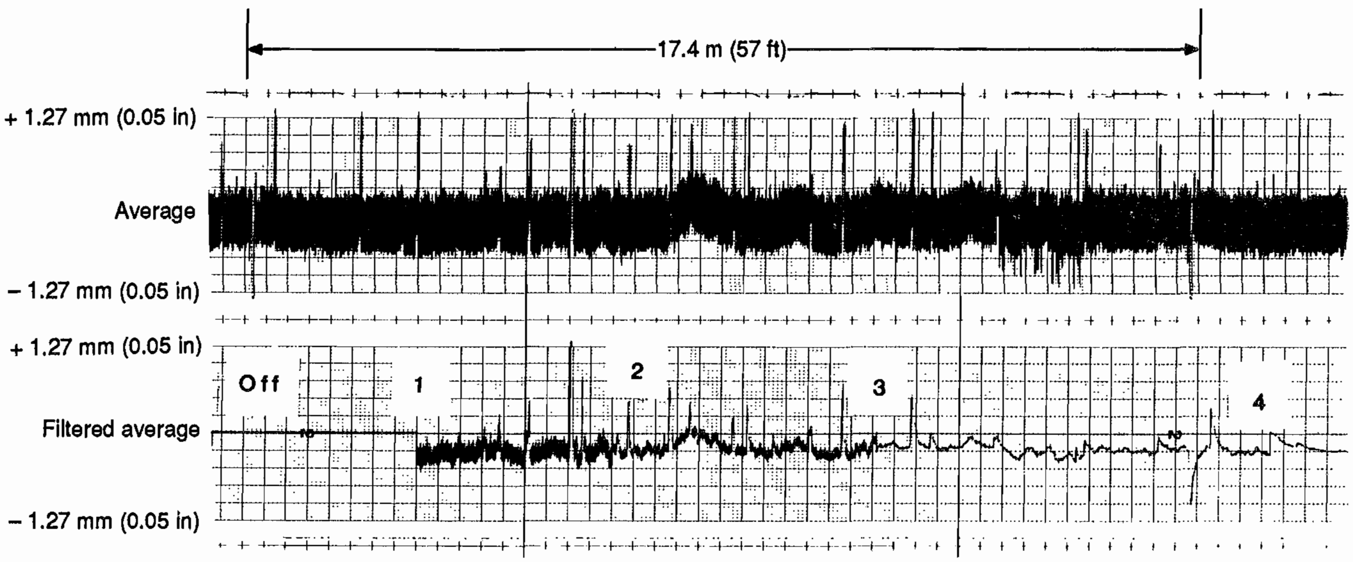
Diameter deviation for average and X diameters.

Figure 9



Low-pass filter.

Figure 10



Trace of rope using low-pass filter. Centerline of chart was 1.9 cm (0.75 in), and sensitivity was 0.051 mm (0.002 in) of diameter change per chart division. Numbers indicate cutoff frequency changes; 1, 2, 3, 4 correspond to 10, 4, 1, and 0.25 Hz, respectively.

DISCUSSION AND CONCLUSIONS

Testing the instrument showed that it was versatile and easy to operate. The "deviation from a set point" method using either X and Y or XY-average and X-diameter provided accurate results at low rope speeds. It must also be emphasized that at a plane through the rope, the X, Y, and XY-average measurements are all different.

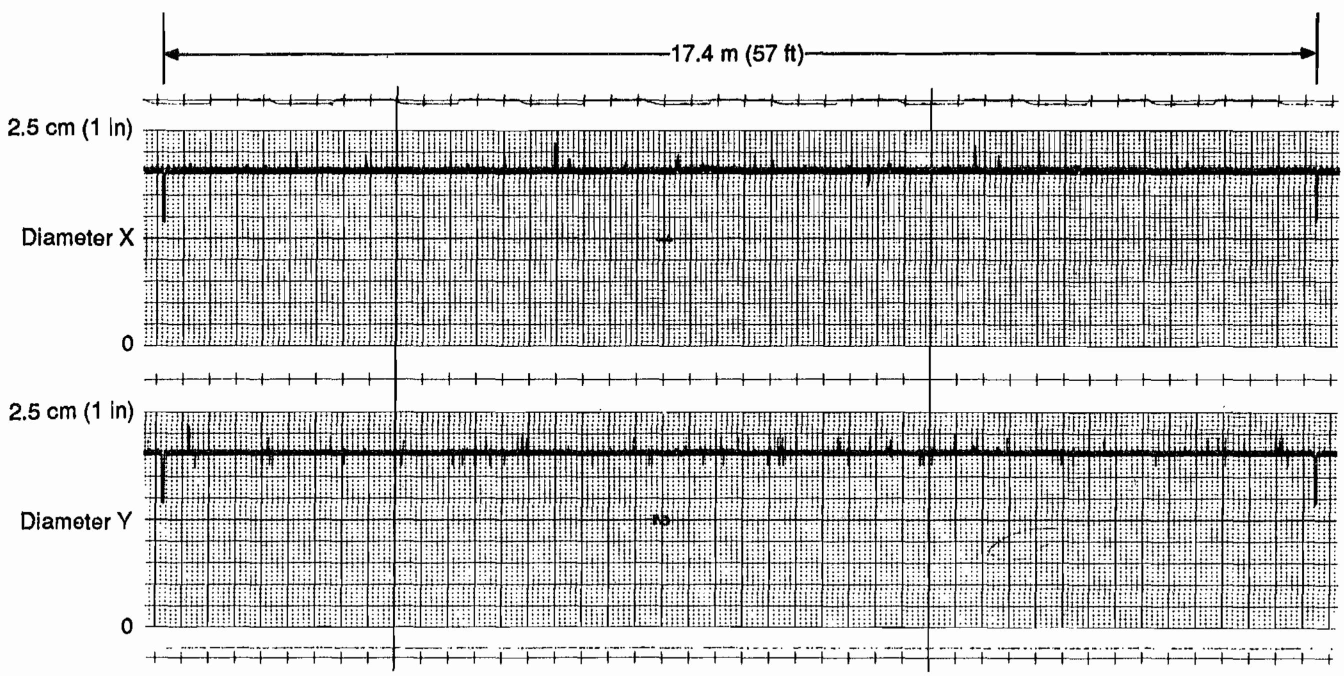
The deviation method traces were made at a scale so that the maximum deviation was 0.254 ±0.127 cm (0.1000 ±0.05 in). This resulted in a very readable trace that encompassed the appropriate range of diameters for wire rope. The user can select other diameter scales if desired. Figure 11 shows a trace of the actual diameter of the rope rather than a deviation in diameter. Sensitivity is greatly reduced, however, and this method is not recommended for wire rope.

Rope speeds faster than 30 m/min (100 ft/min) for a 1.9-cm (0.75-in) diam rope attenuated diameter measurements at the high and low extremes; therefore, the instrument does not provide the needed measurements of maximum diameter. Larger diameter ropes can be run at higher rope speeds before there is attenuation of diameter measurements.

The diameter-monitoring system built under contract for the USBM is adequate for obtaining measurements of wire rope diameter at relatively low rope speeds. Redesign of the sampling hardware and software is necessary to provide analog output of the maximum diameter envelope or other optional configurations without attenuating the signal. These changes should be made by or in consultation with the manufacturer.

If the measurements provided by this instrument are compared with traces from electromagnetic nondestructive tests (NDT), the degree of internal metal loss from wear or corrosion should be obtainable. For every diameter of rope, there is an appropriate cross-sectional area. If there is a discrepancy between the measured (sensed) diameter and the metallic cross-sectional area, then degradation in the interior of the rope is to be suspected. If there is no discrepancy, then a reduction in diameter could be the result of either external wear or elongation of the rope. External wear can be determined visually. Therefore, by combining measurements of wire rope diameter with the area of metallic cross section and visually examining the rope surface, inspectors can determine more about the condition of the rope than can be found out using any one NDT method by itself.

Figure 11



Plot of absolute rope diameter.