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A machine for the tension-torsion testing of steel wire ropes

Summary

The development of steel wire ropes for ultra deep level hoisting requires careful consideration of their torsional behaviour under service conditions. Rope load differentials in a deep shaft cause significant permanent variations of lay angle along the rope length which can have negative effects on the rope endurance. Laboratory based experimental investigations can therefore be of great benefit to rope manufactures in the assessment of the torsional characteristics of rope constructions. It is in view of this reasoning that an advanced machine for the tension-torsion testing of steel wire ropes has been developed at the CSIR laboratories in Johannesburg.

This introductory paper discusses the construction and capabilities of the computer controlled hydraulic testing facility. The methods used for axial load, torque, twist, elongation, diameter and lay length measurement are addressed and the machine control system is described. For illustration, examples of results for constant twist, load and torque tests have been included. These tests were conducted on a 40 mm diameter, right hand Lang's lay, triangular strand rope.

1 Introduction

The South African mining industry is considering the development of single lift shafts to 4000 m within the next five to ten years. The motivation for this is that the present system of reaching deeper gold bearing reefs using sub-vertical and tertiary shaft systems would not be economically viable. A single lift shaft, 2800 m deep is currently being sunk for the JCI South Deep Project, 45 km south west of Johannesburg.

One of the major concerns with these projects is the viability of operating current Lang's lay triangular strand rope designs at such depths. Greenway (1990) states that in-shaft torsional deformations are proportional to rope length, therefore large changes in lay length are predicted for very deep winds. Only a certain amount of lay length change can be tolerated before the stability of inter-wire and inter-strand positions is lost. This can in turn lead to premature fatigue failure of the rope wires by local bending and abnormal inter-wire contact. At this stage, it is not clear to what extent the high torque and rotation values in deep shafts will affect the rope construction and thereby the endurance.

These questions have prompted a research program on the torsional behaviour of triangular strand ropes for drum winders. In South Africa, the majority of research work into the torsional behaviour of wire ropes for mine hoisting has been conducted on friction type Koepe winder ropes. According to Wainwright (1988), conventional round and triangular strand head ropes showed very poor performance in shafts deeper than 1000 m. The performance was characterised by reduced fatigue life and rapid wearing of friction drum treads. The main reason for this was the prominent torsional response of these ropes under load. The problems encountered forced rope manufacturers to develop suitable ropes for deep level friction winding.

Yiassoumis (1992) investigated the torsional behaviour of non-spin steel wire ropes for Koepe winders. Experimental testing was combined with in-situ measurements on a 1800 m deep shaft to determine a correlation for the torsional behaviour. It has now become necessary to extend this work to deep shaft drum winding installations.

2 History of the testing machine

The development of suitable hoisting ropes for sinking and permanent operation requires that the torsional properties of the constructions be determined experimentally during the design stages. This is achieved with the use of a purpose built steel wire rope torque-tension testing machine located at the CSIR Mine Hoisting Technology laboratories in Johannesburg.

The basic concept of the machine originated in the design of a universal fatigue testing machine which was built in the 1960's. In the preliminary design study of the fatigue machine, Kuun (1962) identified torsional strain as a service condition having a direct bearing on service life. At one point the fatigue testing machine was actually used to conduct tension-torsion tests. This proved to be cumbersome and as a result the torque-tension machine was purpose built between 1972 and 1974. Since then a number of modifications have been made to the mechanical, electrical and control systems although financial and time constraints restricted the researchers from achieving the desired levels of sophistication. The result was that the machine was poorly documented and not very reliable. This situation did not encourage further work in the field.

Driven by the need for state of the art research into the torsional behaviour of Lang's lay triangular strand ropes, it was decided in 1994 to completely re-develop the existing torque-tension testing machine. The requirement was that the new machine should automatically perform torsion tests at constant rope load, twist and torque to allow more accurate simulation of in-shaft rope conditions. In the previous form, the machine was only capable of measuring rope torque for manually set constant end rotations and varying values of load.

The upgrading process incorporated:

- The re-design, replacement or overhaul of problematic mechanical components.
- A new design of the electrical control and instrumentation systems.
- Modifications to the hydraulic systems including a new oil cooling circuit.
- Development of customised control and data acquisition software.
- Detailed documentation of all mechanical, hydraulic, electrical, electronic and software components of the machine.

3 Machine description

3.1 General layout

Figure 3.1 shows the physical layout of the main components of the torque-tension machine. The hydraulic cylinder provides the rope load and the motor, with a reduction drive, can twist up or untwist the specimen as required. The scissor mechanism at the rear of the hydraulic cylinder allows axial movement but prevents rotation of the cylinder shaft.

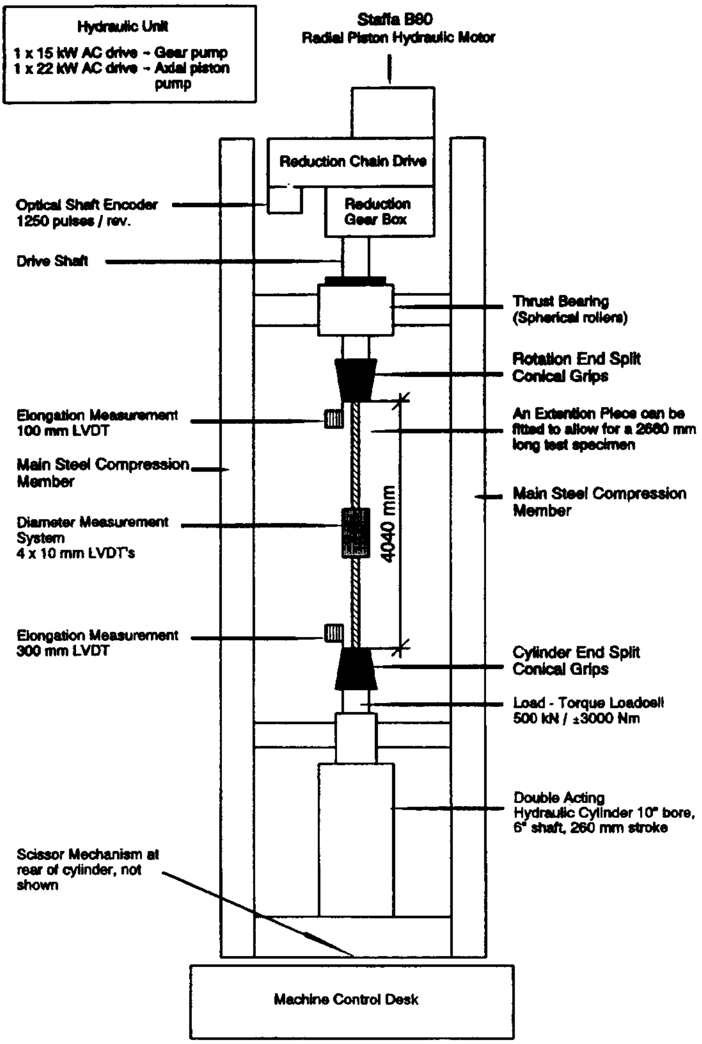

Figure 3.1: Layout of the CSIR Steel Wire Rope Torque-Tension Testing Machine.

3.2 Machine specifications

Test Parameter	Measurement Range	Measurement Accuracy
Load	0 → 500 kN	± 1.8 kN FS
Torque	-3000 → +3000 Nm	± 4.9 Nm FS
Elongation	-130 → +130 mm	± 1.3 mm FS
Diameter change	-5 → +5 mm	± 0.03 mm FS
End rotation	-700 → +700 turns	± 1.0° (Backlash in reduction drive)

Rope diameters up to 64 mm can be accommodated. Depending on the construction, the maximum load may need to be limited so as not to exceed the torque limits of the loadcell.

3.3 Control system

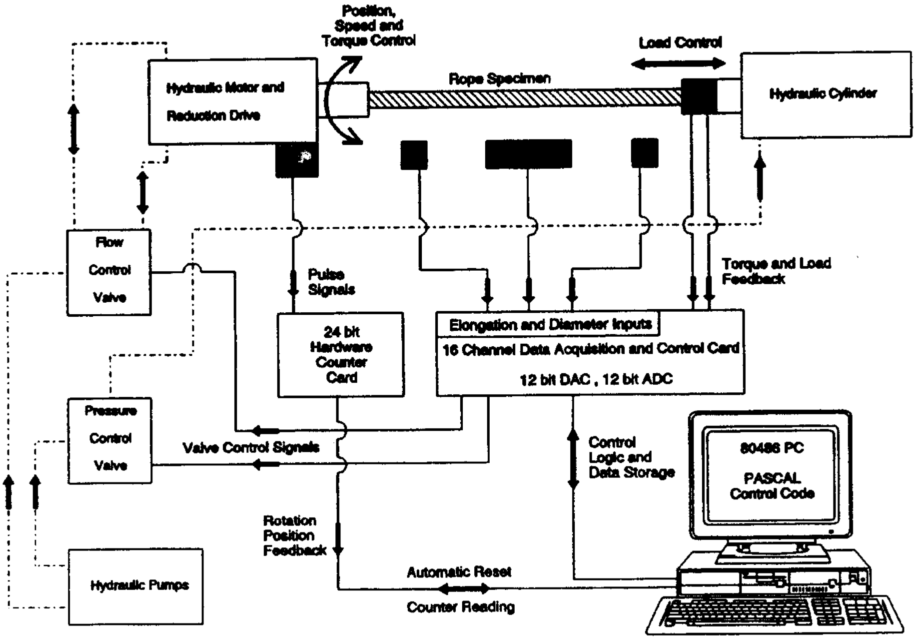

Figure 3.2: Basic configuration of the machine control system.

Closed loop control of rope load, torque and end rotation is achieved with the control system shown in figure 3.2. Customised, PASCAL based, control software and data acquisition provides the machine -operator interface. Proportional pressure relief and flow control valves are used to control the rope load and end rotation respectively.

It was originally anticipated that an electromechanical brake may be required to hold the rotation end drive shaft in a fixed position during testing. This was however not necessary as closed loop control of the five cylinder radial piston motor resulted in position error of less than 1°.

3.4 Load and torque measurement

A combination load-torque loadcell is used to measure the rope load and torque simultaneously. The two strain gauge bridges are applied to an heat treated En30B circular shaft with end fittings which connect to the hydraulic cylinder and the split conical grips. During the dead weight calibration of the loadcell, the cross load and cross torque outputs of the bridges were taken into account in determining the overall accuracy. The bridges are fitted with shunt resistances for in-situ calibration of the load and torque outputs.

3.5 Elongation measurement

Rope specimen elongation as a result of loading and changes in state of twisting is measured by two LVDTs mounted on support pedestals bolted to the laboratory floor. The arrangement of the LVDTs is shown in figure 3.3. When the system was first installed elongation was determined by equation (1).

$$\Delta L = \Delta \mathrm{LVDT}_{\text{Cylinder End}} + \Delta \mathrm{LVDT}_{\text{Rotation End}} \quad (1)$$

It was subsequently discovered that there was an error in the elongation value, depending on the position of the rotation head. The rotation end split collar clamp is attached to the cast white metal collar of the rope and is therefore unlikely to be 100 percent perpendicular to the axis of rotation. The result is a sinusoidal oscillation of the rotation end LVDT plunger which gave rise to the error in the reading. In order to overcome the problem the software executes a check, at constant load, to determine the magnitude of the sinusoidal displacement for angles between -180° to +180°. During testing equation (2) is then used to accurately determine the elongation.

$$\Delta L = \Delta \mathrm{LVDT}_{\text{Cylinder End}} + \Delta \mathrm{LVDT}_{\text{Rotation End}} - \text{Skewness Factor} \quad (2)$$

The Skewness Factor is interpolated from a look up table created during the check and is a function of the current angle of rotation. The look up table is in fact valid for all angles since any angle ϕ can be converted to an angle β between -180° to +180°. The gauge length of the specimen is determined by measuring the distances x and y and adding these to the fixed length between the measurement pedestals.

For constant end rotations, the elongation measurement is used to determine the rope modulus. Accurate elongation measurement is also necessary for the calculation of rope twist which is discussed in more detail in section 5.

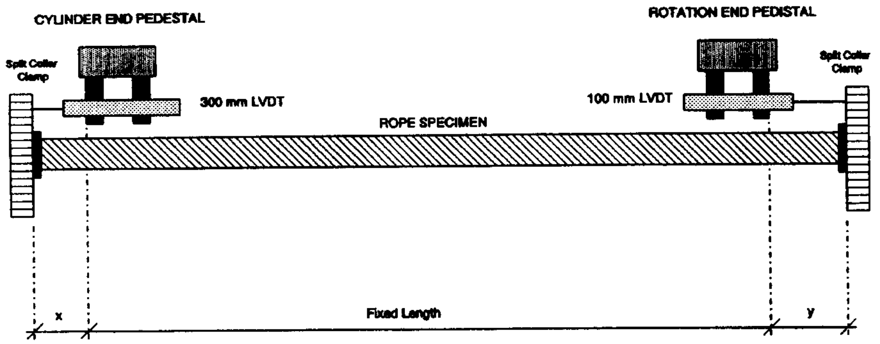

Figure 3.3 : General arrangement of rope elongation measurement system hardware.

3.6 Diameter measurement

Two sets of sprung parallel plates, each with two LVDTs, measure the change in rope diameter. The plate sets are mounted perpendicular to one another as shown in figure 3.4. The change in diameter in calculated from the average of the four displacements measured by the LVDTs. The spring force on the plates result in the jig rotating with the rope when the end rotation is varied. For clarity the springs and steel slides, which keep the plate surfaces parallel, are not shown in Figure 3.4.

Torsional strains in winding installations result in the alteration of rope strand orientations and therefore rope diameter. Similarly, axial elongations are accompanied by reductions in rope diameter. The relationship between the sheave groove radius and rope diameter can affect the in-service endurance of a rope and it is therefore important to determine the variation of diameter due to twisting and loading.

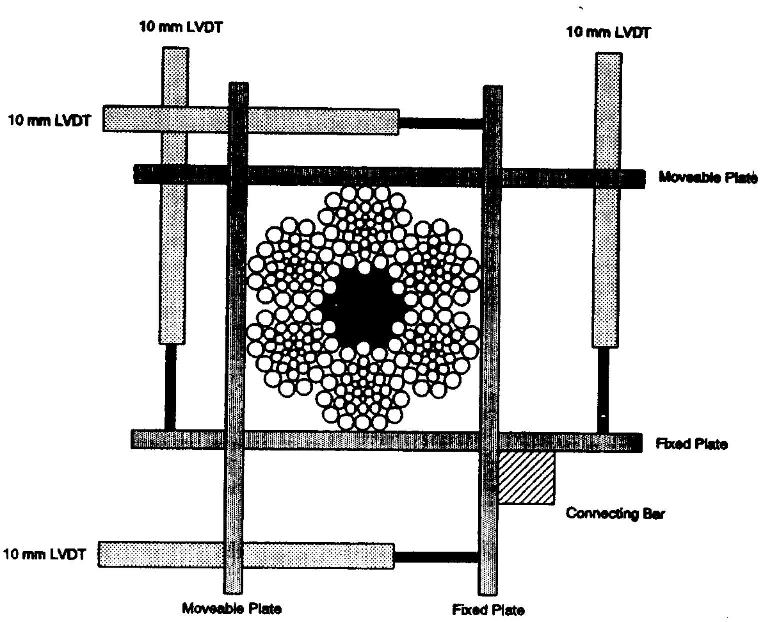

Figure 3.4: Configuration of the rope diameter measurement jig.

3.7 Lay length measurement

The strand lay length of the rope specimen is measured manually with a lay length gauge as shown in figure 3.5. The double slide mechanism with the two V-Blocks ensure that the lay length is measured parallel to the longitudinal axis of the rope. The pointed screws through each block, can be adjusted for depth depending on the rope diameter. Once the blocks and screws have been correctly positioned, the lay length is measured across the centre lines of the screws. The use of this type of lay length gauge results in very accurate and repeatable readings for rope lay length.

On a six strand rope it is advisable to measure the lay length over twelve or eighteen strands and divide the result by two or three respectively to reduce the measurement error.

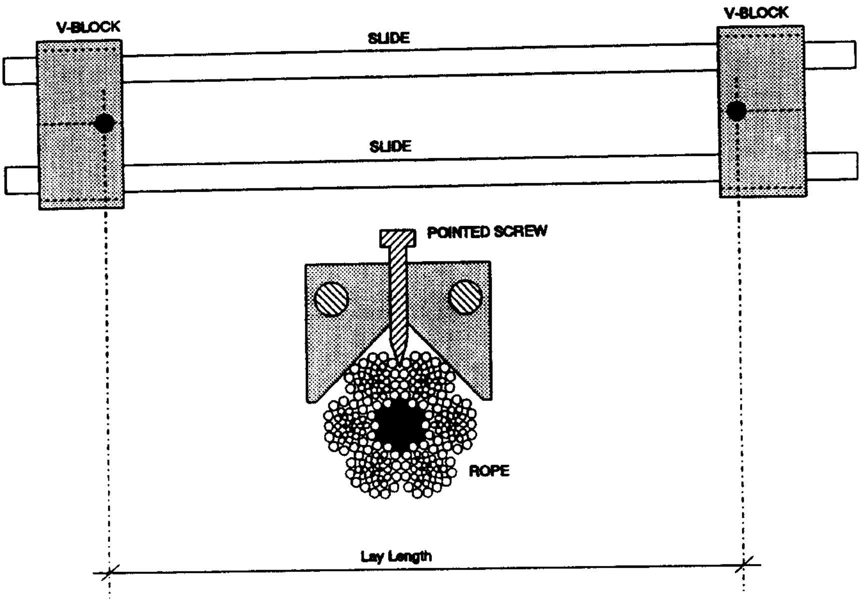

Figure 3.5: Parallel V-Block lay length measurement gauge.

4 Computer based machine control

The machine control software allows the operator to enter the parameters for the various tests. An example of the values entered for the constant end rotation test, described in section 5.1, is shown below:

```
Start Rotation            (deg)  -1000.0
Number of Increments                10.0
Rotation Increment        (deg)    200.0
Load Start Point          (kN)      30.0
Load End Point            (kN)     450.0
Rate of Load              (kN/s)    10.0
Rate of Data Capture      (Hz)       0.8
```

Adequate control of the hydraulic cylinder is achieved through a combination of proportional and integral components in the software algorithms. The hydraulic motor is more responsive than the cylinder so only a proportional component is required. For illustration, a procedure which increases the load while maintaining the end rotation constant is listed. The arctan function in the rotation control reduces the dead band region around the zero output point and limits the maximum output voltage to a predetermined value irrespective of the magnitude of the error. This reduces the likelihood of system instability.

```
Procedure    Go_To_Load_Hold_Rot(Rate,Terminal_Load,Rot_Value    :
real); repeat

    Check_Time          : =  Read_Time - Start_Time;
    Load_Actual         : =  Read_Load;
    Load_Required       : =  Start_Load + Rate * Check_Time;
    Load_Error          : =  Load_Actual - Load_Required ;
    I_Part              : =  I_Part + Ic * Load_Error;
    Load_Volts          : =  Start_Load_Volts{Starting CTRL voltage}
                        + Cc * Check_Time * Rate{Forcing function}
                        -    -Load_Error * Pc      {Proportional CTRL}
    -                        -I_Part;              {Integral CTRL}
    Pull(Load_Volts);                              { Voltage output}
    Rot_Actual          : =  Read_Rotation;
    Rot_Error           : =  Rot_Actual - Rot_Value;
    Rot_Volts           : = -2*arctan(5*Rot_Error)
                                                   {Proportional CTRL}
    Rotate(Rot_Volts)                              {Voltage output }
until Load_Actual >= Terminal_Load;
```

5 Test results

In tension-torsion testing of wire ropes there are six primary measurement parameters namely axial load, torque, twist, elongation, diameter change and strand lay length. Twist is defined as the rate of change of end rotation over the specimen length, $d\phi/dz$, as described in equation (3). For Lang's lay triangular strand ropes there is a geometrical relationship between the twist and the strand lay length.

$$\text{Twist} = \text{End Rotation} / (\text{Gauge Length} + \text{Elongation}) \qquad (3)$$

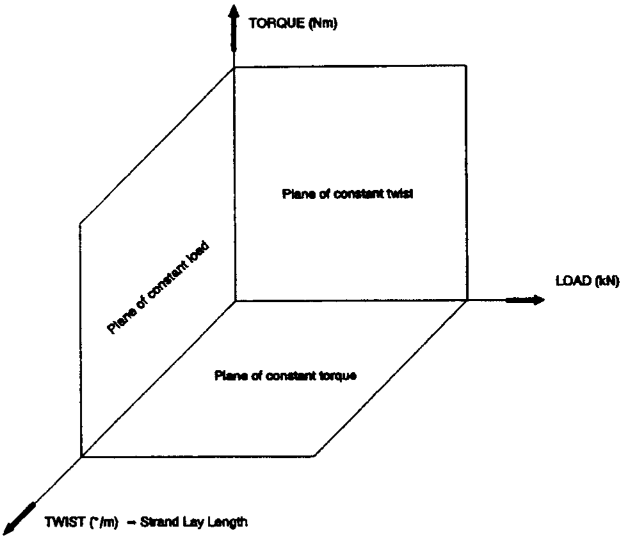

Figure 5.1: A three axis domain defining the torque-tension twist testing of steel wire rope.

Providing that an adequate level of machine control can be achieved, it is possible to conduct tests in all three planes shown in figure 5.1. The constant twist test is conducted as a constant end rotation test. There is however a small error in the assumption that these two are alike. For a fixed end rotation and increasing load, the rope elongation is not constant, therefore the twist as defined in equation (3) will change in proportion to the rope strain. Analysis of tests results have shown that maximum rope strains due to loading are on average less than 0.006 mm/mm.

Examples of tests results for the constant end rotation, load and torque tests are shown in the following three sub-sections. The rope used for the tests was a 40 mm ø6x28(10/12/6+3T) right hand Lang's lay (RHL) triangular strand rope. The 0° gauge length was 2676 mm and the wire tensile grade, 1900 MPa. The convention used for testing states that RHL ropes generate negative torques when tensioned.

Discussion of the analysis of the results will be the topic of a later paper; at this stage the results are only intended to demonstrate the capabilities of the testing machine.

5.1 Constant end rotation test (≈Constant twist)

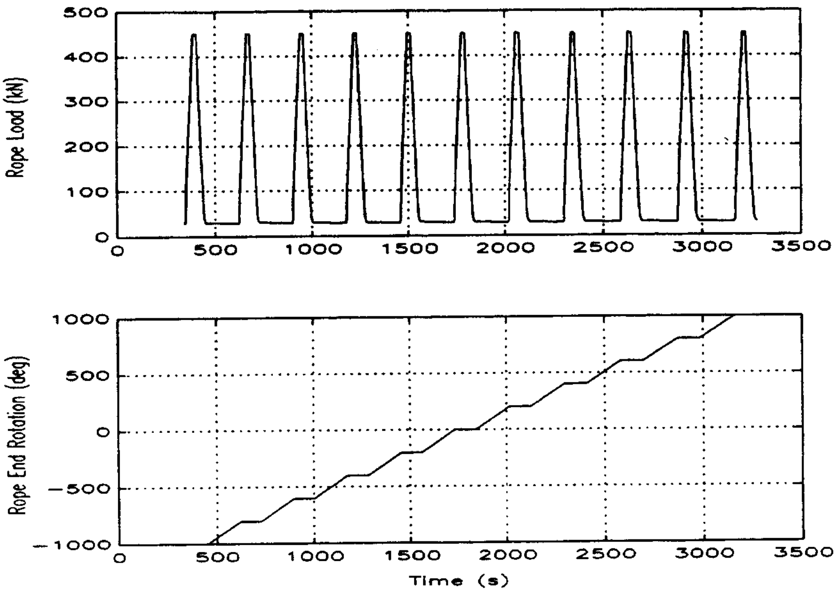

Figure 5.2: Variation of rope load and end rotation during a constant end rotation test

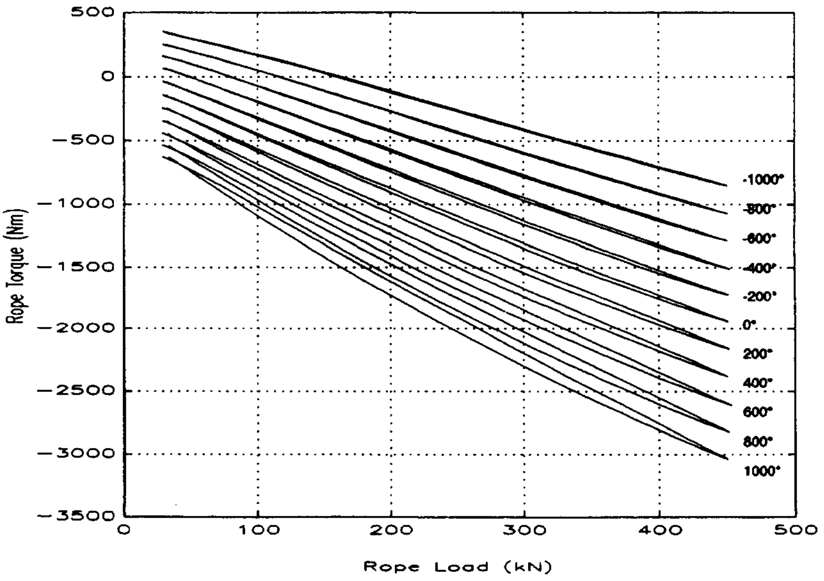

Figure 5.3: Rope torque versus load for a constant end rotation test

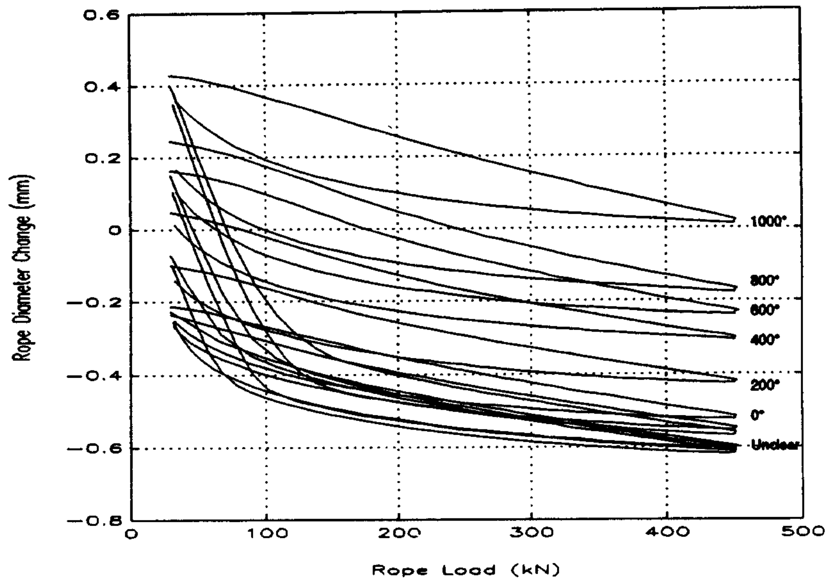

Figure 5.4: Rope diameter versus load for a constant end rotation test

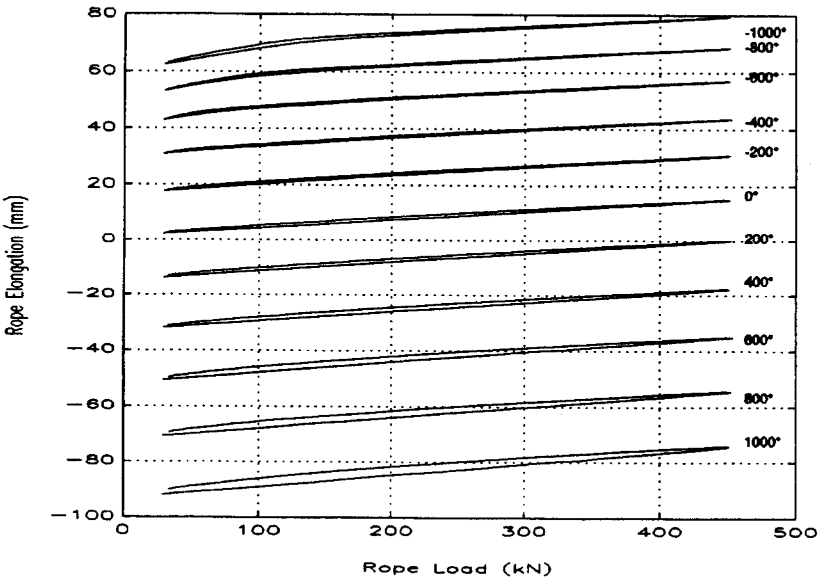

Figure 5.5: Rope elongation versus load for a constant end rotation test

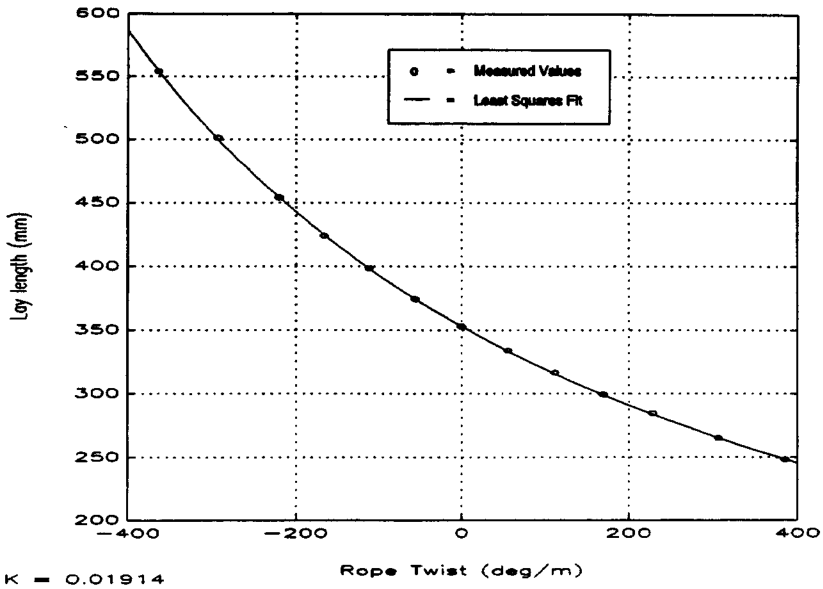

Figure 5.6: Measured rope lay length during a constant end rotation test

The values of twist for the measured lay lengths in figure 5.6 were determined using equation (3). From simple geometrical relationships the strand lay length can be defined as :

$$LL = [\pi.D_0] / [\tan(\theta_0 + K.(d\phi/dz))] \qquad (4)$$

Where D_0 = Measured zero degree rope diameter (mm)

θ_0 = Zero degree strand lay angle (°)

$= \arctan(\pi D_0 / LL_0)$ (5)

LL_0 = Measured zero degree lay length (mm)

$d\phi/dz$ = Twist (°/m) by equation (3)

Theoretically

$$K = D_0 / 2000 . \cos^2(\theta_0) \qquad (6)$$

however, to achieve a fit through the measured data using the least squares criterion, the theoretical value of K may need to be adjusted. For the rope used in this test, the parameters were :

D_0 = 40.95 mm

θ_0 = 20.0239°

LL_0 = 353.0 mm

K_{Theory} = 0.01807°/ (°/m)

$K_{Least\ Squares}$ = 0.01914° / (°/m)

It can be seen that the theoretical value of K had to be increased by 5.896% in order to satisfy the least squares criterion of fit. Continuous electronic lay length measurement is not available on the machine so equation (4), in the least squares form, is used to determine the rope lay length during the constant load and torque tests.

5.2 Constant load test

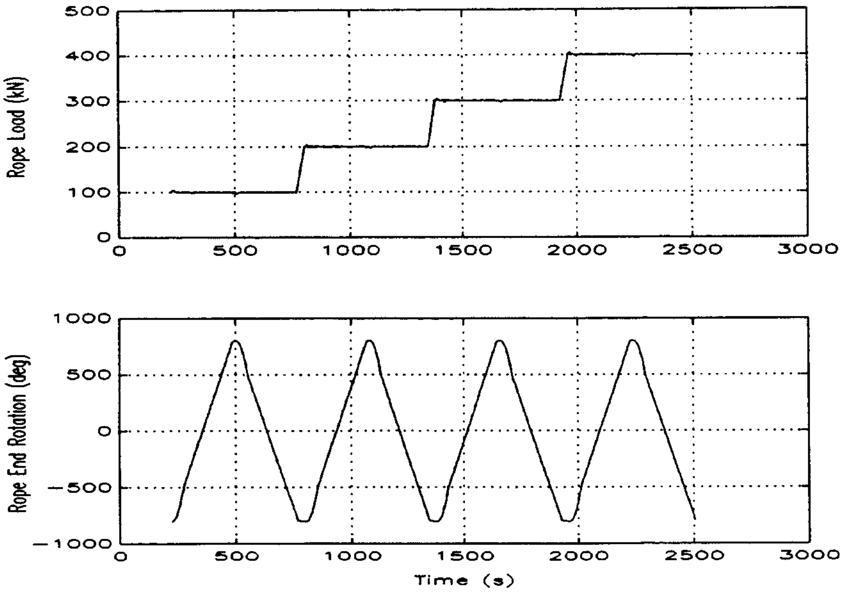

Figure 5.7: Variation of rope load and end rotation during a constant load test

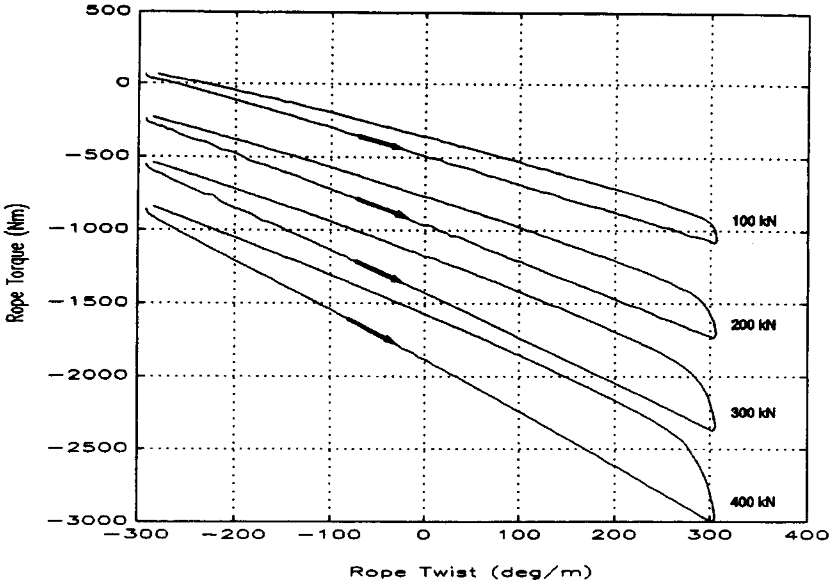

Figure 5.8 : Rope torque versus twist for a constant load test

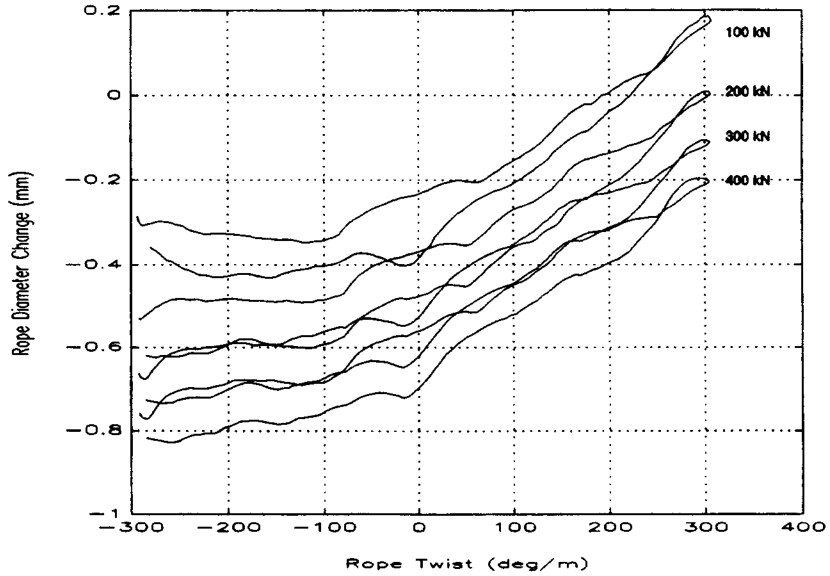

Figure 5.9: Rope diameter versus twist for a constant load test

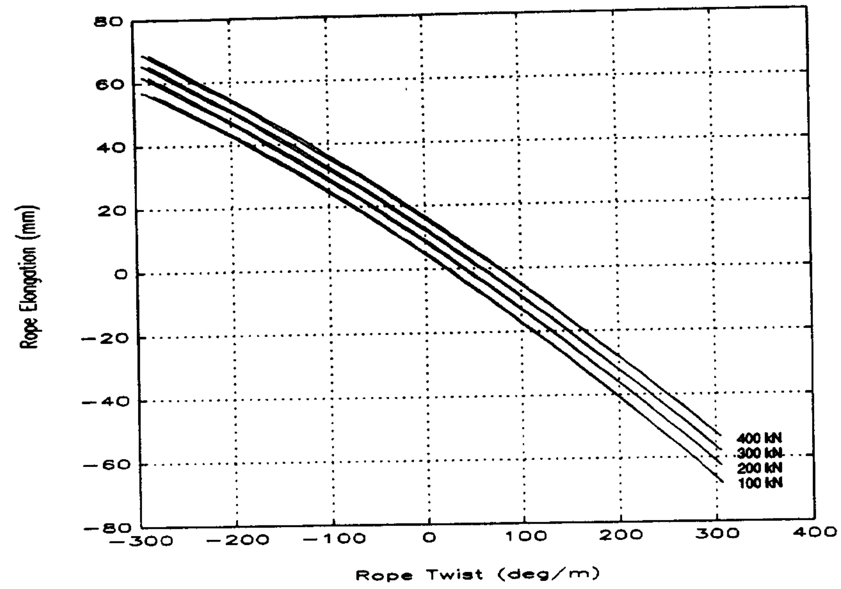

Figure 5.10: Rope elongation versus twist for a constant load test

5.3 Constant torque test

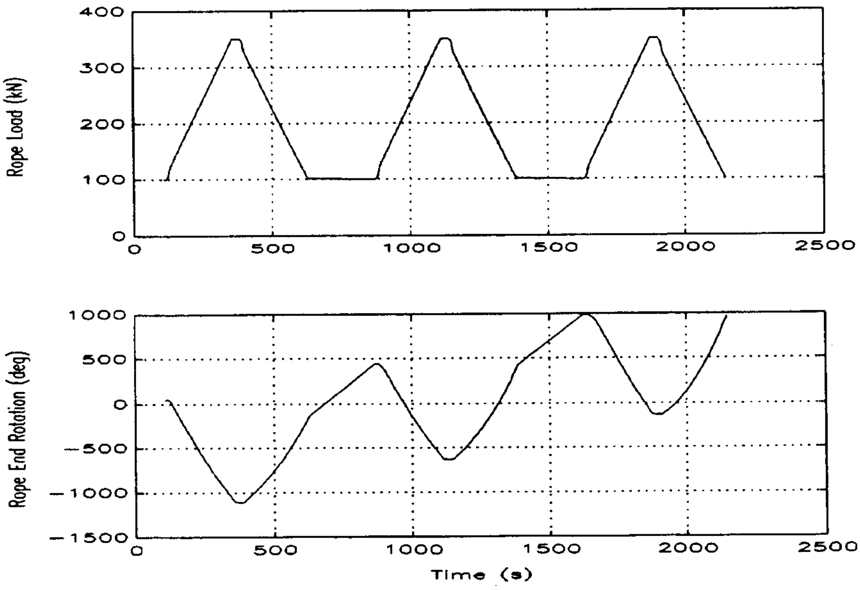

Figure 5.11: Variation of rope load and end rotation during a constant torque test

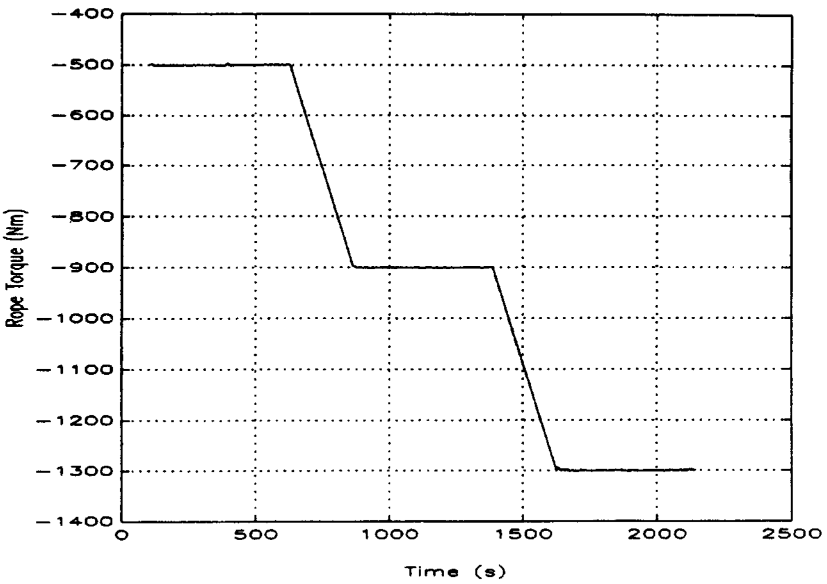

Figure 5.12: Rope torque versus time for a constant torque test

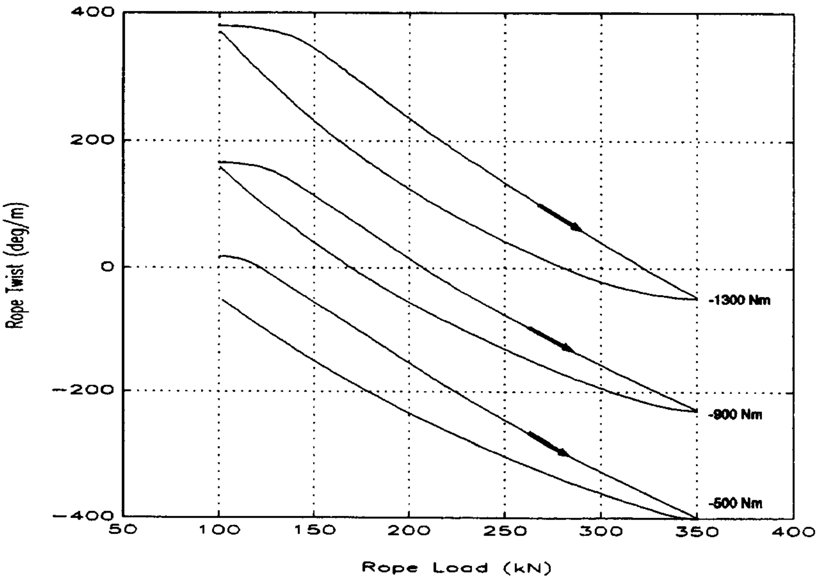

Figure 5.13: Rope twist versus load for a constant torque test

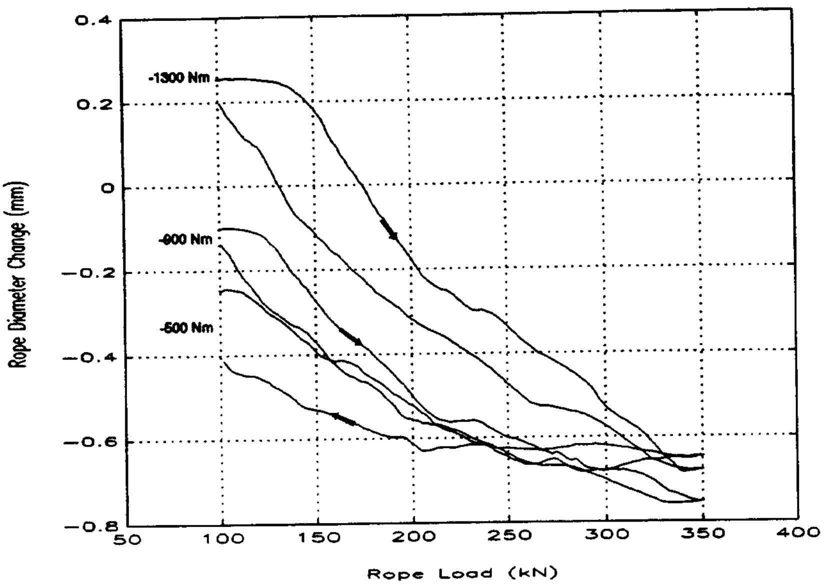

Figure 5.14: Rope diameter versus load for a constant torque test.

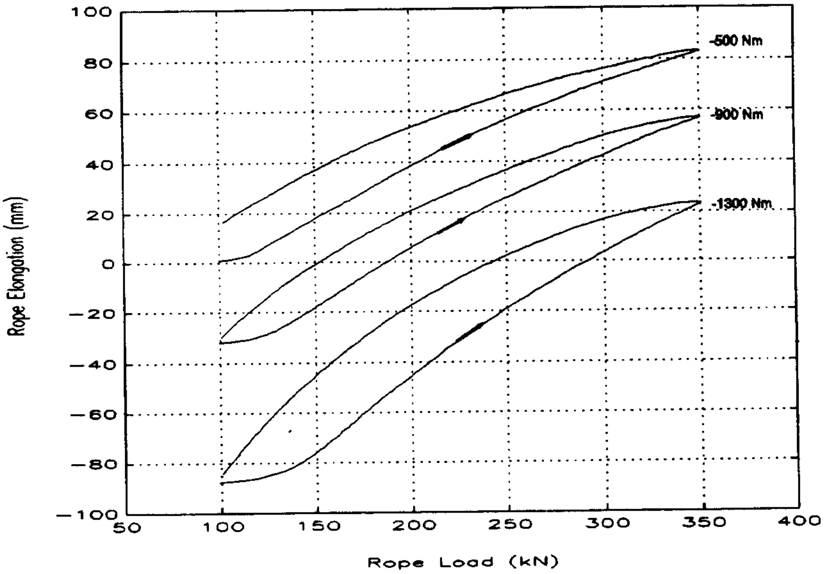

Figure 5.15: Rope elongation versus load for a constant torque test.

6 Conclusions

A machine for tension-torsion testing of steel wire ropes has been developed which allows research to be conducted under constant load, twist and torque conditions.

The implementation of computer based automatic machine control has resulted in significantly reduced time requirements for conducting of tests. High levels of repeatability between tests are achieved since all operations during testing are timed and executed by the control software.

The machine is currently being used in a research program on the torsional behaviour of Lang's lay triangular strand ropes for deepshaft drum winders. The objective of this research project is the determination of an experimental correlation and mathematical model which can predict the torsional behaviour of triangular strand ropes operating in vertical shafts of different depths. The practical result of the work will be a validated laboratory based experimental procedure which will allow rope manufactures to predict how a specific rope construction would behave torsionally in a mine shaft installation.

7 Acknowledgements

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