

T O R S I O N A L B E H A V I O U R O F W I R E R O P E S
F O R K O E P E W I N D E R S

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APPENDIX A

CONSTRUCTION DETAILS AND
PROPERTIES OF WIRE ROPES

Table A.1: Construction details of a 44 mm triangular strand rope

ORIGINAL	11	PRINTED AT	92/01/08 - 13.42.12				HAGGIE RAND LIMITED	PRODUCT CODE				
PRODUCT DEVELOPMENT DEPARTMENT								GG0440J37RBBO				
CURRENT SPEC												
01 PRODUCT		COMPOUND TRIANGULAR STRAND ROPE										
02 CONSTRUCTION	6X30(12/12/6+3T)/F											
03	NOM DIA	EXP DIA	MAX DIA	BREAKING FORCE								
04	44,00	44,66	46,20	1408,00								
05RHL	LAY/S	TENS	FINISH	TOTAL MASS	GRSE MASS	SPEC DATE						
		1800	DRGAL	8,2430	,2732	86/04/03						
WIRE SPECIFICATION	1	2	3	4	5	6	7	8				
NO OF STRANDS	06	06	12	06	03							
NO OF WIRES	07	12										
WIRE	MIN	08	3,180	1,900	1,620	1,220						
DIAMETER	CALC	09	3,200	1,920	1,640	1,240						
	MAX	10	3,230	1,945	1,665	1,260						
WIRE MASS	11	4,9850	1,8180	1,6853		2007						
TENSILE GRADE	12	1800	1800	1600		1600						
WIRE FINISH	13	DRGAL	DRGAL	DRGAL	DRGAL							
CAT	14	0003	0003	0003	0003							
WIRE CODE DIA	15	0320	0192	0164	0124							
TENS	16	18000	18000	16000	16000							
FINISH	17	E	E	E	E							
SPECIAL WIRE	18											
INSTRUCTIONS	19											
STRANDING SPEC.	1	2	3	4	5	6	7	8				
STR DIA/ALT MIN	20	15,79	9,46	5,64								
ON-TENSION CALC	21	15,94	9,57	5,71								
	MAX	22	16,14	9,71	5,79							
STRAND LAY MIN	23	149,7	89,3	36,1								
ON-TENSION MAX	24	157,2	89,6	37,9								
FLAT LAY MIN	25	357,9										
ON-TENSION MAX	26	375,6										
FL/STR LAY RATIO	27	2,39										
LAY DIRECTION	28	RH	RH	RH								
BACK ROTATION	29	15										
POSTFORMING CODE	30	NONE	NONE	NONE								
TYPE	31	DRY	GBEX	GBEX								
LUBRICATION CODE	32	0.0	1.2	1.2								
MASS	33		,0909	,0607								
JOINTS IN STR	34	1/1,10		1/4,10								
STRAND TAKE-UP	35	1,0374	1,0432	1,0626	1,0867							
OPERATION NO	36	2		1								
SPECIAL	37											
STRANDING	38											
INSTRUCTIONS	39											
FIBRE SPECIFICATION	1	2	3	4	5	6	7	8				
CORE CODE	40				101973							
CONSTRUCTION	41				3X76000							
MIN ON/TENS DIA	42				19,73							
MATERIAL	43				SISAL							
LUBRICATION	44				SEPAL							
MASS	45				,2802							
LAY DIRECTION	46				RH							
OPERATION NO	47				3							
CLOSING SPEC	1	2	3	4	5	6	7	8				
ROPE/DIA MIN	48	44,39										
ON-TENSION CALC	49	44,83										
	MAX	50	45,41									
ROPE LAY MIN	51	331,8										
ON-TENSION MAX	52	348,4										
LAY-DIRECTION	53	RH										
FWD ROTATION 1IN	54	26										
PREFORMING CODE	55	85-90										
POSTFORMING CODE	56	NONE										
TYPE	57	GBEX										
LUBRICATION CODE	58	1.2										
MASS	59	1216										
CLOSING JOINT	60	1,10										
ROPE TAKE-UP	61	1,0390	1,0390	1,0495	1,0495							
OPERATION NO	62	3										
SPECIAL	63											
CLOSING	64											
INSTRUCTIONS	65											
CONTROL DATA					NEW SPECIFICATION ISSUE CONTROL							
ROPE/STRAND MIN	66	44,00			PREPARED BY VGP							
DIAMETER MAX	67	46,20			CHECKED BY VS.							
OFF-TENSION VAR	68	01,10										
ROPE/STRAND LAY	69	331,8			REF NUMBER	P00724						
OFF-TENSION MAX	70	348,4										

Table A.2: Construction details of West Driefontein head rope

ORIGINAL

9 PRINTED AT

92/01/08 - 13.42.06

HAGGIE SAND LIMITED

PRODUCT CODE
GG0440P18RBE0

PRODUCT DEVELOPMENT DEPARTMENT
CURRENT SPEC

01PRODUCT 18 STRAND "FISHBACK" NON-SPIN
02CONSTRUCTION 12X10(8/2)/6X29(11/12/6+3T)/WMC

	NOM DIA	EXP DIA	MAX DIA	BREAKING FORCE
04	44,00	44,66	45,76	1468,00
	LAY/S		TENS FINISH	TOTAL MASS
05RHL/LHL/LH			1800 DRGAL	6,6810

CONTROL DATA			
ROPE/STRAND	MIN	66	44,00
DIAMETER	MAX	67	45,76
OFF-TENSION	VAR	68	00,88
ROPE/STRAND			
LAY	MIN	69	345,5
OFF-TENSION	MAX	70	362,8

NEW SPECIFICATION ISSUE CONTROL
PREPARED BY JPD
CHECKED BY VGP

REF NUMBER SR5714

Table A.3: Construction details of West Driefontein tail rope

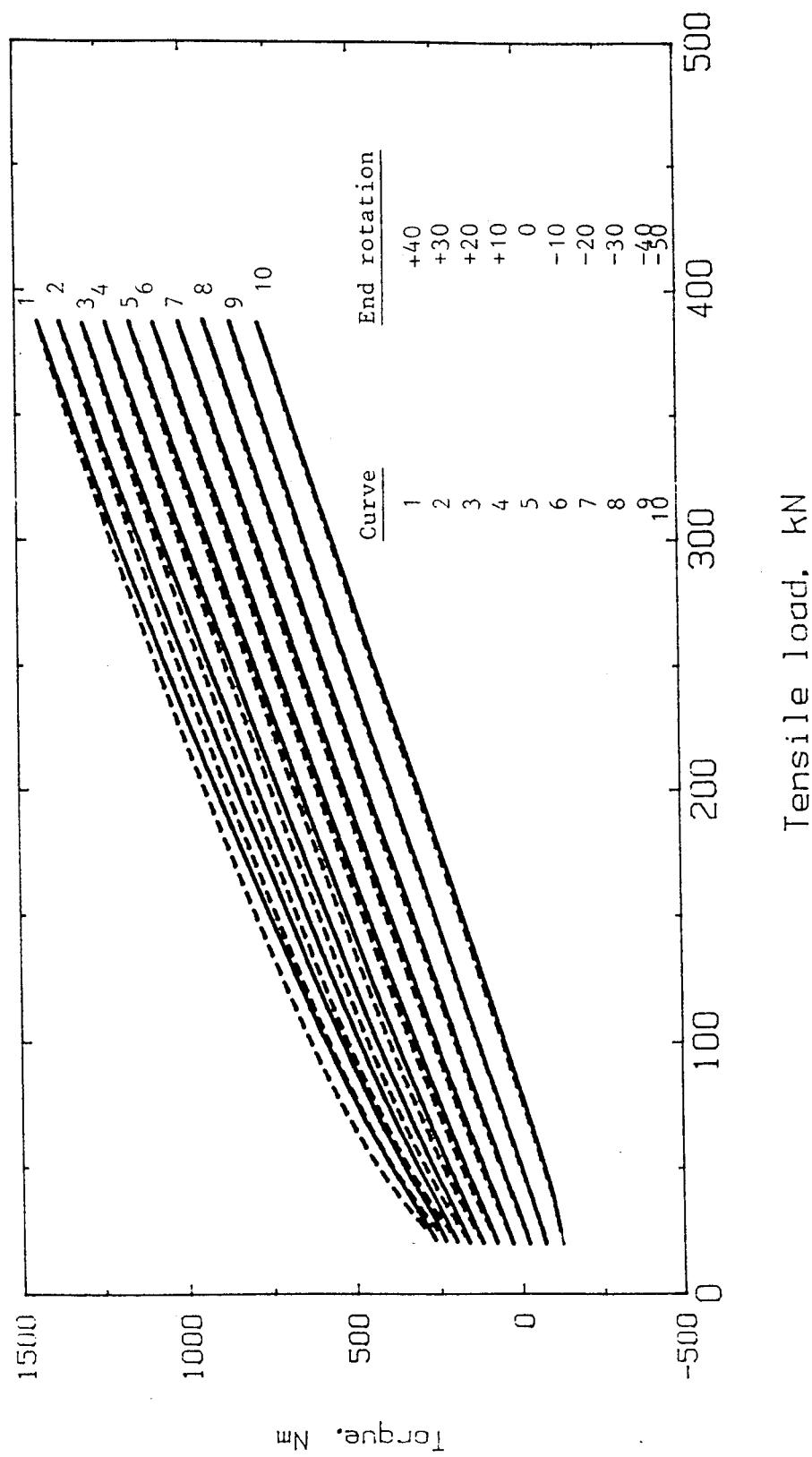


Figure A.1 Torque tension curves of a West Driefontein discarded tail rope

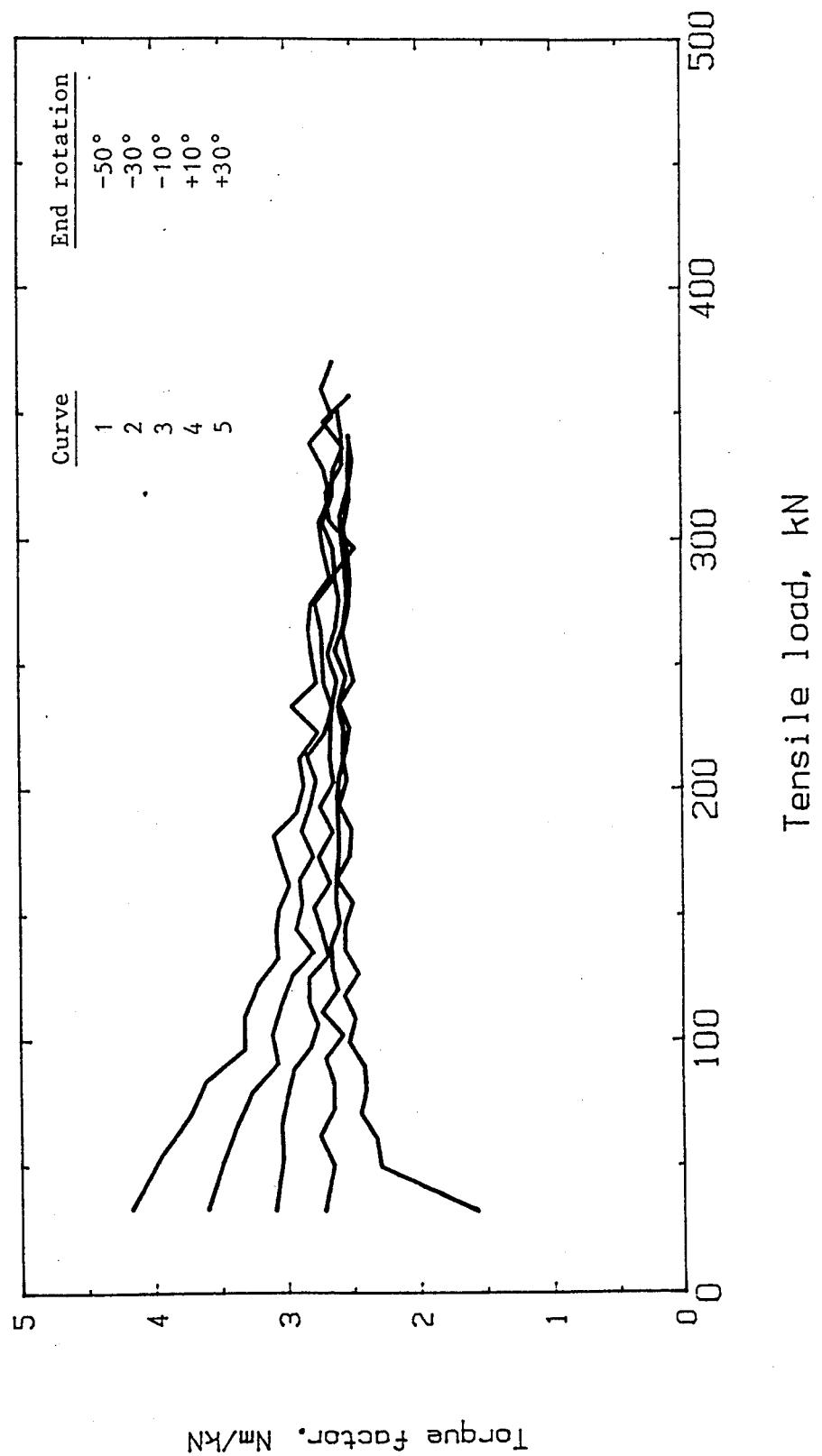


Figure A.2 Torque factor of a West Driefontein discarded tail rope

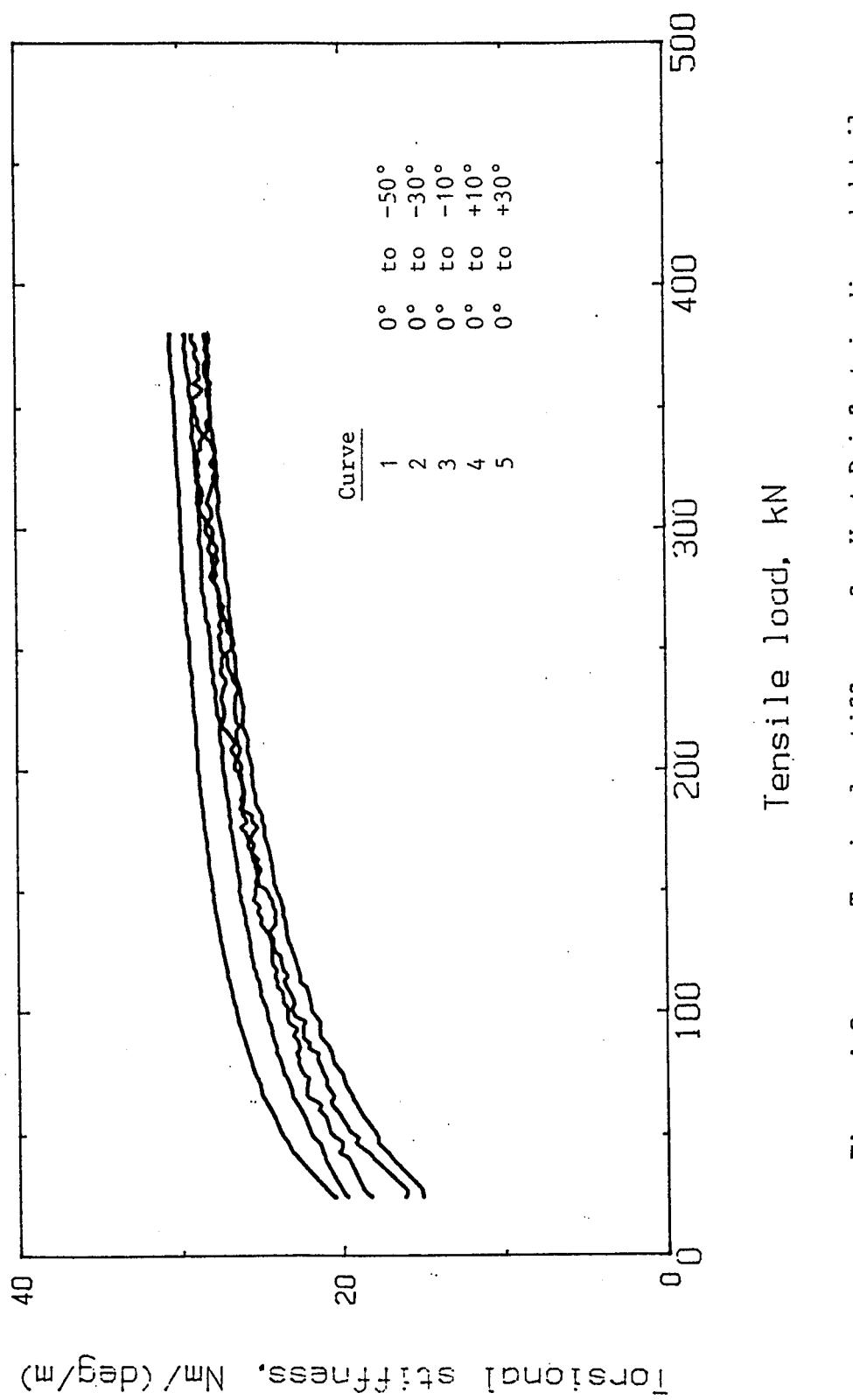


Figure A.3 Torsional stiffness of a West Driefontein discarded tail
rope

APPENDIX B

HEAD ROPE MODEL USING CONSTANT C AND T FACTORS

B.1 Relative rotation of a cross section of the upgoing rope

The upgoing section of the head rope is divided into n elements of length Δz . If the length Δz is small enough it can be assumed that the tensile load along the length of each element is constant. The tensile load in the i -th element is derived with the aid of Figure B.1 as:

$$F_i = P + q(u + z_{1,i}) \quad (B.1)$$

where

u : Is the travelled distance [m].

q : Is the weight of the rope per meter length [N/m].

P : Is the gross weight of the conveyance plus 50% of the weight of the tail sheave and 50% of the weight of the rope in the tail loop below the lower station [m].

$z_{1,i}$: Is the distance of the i -th element from the upgoing conveyance [m].

From equation 2.1 the torque in the i -th element is:

$$M_{1,u} = CF_i + T\Delta\Phi_i/\Delta z \quad (B.2)$$

where $\Delta\Phi_i$ is the relative rotation between the two cross sections of the element.

Rearranging the terms of equation B.2 and substituting F_i from equation B.1 leads to:

$$\Delta\Phi_i = (M_{1,u} - C(P + q(u + z_{1,i})))\Delta z/T \quad (B.3)$$

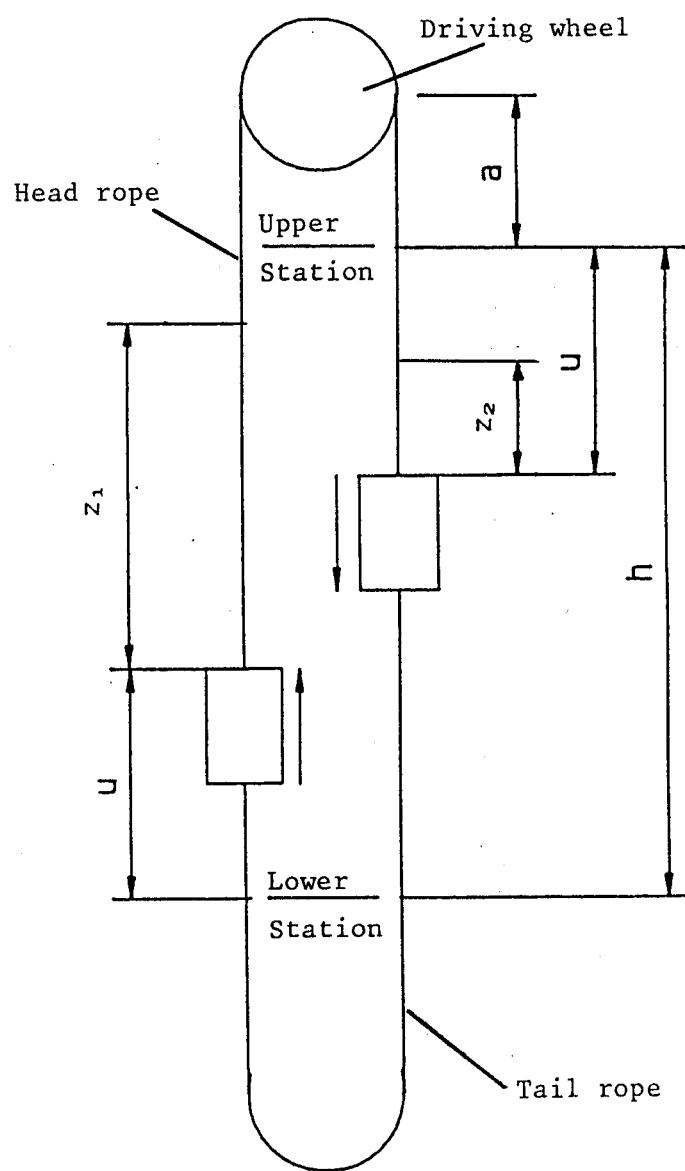


Figure B.1 Configuration of Koepe winder

The relative rotation of the m -th element with respect to the cross section where the rope is attached to the upgoing conveyance is:

$$\Phi_{1,u,m} = \sum_{i=1}^m \Delta\Phi_i \quad (B.4)$$

Substitution of $\Delta\Phi_i$ from equation B.3 into equation B.4 yields:

$$\Phi_{1,u,m} = \sum_{i=1}^m (M_{1,u} - C(P + q(u + z_{1,i}))) \Delta z / T \quad (B.5)$$

Since the C and T factors are constant the summation in the above equation can be replaced by an integral and Δz by dz . That leads to:

$$\Phi_{1,u,z_1} = \int_{\emptyset}^{z_1} (M_{1,u} - C(P+q(u + z))) / T dz \quad (B.6)$$

which after integration yields:

$$\Phi_{1,u,z_1} = (M_{1,u} - C(P + qu)) z_1 / T - Cqz_1^2 / (2T) \quad (B.7)$$

B.2 Relative rotation of a cross section of the downgoing rope

Using the same approach, the tensile load and the torque in the i -th element of the downgoing rope are:

$$F_i = P + q(h - u + zz_{2,i}) \quad (B.8)$$

$$M_{2,u} = C.F_i + T\Delta\Phi_i / \Delta z \quad (B.9)$$

The relative rotation of the m -th element of the downgoing rope in respect to the cross section attached to the downgoing conveyance is:

$$\Phi_{2,u,m} = \sum_{i=1}^m (M_{2,u} - C(P + q(h - u + zz_{2,i}))) \Delta z / T \quad (B.10)$$

which after summation results in:

$$\Phi_{2,u,z2} = (M_{2,u} - C(P + q(h - u)))z_2/T - C.qz_2^2/(2T) \quad (B.11)$$

B.3 Torque in the upgoing rope

At any given instant, the relative rotation at the top of the ascending rope (where $z_1 = h + a - u$), is:

$$\Phi_{1,u,z1} = (M_{1,u} + C(P + qu))z_1/T - C.qz_1^2/(2T) \quad (B.7)$$

An instant earlier, when the conveyance was at $u - \Delta u$, the same section was at the same value of z_1 and its relative rotation was:

$$\Phi_{1,u-\Delta u,z1} = (M_{1,u-\Delta u} + C(P + q(u - \Delta u)))z_1/T - C.qz_1^2/(2T) \quad (B.12)$$

Using the assumption stated in section 3.1, that the relative rotation of the top element Δz is unchanged during the travel Δu , we get for the case of constant C and T factors:

$$M_{1,u} = M_{1,u-\Delta u} + Cq\Delta u, \text{ and as } \Delta u \rightarrow 0$$

$$\partial M_{1,u} / \partial u = Cq \quad (B.13)$$

Hence, on integration,

$$M_{1,u} = M_{1,\emptyset} + Cqu \quad (B.14)$$

B.4 Initial torque value in the upgoing rope

As stated in section 3.1 the total rotation in the head rope is constant and equal to the initial rotation. Thus by adding the rotations at the top of the two sides of the rope:

$$\Phi_{in} = \Phi_{1,u,h+a-u} + \Phi_{2,u,a+u} \quad (B.15)$$

In particular for $u = 0$ substitution of equation B.7 and B.11 in equation B.15 leads to:

$$\begin{aligned} \Phi_{in} = & (M_{1,\emptyset} - CP)(h + a)/T - Cq(h + a)^2/(2T) \\ & + (M_{2,\emptyset} - C(P + qh))a/T - Cqa^2/(2T) \end{aligned} \quad (B.16)$$

or

$$\begin{aligned} \Phi_{in} = & (M_{1,\emptyset}(h + a) + M_{2,\emptyset}a)/T - CP(h + 2a)/T \\ & - Cq(2ha + (h + a)^2 + a^2)/(2T) \end{aligned} \quad (B.17)$$

As stated in section 3.1 and illustrated in figure 3.2 the two sides of the head rope are "equivalent". Therefore, the torque $M_{2,\emptyset}$ is equal to the torque in the ascending rope at the end of the trip i.e. $M_{1,h}$. Hence:

$$\begin{aligned} \Phi_{in} = & (M_{1,\emptyset}(h + a) + M_{1,h}a)/T - CPL_h/T \\ & - Cq(2ha + (h + a)^2 + a^2)/(2T) \end{aligned} \quad (B.18)$$

where $L_h = h + 2a$

Taking into account equation B.14 yields:

$$\Phi_{in} = M_{1,\emptyset}L_h/T - CPL_h/T - Cq((h + a)^2 + a^2)/(2T) \quad (B.19)$$

Rearranging the terms of equation B.19 leads to

$$M_{1,\emptyset} = CP + Cq((h + a)^2 + a^2)/(2L_h) + \Phi_{in}T/L_h \quad (B.20)$$

B5. Mathematical model of the head rope behaviour

Substitution of equation B.20 in B.14 leads to:

$$M_{1,u} = CP + Cq(h/2 + a^2/L_h + u) + \Phi_{in}T/L_h \quad (B.21)$$

from which the torque in the upgoing rope during a trip can be calculated.

Substitution of $M_{1,u}$ from the above equation into equation B.7 leads to:

$$\Phi_{1,u,z_1} = Cq((h/2 + a^2/L_h)z_1 - z_1^2/2)/T + \Phi_{in}z_1/L_h \quad (B.22)$$

or introducing the factor $k = Cq/T$, which combines the three rope constants in one, yields:

$$\Phi_{1,u,z_1} = k((h/2 + a^2/L_h)z_1 - z_1^2/2) + \Phi_{in}z_1/L_h \quad (B.23)$$

from which the relative rotation at any cross section of the upgoing rope can be determined.

Substitution of equations B.11 and B.12 in equation B.15 yields:

$$\begin{aligned} \Phi_{in} = & Cq((h/2 + a^2/L_h)(h + a - u) - (h + a - u)^2/2)/T \\ & + \Phi_{in}(h + a - u)/L_h + (M_{2,u} + C(P + qu))(a + u) \\ & - Cq(a + u)^2/(2T) \end{aligned} \quad (B.24)$$

Rearranging the terms of the above equation, we get for the torque in the downgoing rope:

$$M_{2,u} = CP + Cq(h/2 + a^2/L_h + a(h - u)/(a + u)) + \Phi_{in}T/L_h \quad (B.25)$$

Substituting $M_{2,u}$ from the above equation in equation B.11 the relative rotation of a cross section of the downgoing rope becomes:

$$\begin{aligned} \Phi_{2,u,z_2} = & k((h/2 + a^2/L_h - u(h - u)/(a + u))z_2 - z_2^2/2) \\ & + \Phi_{in}z_2/L_h \end{aligned} \quad (B.26)$$

B.6 Lay angle variation

The geometry of a positive change in the lay angle is shown in figure B.2. From it we derive the following:

$$\tan(\theta) = (CD)/(AC) \quad (B.27)$$

For $\theta \ll \beta$ $CD = CB \cdot \cos(\beta)$ and therefore

$$CD = r \cdot \Delta\Phi \cdot \cos(\beta) \quad (B.28)$$

and

$$AC = \Delta z / \cos(\beta) \quad (B.29)$$

$$CB = \Delta\Phi \cdot \frac{D}{Z}$$

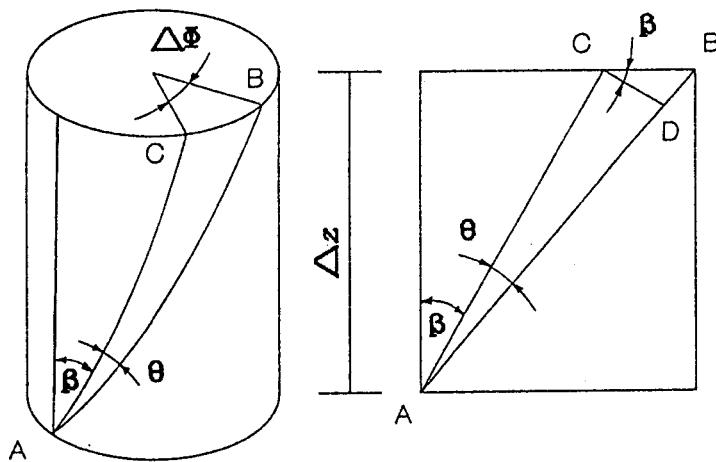


Figure B.2 Lay angle deviation

Substituting CD and AC from equations B.28 and B.29 respectively into equation B.27 as $\Delta z \rightarrow 0$ leads to

$$\tan(\theta) = r \cdot \cos^2(\beta) \cdot d\Phi/dz \quad (B.30)$$

For small angles we have that $\tan(\theta) = \theta$ and so equation B.30 becomes

$$\theta = r \cdot \cos^2(\beta) \cdot d\Phi/dz \quad (B.31)$$

For the upgoing rope from equation B.24 we get

$$d\Phi_{1,u,z_1}/dz = k(h/2 + a^2/L_h - z_1) + \Phi_{in}/L_h \quad (B.32)$$

Substituting $d\Phi/dz$ from the above equation into equation B.31 we get for the lay angle deviation in the upgoing rope:

$$\theta_1 = (k(h/2 + a^2/L_h - z_1) + \Phi_{in}/L_h)r \cdot \cos^2(\beta) \quad (B.33)$$

This equation shows that θ_1 is not a function of u therefore the lay angle of any cross section of the upgoing rope remains constant as long as that section is ascending.

Using the same method the lay angle deviation in the downgoing rope is obtained:

$$\begin{aligned} \theta_2 = & (k(h/2 + a^2/L_h - u(h - u)/(a + u) - z_2) \\ & + \Phi_{in}/L_h)r \cdot \cos^2(\beta) \end{aligned} \quad (B.34)$$

As a cross section of the upgoing rope enters the downgoing section its lay angle deviation changes from θ_1 (with $z_1 = h + a - u$) to θ_2 (with $z_2 = a + u$). In general these two values differ and a sudden change occurs. The change happens to be zero for a particular value of u which is obtained by equating θ_1 and θ_2 . Thus:

$$h/2 + a^2/L_h - h - a + u = h/2 + a^2/L_h - u(h - u)/(a + u) - a - u$$

from where we get that

$$u^2 + 2au - ah = 0 \quad (B.35)$$

The positive root of this equation yields the condition of $\theta_1 = \theta_2$ as:

$$u = \sqrt{a^2 + ah} - a \quad (B.36)$$

B.7 Rotation of the downgoing rope

At any particular time during a trip the rotation of a cross section of the downgoing rope is obtained by subtracting its relative rotation at the beginning of the trip from its current relative rotation. In deriving expressions for the rotation a distinction is made between the portion of the rope which travels only downwards and the portion which comes in over the driving wheel.

The first portion is defined by

$$0 \leq z_2 \leq a$$

The rotation of a cross section belonging to that portion of the rope is:

$$\Delta\Phi = \Phi_{2,u,z_2} - \Phi_{2,0,z_2} \quad (B.37)$$

Taking into account equation B.26 leads to:

$$\begin{aligned} \Delta\Phi &= k((h/2 + a^2/L_h - u(h - u)/(a + u))z_2 - z_2^2/2) \\ &\quad - k((h/2 + a^2/L_h)z_2 - z_2^2/2) \end{aligned} \quad (B.38)$$

From where we get that

$$\Delta\Phi = kz_2u(u - h)/(a + u) \quad (B.39)$$

For $u = h$ the rotation becomes zero. That means that each section of that portion of the rope exhibits as much clockwise rotation as anticlockwise.

The second portion is the rope which initially belongs to the upgoing rope and during the trip enters the downgoing rope: $a \leq z_2 \leq h + a$. This is the section which is marked during the chalk test. The relative rotation in this portion of the rope before the trip is given by equation B.23. Its relative rotation during the trip after it has gone over the driving wheel is given by equation B.26.

Correct comparison of these two relative rotations requires that they have the same reference point. The relative rotation of the upgoing rope, which has as reference point the cross section attached to the upgoing conveyance, was therefore transformed so that it is referred to the cross section attached to the downgoing conveyance. Taking into account that the two reference cross sections are given relative rotation of Φ_{in} during installation, equation B.23 is rewritten with reference point the rope cross section attached to the upgoing conveyance as:

$$\begin{aligned}\Phi_{1,u,z_1} = & \Phi_{in} - k((h/2 + a^2/L_h)z_1 - z_1^2/2) \\ & - \Phi_{in}z_1/L_h\end{aligned}\tag{B.40}$$

Therefore the rotation of the second portion of the rope is:

$$\Delta\Phi = \Phi_{2,u,z_2} - \Phi_{1,\emptyset,z_1}\tag{B.41}$$

which by substitution of equations B.26 and B.42 becomes:

$$\begin{aligned}\Delta\Phi = & k((h/2 + a^2/L_h - u(h - u)/(a + u))z_2 - z_2^2/2) \\ & + k((h/2 + a^2/L_h)z_1 - z_1^2/2) \\ & + \Phi_{in}((z_1 + z_2)/L_h - 1)\end{aligned}\tag{B.42}$$

Where z_1 is the position of the section at the start of the trip and z_2 is its current position. This section reaches the top of the ascending rope when $z_1 + u = h + a$. Its position on the descending rope at that instant is given by $z_2 = a + u$. Eliminating u from the two equations leads to:

$$z_1 + z_2 = h + 2a = L_h\tag{B.43}$$

which substituted in equation B.42 leads to:

$$\Delta\Phi = k(-zz^2 + ((u^2 + ha)/(u + a) + 2a)zz - a(h + a)) \quad (B.44)$$

For $u = h$ the above relation becomes

$$\Delta\Phi = k(-zz^2 + Lhzz - a(a + h)) \quad (B.45)$$

which gives the rotation of each cross section after the trip.

B.8 Chalk Line Test

As stated in Chapter 1 the chalk line test is performed on the downgoing section of the rope, at the level of the driving wheel. While spraying the paint at a single point, the rotation of the rope causes a spiral line to be drawn on the rope.

The spiral line, at the end of the trip, is expressed mathematically by equation B.45, for $a \leq zz \leq h + a$. During the subsequent trip the portion of the rope marked with the spiral line is the upgoing rope. Since the upgoing rope does not rotate, the number of turns drawn on the rope can be counted by observing the rope at the level of the driving wheel.

The rotation given by equation B.45 is a function of zz with origin at the conveyance. To change the origin to the driving wheel we use the substitution $zz = h + a - u$. Then, dividing by 360° the number of turns counted at the driving wheel as the rope ascends is:

$$N = ku(h - u)/360^\circ \quad (B.46)$$

B.9 Change in the lay angle from the upgoing to the downgoing rope

From equations B.21 and B.25 it can easily be shown that the torque difference in the two sections of the head rope is:

$$M_{2,u} - M_{1,u} = Cq(a(h - 2u) - u^2)/(a + u) \quad (B.47)$$

From equations B.33 and B.34 which give the lay angle deviation in the two sections of the rope during the trip it can be shown that the change in lay angle of a rope element that leaves the upgoing section of the head rope ($z_1 = h + a - u$) to enter the downgoing one ($z_2 = a + u$) is:

$$\theta_2 - \theta_1 = k((a(h - 2u) - u^2)/(a + u))r.\cos^2\beta \quad (B.48)$$

Elimination of the term $(a(h - 2u) - u^2)/(a + u)$ from equations B.47 and B.48 leads to:

$$\theta_2 - \theta_1 = ((M_{2,u} - M_{1,u})/T)r.\cos^2\beta \quad (B.49)$$

APPENDIX C

PROGRAM LISTINGS

Program language HP87 BASIC.

1. Head rope model, variable C and T factors

```
10 ! Head rope behaviour
20 !
30 GOSUB Dimensions !
40 GOSUB Winder_data !
50 GOSUB Loading_conditions !
60 GOSUB Upgoing_trip !
70 GOSUB Unload_conveyance !
80 GOSUB Downgoing_trip !
90 GOSUB Load_conveyance !
100 GOSUB Initial_rot !
110 GOSUB Store_results !
120 GOSUB Plot_results !
130 !
140 END
150 ! ****DIMENSIONS ****
160 Dimensions:
170 OPTION BASE 0
180 DIM Fig_label1$(100),Fig_label2$(100),Hor_label$(80),Ver_label$(45),Err_message$(50)
190 SHORT Twist(180,180),Torq(68),Up_torq(68),Down_torq(68),Ent_twist(68)
200 SHORT Torq_loading(10),Load_bot(10),Unload_top(10),Twist_uz(68,70),Twist_load(10,10)
210 SHORT Turns(74),Up_t(34,70),Dn_t(34,70)
220 DEG
230 RETURN
240 !
```

```
250 ! **** WINDER DATA ****
260 Winder_data:
270 h=1700
280 a=25
290 q=85
300 r=.01935
310 Lay_angle=19
320 Conv_weight_1=215000
330 Conv_weight_2=215000
340 Pay_load_1=0
350 Pay_load_2=0
360 Up_torque_0=200
370 !
380 Element=25
390 In_torque_step=1
400 Torque_step_cof=1
410 Max_torque_step=80
420 Loading_steps=10
430 !
440 ASSIGN# 1 TO "f100 t+ 20"
450 READ# 1 ; F_min,F_max,F_cof,M_min,M_max,M_cof,Twist()
460 ASSIGN# 1 TO *
470 RETURN
480 !
490 ! **** LOADING CONDITIONS ****
500 Loading_conditions:
510 Up_length=h+a
520 Up_load=Conv_weight_1+Pay_load_1
530 RETURN
540 !
550 ! **** UPGOING TRIP ****
560 Upgoing_trip:
570 Rope$="Upgoing"
580 R_length=Up_length
590 Conv_load=Up_load
600 u=0
610 Torq(u)=Up_torque_0
620 Torq=Torq(u)
630 GOSUB Rope_twist
640 Ref_twist=R_twist
650 PRINT "Upgoing rope "
660 PRINT "u=";u,"Torque=";Torq
670 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist
680 GOSUB Run_trip
690 FOR I=0 TO h/Element
700 Up_torque(I)=Torq(I)
710 NEXT I
720 RETURN
730 !
```

```
740 ! ***** UNLOAD CONVEYANCE *****
750 Unload_conveyance:
760 IF Pay_load_1=0 THEN Torq_top=Up_torq(h/Element) @ RETURN
770 First_step=0
780 Rope$="Stand_unloading"
790 Load_beg=Up_load
800 Load_end=Conv_weight_1
810 GOSUB Load_unload
820 Torq_top=Torq
830 RETURN
840 !
850 ! ***** DOWNGOING TRIP *****
860 Downgoing_trip:
870 Down_length=a
880 Down_load=Conv_weight_2
890 Rope$="Downgoing"
900 R_length=Down_length
910 Conv_load=Down_load
920 u=0
930 Torq(u)=Torq_top
940 Torq=Torq(u)
950 GOSUB Rope_twist
960 Ref_twist=R_twist
970 PRINT
980 PRINT " Downgoing rope "
990 PRINT "u=";u,"Torque=";Torq
1000 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist
1010 GOSUB Run_trip
1020 FOR I=0 TO h/Element
1030 Down_torq(I)=Torq(I)
1040 NEXT I
1050 RETURN
1060 !
1070 ! ***** LOAD CONVEYANCE *****
1080 Load_conveyance:
1090 IF Pay_load_2=0 THEN RETURN
1100 First_step=Loading_steps+1
1110 Rope$="Stand_loading"
1120 Load_beg=Down_load
1130 Load_end=Conv_weight_2+Pay_load_2
1140 GOSUB Load_unload
1150 Torq_bottom=Torq
1160 RETURN
1170 !
1180 ! ***** INITIAL ROTATION *****
1190 Initial_rot:
1200 Initial_rot=0
1210 FOR J=1 TO INT ((h+2*a)/Element)
1220 Initial_rot=Initial_rot+Twist_uz(0,J)
1230 NEXT J
1240 Initial_rot=Initial_rot*Element
1250 PRINT "Initial rotation = ";Initial_rot
1260 PRINT "Number of turns = ";Initial_rot/360
1270 RETURN
1280 !
```

```
1290 ! ***** STORE RESULTS *****  
1300 Store_results:  
1310 CREATE "Tq"&VAL$ (Up_torque_0),1,(h/Element+2)*16  
1320 CREATE "Tw"&VAL$ (Up_torque_0),2,(h/Element/2+2)*((h+2*a)/Element+2)*8  
1330 FOR I=0 TO INT (h/Element)/2  
1340 FOR J=1 TO INT ((h+2*a)/Element)  
1350 Up_t(I,J)=Twist_uz(I,J)  
1360 Dn_t(I,J)=Twist_uz(I+INT (h/Element/2),J)  
1370 NEXT J  
1380 NEXT I  
1390 ASSIGN# 1 TO "Tq"&VAL$ (Up_torque_0)  
1400 PRINT# 1,1 ; Initial_rot,Up_torque(),Down_torque()  
1410 ASSIGN# 1 TO *  
1420 ASSIGN# 1 TO "Tw"&VAL$ (Up_torque_0)  
1430 PRINT# 1,1 ; Up_t()  
1440 PRINT# 1,2 ; Dn_t()  
1450 ASSIGN# 1 TO *  
1460 RETURN  
1470 !  
1480 ! ***** RUN TRIP *****  
  
1490 Run_trip:  
1500 FOR u=1 TO INT (h/Element)  
1510 Torq_step=In_torque_step  
1520 IF Rope$="Upgoing" THEN GOTO Up_step ELSE GOTO Down_step  
1530 !  
1540 Up_step:  
1550 R_length=R_length-Element  
1560 Ref_twist=Ref_twist-Twist*Element  
1570 Ent_twist(u)=Twist*Element  
1580 GOTO Find_torque  
1590 !  
1600 Down_step:  
1610 R_length=R_length+Element  
1620 Ref_twist=Ref_twist+Ent_twist(u)  
1630 GOTO Find_torque  
1640 !  
1650 Find_torque:  
1660 GOSUB Torque_calculations  
1670 PRINT "u=";u,"Torque=";Torq  
1680 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist  
1690 Torq(u)=Torq  
1700 NEXT u  
1710 RETURN  
1720 !  
1730 ! ***** TORQUE CALCULATIONS *****  
  
1740 Torque_calculations:  
1750 New_torque_step:  
1760 Torq_1=Torq(u-1)+Torq_step  
1770 Torq_2=Torq(u-1)-Torq_step  
1780 Torq=Torq_1  
1790 GOSUB Rope_twist  
1800 R_twist_1=R_twist  
1810 Torq=Torq_2  
1820 GOSUB Rope_twist  
1830 R_twist_2=R_twist  
1840 IF R_twist_1>= Ref_twist THEN Help_1$="One" ELSE GOTO Second_if  
1850 IF R_twist_2<= Ref_twist THEN GOTO Check_result ELSE GOTO Torque_step  
1860 !
```

```
1870 Second_if:  
1880 IF R_twist_2>= Ref_twist THEN Help_1$="Two" ELSE GOTO Torque_step  
1890 GOTO Check_result  
1900 !  
1910 Torque_step:  
1920 Torq_step=Torq_step+Torq_step_cof  
1930 IF Torq_step>Max_torque_step THEN Err_message$="Torque step too big" ELSE GOT  
O New_torque_step  
1940 GOTO Something_wrong  
1950 !  
1960 Check_result:  
1970 Torq=(Torq_1+Torq_2)/2  
1980 GOSUB Rope_twist  
1990 IF ABS (R_twist-Ref_twist)<= .3 THEN GOTO Go_back  
2000 IF R_twist>Ref_twist THEN GOTO Greater ELSE GOTO Smaller  
2010 !  
2020 Greater:  
2030 IF Help_1$="One" THEN GOTO Change_one ELSE GOTO Change_two  
2040 !  
2050 Smaller:  
2060 IF Help_1$="One" THEN GOTO Change_two ELSE GOTO Change_one  
2070 !  
2080 Change_one:  
2090 Torq_1=Torq  
2100 R_twist_1=R_twist  
2110 GOTO Check_result  
2120 !  
2130 Change_two:  
2140 Torq_2=Torq  
2150 R_twist_2=R_twist  
2160 GOTO Check_result  
2170 !  
2180 Go_back:  
2190 RETURN  
2200 !  
2210 ! ***** LOAD UNLOAD *****  
2220 Load_unload:  
2230 PRINT  
2240 PRINT "***** Loading/Unloading *****"  
2250 Load_step=(Load_end-Load_beg)/10  
2260 Loading_step=First_step  
2270 FOR Conv_load=Load_beg TO Load_end STEP Load_step  
2280 Torq_step=In_torque_step  
2290 Torq_1=Torq+Torq_step  
2300 Torq_2=Torq-Torq_step  
2310 GOSUB Torque_calculations  
2320 Torq_loading>Loading_step)=Torq  
2330 PRINT "Conv_load=";Conv_load,"Torque=";Torq  
2340 Loading_step=Loading_step+1  
2350 NEXT Conv_load  
2360 RETURN  
2370 !
```

```
2380 ! ***** ROPE TWIST *****  
2390 Rope_twist:  
2400 R_twist=0  
2410 FOR z=1 TO R_length/Element  
2420 Force=Conv_load+(z-1/2)*Element*q+(h+a-R_length)*q  
2430 F=Force  
2440 M=Torq  
2450 GOSUB Interpolation  
2460 R_twist=R_twist+Twist*Element  
2470 IF Rope$="Upgoing" THEN Twist_uz(u,z)=Twist  
2480 IF Rope$="Downgoing" THEN Twist_uz(u,INT ((h+2*a)/Element)-z+1)=Twist  
2490 IF Rope$="Stand_unloading" THEN Twist_loading(Loading_step,z)=Twist  
2500 IF Rope$="Stand_loading" THEN Twist_loading(Loading_step,(h+2*a)/Element-z+1)=Twist  
2510 NEXT z  
2520 RETURN  
2530 !  
2540 ! ***** INTERPOLATION *****  
2550 Interpolation:  
2560 M1=IP ((M-M_min)/M_cof)  
2570 M1=ABS (IP ((M-M_min)/M_cof))  
2580 M2=M1+1  
2590 F1=IP ((F-F_min*1000)/F_cof/1000)  
2600 F2=F1+1  
2610 Twist_1=Twist(F1,M1)+(Twist(F1,M2)-Twist(F1,M1))*(M-(M_min+M1*M_cof))/M_cof  
2620 Twist_2=Twist(F2,M1)+(Twist(F2,M2)-Twist(F2,M1))*(M-(M_min+M1*M_cof))/M_cof  
2630 Twist=Twist_1+(Twist_2-Twist_1)*(F-(F_min+F1*M_cof)*1000)/(F_cof*1000)  
2640 RETURN  
2650 !  
2660 ! ***** PLOT RESULTS *****  
2670 Plot_results:  
2680 ON KEY# 1,"TORQUE" GOSUB Plot_torque  
2690 ON KEY# 3,"LAY ANGLE" GOSUB Plot_angle_dev  
2700 ON KEY# 5,"CHALK TEST" GOSUB Plot_chalk_test  
2710 CLEAR @ KEY LABEL  
2720 Soft_key_control: GOTO Soft_key_control  
2730 !  
2740 ! ***** PLOT TORQUE *****  
2750 Plot_torque:  
2760 GOSUB Torq_graph  
2770 GOSUB Set_plotter  
2780 PEN 2  
2790 MOVE 0,Up_torq(0)  
2800 FOR I=0 TO h/Element  
2810 DRAW I*Element/h,Up_torq(I)  
2820 NEXT I  
2830 PEN 1  
2840 IMOVE -.4,-22  
2850 LABEL "Upgoing rope"  
2860 PEN 2  
2870 IF Pay_load_1=0 THEN GOTO Draw_down  
2880 MOVE 1,Up_torq(h/Element)  
2890 FOR i=0 TO Loading_steps  
2900 DRAW 1,Torq_loading(i)  
2910 NEXT i
```

```
2920 Draw_down:
2930 MOVE 0,Down_torque(0)
2940 FOR I=0 TO h/Element
2950 DRAW I*Element/h,Down_torque(I)
2960 NEXT I
2970 PEN 1
2980 IMOVE -.4,-20
2990 LABEL "Downgoing rope"
3000 !
3010 IF Pay_load_2=0 THEN GOTO Draw_up
3020 PEN 2 @ MOVE 1,Down_torque(h/Element)
3030 FOR i=Loading_steps+1 TO 2*Loading_steps+1
3040 DRAW 1,Torque_loading(i)
3050 NEXT i
3060 Draw_up:
3070 Input_Ans:
3080 DISP "Do you want GRID ? (Y/N)"
3090 INPUT Ans$
3100 Ans$=UPC$(Ans$)
3110 IF Ans$=="N" THEN GOTO Go_main
3120 IF Ans$=="Y" THEN GOTO Draw_grid ELSE GOSUB Wrong_input
3130 GOTO Input_Ans
3140 Go_main:
3150 CLEAR @ KEY LABEL
3160 RETURN
3170 !
3180 ! ***** PLOT ANGLE DEVIATION *****
3190 Plot_angle_dev:
3200 DISP "ENTER Distance of gross section from upgoing conveyance. Z=";
3210 INPUT Z
3220 Trip_no=0
3230 GOSUB Angle_dev_graph
3240 GOSUB Set_plotter
3250 FOR i=0 TO 1 STEP .2
3260 MOVE i-.033,-.216 @ LABEL i
3270 NEXT i
3280 FOR i=0 TO 1 STEP .2
3290 MOVE 1-.033+i,-.216 @ LABEL 1-i
3300 NEXT i
3310 MOVE .4,-.235 @ LABEL "First trip"
3320 MOVE 1.4,-.235 @ LABEL "Second trip"
3330 MOVE 1,Ver_min
3340 DRAW 1,Ver_max
3350 Next_graph:
3360 IF Z<= a THEN Last_u=h/Element ELSE Last_u=(h+a-Z)/Element
3370 Zi=INT (Z/Element)
3380 Angle_dev=FNe(0,Zi)
3390 PEN 2
3400 MOVE Trip_no,Angle_dev
3410 FOR u=0 TO Last_u
3420 Angle_dev=FNe(u,Zi)
3430 DRAW u*Element/h+Trip_no,Angle_dev
3440 NEXT u
3450 IF Z<= a THEN GOTO End_of_plot
3460 LINE TYPE 3,1
3470 DRAW (u-1)*Element/h+Trip_no,FNe(u,Zi)
3480 LINE TYPE 1
3490 FOR u=Last_u+1 TO h/Element
3500 Angle_dev=FNe(u,Zi)
3510 DRAW u*Element/h+Trip_no,Angle_dev
3520 NEXT u
```

```
3530 End_of_plot:  
3540 IF Trip_no=1 THEN GOTO Fin_of_plot  
3550 Trip_no=1  
3560 IF Pay_load_1=0 THEN GOTO Cont_next  
3570 IF Z>a THEN GOTO Cont_next  
3580 FOR i=0 TO Loading_steps  
3590 DRAW 1,r*COS (Lay_angle)^2*Twist_loading(i,Zi)  
3600 NEXT i  
3610 Cont_next:  
3620 Z=h+2*a-Z  
3630 GOTO Next_graph  
3640 Fin_of_plot:  
3650 IF Pay_load_2=0 THEN GOTO Cont_next_1  
3660 FOR i=Loading_steps+1 TO 2*Loading_steps+1  
3670 DRAW 2,r*COS (Lay_angle)^2*Twist_loading(i,Zi)  
3680 NEXT i  
3690 Cont_next_1:  
3700 LINE TYPE 3,1  
3710 MOVE -.05,.175  
3720 IDRAW .15,0  
3730 LINE TYPE 1 @ LORG 2 @ PEN 1  
3740 IMOVE .01,0 @ LABEL "Cross section over the driving wheel"  
3750 CLEAR @ KEY LABEL  
3760 RETURN  
3770 !  
3780 ! ***** CHALK TEST *****  
3790 Plot_chalk_test:  
3800 !  
3810 GOSUB Chalk_test_graph  
3820 GOSUB Set_plotter  
3830 MOVE 0,0  
3840 Total_twist=0  
3850 FOR z=1 TO (h+2*a)/Element  
3860 Element_twist=(Twist_uz(0,z)-Twist_uz(h/Element,z))*Element  
3870 Total_twist=Total_twist+Element_twist  
3880 Turns(z)=Total_twist/360  
3890 DRAW z*Element/(h+2*a),Turns(z)  
3900 NEXT z  
3910 CLEAR @ KEY LABEL  
3920 RETURN  
3930 !  
3940 ! ***** GRAPH DETAILS *****  
3950 Chalk_test_graph:  
3960 !  
3970 Fig_label1$="Chalk test"  
3980 Fig_label2$=""  
3990 Hor_label$="Rope_length (Z/(h+2*a)) m/m"  
4000 Ver_label$="Number of turns "  
4010 Hor_min=-.1  
4020 Hor_max=1.1  
4030 Hor_lspac=.1  
4040 Hor_spac=1  
4050 Hor_org=Hor_min  
4060 Hor_dec=1  
4070 Ver_min=-2  
4080 Ver_max=10  
4090 Ver_lspac=1  
4100 Ver_spac=2  
4110 Ver_org Ver_min  
4120 Ver_dec=0  
4130 RETURN
```

```
4140 !
4150 ! ****
4160 Angle_dev_graph:
4170 !
4180 Fig_label1$="Lay angle deviation during a trip, at agross section S"
4190 Help_s1$=VAL$ (Z)
4200 Fig_label2$="Distance of cross section from upgoing rope Z1=&Help_s1$&" m"
4210 Hor_label$="Distance travelled (u/h) m/m"
4220 Ver_label$="Lay angle deviation Deg."
4230 Hor_min=-.1
4240 Hor_max=2.1
4250 Hor_lspac=.1
4260 Hor_spac=23
4270 Hor_org=Hor_min
4280 Hor_dec=1
4290 Ver_min=-.2
4300 Ver_max=.2
4310 Ver_lspac=.01
4320 Ver_spac=5
4330 Ver_org=Ver_min
4340 Ver_dec=2
4350 RETURN
4360 !
4370 ! ****
4380 Torq_graph:
4390 Fig_label1$="Torque in the rope"
4400 Fig_label2$=""
4410 Hor_label$="Distance travelled (u/h) m/m"
4420 Ver_label$="Torque Nm"
4430 Hor_min=-.1
4440 Hor_max=1.1
4450 Hor_lspac=.1
4460 Hor_spac=1
4470 Hor_org=Hor_min
4480 Hor_dec=1
4490 Ver_min=0
4500 Ver_max=600
4510 Ver_lspac=50
4520 Ver_spac=2
4530 Ver_org=Ver_min
4540 Ver_dec=0
4550 RETURN
4560 !
4570 ! ***** SET PLOTTER *****
4580 Set_plotter:
4590 Plot_device: CLEAR
4600 DISP "Plot to Plotter or Screen ? (P/S)"
4610 INPUT Plot_dev$
4620 Plot_dev$=UPC$ (Plot_dev$)
4630 IF Plot_dev$="P" THEN GOTO Plotter
4640 IF Plot_dev$="S" THEN PLOTTER IS 1 @ GOTO Screen
4650 GOSUB Wrong_input
4660 GOTO Plot_device
4670 Plotter: DISP "Put at PEN1 a 0.3mm Pen and at PEN2 a 0.7mm Pen. press CONTINUE"
4680 PAUSE
4690 PLOTTER IS 705
```

```
4700 Screen: CLEAR
4710 DISP "Fig_no$=?"
4720 INPUT Fig_no$
4730 GCLEAR
4740 PEN 1
4750 LIMIT 16,250,22,162 ! Xmin=0,Xmax=181,Ymin=0,Ymax=100
4760 CSIZE 3,.6
4770 MOVE 0,7 @ LABEL "F i g u r e    ";Fig_no$
4780 MOVE 28,7 @ LABEL Fig_label1$
4790 MOVE 28,3 @ LABEL Fig_label2$
4800 MOVE 33,20 @ LABEL Hor_label$
4810 LDIR 90
4820 MOVE 15,33 @ LABEL Ver_label$
4830 LDIR 0
4840 LOCATE 25,155,30,98
4850 FRAME
4860 SCALE Hor_min,Hor_max,Ver_min,Ver_max
4870 FXD Hor_dec,Ver_dec
4880 LAXES Hor_lspac,Ver_lspac,Hor_org,Ver_org,Hor_spac,Ver_spac
4890 RETURN
4900 !
4910 ! ***** WRONG INPUT *****
4920 Wrong_input:
4930 !
4940 BEEP
4950 DISP "WRONG DATA !!! Try again"
4960 RETURN
4970 !
4980 ! ***** DRAW GRID *****
4990 Draw_grid:
5000 !
5010 PEN 1
5020 FXD Hor_dec,Ver_dec
5030 LGRID Hor_lspac,Ver_lspac,Hor_org,Ver_org,Hor_spac,Ver_spac
5040 RETURN
5050 !
5060 ! ***** SOMETHING WRONG *****
5070 Something_wrong:
5080 !
5090 CLEAR
5100 DISP "There is something wrong with:";Err_message$
5110 DISP
5120 DISP "Program has stoped . Please correct it !!!"
5130 PAUSE
5140 !
5150 Program_end:
5160 STOP
5170 ! *****
5180 DEF FNe(u,z) = r*COS (Lay_angle)^2*Twist_uz(u,z)
5190 END
```

2. Tail rope model, variable C and T factors

```
10 ! Tail rope behaviour - Tail sheave, no swivels
20
30 GOSUB Dimensions !                               Subroutine where arrays are
40 GOSUB Winder_data !                            dimensioned
50 GOSUB Downgoing_trip !                         Subroutine to read winder and
60 GOSUB Upgoing_trip !                           rope data
70 GOSUB Initial_rot !                           Subroutine to calculate torque
80 GOSUB Store_results !                          and twist for downgoing rope
90 GOSUB Plot_results !                          Subroutine to calculate torque
100 !                                         and twist for upgoing rope
110 ! ***** DIMENSIONS *****
120 Dimensions:
130 OPTION BASE 0
140 DIM Fig_label1$(100),Fig_label2$(100),Hor_label$(80),Ver_label$(45),Err_message$(50)
150 SHORT Twist(180,180),Torq(68),Up_torq(68),Down_torq(68),Ent_twist(68)
160 SHORT Twist_uz(68,70)
170 SHORT Up_t(34,70),Dn_t(34,70)
180 DEG
190 RETURN
200 !
210 ! ***** WINDER DATA *****
220 Winder_data:
230 h=1700
240 b=25
250 Lt=h+2*b
260 q=85
270 r=.02
280 Lay_angle=18
290 Ft=6000
300 !
310 Dn_torq_0=-100
320 !
330 Element=25
340 In_torq_step=1
350 Torq_step_cof=1
360 Max_torq_step=200
370 !
380 ASSIGN# 1 TO "F030T-070t"
390 READ# 1 ; F_min,F_max,F_cof,M_min,M_max,M_cof,Twist()
400 ASSIGN# 1 TO *
410 DISP F_min,F_max,F_cof
420 DISP M_min,M_max,M_cof
430 RETURN
440 !
```

```
450 ! ----- DOWNGOING TRIP -----

460 Downgoing_trip:
470 Rope$="Downgoing"
480 Down_length=h+b
490 R_length=Down_length
500 u=0
510 Torq(u)=Dn_torque_0
520 Torq=Torq(u)
530 GOSUB Rope_twist
540 Ref_twist=R_twist
550 PRINT "                               Downgoing rope   "
560 PRINT "u=";u,"Torque=";Torq
570 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist
580 GOSUB Run_trip
590 FOR I=0 TO h/Element
600 Down_torque(I)=Torq(I)
610 NEXT I
620 Torq_top=Down_torque(h/Element)
630 RETURN
640 !
650 ! ----- UPGOING TRIP -----

660 Upgoing_trip:
670 Up_length=b
680 Rope$="Upgoing"
690 R_length=Up_length
700 u=0
710 Torq(u)=Torq_top
720 Torq=Torq(u)
730 GOSUB Rope_twist
740 Ref_twist=R_twist
750 PRINT "                               Upgoing rope   "
760 PRINT "u=";u,"Torque=";Torq
780 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist
790 GOSUB Run_trip
800 FOR I=0 TO h/Element
810 Up_torque(I)=Torq(I)
820 NEXT I
830 RETURN
840 !
850 ! ***** INITIAL ROTATION *****
860 Initial_rot:
870 Initial_rot=0
880 FOR J=1 TO INT ((h+2*b)/Element)
890 Initial_rot=Initial_rot+Twist_uz(0,J)
900 NEXT J
910 Initial_rot=Initial_rot*Element
920 PRINT "Initial rotation = ";Initial_rot
930 PRINT "Number of turns = ";Initial_rot/360
940 RETURN
950 !
```

```
960 ! ***** STORE RESULTS *****  
970 Store_results:  
980 CREATE "Tq"&VAL$ (Dn_torque_0),1,(h/Element+2)*16  
990 CREATE "Tw"&VAL$ (Dn_torque_0),2,(h/Element/2+2)*((h+2*b)/Element+2)*8  
1000 FOR I=0 TO INT (h/Element)/2  
1010 FOR J=1 TO INT ((h+2*b)/Element)  
1020 Up_t(I,J)=Twist_uz(I,J)  
1030 Dn_t(I,J)=Twist_uz(I+INT (h/Element/2),J)  
1040 NEXT J  
1050 NEXT I  
1060 ASSIGN# 1 TO "Tq"&VAL$ (Dn_torque_0)  
1070 PRINT# 1,1 ; Initial_rot,Up_torque(),Down_torque()  
1080 ASSIGN# 1 TO *  
1090 ASSIGN# 1 TO "Tw"&VAL$ (Dn_torque_0)  
1100 PRINT# 1,1 ; Up_t()  
1110 PRINT# 1,2 ; Dn_t()  
1120 ASSIGN# 1 TO *  
1130 RETURN  
1140 !  
1150 ! ***** RUN TRIP *****  
  
1160 Run_trip:  
1170 FOR u=1 TO INT (h/Element)  
1180 Torq_step=In_torque_step  
1190 IF Rope$="Upgoing" THEN GOTO Up_step ELSE GOTO Down_step  
1200 !  
1210 Down_step:  
1220 R_length=R_length-Element  
1230 Ref_twist=Ref_twist-Twist*Element  
1240 Ent_twist(u)=Twist*Element  
1250 GOTO Find_torque  
1260 !  
1270 Up_step:  
1280 R_length=R_length+Element  
1290 Ref_twist=Ref_twist+Ent_twist(u)  
1300 GOTO Find_torque  
1310 !  
1320 Find_torque:  
1330 GOSUB Torque_calculations  
1340 PRINT "u=";u,"Torque=";Torq  
1350 PRINT "R_length=";R_length,"Ref_twist=";Ref_twist  
1360 Torq(u)=Torq  
1370 NEXT u  
1380 RETURN  
1390 !  
1400 ! ***** TORQUE CALCULATIONS *****  
  
1410 Torque_calculations:  
1420 New_torque_step:  
1430 Torq_1=Torq(u-1)+Torq_step  
1440 Torq_2=Torq(u-1)-Torq_step  
1450 Torq=Torq_1  
1460 GOSUB Rope_twist  
1470 R_twist_1=R_twist  
1480 Torq=Torq_2  
1490 GOSUB Rope_twist  
1500 R_twist_2=R_twist  
1510 IF R_twist_1>= Ref_twist THEN Help_1$="One" ELSE GOTO Second_if  
1520 IF R_twist_2<= Ref_twist THEN GOTO Check_result ELSE GOTO Torque_step  
1530 !  
1540 Second_if:  
1550 IF R_twist_2>= Ref_twist THEN Help_1$="Two" ELSE GOTO Torque_step  
1560 GOTO Check_result  
1570 !
```

```
1580 Torque_step:  
1590 Torq_step=Torq_step+Torq_step_cof  
1600 IF Torq_step>Max_torque_step THEN Err_message$="Torque step too big" ELSE GOT  
0 New_torque_step  
1610 GOTO Something_wrong  
1620 !  
1630 Check_result:  
1640 Torq=(Torq_1+Torq_2)/2  
1650 GOSUB Rope_twist  
1660 IF ABS (R_twist-Ref_twist)<=.3 THEN GOTO Go_back  
1670 IF R_twist>Ref_twist THEN GOTO Greater ELSE GOTO Smaller  
1680 !  
1690 Greater:  
1700 IF Help_1$="One" THEN GOTO Change_one ELSE GOTO Change_two  
1710 !  
1720 Smaller:  
1730 IF Help_1$="One" THEN GOTO Change_two ELSE GOTO Change_one  
1740 !  
1750 Change_one:  
1760 Torq_1=Torq  
1770 R_twist_1=R_twist  
1780 GOTO Check_result  
1790 !  
1800 Change_two:  
1810 Torq_2=Torq  
1820 R_twist_2=R_twist  
1830 GOTO Check_result  
1840 !  
1850 Go_back:  
1860 RETURN  
1870 !  
1880 ! ***** ROPE TWIST *****  
  
1890 Rope_twist:  
1900 R_twist=0  
1910 FOR z=1 TO R_length/Element  
1920 Force=Pt-(z-1/2)*Element*q+R_length*q  
1930 F=Force  
1940 M=Torq  
1950 GOSUB Interpolation  
1960 R_twist=R_twist+Twist*Element  
1970 IF Rope$="Downgoing" THEN Twist_uz(u,z)=Twist  
1980 IF Rope$="Upgoing" THEN Twist_uz(u, INT ((h+2*b)/Element)-z+1)=Twist  
1990 NEXT z  
2000 RETURN  
2010 ! ***** INTERPOLATION *****  
2020 ! *****  
  
2030 Interpolation:  
2040 M11=IP ((M-M_min)/M_cof)  
2050 M1=ABS (IP ((M-M_min)/M_cof))  
2060 M2=M1+1  
2070 F1=IP ((F-F_min*1000)/F_cof/1000)  
2080 F2=F1+1  
2090 Twist_1=Twist(F1,M1)+(Twist(F1,M2)-Twist(F1,M1))*(M-(M_min+M11*M_cof))/M_cof  
2100 Twist_2=Twist(F2,M1)+(Twist(F2,M2)-Twist(F2,M1))*(M-(M_min+M11*M_cof))/M_cof  
2110 Twist=Twist_1+(Twist_2-Twist_1)*(F-(F_min+F1*M_cof)*1000)/(F_cof*1000)  
2120 RETURN  
2130 !
```

```
2140 ! ***** PLOT RESULTS *****  
2150 Plot_results:  
2160 ON KEY# 1,"TORQUE" GOSUB Plot_torque  
2170 ON KEY# 3,"LAY ANGLE" GOSUB Plot_angle_dev  
2180 CLEAR @ KEY LABEL  
2190 Soft_key_control: GOTO Soft_key_control  
2200 !  
2210 ! ***** PLOT TORQUE *****  
  
2220 Plot_torque:  
2230 GOSUB Torq_graph  
2240 GOSUB Set_plotter  
2250 PEN 2  
2260 MOVE 0,Up_torq(0)  
2270 FOR I=0 TO h/Element  
2280 DRAW I*Element/h,Up_torq(I)  
2290 NEXT I  
2300 PEN 1  
2310 IMOVE -.4,-22  
2320 LABEL "Upgoing rope"  
2330 PEN 2  
2340 Draw_down:  
2350 MOVE 0,Down_torq(0)  
2360 FOR I=0 TO h/Element  
2370 DRAW I*Element/h,Down_torq(I)  
2380 NEXT I  
2390 PEN 1  
2400 IMOVE -.4,-20  
2410 LABEL "Downgoing rope"  
2420 !  
2430 Draw_up:  
2440 Input_Ans:  
2450 DISP "Do you want GRID ? (Y/N)"  
2460 INPUT Ans$  
2470 Ans$=UPC$(Ans$)  
2480 IF Ans$="N" THEN GOTO Go_main  
2490 IF Ans$="Y" THEN GOTO Draw_grid ELSE GOSUB Wrong_input  
2500 GOTO Input_Ans  
2510 Go_main:  
2520 CLEAR @ KEY LABEL  
2530 RETURN  
2540 !  
2550 ! ***** PLOT ANGLE DEVIATION *****  
  
2560 Plot_angle_dev:  
2570 DISP "ENTER Distance of gross section from upgoing conveyance. Z=";  
2580 INPUT Z  
2590 Trip_no=0  
2600 GOSUB Angle_dev_graph  
2610 GOSUB Set_plotter  
2620 FOR i=0 TO 1 STEP .2  
2630 MOVE i-.033,-.216 @ LABEL i  
2640 NEXT i  
2650 FOR i=0 TO 1 STEP .2  
2660 MOVE 1-.033+i,-.216 @ LABEL 1-i  
2670 NEXT i  
2680 MOVE .4,-.235 @ LABEL "First trip"  
2690 MOVE 1.4,-.235 @ LABEL "Second trip"  
2700 MOVE 1,Ver_min  
2710 DRAW 1,Ver_max
```

```
2720 Next_graph:
2730 IF Z<= a THEN Last_u=h/Element ELSE Last_u=(h+a-Z)/Element
2740 Zi=INT (Z/Element)
2750 Angle_dev=FNe(0,Zi)
2760 PEN 2
2770 MOVE Trip_no,Angle_dev
2780 FOR u=0 TO Last_u
2790 Angle_dev=FNe(u,Zi)
2800 DRAW u*Element/h+Trip_no,Angle_dev
2810 NEXT u
2820 IF Z<= a THEN GOTO End_of_plot
2830 LINE TYPE 3,1
2840 DRAW (u-1)*Element/h+Trip_no,FNe(u,Zi)
2850 LINE TYPE 1
2860 FOR u=Last_u+1 TO h/Element
2870 Angle_dev=FNe(u,Zi)
2880 DRAW u*Element/h+Trip_no,Angle_dev
2890 NEXT u
2900 End_of_plot:
2910 IF Trip_no=1 THEN GOTO Fin_of_plot
2920 Trip_no=1
2930 Cont_next:
2940 Z=h+2*a-Z
2950 GOTO Next_graph
2960 Fin_of_plot:
2970 Cont_next_1:
2980 LINE TYPE 3,1
2990 MOVE -.05,.175
3000 IDRAW .15,0
3010 LINE TYPE 1 @ LORG 2 @ PEN 1
3020 !
3030 CLEAR @ KEY LABEL
3040 RETURN
3050 !
3060 ! ****
3070 Angle_dev_graph:
3080 !
3090 Fig_label1$="Lay angle deviation during a trip, at agross section S"
3100 Help_s1$=VAL$(Z)
3110 Fig_label2$="Distance of cross section from upgoing rope Zi=""&Help_s1$&" m"
3120 Hor_label$="Distance travelled (u/h) m/m"
3130 Ver_label$="Lay. angle deviation Deg."
3140 Hor_min=-.1
3150 Hor_max=2.1
3160 Hor_lspac=.1
3170 Hor_spac=23
3180 Hor_org=Hor_min
3190 Hor_dec=1
3200 Ver_min=-.2
3210 Ver_max=.2
3220 Ver_lspac=.01
3230 Ver_spac=5
3240 Ver_org=Ver_min
3250 Ver_dec=2
3260 RETURN
3270 !
```

```
3280 ! ****
3290 Torq_graph:
3300 Fig_label1$="Torque in the rope"
3310 Fig_label2$=""
3320 Hor_label$="Distance travelled (u/h) m/m"
3330 Ver_label$="Torque Nm"
3340 Hor_min=-.1
3350 Hor_max=1.1
3360 Hor_lspac=.1
3370 Hor_spac=1
3380 Hor_org=Hor_min
3390 Hor_dec=1
3400 Ver_min=0
3410 Ver_max=600
3420 Ver_lspac=50
3430 Ver_spac=2
3440 Ver_org=Ver_min
3450 Ver_dec=0
3460 RETURN
3470 !
3480 ! **** SET PLOTTER ****
3490 Set_plotter:
3500 Plot_device: CLEAR
3510 DISP "Plot to Plotter or Screen ? (P/S)"
3520 INPUT Plot_dev$
3530 Plot_dev$=UPC$(Plot_dev$)
3540 IF Plot_dev$=="P" THEN GOTO Plotter
3550 IF Plot_dev$=="S" THEN PLOTTER IS 1 @ GOTO Screen
3560 GOSUB Wrong_input
3570 GOTO Plot_device
3580 Plotter: DISP "Put at PEN1 a 0.3mm Pen and at PEN2 a 0.7mm Pen. press CONTINUE"
3590 PAUSE
3600 PLOTTER IS 705
3610 Screen: CLEAR
3620 DISP "Fig_no$=?"
3630 INPUT Fig_no$
3640 GCLEAR
3650 PEN 1
3660 LIMIT 16,250,22,162 ! Xmin=0,Xmax=181,Ymin=0,Ymax=100
3670 CSIZE 3,.6
3680 MOVE 0,7 @ LABEL "Figure ";Fig_no$
3690 MOVE 28,7 @ LABEL Fig_label1$
3700 MOVE 28,3 @ LABEL Fig_label2$
3710 MOVE 33,20 @ LABEL Hor_label$
3720 LDIR 90
3730 MOVE 15,33 @ LABEL Ver_label$
3740 LDIR 0
3750 LOCATE 25,155,30,98
3760 FRAME
3770 SCALE Hor_min,Hor_max,Ver_min,Ver_max
3780 FXD Hor_dec,Ver_dec
3790 LAXES -Hor_lspac,Ver_lspac,Hor_org,Ver_org,Hor_spac,Ver_spac
3800 RETURN
3810 !
3820 ! **** WRONG INPUT ****
3830 Wrong_input:
3840 !
3850 BEEP
3860 DISP "WRONG DATA !!! Try again"
3870 RETURN
3880 !
```

```
3890 ! ***** DRAW GRID *****  
3900 Draw_grid:  
3910 !  
3920 PEN 1  
3930 FXD Hor_dec,Ver_dec  
3940 LGRID Hor_lspac,Ver_lspac,Hor_org,Ver_org,Hor_spac,Ver_spac  
3950 RETURN  
3960 !  
3970 ! ***** SOMETHING WRONG . *****  
  
3980 Something_wrong:  
3990 !  
4000 CLEAR  
4010 DISP "There is something wrong with:";Err_message$  
4020 DISP  
4030 DISP "Program has stoped . Please correct it !!!"  
4040 PAUSE  
4050 !  
4060 Program_end:  
4070 STOP  
4080 ! *****  
4090 DEF FNe(u,Z) = r*COS (Lay_angle)^2*Twist_uz(u,Z)  
4100 END
```

APPENDIX D

TAIL ROPE MODEL USING CONSTANT C AND T FACTORS

D.1 Relative rotation of a cross section of the upgoing rope

The upgoing section of the tail rope is divided into elements of length Δz . If Δz is small enough it can be assumed that the tensile load along the length of each element is constant. The tensile load in the i-th element is derived with the aid of Fig. D.1 as:

$$F_i = P_t + q(u + b - z_{1,i}) \quad (D.1)$$

P_t : Is half of the gross weight of the rope in the tail rope loop plus half of the weight of the tail sheave, if there is one.

q : Is the weight of the tail rope in N/m.

b : Is the distance between the lower station and the tail rope loop [m].

u : Is the distance travelled by the conveyances from the stations [m].

$z_{1,i}$: is the distance of the i-th element from the upgoing conveyance.

From equation 2.1 the torque in the i-th element is:

$$M_{1,u} = CF_i + T\Delta\Phi_i/\Delta z \quad (D.2)$$

where $\Delta\Phi_i$ is the relative rotation between the ends of the element Δz .

Rearranging the terms of equation D.2 and substituting F_i from equation D.1 leads to

$$\Delta\Phi_i = (M_{1,u} - CP_t - Cq(u + b - z_{1,i}))\Delta z/T \quad (D.3)$$

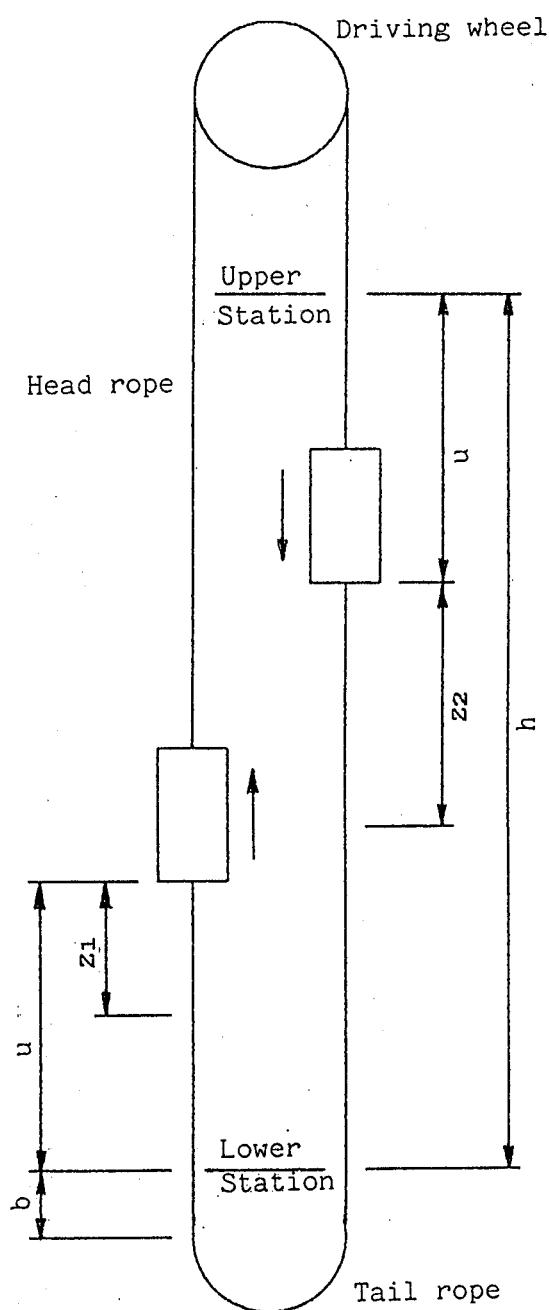


Figure D.1

Tail rope notation

The relative rotation of the m -th element with respect to the cross section where the rope is attached to the upgoing conveyance is:

$$\Phi_{1,u,m} = \sum_{i=1}^m \Delta\Phi_i \quad (D.4)$$

Substitution of $\Delta\Phi_i$ from equation D.3 into equation D.4 yields

$$\Phi_{1,u,m} = \sum_{i=1}^m (M_{1,u} - CP_t - Cq(u + b - z_{1,i})) \Delta z / T \quad (D.5)$$

Since the C and T factors are constant the summation in the above equation can be replaced by an integral and Δz by dz . Equation D.5 therefore becomes

$$\Phi_{1,u,z_1} = \int_0^{z_1} ((M_{1,u} - CP_t - Cq(u + b - z)) / T) dz \quad (D.6)$$

which after integration leads to

$$\Phi_{1,u,z_1} = (M_{1,u} - C(P_t + q(u + b))) z_1 / T + Cq z_1^2 / (2T) \quad (D.7)$$

D.2 Relative rotation of a cross section of the downgoing rope

Using the same approach, the tensile load in the i -th element is:

$$F_i = P_t + q(h + b - u - z_{2,i}) \quad (D.8)$$

while the relative rotation at the rope element z_2 is:

$$\Phi_{2,u,z_2} = (M_{2,u} - C(P_t + q(h + b - u))) z_2 / T + Cq z_2^2 / (2T) \quad (D.9)$$

D.3 Mathematical model of the tail rope without tail sheave

As stated in section 4.1.1 the rotation in each of the two sections of the tail rope at any instant is equal to the algebraic sum of the rotation introduced through rotation of the swivels and through rotation of the tail loop.

$$\Phi_{1,u,b+u} = \Phi_{s1} + \Phi_t \quad (D.10)$$

$$\Phi_{2,u,h+b-u} = \Phi_{s2} + \Phi_t \quad (D.11)$$

where

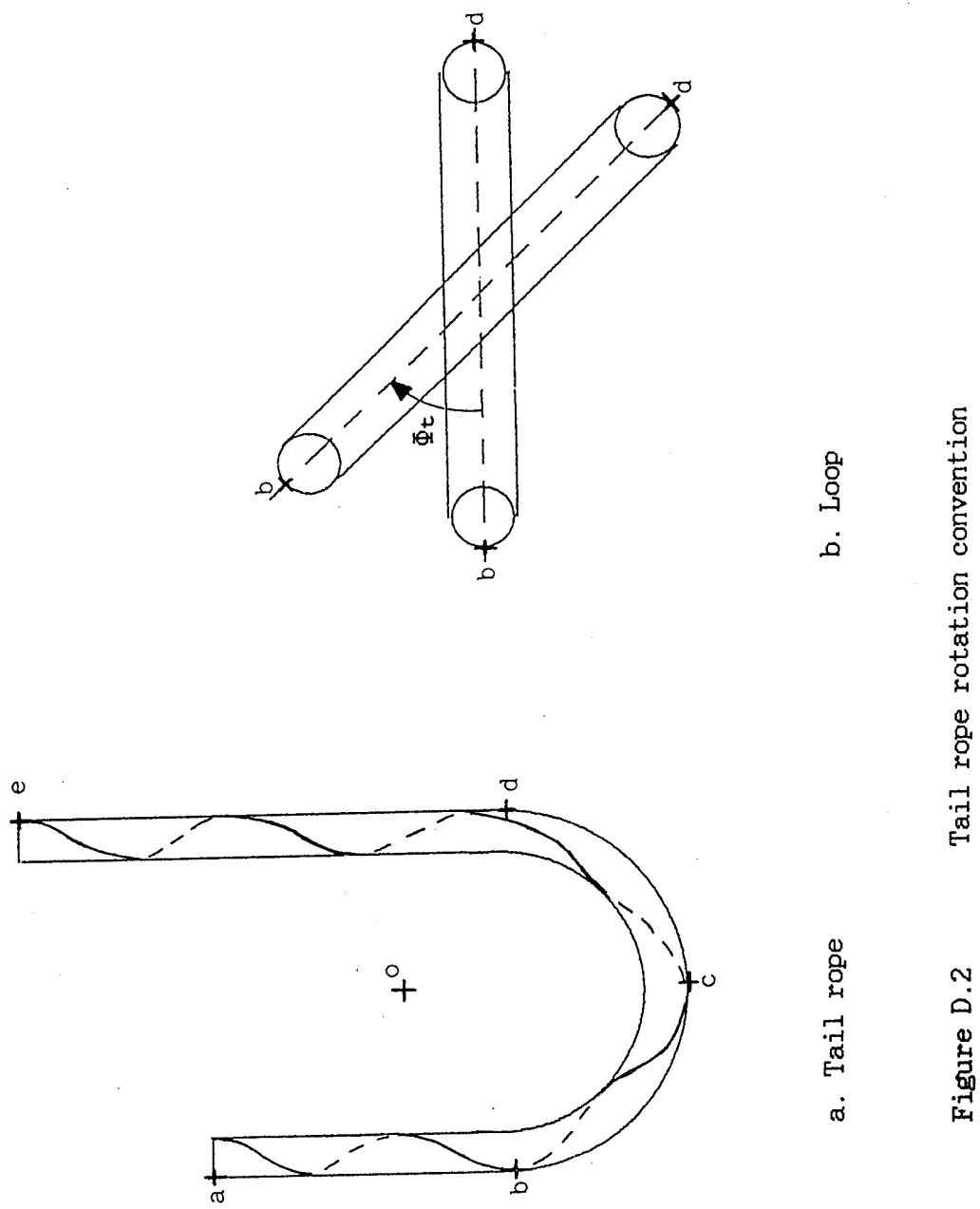
Φ_{s1} : Is the total angle that the upgoing swivel has rotated.

Φ_{s2} : Is the total angle that the downgoing swivel has rotated.

Φ_t : Is the rotation of the tail loop in a horizontal plane.

The consistent sign convention implied in equations D.10 and D.11 is explained here with the aid of Fig. D.2. Assume that the tail rope has a right-hand lay. Then, the outer strands appear as in Fig. D.2a and progress clockwise along the rope, in either direction. To an observer situated in position O, below both conveyances but above the loop, a clockwise rotation of the ends a, e or the loop, will be positive. Thus, with the loop b c d fixed, a clockwise rotation Φ_{s1} of swivel a or e, as viewed by the observer, is positive because it is in the direction of the helix lay and adds a positive increment to the relevant relative rotation. Similarly, with swivels a and e fixed, a clockwise rotation Φ_t of the loop, as viewed by the observer and as illustrated in Fig. D.2b, adds a positive increment to the relative rotation of both legs of the tail rope.

Figure D.2b also illustrates the second boundary condition stated at the end of section 4.1.1: There is no relative rotation between ends b and d of the rope in the loop. Hence the validity of equations D.10 and D.11.



Substitution of Φ_t from equation D.11 into equation D.10 leads to:

$$\Phi_{s1} - \Phi_{s2} = \Phi_{1,u,b+u} - \Phi_{2,u,h+b-u} \quad (D.12)$$

Substitution of $\Phi_{1,u,b+u}$ and $\Phi_{2,u,h+b-u}$ from equations D.7 and D.9 respectively into equation D.12 yields:

$$\begin{aligned} \Phi_{s1} - \Phi_{s2} = & (M_{1,u} - C(P_t + q(b + u)))(b + u)/T \\ & + Cq(b + u)^2/(2T) \\ & - (M_{2,u} - C(P_t + q(h + b - u)))(h + b - u)/T \\ & - Cq(h + b - u)^2/(2T) \end{aligned} \quad (D.13)$$

Since no external torques are applied to the rope along its length, the static equilibrium condition for the torque in the tail rope is:

$$M_{1,u} + M_{2,u} = 0 \quad (D.14)$$

Substituting $M_{2,u}$ from the above equation into equation D.13, taking into account that $h + 2b = L_t$ leads to

$$M_{1,u} = CP_t(2u - h)/L_t + Cq(2u - h)/2 + (\Phi_{s1} - \Phi_{s2})T/L_t \quad (D.15)$$

and the torque in the downgoing rope, taking into account equation D.12, is:

$$M_{2,u} = CP_t(h - 2u)/L_t + Cq(h - 2u)/2 + (\Phi_{s2} - \Phi_{s1})T/L_t \quad (D.16)$$

Substituting $M_{1,u}$ from equation D.15 into D.7 and $M_{2,u}$ from equation D.16 into D.9 yields for the relative rotation of cross sections in the upgoing and downgoing sections of the rope respectively:

$$\begin{aligned} \Phi_{1,u,z1} = & ((\Phi_{s1} - \Phi_{s2})/L_t - 2CP_t(h + b - u)/(TL_t) \\ & - CqL_t/(2T))z_1 + Cqz_1^2/(2T) \end{aligned} \quad (D.17)$$

$$\begin{aligned} \Phi_{2,u,z2} = & ((\Phi_{s2} - \Phi_{s1})/L_t - 2CP_t(b + u)/(TL_t) \\ & - CqL_t/(2T))z_2 + Cqz_2^2/(2T) \end{aligned} \quad (D.18)$$

The tail loop rotation from equation 4.10 is:

$$\Phi_t = \Phi_{1,u,b+u} - \Phi_{s1} \quad (D.19)$$

Substituting $\Phi_{1,u,b+u}$ from equation D.17 into the above equation yields for the loop rotation:

$$\begin{aligned} \Phi_t = & -(\Phi_{s1}(h + b - u) + \Phi_{s2}(b + u))/L_t \\ & - 2CP_t(h + b - u)(b + u)/(TL_t) \\ & - Cq(h + b - u)(b + u)/(2T) \end{aligned} \quad (D.20)$$

As was shown in Appendix B the lay angle deviation is given by

$$\theta = r \cos^2(\beta) \cdot d\Phi/dz \quad (D.21)$$

For the upgoing section of the tail rope from equation D.17 we have that

$$\begin{aligned} d\Phi_{1,u,s1}/dz = & (\Phi_{s1} - \Phi_{s2})/L_t - 2CP_t(h + b - u)/(TL_t) \\ & - CqL_t/(2T) + Cqz_1/T \end{aligned} \quad (D.22)$$

Substituting $d\Phi/dz$ into eq. D.21 leads to

$$\begin{aligned} \theta_1 = & ((\Phi_{s1} - \Phi_{s2})/L_t - 2CP_t(h + b - u)/(TL_t) \\ & - CqL_t/(2T) + Cqz_1/T)r \cdot \cos^2(\beta) \end{aligned} \quad (D.23)$$

Using the same approach for the downgoing section of the rope the lay angle variation is:

$$\begin{aligned} \theta_2 = & ((\Phi_{s2} - \Phi_{s1})/L_t - 2CP_t(b + u)/(TL_t) \\ & - CqL_t/(2T) + Cqz_2/T)r \cdot \cos^2(\beta) \end{aligned} \quad (D.24)$$

D.4 Mathematical model of the tail rope with tail sheave

At any given instant, the relative rotation at the bottom of the downgoing rope (where $z_2 = h + b - u$) is:

$$\Phi_{2,u,z_2} = (M_{2,u} - C(P_t + q(h + b - u)))z_2/T + Cqz_2^2/(2T) \quad (D.9)$$

An instant earlier when the conveyance was at $u - \Delta u$, the same section was at the same value of z_2 and its relative rotation was:

$$\Phi_{2,u-\Delta u,z_2} = (M_{2,u-\Delta u} - C(P_t + q(h + b - (u - \Delta u))))z_2/T + Cqz_2^2/(2T) \quad (D.25)$$

The assumption stated in section 4.1.2 that the relative rotation of an element Δz about to enter the tail sheave is unchanged during the travel Δu , leads to

$$\Phi_{2,u,z_2} = \Phi_{2,u-\Delta u,z_2} \quad \text{for } \Delta u \rightarrow 0 \quad (D.26)$$

where $z_2 = h + b - u$

Equation D.26 after substitution of Φ_{2,u,z_2} and $\Phi_{2,u-\Delta u,z_2}$ from equations D.9 and D.25 respectively leads to

$$M_{2,u} = M_{2,u-\Delta u} - Cq\Delta u \quad (D.27)$$

and as $\Delta u \rightarrow 0$

$$d(M_{1,u})/du = -Cq \quad (D.28)$$

Hence, on integration

$$M_{2,u} = M_{2,0} - Cqu \quad (D.29)$$

This simple result is explained as follows:

Since the tension in any element of the descending tail rope decreases linearly with the travelled distance, u and the C and T factors are constant, the torque, $M_{2,u}$, decreases linearly with u as well.

The second boundary condition in section 4.1.2 states that the total rotation in the tail rope is constant and equal to the initial rotation Φ_{in} . Thus by adding the rotations at the bottom of the two sides of the rope

$$\Phi_{in} = \Phi_{1,u,b+u} + \Phi_{2,u,h+b-u} \quad (D.30)$$

In particular for $u = 0$ substitution of equations D.7 and D.9 in equation D.30 yields:

$$\begin{aligned} \Phi_{in} = & (M_{1,\theta b} + M_{2,\theta}(h + b) - CP_t L_t \\ & - Cq(b^2 + (h + b)^2)/T) \end{aligned} \quad (D.31)$$

As stated in section 4.1.2, the two sides of the tail rope are "equivalent". Therefore, the torque $M_{1,\theta}$ is equal to the torque in the downgoing rope at the end of the trip i.e. $M_{2,h}$. Hence

$$\begin{aligned} \Phi_{in} = & (M_{2,hb} + M_{2,\theta}(h + b) - CP_t L_t \\ & - Cq(b^2 + (h + b)^2)/T) \end{aligned} \quad (D.32)$$

Taking into account equation D.29, $M_{2,h}$ is eliminated from the above equation which leads to

$$M_{2,\theta} = CP_t + Cq(b^2 + 2hb + (h + b)^2)/(2L_t) + \Phi_{in}T/L_t \quad (D.33)$$

Substituting $M_{2,\theta}$ from the above equation into equation D.29, yields for the torque in the downgoing section of the tail rope:

$$M_{2,u} = CP_t + Cq((h - 2u)L_t + 2(h + b)b)/(2L_t) + \Phi_{in}T/L_t \quad (D.34)$$

Substitution of $M_{2,u}$ from equation D.34 into equation D.9 leads to

$$\begin{aligned} \Phi_{2,u,z2} = & -k(((h + b)^2 + b^2)zz/(2L_t) - zz^2/2) \\ & + \Phi_{in}zz/L_t \end{aligned} \quad (D.35)$$

where $k = Cq/T$

Substitution of Φ_{1,u,z_1} and Φ_{2,u,z_2} from equations D.7 and D.35 respectively into equation D.30 yields for the torque in the upgoing section of the rope

$$M_{1,u} = CP_t + Cg((2u - h)L_t^2 + (h + b - u)((h + b)^2 + b^2))/(2(b + u)L_t) + \Phi_{in}T/L_t \quad (D.36)$$

As a check of equations D.34 and D.36 we note that

$$M_{1,h} = M_{2,\emptyset} = CP_t + Cg(h/2 + b(b+h)/L_t) + \Phi_{in}T/L_t$$

The relative rotation in the upgoing section of the rope is given by equation D.7 after substitution of $M_{1,u}$ from the above relation.

$$\Phi_{1,u,z_1} = k(((2u - h)L_t^2 + (h + b - u)((h + b)^2 + b^2) - 2(b + u)^2L_t)z_1/(2(b + u)L_t) + z_1^2/2) + \Phi_{in}z_1/L_t \quad (D.37)$$

The lay angle deviation is calculated according to equation D.21 where $d\Phi/dz$ for the upgoing rope is:

$$d\Phi_{1,u,z_1}/dz = k(((2u - h)L_t^2 + (h + b - u)((h + b)^2 + b^2) - 2(b + u)^2L_t)/(2(b + u)L_t) + z_1) + \Phi_{in}/L_t \quad (D.38)$$

and for the downgoing rope

$$d\Phi_{2,u,z_2}/dz = -k(((h + b)^2 + b^2)/(2L_t) - z_2) + \Phi_{in}/L_t \quad (D.39)$$

The lay angle deviation for the two sections of the rope is therefore

$$\theta_1 = (k(((2u - h)L_t^2 + (h + b - u)((h + b)^2 + b^2) - 2(b + u)^2L_t)/(2(b + u)L_t) + z_1) + \Phi_{in}/L_t)r.\cos^2(\beta) \quad (D.40)$$

$$\theta_2 = (-k(((h + b)^2 + b^2)/(2L_t) - z_2) + \Phi_{in}/L_t)r.\cos^2(\beta) \quad (D.41)$$

APPENDIX E

TORSIONAL AND LONGITUDINAL VIBRATIONS OF A KOEPE HEAD ROPE

1. Free Torsional Vibrations^(35, 36)

The free body diagram of a torsionally vibrating rope element is depicted in Fig. E.1. The equation of torque equilibrium of the element is.

$$J(\partial^2\Phi/\partial t^2) = M + (\partial M/\partial z)dz - M \quad (E.1)$$

where

J : The moment of inertia of the rotating element

$M(z, t)$: The torsional moment

$\Phi(z, t)$: The angle of twist

The differential equation of the motion of that element during torsional vibrations is

$$J\partial^2\Phi/\partial t^2 = \partial M/\partial z dz \quad (E.2)$$

For the torsional moment according to Hooke we have

$$M = GI_p\partial\Phi/\partial z \quad (E.3)$$

where

G : The effective shear modulus of the rope

I_p : The polar second moment of area (cross section)

The moment of inertia of the rope element and the polar second moment of area are related by the following equation.

$$J = \rho I_p dz \quad (E.4)$$

where ρ is the density of the rope material.

Substituting M and J from equation E.3 and E.4 respectively into E.2 yields

$$\partial^2\Phi/\partial t^2 - c^2\partial^2\Phi/\partial z^2 = 0 \quad (E.5)$$

where

$$c = \sqrt{G/\rho} \quad (E.6)$$

Equation E.5 is a partial differential equation which can be solved according to Bernoulli's method. The solution of the equation is of the form

$$\Phi = u(z).v(t) \quad (E.7)$$

and

$$\partial^2\Phi/\partial t^2 = u\partial^2v/\partial t^2 \quad (E.8)$$

$$\partial^2\Phi/\partial z^2 = \partial^2u/\partial z^2.v \quad (E.9)$$

Substituting E.8 and E.9 into E.5 leads to

$$u\partial^2v/\partial t^2 = c^2\partial^2u/\partial z^2.v \quad (E.10)$$

or by rearranging the terms

$$(\partial^2v/\partial t^2)/v = c^2.(\partial^2u/\partial z^2)/u \quad (E.11)$$

Since equation E.11 must be true for every t and z, we get

$$(\partial^2v/\partial t^2)/v = K \quad (E.12)$$

and

$$c^2 \cdot (\partial^2 u / \partial z^2) / u = K \quad (E.13)$$

where K is a constant

which leads to the two homogeneous differential equations

$$\partial^2 v / \partial t^2 + Kv = 0 \quad (E.14)$$

and

$$\partial^2 u / \partial z^2 + K/c^2 \cdot u = 0 \quad (E.15)$$

The solution of equation E.14 is of the form

$$v = A_t \cos(\omega t) + B_t \sin(\omega t) \quad (E.16)$$

where

$$\omega^2 = K \quad (E.17)$$

The solution of equation E.15 is

$$u = A_z \cos(\lambda z) + B_z \sin(\lambda z) \quad (E.18)$$

where

$$\lambda^2 = K/c^2 \quad (E.19)$$

From E.17 and E.19 we have that

$$\omega = c \lambda \quad (E.20)$$

The constants A_z and B_z of equation E.18 and the values of λ are calculated from the boundary condition. The frequency ω is thereafter calculated from equation E.20. The constants A_t and B_t can be calculated from the initial conditions.

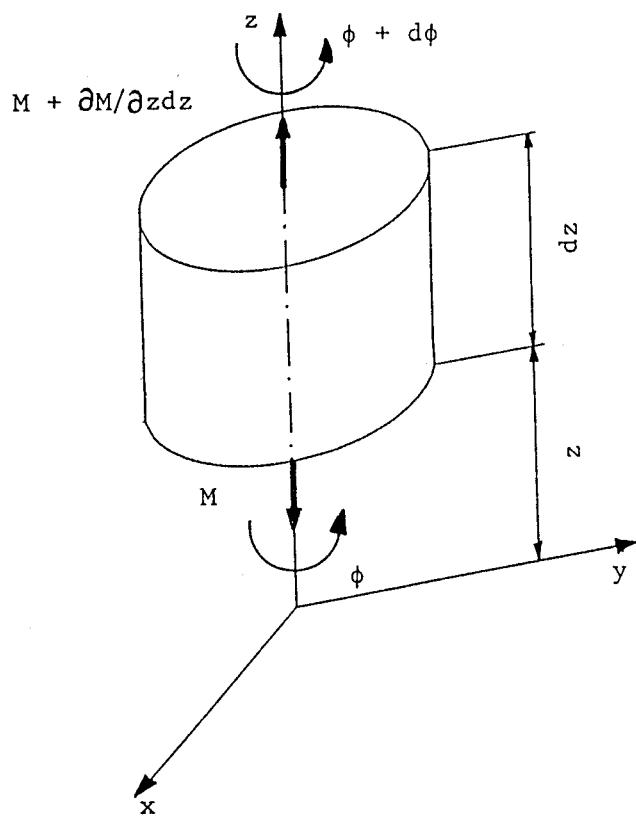


Figure E.1 Free body diagram of a torsionally vibrating rope element

2. Free Longitudinal Vibrations

The free body diagram of a longitudinally vibrating rope element is shown in Fig. E.2. The equation of force equilibrium of the element is

$$Adz\rho(\partial^2u/\partial t^2) = F + (\partial F/\partial z)dz - F \quad (E.21)$$

where

- u : The longitudinal displacement of any cross section.
 A : The metallic cross sectional area of the rope
 ρ : The density of the rope material

The tensile force F acting on the element is

$$F = A.E.\partial u/\partial z \quad (E.22)$$

where E the effective modulus of elasticity of the rope.

Substituting F from equation E.22 into equation E.21 leads to

$$\partial^2u/\partial t^2 - \alpha\partial^2u/\partial z^2 = 0 \quad (E.23)$$

where

$$\alpha = \sqrt{E/\rho} \quad (E.24)$$

is the velocity of propagation of waves along the rope.

Equation E.23 is the differential equation of motion of the longitudinally vibrating rope element. Equation E.23 has the same form as equation E.5 for the torsional vibrations. Therefore the frequency and the eigenvalues can be calculated from equations E.16 and E.18. For the longitudinal vibration the relation between the frequency ω and the eigenvalue is

$$\omega = \alpha \lambda \quad (E.25)$$

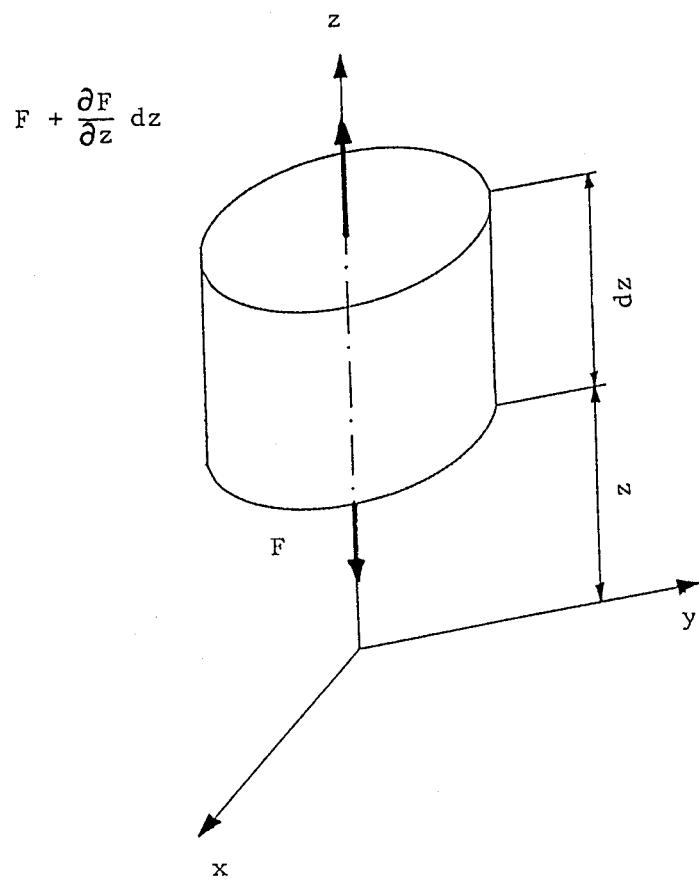


Figure E.2 Free body diagram of a longitudinally vibrating rope element

APPENDIX F

POLAR SECOND MOMENT OF AREA OF HEAD ROPE AND EFFECTIVE SHEAR MODULUS

Polar moment

A cross section of the head rope is shown in Fig. F1. I assume that the cross section of each wire is a circle with a diameter equal to the nominal wire diameter. A copy of the "Works Order Specification Sheet" where the rope's construction details are recorded is shown in Appendix A, Table A.2. Due to the great number of wires in each strand, the notation shown in Fig. F.2 is established in order to facilitate calculations. The wire diameters and their distance from the centre of the rope are shown in Table F.1.

The polar second moment of area of the rope section will be the sum of the polar moments of all the wire sections. The calculation is simplified by noting the polar symmetry of Fig. F.1 so that it is sufficient to calculate the polar moments of one outer strand, one inner strand and the core strand.

For the outer strands we have

$$I_{p,out} = 3 I_{\theta,1} + 2 I_{\theta,2} + 2 I_{\theta,3} + I_{\theta,4} + 2 I_{\theta,5} \quad (F.1)$$

for the inner ones

$$\begin{aligned} I_{p,in} = & 2 I_{n,1} + 2 I_{n,2} + 2 I_{n,3} + 2 I_{n,4} + 2 I_{n,5} \\ & + I_{n,6} + I_{n,7} + 2 I_{n,8} + 2 I_{n,9} + 2 I_{n,10} \\ & + 2 I_{n,11} + 2 I_{n,12} + I_{n,13} + 2 I_{n,14} + 2 I_{n,15} \\ & + I_{n,16} + I_{n,17} + I_{n,18} + 2 I_{n,19} \end{aligned} \quad (F.2)$$

and for the core

$$I_{p,c} = 9 I_{c,1} + 9 I_{c,2} + I_{c,3} \quad (F.3)$$

The polar moment of any wire about the centre of the rope is

$$I = \pi d^4/32 + r^2 \pi d^2/4 \quad (\text{F.4})$$

where

d: the wire diameter

r: the distance of the centre of the wire from the centre of the rope

and for the total rope

$$I_p = 12 I_{p,out} + 6 I_{p,in} + I_{p,c} \quad (\text{F.5})$$

From equations F.1, F.2, F.3 and F.4 using data from Table F.2 the polar moments of the outer, inner and core strands were calculated:

$$I_{p,out} = 14475 \text{ mm}^4$$

$$I_{p,in} = 10414 \text{ mm}^4$$

$$I_{p,c} = 874 \text{ mm}^4$$

Substituting these values into equation F.5, the polar moment of the head rope cross section was calculated.

$$I_p = 237058 \text{ mm}^4$$

Effective shear modulus

For a solid shaft the shear modulus is related to the torque according to the relation

$$M = GI_p\Phi \quad (\text{F.6})$$

where

I_p = The second polar moment of area of the solid shaft

Φ = The twist in the shaft in rad/m

For a wire rope under constant tensile load the equivalent relation from Chapter 2 is

$$M = T \cdot \Phi \quad (F.7)$$

where T the torque factor of a rope which is not necessarily constant.

Comparing equation F.6 and F.7 leads to the conclusion that the effective shear modulus of a rope is

$$G = T / I_p \quad (F.8)$$

The torsional stiffness of the head rope as is shown in Fig. 2.9 is a function of both torque and tension in the rope. For the range of loads experienced on the particular winder we can assume a constant value of 50 Nm/(deg/m) or 2864,8 Nm(rad/m)

Substituting the value of T and I_p into equation F.8 yields for the effective rope shear modulus.

$$G = 12 \text{ GPa}$$

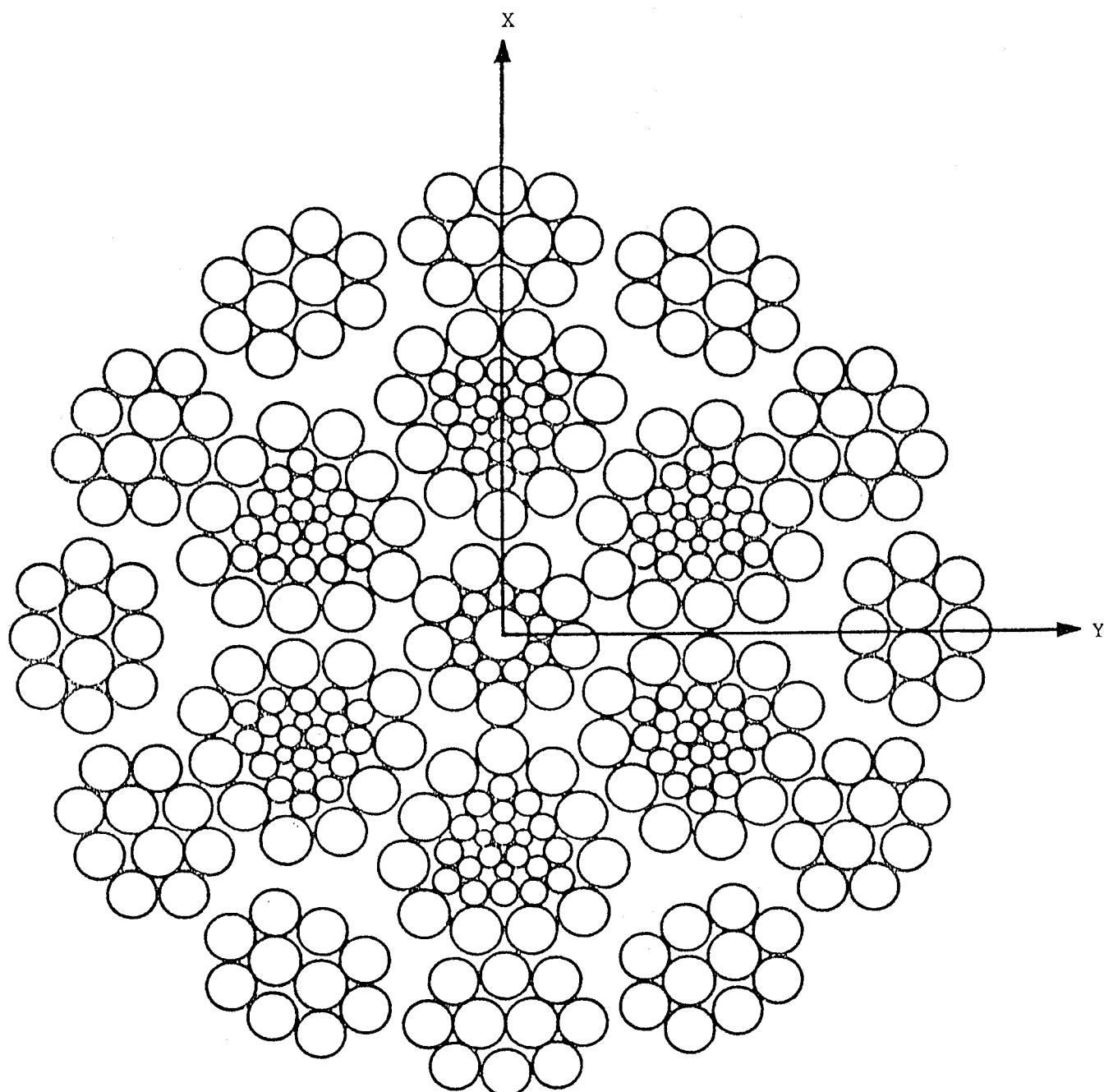


Figure F.1 Head rope cross section

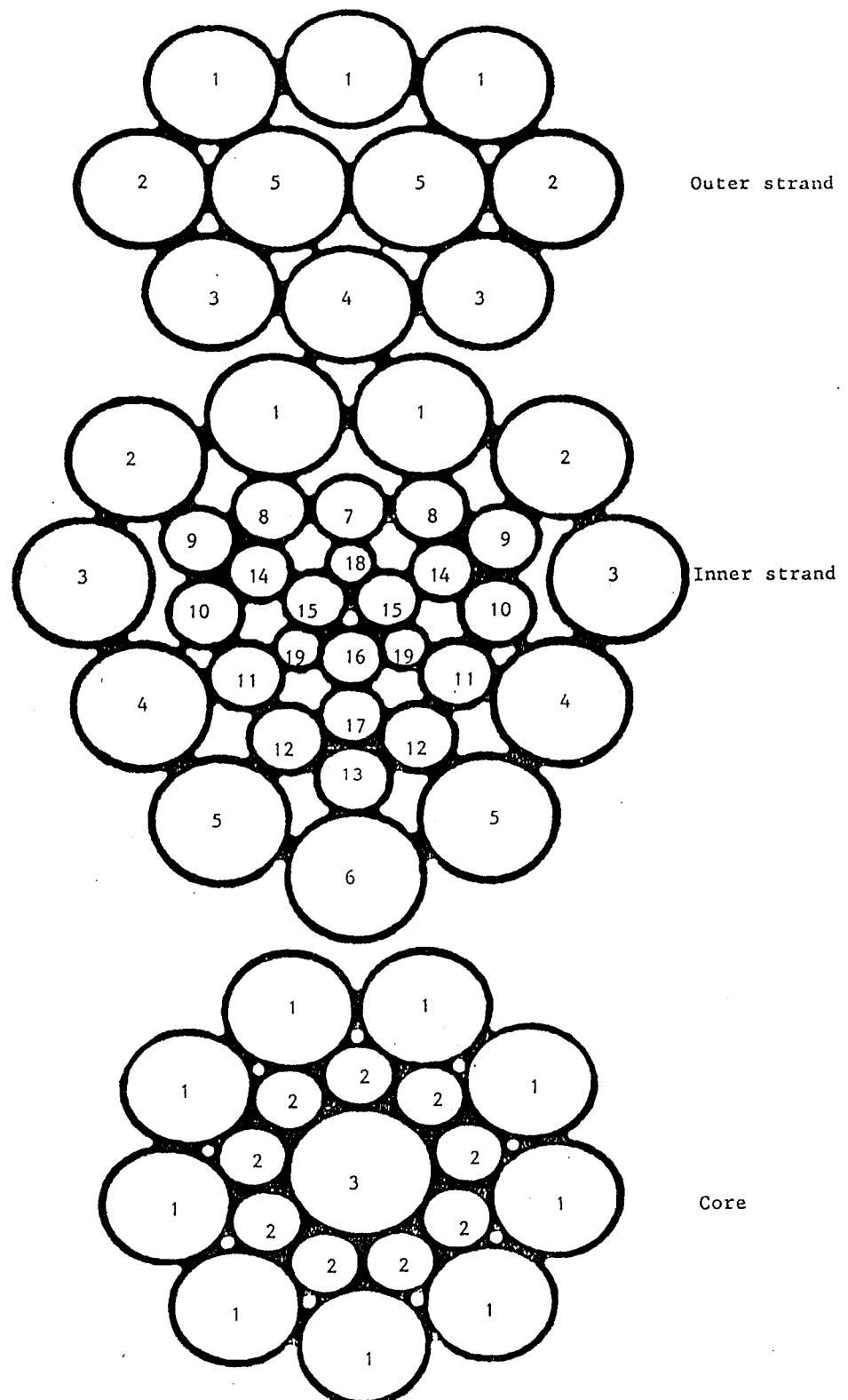


Figure F.2 Head rope wire notation

$I_{o,i}$: Polar moment of area of the i -th wire of an outer strand

$I_{in,i}$: Polar moment of area of the i -th wire of an inner strand

$I_{c,i}$: Polar moment of area of the i -th wire of the core strand

TABLE F.1: Head rope construction details

STRAND	WIRE	NOTATION	DIAMETER mm	DISTANCE mm	NUMBER OF WIRES	
Outer	Outer	I _{ø,1}	2,16	21,50	3	
Outer	Outer	I _{ø,2}	2,16	19,50	2	
Outer	Outer	I _{ø,3}	2,16	17,80	2	
Outer	Outer	I _{ø,4}	2,16	17,30	1	
Outer	Inner	I _{ø,5}	2,32	19,35	2	
Inner	Outer	I _{n,1}	2,44	15,22	2	
Inner	Outer	I _{n,2}	2,44	14,35	2	
Inner	Outer	I _{n,3}	2,44	12,62	2	
Inner	Outer	I _{n,4}	2,44	10,25	2	
Inner	Outer	I _{n,5}	2,44	7,81	2	
Inner	Outer	I _{n,6}	2,44	6,61	1	
Inner	Inner	I _{n,7}	1,32	13,33	1	
Inner	Inner	I _{n,8}	1,32	13,34	2	
Inner	Inner	I _{n,9}	1,32	12,80	2	
Inner	Inner	I _{n,10}	1,32	11,52	2	
Inner	Inner	I _{n,11}	1,32	10,14	2	
Inner	Inner	I _{n,12}	1,32	8,82	2	
Inner	Inner	I _{n,13}	1,32	8,16	1	
Inner	Core	I _{n,14}	1,08	12,25	2	
Inner	Core	I _{n,15}	1,08	11,51	2	
Inner	Core	I _{n,16}	1,08	10,44	1	
Inner	Core	I _{n,17}	1,08	9,36	1	
Inner	Filler	I _{n,18}	0,81	12,25	1	
Inner	Filler	I _{n,19}	0,81	10,65	2	
Core	Outer	I _{c,1}	2,50	4,14	9	
Core	Inner	I _{c,2}	1,44	2,21	9	
Core	Core	I _{c,3}	2,90	Ø	1	

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