LABORATORY DEVICE FOR CHECKING THE FUNCTIONALITY
OF THE ELEVATOR ROPE SENSORS

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Abstract:
The paper describes the structural design of a laboratory device that allows for presenting operation, simulating work procedures and checking functionality of the elevator "rope sensors" when equalizing different tensile forces in partial ropes of a rope system of traction elevators. The laboratory device is modified for checking operations of commonly used rope sensors. In an overwhelming number of cases, elevator technicians use them for setting up the unequally distributed tensile forces in elevator ropes. The device is equipped with three, mutually attached pulleys, over which the rope is installed. The unknown tensile force in the rope is determined by an "indirect method", i.e. from the resultant of the forces of the rope bent over the pulleys, which have an effect on the force sensor. The tensile force along the rope axis can be determined numerically, but also experimentally, from the inclination angle of the rope installed on the pulleys, diameter of the pulleys, diameter of the rope and the force detected by the force sensor of the stretched rope. The paper presents experimentally obtained tensile force values at the rope sensor, deduced from stretching the rope. The paper also describes the procedure for determining the measured load in the rope by rope sensors of the SWR, SWK and RMT-1 types based on the variable axial force in the rope.

Key words: *rope equalizer, sensor, steel rope, tensile force, traction lift*

INTRODUCTION

Elevators used in high rise and highspeed applications are particularly sensitive to uneven rope tensions [24], suffering from unnecessary wear, excessive vibrations, and unwelcome noise as a result [9].

In most static systems, the balance must be checked by an installer who manually evaluates the ropes. Unfortunately, these checks are not necessarily based on skill or training, making the process guesswork rather than a science.

The increasing importance of precise tensioning in elevators has created significant demand for better diagnostics [26, 27, 28, 30].

To that end, manufacturers have developed a wide variety of measurement solutions [34], as well as dynamic equalizing tools to respond to balance struggles in real time [25].

There are two basic principles of devices, by the means of which one can set (i.e. "equalize") tensile forces in individual ropes of traction elevator rope systems [29, 31, 32, 33]. Both systems can be characterized by the same advantage, which consists of the possibility to detect tensile forces by a nondestructive method. It means that the tensile force along the longitudinal axis of the rope can be determined without the need to break the rope length.

LITERATURE REVIEW

One of the device variant [2, 3, 4, 5, 7, 9] is, at the moment the tensile force in the rope needs to be recorded, placed in a space where the rope is attached using suspension bolt [2, 3] to console [6], built-in in the elevator shaft of the given traction elevator or attached to the frame of the given elevator cage [9, 16, 18, 22].

One of the several [3, 10, 17] structural designs of the hydraulic rope equalizers is presented in [9]. The structural design of the mechanical rope equalizer, which uses a foil tensiometer for detecting the tensile force, is presented in [2, 7]. The operation and principle of the equalizing tensile forces using a mechanical rope equalizer that utilizes a tensile force sensor are described in [6, 35].

The other variant of the mechanical rope equalizer is based on the principle of bending a girder, propped on two supports [1, 6, 21]. In the technical world, these rope force equalizers are known under the name of "elevator

rope sensors". A rope sensor [11, 13, 36] is essentially a girder made of steel or casted from an aluminum alloy. Two pulleys [14] with a predefined span are installed on the pegs against the sensor in a revolving way. The third pulley, with its vertical axis being equally far from the other two pulleys, is sliding in the vertical plane that is perpendicular to the horizontal plane that passes through the pulley centers [37].

Paper [6] described some of the deficiencies of the rope sensors. The paper also deduced the relation between the applied force F [N] and its impacts on the sensor. Force F [N], applied to the sensor, depends on the axial force T [N] in the rope and on the mutual distance of the pulley centers along both axes of the horizontal plane.

METHODOLOGY OF RESEARCH

For the purpose of verifying the measured values of the applied tensile forces in the loadbearing rope T [N] [6] using rope tension sensors [11, 14, 19], a measuring device, see Fig. 4 (structural proposal in AutoCAD 2010) and Fig. 3 (3D model in SolidWorks 2012x64 SP 5.0), was proposed and assembled (Fig. 7). This measuring device allows for detecting tensile forces in the ropes utilizing two independent procedures.

In the horizontal plane, the distances of the axes of the pulley centers, over which the rope is placed, are x [m] and y [m], Fig. 1a.
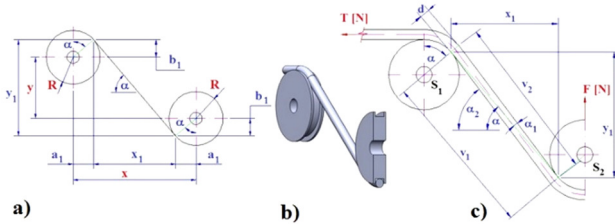

Fig. 1 Rope installed on the pulleys of a rope sensor, i.e. a rope equalizer

Governing equations

Based on Fig. 1a, (1) through (4) are valid, provided $R = D/2$ [m] is the span radius of the semicircular groove of the rope pulley.

$$a_1 = R \cdot \sin\alpha \ [m], b_1 = R \cdot \cos\alpha \ [m] \tag{1}$$

$$x_1 = x - 2 \cdot a_1 = x - 2 \cdot R \cdot \sin\alpha \ [m] \tag{2}$$

$$y_1 = y + 2 \cdot b_1 = y + 2 \cdot R \cdot \cos\alpha \ [m] \tag{3}$$

$$\alpha = \text{arctg} \frac{y_1}{x_1} \ [deg] \tag{4}$$

Line segment length v_1 [m] (which is, pursuant to Fig. 1c, tangent to the circles) can be expressed by formula (5) and angle α_1 [deg] pursuant to formula (6), when d [m] is the rope diameter.

$$v_1 = \sqrt{x_1^2 + y_1^2} \ [m] \tag{5}$$

$$\alpha_1 = \text{arctg} \frac{d}{v_1} \ [deg] \tag{6}$$

Angle α_2 [deg] between the rope longitudinal axis with the horizontal plane (see Fig. 1c) can be determined from formula (7).

$$\alpha_2 = \alpha + \alpha_1 = \text{arctg} \frac{y_1}{x_1} + \text{arctg} \frac{d}{v_1} \ [deg] \tag{7}$$

Fig. 2 shows theoretical values (pursuant to (8) of force $F_{(\alpha 2)}$ [N] [6] based on changes of angle α_2 = 0-55° for the unit value of tensile force T [N] (i.e. T = 1 N), see Table 1, in the rope.
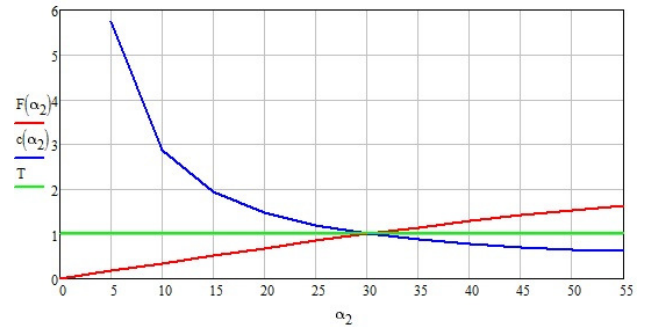

Fig. 2 Force $F_{(\alpha 2)}$ and constant $c_{(\alpha 2)}$ for angle α_2 and unit value of tensile force T

It is clear from Fig. 2 that force $F_{(\alpha 2)} = T$ [N] when angle $\alpha_2 = \pi/6 = 30°$. For $\alpha_2 < 30°$, $F_{(\alpha 2)} < T$, and for $\alpha_2 > 30°$, $F_{(\alpha 2)} > T$.

Table 1
Relation between the measured force $F_{(\alpha 2)}$, and constant $c_{(\alpha 2)}$ and angle α_2 (rope inclination)

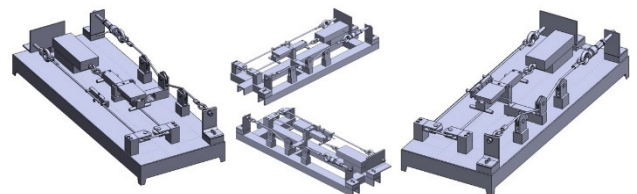| α_2 [rad]	0	0.09	0.17	0.26	0.35	0.44	0.52	0.61	0.70	0.79	0.87	0.96
α_2 [deg]	0	5	10	15	20	25	30	35	40	45	50	55
$F_{(\alpha 2)}$ [N]	0	0.17	0.35	0.52	0.68	0.85	1.00	1.15	1.29	1.41	1.53	1.64
$c_{(\alpha 2)}$ [-]	-	5.88	2.86	1.92	1.47	1.18	1	0.87	0.78	0.71	0.65	0.61

Fig. 3 3D model of the measuring device, created in the Solid-Works 2012x64 SP 5.0 environment

RESULTS

The first option for detecting the tensile force in the rope using the measuring device (Fig. 7) uses two tensiometric force sensors 3 [15] and 4 [12] (Fig. 4).

The ends of the cable conductors of both sensors 3, 4 are soldered to the connectors of the "D Sub" connector plug. The connector plugs are plugged into two of the four outlets in the measuring system DS-NET [13, 20] DEWESoft. A network cable (with an "RJ45" connector on its both ends) is used for connecting the DEWESoft DS-NET measuring set with a PC. Applied forces F [N] and T [N] (detected by force sensors 3 a 4) were displayed in the DEWESoft X2 SP5 software environment, installed on the PC, see Table 2 (Fig. 5, 6).

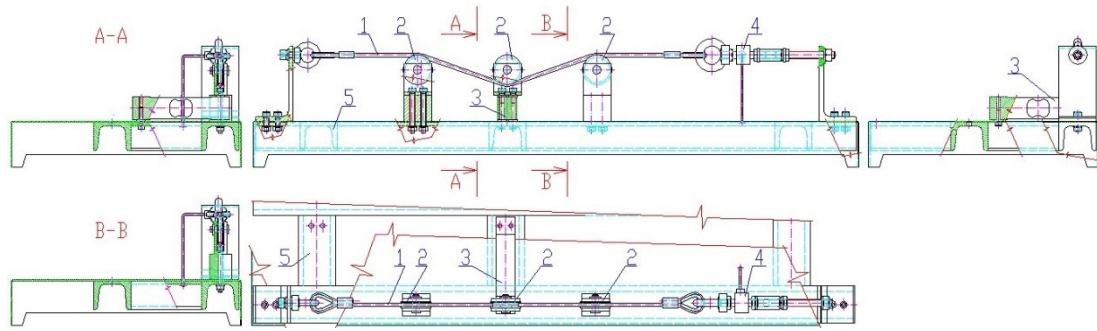**Fig. 4 2D structural proposal of the 1st variant of the measuring device**

Forces T and F detected by force sensors 3 and 4 pursuant to the 1st variant on the measuring device

i		1	2	3	4	5	6	7	8	9
T [N]	j	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
F [N]		**66.60**	**99.91**	**133.21**	**166.51**	**199.81**	**233.11**	**266.41**	**299.72**	**333.02**
	1[1]	70.09	103.36	136.86	169.67	202.44	236.19	265.87	*295.82*	329.33
	2[2]	69.86	104.24	141.62	176.25	*206.49*	244.59	278.47	307.82	335.26
$F_{i,j}$ [N]	3	68.23	103.51	139.14	173.76	205.85	241.34	269.19	302.86	334.15
	4	69.11	102.97	138.75	170.66	202.67	238,78	274.42	297.17	329.94
	5	68.78	103.16	140.92	173.58	203.92	239.96	264.95	298.34	330.05
F_{iv} [N]		**69.01**	**103.45**	**139.46**	**172.78**	**204.27**	**240.17**	**270.58**	**301.00**	**331.75**
		± 1.25	± 0.67	± 2.34	± 3.28	± 2.28	± 3.87	± 7.16	± 5.44	± 3.41
$F_i \cdot c_{(\alpha 2)}$ [N]		**103.62**	**155.31**	**209.38**	**259.41**	**306.70**	**360.60**	**406.26**	**451.92**	**498.09**

[1] see Fig. 5, [2] see Fig. 6

Fig. 5 Records of the monitored forces T [N] and F [N] in the environment of the DEWESoft X2 SP5 software during the experimental test on the measuring device
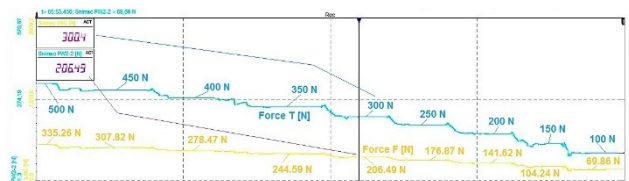

Fig. 6 Records of the monitored forces T and F by force sensors 3 and 4 in the environment of the DEWESoft X2 SP5 software

A standardized eye is formed at each end of the rope 1 [20, 21, 23]. The eye is pressed using an aluminum socket. Using a plastic nut, tensile force T [N] along the longitudinal axis of rope 1 is being increased. The immediate value of tensile force T [N] is monitored by force sensor 4. The rope is installed (Fig. 4) over three pulleys 2 (inner ϕ = 35 mm); the middle pulley is attached by bolts to force sensor 3. Tensile force T [N] in rope 1 is created by stretching rope 1 (ϕd = 5 mm). This force (for x = 120 mm, y = 0 mm and α_2 = 19.45°) generates force F [N] (8) applied to sensor 3.

$$F = 2 \cdot T \cdot \sin\alpha_2 \ [N] \qquad (8)$$

All ropes of the same construction must be used for the lift. Steel ropes 6-strand structure are less flexible and have been used in older types of elevators with machines with large diameter pulleys. With modern elevators, the drive components are constantly shrinking. This also reduces the diameter of the pulleys and increases the demand for greater flexibility of the rope, which is an 8-strand structure, wound in a parallel manner. The layer consists of strands with larger and smaller diameter wires, such as Seal, Filler and Warrington.

The second row of Table 2 includes the values of force F [N], calculated pursuant to formula (8). The second through fifth rows of Table 2 shows the values of force $F_{i,j}$ [N], which were measured by force sensor 3 on the measuring device (Fig. 7) upon a change of tensile force T [N] in the rope.

The last row of Table 2 shows the value of measured force F_i [N] multiplied by constant $c_{(\alpha 2)}$ [-]. Constant $c_{(\alpha 2)}$ [-] can be expressed as a ratio of the two forces (T a F_i [N]) measured on the measuring device (Fig. 7).
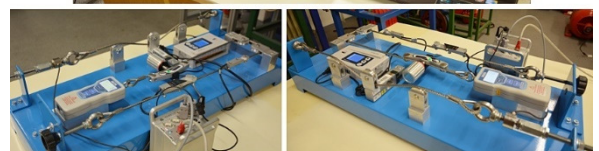

Fig. 7 Laboratory device for checking the functionality of the elevator rope sensors

By adjusting formula (8), constant $c_{(\alpha 2)}$ [-] can be subsequently determined (9).

$$c_{(\alpha 2)} = \frac{T}{F_i} = \frac{1}{2 \cdot \sin \alpha_2} \; [-] \qquad (9)$$

Force $F_{i,j}$ [N] measured by force sensor 3, multiplied by constant $c_{(\alpha 2)}$ [-] determines the actual value of tensile force T [N] in rope 1. Should the measured force $F_{i,j}$ [N] not be multiplied by constant $c_{(\alpha 2)}$ [-], then, for:

a) $\alpha_2 < \pi/6$ (= 30°), its value would be smaller than T [N] ($F_{i,j} < T$),
b) $\alpha_2 = \pi/6$, its value would be equal to T [N] ($F_{i,j} = T$),
c) $\alpha_2 > \pi/6$, its value would be higher than T [N] ($F_{i,j} > T$).

The arithmetic mean F_i [N] of measured values of holding forces $F_{i,j}$ [N] was calculated with the help of relation (10) and using relation (11), the deviations $\Delta_{i,j}$ [N] of measured values $F_{i,j}$ [N] from the arithmetic mean F_i [N] was obtained.

$$F_i = \frac{\sum_{j=1}^n F_{i,j}}{n} \; [N] \qquad (10)$$

$$\Delta_{i,j} = F_i - F_{i,j} \; [N] \qquad (11)$$

The sample standard deviation s_{vi} [N] of the arithmetic mean F_i [N] was calculated using relationship (12) [8, 21], and the standard deviation s_{oi} [N] of the arithmetic mean F_i [N] by relation (13) [8].

$$s_{vi} = \sqrt{\frac{\sum_{j=1}^n \Delta_{i,j}^2}{n-1}} \; [N] \qquad (12)$$

$$s_{oi} = \frac{s_{vi}}{\sqrt{n}} = \sqrt{\frac{\sum_{j=1}^n \Delta_{i,j}^2}{n \cdot (n-1)}} \; [N] \qquad (13)$$

In the Table [8] of critical values of Student's distribution, the chosen risk was set to be 5%, and therefore $t_{a,n}$ [-], for the number of measurements "$n = 5$" and the risk $a = 5\%$ the Student's coefficient is $t_{5\%,5} = 2.78$.

The error margin k_i [N] was calculated by relationship (14).

$$k_i = t_{5\%,5} \cdot s_{oi} \; [N] \qquad (14)$$

The last row of Table 3 contains the results of the measured holding force values F_{iv} [N], given by relation (15).

$$F_{iv} = F_i \pm k_i \; [N] \qquad (15)$$

Table 3
Measured values of force $F_{1,j}$, deviances of the measured $\Delta_{1,j}$

j	$F_{1,j}$ [N]	$\Delta_{1,j}$ [N] (11)	$|\Delta_{1,j}|$ [N]	$\Delta_{1,j}^2$ [N²]
1	70.09	1.08	1.08	1.16
2	69.86	0.85	0.85	0.72
3	68.23	- 0.78	0.78	0.61
4	69.11	0.10	0.10	0.01
5	67.78	- 1.23	1.23	1.52
$\Sigma F_{1,j}$ [N]	**345.07**		$\Sigma \Delta_{1,j}^2$ [N]	**4.02**
F_1 [N] (10)	**69.01**			

The measuring station has been also modified (second variant of the tensile force detection in the rope on the measuring device) for simulating the operation for equalizing tensile forces in the ropes utilizing industrially made rope sensors. Fig. 7 shows rope sensors RMT-1, SWK and SWR installed on the rope of the measuring station [14].

DISCUSSION

For the purpose of verifying the measured values of the applied tensile forces in the loadbearing rope T [N] [6] using rope tension sensors [11, 14] was proposed and assembled (Fig. 3). This measuring device allows for detecting tensile forces in the ropes utilizing two independent procedures.

The first option for detecting the tensile force in the rope using the measuring device uses two tensiometric force sensors 3 and 4.

In the case of experimental measurements at a laboratory station, the value of the created axial force T [N] in the rope can be monitored on the display of the digital dynamometer. Changes of the generated axial force T [N] over time can be saved in the computer memory and the graphic representation (of axial force T [N]) can be displayed on the PC monitor in the environment of the software supplied by the manufacturer of the digital dynamometer, i.e. Force Logger version 1.01.

When we know the value of axial force T [N], and when we install one of the RMT-1, SWR or SWK rope sensors on the rope, tensile force T [N] is created in the loadbearing rope (by tightening the manual plastic nut). This tensile force is monitored by partial sensors as tensile load T_G [kg]. Its value can be read on the display of the OMEGA 806 control unit [14].

Rope elevators, also referred to as traction elevators, have a cabin suspended from a system of ropes. Lifting or lowering of the car, run between the guides, is ensured by the frictional force of the steel ropes in the grooves of the traction disk of the elevator machinery. As the load-bearing capacity of the elevator increases, the required number of load-bearing ropes also increases, especially in the case where small diameter ropes are used in traction elevators. The actual weight of the car and the weight of the load must be evenly distributed amongst all supporting ropes that are used in the given layout of the elevator. Currently, several principles are known by which it is possible to detect and also change the values of the instantaneous magnitudes of the tensile forces acting in a system of ropes.

The collaboration of lift company (Liftcomp a.s.) s with authors of this paper a technical problem was chosen, which was to ensure uniform tension in the elevator ropes at various operating conditions. Using the design methods, three ways of solving the uniform tension in elevator ropes were specified. An important result of the cooperation was granted Czech patent No. 306797 named "A tension equalizer in lift carrying rope" (see www.upv.cz). Currently, the patent granted is offered to lift companies for use under licenses.

The presented solution has a practical application [2, 3, 5, 6, 7]. Authors of Czech patent No. 306797 built four design prototypes, the functionality of which was presented to companies that deal with the installation and servicing of elevators. The practical usability was thus verified, and the functionality approved.

CONCLUSION

The paper presents and describes one of the additional technical devices that is used for equalizing initially different tensile forces in the loadbearing ropes of individual elevators.

The technical device called a "rope sensor" is a girder that is attached to the rope using its supports (two pegs). A fixed or sliding peg is located in the center between the rope sensor girder supports.

The system of ropes consists of at least two load-bearing steel ropes with six strands or, from the point of view of easier bending, and currently more widespread, ropes with eight strands.

Rope elevators, also referred to as traction elevators, have a cabin suspended from a system of ropes. The system of ropes consists of at least two load-bearing steel ropes with six strands or, from the point of view of easier bending, and currently more widespread, ropes with eight strands. Lifting or lowering of the car, run between the guides, is ensured by the frictional force of the steel ropes in the grooves of the traction disk of the elevator machinery. As the load-bearing capacity of the elevator increases, the required number of load-bearing ropes also increases, especially in the case where small diameter ropes are used in traction elevators. The construction of the rope does not affect the result of the experiment, because the rope is attached to the steel rope clamps by means of eye rope screw. It is installed on the screw of the rope suspension, see Fig. 4 or Fig. 7.

The rope, in which the tensile force is supposed to be determined, is threaded through the three pegs, of the rope sensor girder. The increasing tensile force in the rope struggles to straighten the twice-bent longitudinal axis of the rope into a straight line. The force that struggles to straighten the bent rope is applied perpendicularly to the rope axis. The force is directly proportional to the tensile force in the rope.

In the paper, we determined the angle, under which the rope longitudinal axis is inclined when the rope passes through three pegs of the rope sensor. The horizontal as well as vertical distances of the center axes of all three pegs have a fundamental impact on the resultant of the measured force. For an angle of the rope inclination smaller than 30°, the value of the measured force is smaller than the real value of the tensile force in the rope. For an angle of the rope inclination bigger than 30°, the value of the measured force is bigger than the tensile force in the rope.

In the paper, we present a structural proposal, 3D model and an implemented laboratory device for checking the functionality of the elevator rope sensors, which was assembled in the Research and testing laboratory for the purpose of verifying equalized forces in the elevator ropes by rope sensors with an accuracy of the equalized forces in the elevator ropes, while using mechanical or hydraulic tensile force equalizers.

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