Research Article

Leopold Hrabovský* and Karel Frydrýšek

Testing Device for Hydraulic Rope System Tensile Force Equalizing Unit

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Abstract: 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 actual weight of the car and the weight of the load must be evenly distributed among 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 paper describes the principle of operation of hydraulic balancing of tensile forces in the system of supporting ropes, which uses the laws of hydromechanics and knowledge of pressure transfer to any place in the fluid, known as Pascal's law. Balancing of differently set values of tensile forces in three supporting ropes, to values of the same size, can be simulated on a test device. This presents the correct operation of the hydraulic system and the possibility of balancing tensile forces in the system of supporting ropes described by the principle of hydraulic device.

Keywords: rope elevator, rope tensile force, fluid pressure, hydraulic tensile force equalizers

***Corresponding Author: Leopold Hrabovský:** VSB Technical University of Ostrava, Faculty of Mechanical Engineering, Institute of Transport, 17. listopadu 2172/15, 708 00 Ostrava – Poruba, Czech Republic; Email: leopold.hrabovsky@vsb.cz
Karel Frydrýšek: VSB Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Applied Mechanics, 17. listopadu 2172/15, 708 00 Ostrava – Poruba, Czech Republic; Email: karel.frydrysek@vsb.cz

1 Introduction

The traction capacity of rope elevators is defined by the fact that it is possible to transfer the force between the support means (steel ropes) and the grooves of the traction disc by friction, see Figure 1.

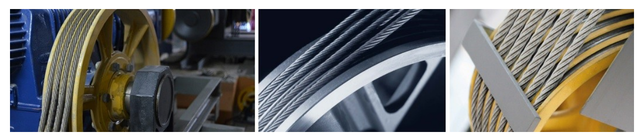

Figure 1: Load-bearing steel ropes threaded through grooves of the traction wheel.

Mobile mechanical [7] and hydraulic [9] tensile force equalizers, which allow to detect and equalize tensile forces in the system of supporting ropes of elevators, are described in [1–5].

The article [1] describes an apparatus that allows an even distribution of the strain into lift carriers, which use springe hinge of carrier ropes.

The methodology described in the article [2] by which it is possible to compare different tensile forces that are caused by the uneven distribution of loads in carrier ropes of lifts. In order to compare the applied tensile forces in a certain number of carrier ropes, it is possible to use the device called "rope hydraulic tension compensator," when, for example, building new elevators, changing carrier ropes during renovations or servicing existing lifts.

The paper [3] describes the basic principles of devices currently in use, the so-called rope tensioners, which allow detecting and adjusting primarily different tensile forces in the hoist ropes to the same value. The paper refers to two, already published design variants of portable rope straighteners, which use foil strain gauges or strain gauge sensors to detect the acting tensile forces [1] in the hoist ropes [2].

A specific design and technical solution of the device for detecting and offsetting tensile forces in the elevator carrier ropes is described in [4, 5]. The described device [4] is capable of continuously recording the time course of the instantaneous tensile forces, acting on elevator carrier ropes, when one free ends of the carrier ropes are mechanically attached to the openings of the suspension screws, which are mechanically tied to the bearing bracket [5].

The authors of this paper have not been able to find any other references that would describe a device that allows to obtain satisfactory results of balancing the tensile force of ropes.

The above-mentioned design principles of tensile force equalizers in the system of elevator supporting ropes are devices that are installed at the end points of the threaded parts of the suspension bolts, which are threaded through the holes in the supporting brackets. Hexagon nuts are screwed onto the shank of the suspension bolts in the space above the upper surface of the bracket to prevent the threaded parts of the shank bolts from sliding out of the holes in the brackets.

The advantage of mobile equalizers is that, after precise distribution of tensile forces into individual cross-sections of ropes, the equalizers are dismantled from rope suspensions and can be moved to another elevator, where the load is distributed unevenly into supporting ropes.

The device described in [8], developed for balancing tensile forces in a system of supporting ropes, has not found application in traction elevators, and is, therefore, not commonly used for balancing tensions in elevator ropes. However, the application of a hydraulic tensile force compensator in ropes has found application and is commonly used in mining equipment with friction discs.

2 Testing device designed to equalize tensile forces in ropes

The testing device, see Figure 2 and Figure 3, consists of a welded steel frame structure I, which consists of stands, upper and lower platform; hydraulic unit II with hydraulic cylinders *2.1* to *2.3* [12]; and measuring apparatus III with tension force sensors *12.1* to *12.3* [13].

The upper platform of the frame structure I is welded from nine pieces of TR 4HR 40 × 3, the lower platform is also welded from nine TR 4HR 40 × 3 profiles. The upper and lower platforms are 1.200 mm apart; this distance is defined by stands made of TR 4HR 40 × 3 profiles.

Seven suspension nuts M8 (ČSN 021669) are attached to the profile *1.2* of the upper platform of the steel frame structure I by means of three M8 × 55 screws. Carabiners are threaded into the eyelets of the suspension nuts, which at the same time are also threaded into the eyelets of the suspension bolts. The threaded parts of the suspension

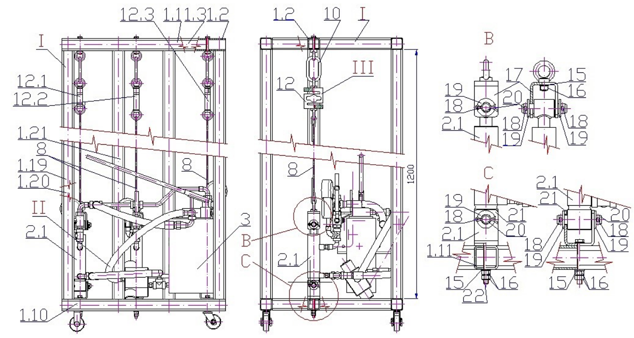

Figure 2: Test device – hydraulic equalizer of rope tensile force, 2D construction design

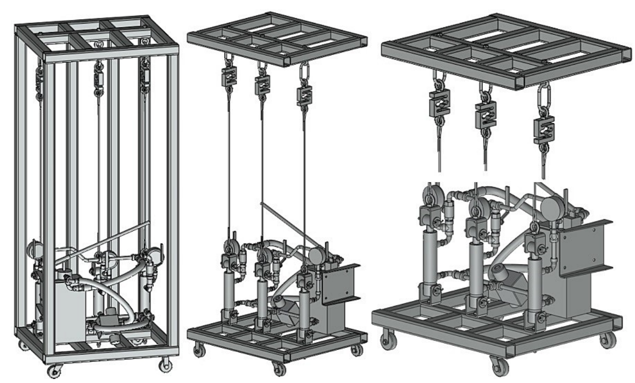

Figure 3: 3D model of hydraulic equalizer of rope tensile force test device created in SolidWorks 2012×64 SP 5.0

bolts are screwed into the internal M8 × 1.25 threads in the upper surfaces of the tensile force transducers *12.1* to *12.3*.

Hanging screws are screwed into each sensor *12*, into a hole with an internal thread M8 × 1.25 in their lower faces. The carabiners are threaded through the eyes of the suspension bolts, and the carabiners are also threaded through the rope eyelets. The ends of the six-strand steel ropes *8* are threaded through the cable eyelets of the construction 6 × 19M – WSC [6, 11] (of nominal diameter 4 mm, nominal strength of wires $1.77{\cdot}10^9$ Pa, and minimum breaking forces $10.25{\cdot}10^3$ N), which are terminated by eyes by rope clamps. The other ends of the steel ropes *8* are threaded onto carabiners. Rope eyelets are threaded onto the carabiners, which form the eyes of the suspension bolts. The rope *8* is connected to the eye by three rope clamps. To form eyelets at both ends of all three steel ropes *8*, three pieces of rope clamps are used (rope clamps *14* reduce the load-bearing capacity of the rope to 50%).

The threaded parts of the suspension bolts are slid into holes ϕ 9 mm in the brackets *17*, see view B in Figure 2 shown for the hydraulic cylinder *2.1*. To prevent the hinge screw from sliding out of the piston rod bracket *17*, a nut *15* is threaded on the threaded part of the hinge screw *11* from the inner underside of the bracket surface *17* and a nut *16* is screwed on. The bracket *17* is mechanically connected to the piston rod of the hydraulic cylinder *2.1* by a pin *20* (ϕ = 16 mm). To prevent the pin *20* from sliding out of the holes in the bracket *17*, the pin *20* is fitted on the left and right sides with a washer *19* and a cotter pin *18*.

The interconnection of the profile *1.2* of the upper platform of the steel construction *I* with one of the three hydraulic cylinders *2.1* to *2.3* is secured by the interconnection of machine parts (see central upper view in Figure 2) screw, suspension nut, carabiner, steel rope *8*, carabiner, suspension screw, tensile force sensor *12*, suspension screw, bracket, pin and piston rod of hydraulic cylinder *2*.

The bodies of the hydraulic cylinders *2.1* to *2.3* are mechanically connected by pins *20* to the brackets *17*, see view C in Figure 2. M8 × 70 *22* screws are threaded through a ϕ 9 mm hole in the brackets *17*, their shafts passing through holes in the profile *1.11* of the lower platform of the steel construction *I*. Washers *15* are threaded on the threaded part of the screws *22* protruding from the lower part of the profile *1.11*.

The prestressing of the rope *8*, the so-called derivation of a certain magnitude of the tensile force F_i [N] in the rope *8*, is achieved by tightening the screw against the profile *1.2* of the upper platform, or the screw against the profile *1.11* of the lower platform, of the frame construction *I* of the test device designed for equalizing tensile forces in the ropes.

If, in the case of "i" identical hydraulic cylinders, the spaces under the pistons are filled with fluid, then at different tensile forces F_i [N] in the "i" support ropes (assuming prevention of leakage of hydraulic fluid from the spaces under the hydraulic cylinder pistons), different pressures p_i [Pa] are derived in "I" hydraulic cylinders. A higher tensile force in the "i" support rope mechanically transmitted to the piston rod of the hydraulic cylinder exerts a higher pressure in the space under the piston of the body of this hydraulic cylinder than a tensile force of lower magnitude, see (1). If the different "i" pressures under the pistons "i" of the hydraulic cylinders are to be equalized, it is necessary to interconnect the spaces under the pistons, see Figure 5, of all hydraulic cylinders by hydraulic lines, which are a part of the hydraulic unit *II*, see Figure 4.

3 Hydraulic unit of testing device designed to equalize tensile forces

The hydraulic unit *II*, see Figure 4, of the testing device for tensile force in the ropes makes it possible to achieve, in the final state, the setting of equal magnitudes of tensile forces F_i [N] in the "i" load-bearing ropes (*i.e.*, the rope system, see Figure 1, which were different in the initial state).

Fluid is supplied under pressure p [Pa] via the manual lever of the hydraulic single-action pump *3* [10], through the open valve *4.4* via a hydraulic line (shown in green in Figure 5a) to valves *4.1* to *4.3*. If valves *4.1* to *4.3* are closed and valve *4.4* is open, then it is possible to read the magnitude of pressure p [Pa] of the hydraulic fluid in the line on the pressure gauge 5.4, which is connected to the safety valve *6*.

In this case, the pressure gauges *5.1* to *5.3* show the magnitudes of the pressures p_{0i} [Pa] under the pistons in the hydraulic cylinders *2.1* to *2.3* [12]. As all three cylinders *2.1* to *2.3* are of identical design, it can theoretically be assumed that the diameters of the pistons d_1 [m] to d_3 [m] and the diameters of the piston rods d_{p1} [m] to d_{p3} [m] of the hydraulic cylinders 2.1 to *2.3* are identical ($d_i = 3.2 \cdot 10^{-2}$ m, $d_{pi} = 2 \cdot 10^{-2}$ m), and the cross-sections of the cylinders below the pistons *2.1* to *2.3* can thus be expressed as $S_i = 4.9 \cdot 10^{-4}$ m^2, and the cross-sections of the cylinders above the pistons *2.1* to *2.3* as $S_{pi} = 8.04 \cdot 10^{-4}$ m^2. The permissible pressure in the hydraulic cylinders is set by the manufacturer to p_{dov} = 150 bar = $1.5 \cdot 10^7$ Pa, and the maximum tensile force of the pistons $F_{max} = p_{dov} \cdot S_i = 7.35 \cdot 10^3$ N.

The magnitude of the pressure p_{0i} [Pa] in the ith hydraulic cylinder (where i = 1 to 3) is given by the size of the tensile force F_i [N] (must by less than F_{max} [N]), which acts in the ith load-bearing rope, see (1):

$$p_{01} = \frac{F_1}{S_i}\ [\text{Pa}], \quad p_{02} = \frac{F_2}{S_i}\ [\text{Pa}] \quad p_{03} = \frac{F_3}{S_i}\ [\text{Pa}] \qquad (1)$$

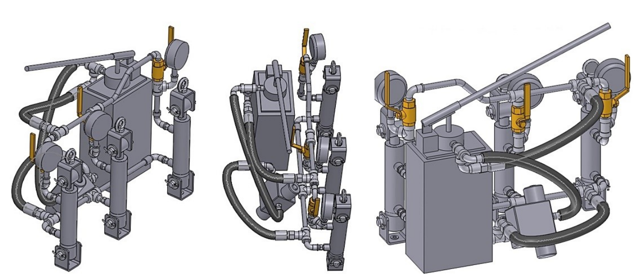

Figure 4: Hydraulic unit of the rope tensile forces testing device

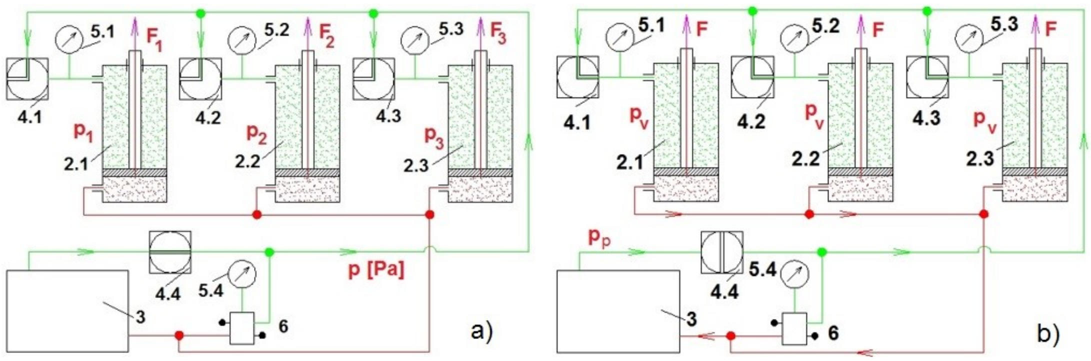

Figure 5: Diagram of the hydraulic circuit of the rope tensile force testing device

If the magnitudes of tensile forces F_i [N] are different, then, based on the relationship (1), it is evident that even the magnitudes of the pressures p_{0i} [Pa] in the ith hydraulic cylinder are different. Equalizing the different pressures p_{0i} [Pa] in all three hydraulic cylinders and also the pressure p_p [Pa] of the hydraulic fluid in the lines is ensured as follows: first, it is necessary to close valve *4.4* of the hydraulic pump *3*, then open valves *4.1* to *4.3*, see Figure 5b, whereby the mutual pressures (in the spaces below the pistons) in hydraulic cylinders are equalized to the value p_v [Pa] (2), under the assumption that the volume V_p [m^3] of the fluid in the inflow lines of the hydraulic unit and even the volume V_{vi} [m^3] of the fluid under the pistons of all "i" cylinders are of equal size ($V_{v1} = V_{v2} = V_{v3} = V_p = V$ [m^3]):

$$p_v = \frac{\sum p_{0i} + p_p}{4} = \frac{p_{01} + p_{02} + p_{03} + p_p}{4} \text{ [Pa]} \qquad (2)$$

When extending the piston rods from the hydraulic cylinder bodies *2.1* to *2.3*, underpressure occurs in the spaces above the pistons of the hydraulic cylinders *2*, due to which hydraulic fluid is sucked from the tank of the manual pump *3* through the lines (shown on Figure 5a and Figure 5b in red) and injected above the pistons of the hydraulic cylinders *2*.

As the pistons slide into the hydraulic cylinders *2.1* to *2.3*, the hydraulic fluid is pushed out of the space above the pistons and taken by the lines to the reservoir of the manual pump *3*.

4 Experimental measurement of tensile forces in ropes

Experimental measurement performed on the testing device (see Figure 8) was undertaken in three separate and independent experiments.

I. Experimental measurement No. 1

Via the manual pump *3*, hydraulic fluid was introduced through open valves *4.1* and *4.4* and closed valves *4.2* and *4.3*, under pressure p_p [Pa] under the piston of the hydraulic cylinder *2.1*. After closure of valve *4.4* and subsequently even valve *4.1*, the pressure $p_{5.1}$ [Pa] of the fluid under the piston of the hydraulic cylinder *2.1* was read on the pressure gauge *5.1*. The pressure of the fluid under the piston of the cylinder *2.1* caused the piston to slide into the body of the cylinder *2.1* and created a pressure force F_1 [N] in the rope *8.1*, which was recorded by the force sensor *12.1*, see Figure 6. According to the relationship (1), a theoretical pressure p_{01} [Pa] was created below the cylinder piston *2.1*. The fluid pressure under the cylinder piston $p_{5.1}$ [Pa], p_{01} [Pa] and the tensile force F_1 [N] were recorded in Table 1.

At this point, valve *4.4* was opened (with valves *4.1* and *4.3* closed), and then valve *4.2* was opened. Via the manual pump *3*, the hydraulic fluid was under pressure p_p [Pa] under the piston of the hydraulic cylinder *2.2*. With the closing of valve *4.4* and subsequently also valve *4.2*, a reading was taken on the pressure gauge *5.2* of the pressure $p_{5.2}$ [Pa] of the fluid under the piston of the hydraulic cylinder *2.2*. From the pressure of the fluid under the piston of cylinder *2.2* the tensile force F_2 [N] in the rope *8.2* was derived, which was recorded by the force sensor *12.2*, see Figure 6. According to the relationship (1), the theoretical pressure p_{02} [Pa] under the cylinder *2.2* was calculated. The pressures of the fluid under the piston of the cylinder $p_{5.2}$ [Pa], p_{02} [Pa] and the tensile force F_2 [N] were recorded in Table 1.

Now, valve *4.4* was opened (with closed valves *4.1* and *4.2*) followed by valve *4.3*. The manual pump *3* was used to bring the hydraulic fluid under pressure p_p [Pa] under the piston of the hydraulic cylinder *2.3*. Upon the closing of valve *4.4* and then even valve *4.3*, the pressure gauge *5.3* showed a pressure of $p_{5.3}$ [Pa] for the fluid under the piston of the hydraulic cylinder *2.3*. The pressure of the fluid under the piston of cylinder *2.3* created a tensile force F_3 [N] in

Table 1: Tensile forces in ropes and the pressure of fluid in the hydraulic cylinders

i	F_1	F_2	F_3	p_{01}	p_{02}	p_{03}	$p_{5.1}$	$p_{5.2}$	$p_{5.3}$	p_p	F	p_v	p_v
		N			Bar			Bar			N	bar	10^6 Pa
1*[1]	1,238.9	692.5	2,022.0	25.3	14.1	41.3	26	16	42	42	790.5	16.3	1.6
2	1,238.9	1,248.7	2,205.0	25.3	25.5	45.0	26	26	46	46	906.1	18.5	1.8
3*[2]	1,254.8	1,167.5	1,210.5	25.6	23.8	24.7	26	25	26	26	560.9	11.4	1.1

*[1] see Figure 6. Tensile forces in ropes *8* detected by sensors *12* derived from fluid pressure in hydraulic cylinders *2*

*[2] see Figure 7. Tensile forces in ropes *8* detected by sensors *12*

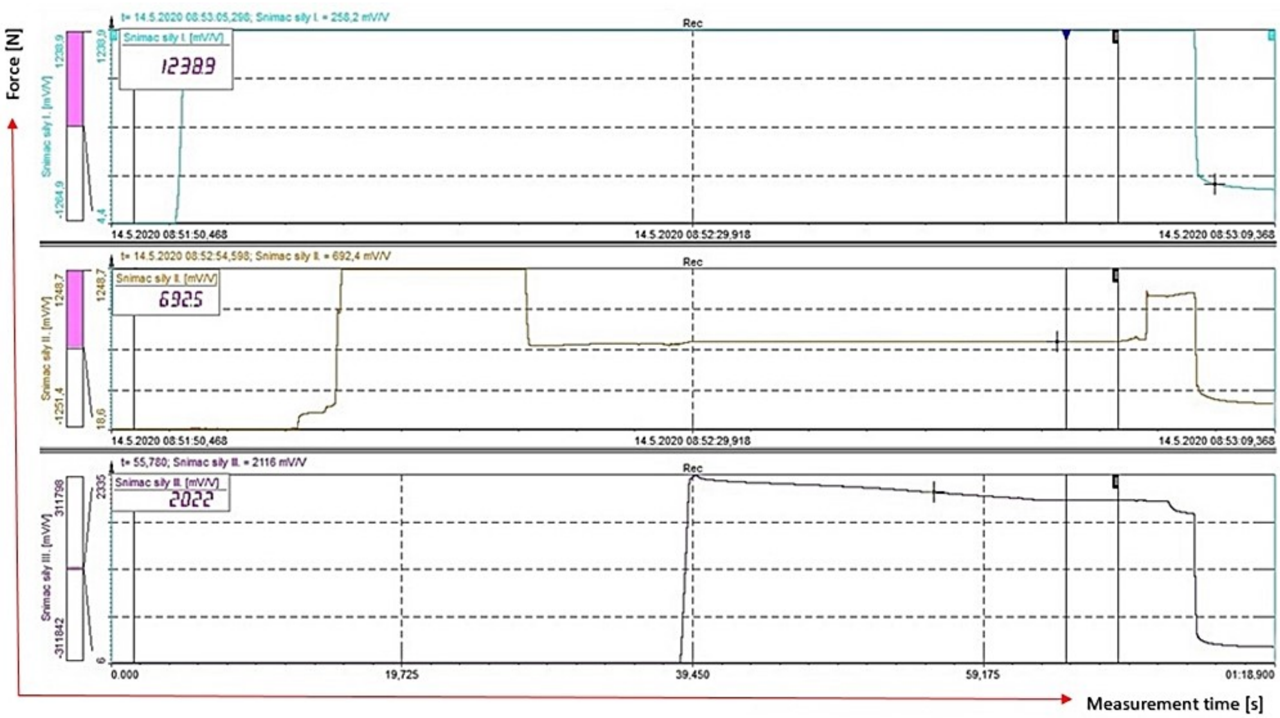

Figure 6: Tensile forces in ropes *8* detected by sensors *12* created by the fluid pressure in the cylinders *2*

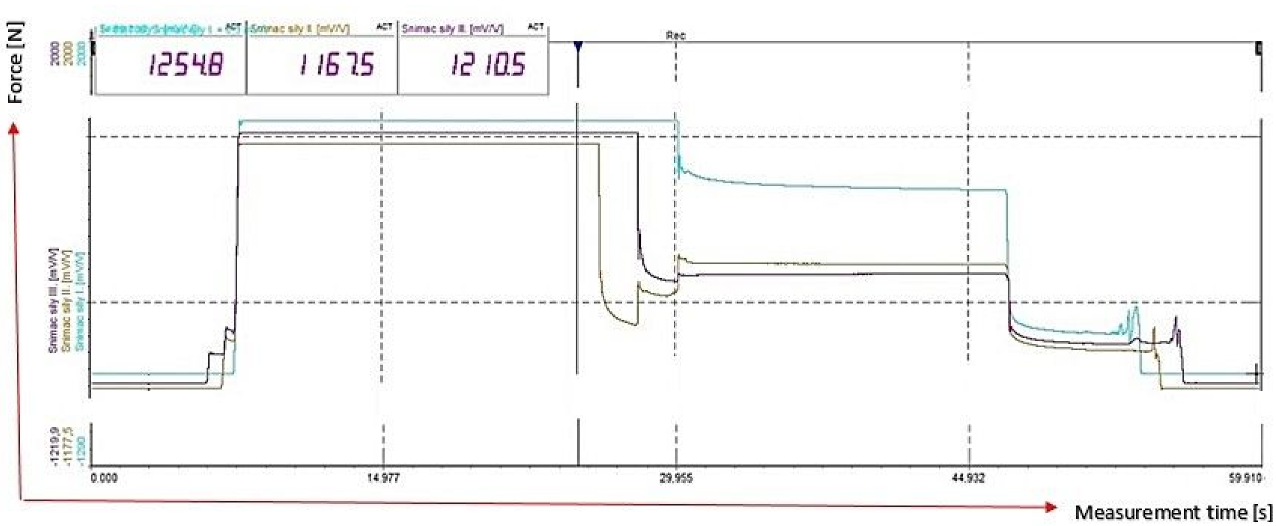

Figure 7: Tensile forces in ropes *8* detected by tensile force sensors *12*

the rope *8.3*, which was recorded by the force sensors *12.3*, see Figure 6. According to the relationship (1), a theoretical pressure p_{03} [Pa] under the piston of the cylinder *2.3* was calculated. The pressures of the fluid under the pistons of the cylinders $p_{5.3}$ [Pa], p_{03} [Pa] and tensile force F_3 [N] were recorded in Table 1.

With valves *4.1* to *4.4* shut, valves *4.1* to *4.3*, were gradually opened, which equalized the pressure of the fluid below the cylinder pistons *2.1* to *2.3* with the pressure of the fluid in the hydraulic lines.

After opening valves *4.1* to *4.3*, the pressures of the fluid beneath the cylinder pistons *2i* and the pressure in the lines of the hydraulic unit were equalized to the same magnitude p_v [Pa], and all ropes *8i* had a tensile force F_i [N] of equal magnitude.

The graphical course of the tensile forces F_1 [N] to F_3 [N], detected by the force sensors *12*, which were derived from the pressure of the fluid brought under the pistons of the hydraulic cylinders *2*, with valves *4.1* to *4.4* open, recorded in the environment of Dewesoft X2 SP5 software, are shown in Figure 7.

II. Experimental measurement No. 2

The hydraulic pump *3* was used to bring fluid under pressure of magnitude *p* [Pa] via the hydraulic lines (with valves *4.1* to *4.4* open, see Figure 5) below the cylinder pistons *2i*. The pressure of the fluid below the cylinder pistons *2i* caused the pistons to slide into the bodies of the cylinders *2i* and the derivation of pressure forces in the ropes *8i*, whose magnitudes *F* [N] were registered by the force sensors *12.i*. With valve *4.4* closed, the pressure of the fluid in the hydraulic circuit and below the cylinder pistons *2i* reached p_p [Pa], which can be expressed according to the relationship (3), when the value of the force F [N], which was detected by the sensors *12i* is known, and subtracted on computer in the Dewesoft X2 SP5 software environment.

$$p_p = \frac{F}{S_i} \text{[Pa]} \quad (3)$$

With valves *4.1* to *4.3* closed and a gradual tightening of the screws *7* against the suspension nuts *9* in the rope tensile force testing device, see Figure 2, differing tensile forces F_i [N] (where $i = 1$ to 3) were derived in individual cross-sections of the load-bearing ropes *8* [11], see Figure 2. The maximum tensile force F_{sD} [N], which it was possible to generate in the rope, was given by $m_{sD} = 250$ kg ($F_{sD} = 2.45{\cdot}10^3$ N), the load permitted by the tensile force sensor *12* [13].

The magnitudes of the tensile forces F_i [N] registered by the tensile force sensors *12* were recorded by the Dewesoft DS-NET measuring equipment and displayed on a PC monitor in the Dewesoft X2 SP5 software environment.

From the registered tensile forces F_i [N], the effective pressures in the cylinders p_{0i} [Pa] were calculated with a known diameter S_i [m^2] of cylinders *2.1* to *2.3*, according to relationship (1). The calculated pressures p_{0i} [Pa] were compared with the values of the pressures $p_{5.1}$ [Pa] to $p_{5.4}$ [Pa], read from the pressure gauges *5.1* to *5.4*, see Tables 2 to 4.

When opening valve *4.1*, with valves *4.2* to *4.4* closed, the fluid pressure p_{01} [Pa] under the piston of cylinder *2.1* (fluid volume under piston of cylinder V_{v1} [m^3]) and a pressure p_p [Pa] in the inlet lines (fluid volume in lines V_p [m^3]) of the hydraulic unit were equalized to a pressure of p_1 [Pa],

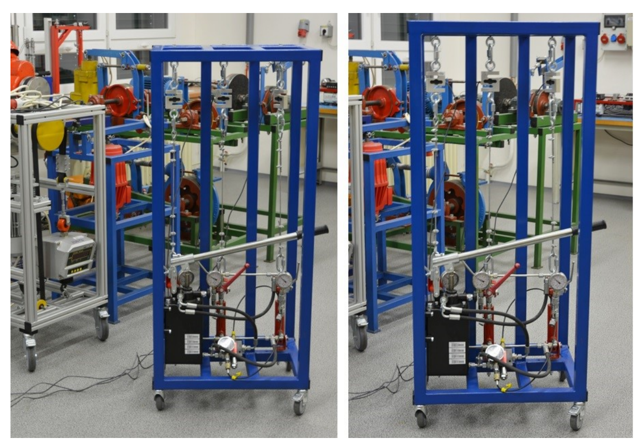

Figure 8: Executed testing device of a hydraulic tensile force equalizer

Table 2: Tensile force in rope *8.1* and pressure of the fluid in the hydraulic lines and cylinder *2.1*

i	F	F_1	p_p	p_{01}	$p_{5.4}$	$p_{5.1}$	p_1	$p_{5.4-1}$	F_{1k}
	N		10^6. Pa		bar		10^6. Pa	bar	N
1*1	406.5	938.2	0.83	1.91	10	20	1.37	15	672.4
2	714.7	1,238.9	1.46	2.53	15	30	1.99	20	976.8
3*2	986.7	1,241.9	2.01	2.53	20	30	2.27	25	1,114.3

*1 see Figure 9, *2 see Figure 10, and Figure 11

Table 3: Tensile force in the rope *8.2* and fluid pressure in the hydraulic line and cylinder *2.2*

i	F_{1k}	F_2	p_1	p_{02}	$p_{5.4}$	$p_{5.2}$	p_2	$p_{5.4-2}$	F_{2k}
	N		10^6. Pa		bar		10^6. Pa	bar	N
1	672.4	1,056.3	1.76	2.16	20	20	1.76	20	864.3
2	976.8	811.2	1.99	1.66	20	20	1.82	20	894.0
3*1	1,114.3	1,256.7	2.27	1.66	25	20	1.96	20	962.8

*1 see Figure 10 and Figure 11

Table 4: Tensile force in rope *8.3* and fluid pressure in the hydraulic lines and cylinder *2.3*

i	F_{2k}	F_3	p_2	p_{03}	$p_{5.4}$	$p_{5.3}$	p_3	$p_{5.4-2}$	F_k
	N		10^6. Pa		bar		10^6. Pa	bar	N
1	864.3	816.7	1.76	1.67	20	20	1.72	20	840.5
2	894.0	1,126.8	1.82	2.30	20	25	2.06	20	1,010.4
3*1	962.8	1,259.0	1.96	2.3	20	25	2.13	25	1,044.8

*1 see Figure 10 and Figure 11

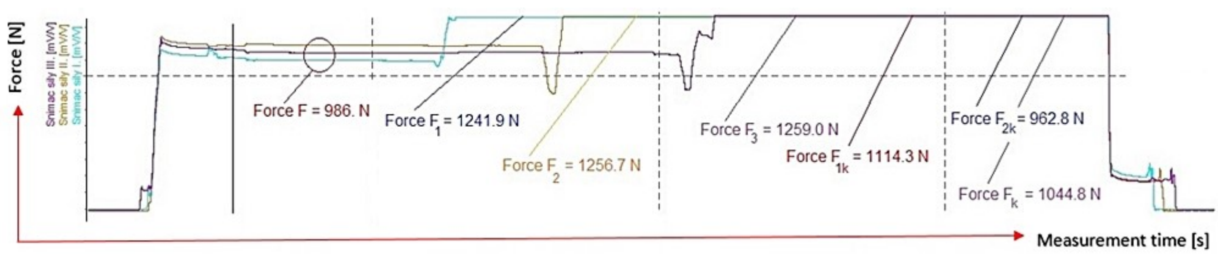

Figure 9: Tensile force in rope *8.1* detected by tensile force sensor *12.1*

see (4):

$$p_{01} \cdot V_{v1} + p_p \cdot V_p = p_1 \cdot (V_{v1} + V_p) \Rightarrow \quad (4)$$

$$p_1 = \frac{p_{01} \cdot V_{v1} + p_p \cdot V_p}{(V_{v1} + V_p)} \text{ [Pa]}$$

Under the assumption that the fluid volume in the inlet lines V_p [m^3] of the hydraulic unit is equal to the volume of fluid under the piston *2.1* of the hydraulic cylinder V_{v1} [m^3], this means $V_{v1} = V_p = V$ [m^3], relationship (4) can be modified into the form of (5), which is equal to the relationship (2):

$$p_1 = \frac{V \cdot (p_{01} + p_p)}{2 \cdot V} = \frac{F_1 + F}{2 \cdot S_i} \text{ [Pa]} \quad (5)$$

With a drop in pressure p_{01} [Pa] under the piston of cylinder *2.1* to a pressure value of p_1 [Pa], a change in tensile force occurred in rope *8.1*, to the value F_{1k} [N], see (5) and Table 2.

$$F_{1k} = p_1 \cdot S_i = \frac{F_1 + F}{2} \text{ [N]} \quad (6)$$

Figure 9 shows show the graphical course of the magnitude of tensile force in rope *8.1* registered by the force sensor *12.1* (see Figure 2) in the Dewesoft X2 SP5 software environment.

With valve *4.1* open and the opening of valve *4.2*, with valves *4.3* and *4.4* closed, the fluid pressure p_{02} [Pa] under the piston of cylinder *2.2* and a pressure p_1 [Pa] in the inlet lines of the hydraulic unit were equalized to a pressure of p_2 [Pa], see (7) and Table 3.

$$p_{02} \cdot V_{v2} + p_1 \cdot V_p = p_2 \cdot (V_{v2} + V_p) \Rightarrow \quad (7)$$

$$p_2 = \frac{p_{02} \cdot V_{v2} + p_1 \cdot V_p}{V_{v2} + V_p} \text{ [Pa]}$$

Under the assumption that the fluid volume in the inlet lines V_p [m^3] of the hydraulic unit is equal to the volume of fluid under the piston *2.2* of the hydraulic cylinder V_{v2} [m^3], this means $V_{v2} = V_p = V$ [m^3], relationship (7) can be modified into the form of (8):

$$p_2 = \frac{V \cdot (p_{02} + p_1)}{2 \cdot V} == \frac{2 \cdot F_2 + F_1 + F}{4 \cdot S_i}] \text{ [Pa]} \quad (8)$$

With a drop in pressure p_{02} [Pa] under the piston of cylinder *2.2* to a pressure value of p_2 [Pa], a change in tensile force occurred in rope *8.2*, to the value F_{2k} [N], see (9) and Table 3.

$$F_{2k} = p_2 \cdot S_i = \frac{2 \cdot F_2 + F_1 + F}{4} \text{ [N]} \quad (9)$$

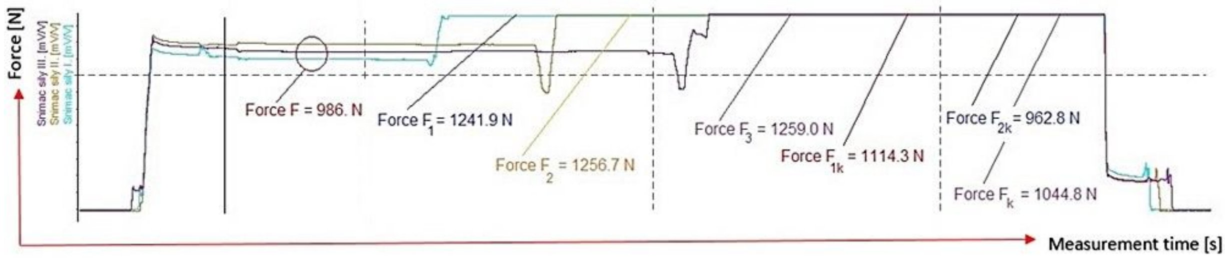

Figure 10: Tensile force in ropes *8.1* to *8.3* detected by tensile force sensors *12.1* to *12.3*

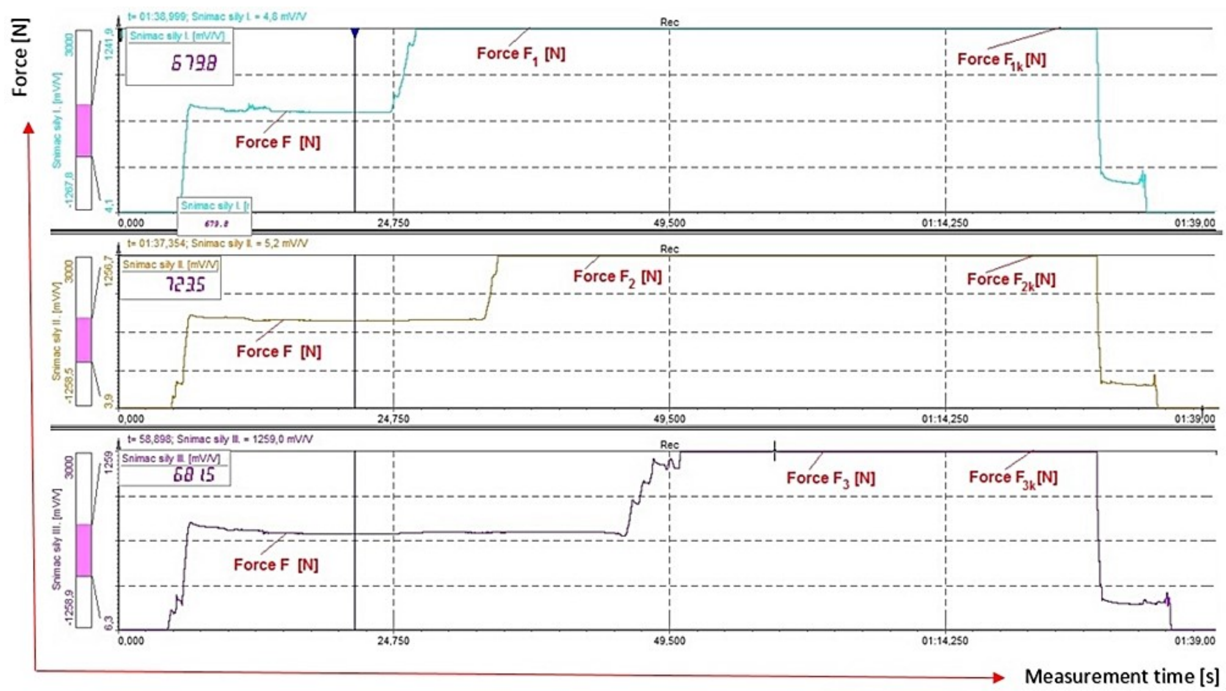

Figure 11: Tensile force in ropes *8.1* to *8.3* detected by the tensile force sensors *12.1* to *12.3*

With valves *4.1* and *4.2* open and opening valve *4.3*, while closing valve *4.4*, the pressure fluid pressure p_{03} [Pa] under the piston of cylinder *2.3* and a pressure p_2 [Pa] in the inlet lines of the hydraulic unit were equalized to a pressure of p_3 [Pa], see (10) and Table 4.

$$p_{03} \cdot V_{v3} + p_2 \cdot V_p = p_3 \cdot (V_{v3} + V_p) \Rightarrow \qquad (10)$$

$$p_3 = \frac{p_{03} \cdot V_{v3} + p_2 \cdot V_p}{V_{v3} + V_p} \text{ [Pa]}$$

Under the assumption that the fluid volume in the inlet lines V_p [m^3] of the hydraulic unit is equal to the volume of fluid under the piston *2.3* of the hydraulic cylinder V_{v3} [m^3], this means $V_{v3} = V_p = V$ [m^3], relationship (10) can be modified into the form of (11):

$$p_3 = \frac{p_{03} + p_2}{2} = \frac{4 \cdot F_3 + 2 \cdot F_2 + F_1 + F}{8 \cdot S_i} \text{ [Pa]} \qquad (11)$$

$$F_k = p_3 \cdot S_i = \frac{4 \cdot F_3 + 2 \cdot F_2 + F_1 + F}{8} \text{ [N]} \qquad (12)$$

Figure 10 and Figure 11 show the graphical course of the magnitude of the tensile forces in ropes *8i*, registered by the tensile force sensor *12i* (see Figure 2) in the Dewesoft X2 SP5 software environment.

III. Experimental measurement No. 3

With valves *4.1* to *4.4* closed, the screws *7i* were gradually tightened against the nuts *9.1* in the rope tensile force testing device, see Figure 2. By tightening of the screws *7i*, tensile forces F_i [N] (where $i = 1$ to 3) were derived in ropes *8i*, which were registered by the tensile force sensors *12i*.

The magnitudes of tensile forces F_i [N] were recorded in Table 5. According to the relationship (1), pressures p_{0i} [Pa] below the cylinder pistons *2i* were calculated. The theoretically calculated pressures p_{0i} [Pa] were verified with the pressures measured $p_{5.i}$ [bar] by the pressure gauges *5i*.

Table 5: Rope tensile forces *8.i* and the fluid pressures in the hydraulic lines and cylinders *2.i*

i	F_1	p_{01}	$p_{5.1}$	F_{1k}	p_1	$p_{5.4-1}$	F_2	p_{02}	$p_{5.2}$
	N	10^6. Pa	bar	N	10^6. Pa	Bar	N	10^6. Pa	bar
1	**645.8**	1.32	15	201.2	0.41	6	**1,187.5**	2.42	25
2	**601.7**	1.23	15	202.6	0.41	6	**1,007.2**	2.06	20
3	**399.2**	0.81	10	134.4	0.27	4	**342.7**	0.70	8
i	F_{2k}	p_2	$p_{5.4-2}$	F_3	p_{03}	$p_{5.3}$	F_k	p_3	$p_{5.4-2}$
	N	10^6. Pa	bar	N	10^6. Pa	bar	N	10^6. Pa	bar
1	432.6	0.88	10	**596.8**	1.21	15	310.2	0.65	8
2	304.8	0.62	6	**841.6**	1.72	18	230.7	0.62	8
3	120.2	0.25	4	**345.7**	0.71	8	98.6	0.19	2

The subtracted values of the pressures $p_{5.i}$ [bar] below the cylinder pistons *2i* were recorded in Table 5.

After opening valve *4.4*, it can be assumed that the pressure in the hydraulic lines (with a volume of V_p [m^3]) is equal to zero (*i.e.*, $p_p = 0$ Pa).

After closing valve *4.4* and opening valve *4.1*, the pressures under the piston of cylinder *2.1* and in the hydraulic line were equalized. According to the relationship (4), it is possible to determine the magnitude of the pressure p_1 [Pa] in the hydraulic circuit, see Table 5, which was compared with the pressure $p_{5.4-1}$ [bar] read on the pressure gauges *5.4* and *5.1*. The theoretically calculated pressure p_{02} [Pa] according to (1) was compared with the measured pressure $p_{5.2}$ [bar], read on the pressure gauge *5.2*.

After this, valve *4.2* was opened, and the pressure p_2 [Pa] was determined in the hydraulic circuit according to relationship (8). The force of the pressure p_2 [Pa] in the hydraulic circuit was compared with the pressure $p_{5.4-2}$ [bar] read on the pressure gauges *5.4*, *5.2*, and *5.1*.

Finally, valve *4.3* was opened, and according to relationship (11), the end pressure p_3 [Pa] in the hydraulic circuit was determined. The theoretically calculated pressure p_3 [Pa] according to (11) was compared with the measured pressure $p_{5.4-3}$ [bar], read on the pressure gauges *5.4*, *5.1*, *5.2*, and *5.3*.

The theoretically calculated pressure, p_3 [Pa], in the hydraulic circuit of the testing device for tensile forces in ropes derives tensile forces F [N] in ropes *8i* with a size of F_k [N], see relationship (12). Tensile forces F_1 [N] to F_3 [N], F_{1k} [N], F_{2k} [N], F_k [N] subtracted from PC z in the Dewesoft X2 SP5 software environment were recorded in Table 5.

5 Conclusion

The paper deals with a test device, the so-called hydraulic rope tensile force equalizer, which can equalize (originally different magnitudes) tensile forces in ropes by changing the fluid pressure in interconnected hydraulic cylinders.

The second section of this paper presents a 2D structural design as well as a 3D model of the test equipment and lists and describes the basic machine components that were used to implement a laboratory model of a hydraulic equalizer of tensile forces in ropes.

Part of the paper is a description of the interconnection of hydraulic elements and a description of the operation of the hydraulic unit, which brings fluid from the tank to these elements under the pistons of hydraulic cylinders.

The main part of the paper is a section in which the procedures of three performed experimental measurements are defined, which were undertaken to verify the correct functionality and simulate the operation of the hydraulic equalizer of tensile forces in ropes.

The possible way of how to achieve uniform load distribution into two or more carrier ropes in the traction lift using a rope hydraulic tension compensator is given in the text of this paper.

If the pressure in the liquid is reached below the pistons of hydraulic cylinders, then the compressive force (proportional to the highest value of all the loads acting on all the springs before installation of tension compensator) acts on the first most compressed spring. Also, for all other springs of all suspension bolts, this pressure force acts when the pressure in the liquid is reached below the pistons of the hydraulic cylinders.

By increasing the applied pressure under the pistons of the hydraulic cylinders above the pressure, all the springs are compressed by the compressive force transmitted by the cylindrical bodies from the hydraulic cylinders.

If a uniform load distribution to all cross-sections of carrier ropes is achieved as described above, all components of the rope hydraulic tension compensator must be removed from the screw hinge of carrier ropes. When disassembling, it is necessary to extend all piston rods from hydraulic cylinders to the maximum possible position. This is ensured by the hydraulic power unit. The lever of the manual hydraulic pump pumps the hydraulic fluid through a line through the open one- and the two-way valve (adjusted to a suitable position) to the quick coupling. A hydraulic hose is connected to the quick coupling, which supplies the liquid above the pistons of hydraulic cylinders. Another hydraulic hose connects the spaces under the pistons of hydraulic cylinders. The fluid from under the pistons of hydraulic cylinders is discharged through the hydraulic hose to the quick coupling. The hydraulic fluid is routed via a pipeline in the hydraulic power unit via a two-way valve (adjusted to a suitable position into the hydraulic pump tank.

In contrast to the known principle of the hydraulic compensator, the described device can be provided with strain gauge load cells that can detect instantaneous tensile forces in carrier cables, record them, and use them for certificate processing purposes.

The described rope hydraulic tension compensator can fully fulfill the function for which it has been designed without the use of strain gauge load cells. If the compensator is not equipped with a strain gauge, then the piston rod of the hydraulic cylinder is connected to the cylindrical body mechanically. The threaded end portion of the shank of bolt is screwed onto the internal thread of the body.

Double-acting hydraulic cylinders, which equalize the initially different tensile forces in the ropes to the same values, are connected via hydraulic pressure hoses to the hydraulic power unit. With the hydraulic power unit, the hydraulic fluid is pumped from the tank through the manual hydraulic pump via suitably open or closed hydraulic valves to the spaces below or above the hydraulic cylinder pistons. In the "under/above the piston" space of cylinders, where the hydraulic fluid pressure is supplied by the hand pump, the piston moves in the cylinder, and the hydraulic fluid from the "below/above the piston" space moves to drain the hydraulic fluid back into the tank.

The device described in this paper, developed for balancing tensile forces in a system of supporting ropes, has not found application in traction elevators and is therefore not commonly used for balancing tensions in elevator ropes. However, the application of a hydraulic tensile force compensator in ropes has found application and is commonly used in mining equipment [13] with friction discs.

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