Friction Coefficient of Load-Bearing Elements of Building Technical Facilities

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Abstract. The engineering activities in construction are a set of a wide range of activities that are performed, for example, for the purpose of the installation or mandatory replacement or modernisation of lifts. On the territory of the Czech Republic, there are standards that strictly prescribe what is required to repair and replace on an existing lift in order to ensure the greatest possible safety when riding the lift, but also the high reliability and dependability of the lift. Polyurethane lift belts were developed and used for the vertical movement of lifts at the turn of the millennium. Due to patent rights, they were reserved solely for selected manufacturers of lifts. The classic ropes with a circular cross-section are currently being replaced more and more frequently in construction engineering by flat ropes or belts due to their undisputed advantages.

This paper describes the construction design and implemented equipment on which it is possible to determine, in the laboratory, the value of the rope friction coefficient in the given type of traction disc grooves. To be specific, this paper describes the friction coefficient determined in a laboratory, in dry and clean conditions, of a flat rope with a polyurethane sheath on the circumference of the traction disc. The friction coefficient values were acquired indirectly, i.e. by measuring the tractive forces in the approaching and receding rope branches on the rotating traction disc powered by an electric drive. The friction coefficient was determined from the measured values of both tractive forces during the course of a single experimental measuring through a calculation from Euler’s relation. The value of the receding force was obtained using two methods that differ from each other in the manner of attachment (by a screw or compression springs) of the end of the rope to the load-bearing construction of the measuring device. The information obtained from the experimental measurements made it possible to compare the measured values of the rope friction coefficients with the values given by the manufacturers and to make the conclusion that the method used to determine the friction coefficients and the set of laboratory activities and procedures for determining the friction coefficients on the testing equipment is suitable and usable in practice.

1. Introduction

The provisions of Section 28 (2) of Decree No. 268/2009 Coll., on Technical Requirements for Construction [8] specify: “Lifts must be installed in new blocks of flats with entrances to flats on the level of the fifth and higher storeys (the 2nd storey = 1st floor) or an attic on the same level. When renovating completed blocks of flats with entrances to flats on the level of the fifth and higher storeys or an attic on the same level, lifts do not have to be installed nor do existing lifts need to be extended to
The most commonly installed lifts are electric traction or rope lifts \([9]\) driven by a motor whose rotor is connected to a traction disc, i.e. a rope pulley. The lift cabin is suspended on one end of the system by (at least two) ropes, which are subsequently wrapped over a friction disc (through the disc grooves) and it is suspended on the other end of the system by a counterweight.

Traction lifts have these advantages compared to the second-most common hydraulic lifts: higher speed, a longer life and lower expenses for operation and maintenance. The disadvantages of these lifts are considered to be - lower lifting capacity and the need for counterweights, which limit the space in the shaft and thus also the size of the cabin. Drum lifts are installed in the case of older buildings where the shafts from the former skylights did not permit the installation of a sufficiently large cabin \([10]\).

Unlike traction lifts, drum lifts do not have counterweights, which permits the maximum use of the space of the shaft for the cabin. Drum lifts \([1]\) have these advantages: higher load capacity, the maximum use of the space in the shaft (a larger cabin), more precise stopping at stations and the lower occurrence of bumps (a smoother ride). A disadvantage is the greater consumption of electricity (about 40%) as well as a higher noise level.

2. Transmission of driving force from friction disc to traction ropes

For more than a hundred years, it was not possible to imagine the replacement of the suspension devices for lifts in the form of steel ropes by another type of traction element. The means of support currently used in lifts are steel ropes \([6]\), articulated chains and flat ropes \([11, 16]\) or belts \([17]\) with a synthetic surface.

We understand the term traction (friction) drive to mean the drive of the elevator machinery with a driving pulley, where the transmission of the driving circumferential force from the disc to the rope is carried out exclusively through friction. The band of the driving pulley is grooved. Four types of grooves are known and used, i.e. U, undercut U, V and undercut V. The grooves must be made very precisely and kept in good condition, since imprecise production or uneven wear can cause the ropes to run at different radii and at different speeds as they cross the pulley. This would lead to slippage and thus to the wear and tear of the ropes and grooves. The material of the band of the pulleys with multiple grooves should be homogeneous with the same hardness in the area of all the grooves, the wear and tear is the same everywhere.

The ability to transmit the driving force by friction increases for V grooves as the angle of the wedge \(\gamma [deg]\) decreases \([4]\), while life expectancy decreases at the same time. For U or undercut U grooves, the traction ability is considerably lower than for V grooves, which often must be resolved by double wrapping of the pulley.

We understand the traction ability of a rope driving pulley to be the ability to transmit the driving force to the traction ropes. If the force is to be transmitted safely, it must also apply during the worst-case ratio of forces in the ropes (1).

\[
\frac{T_1}{T_2} \leq e^{f_\alpha} \tag{1}
\]

where \(T_1 [N]\) is the tractive force in the ropes on the approaching side of the rope pulley, \(T_2 [N]\) the tractive force in the ropes on the receding side of the rope pulley, \(f [N]\) the coefficient of the shear friction in the grooves of the rope pulley and \(\alpha [rad]\) the rope angle.
The value of the rope friction coefficient in the groove $f$ for the individual types of grooves can be calculated according to [4]. The size $f$ depends on the friction coefficient $\mu [-]$, the angle of the undercut $\beta [\text{rad}]$ and the angle of the wedge $\gamma$.

Polyurethane flat belts [11] successfully replace steel ropes [6] in passenger and freight elevators. They are an innovative lifting device for passenger and freight elevators certificated for passenger elevators according to the standard [5] and standard [4] and the Lift Directive 2014/33/EC. They represent a reliable, quiet and maintenance-free solution for modern elevators.

Elevator belts for the automotive industry [2, 3] are made of special high-resistant rubber with steel tension member. The belts are capable of transmitting very high tensile forces, have excellent flexibility and wear resistance [17]. The flat Polyrope ContiTech rope [17] (approved on the basis of the EU Lifts Directive 2014/33/16/EU) contains strong steel ropes with a diameter of 2 mm, comprised of 49 individual wires inserted and sheathed in a polyurethane sheath.

In 2006, Otis Elevator [12] announced the introduction a new model of lift [7] with a patented drive system using flat steel cables with a coating. The weight of the flat ropes is (up to 20%) lighter than regular (round cross-section) ropes and the make it possible to decrease the size of the machinery for driving the lift by up to 70%. A smaller lift machine located in the lift shaft removes the need for a separate machine room in the building.

3. Experimental determination of friction coefficient of flat rope

For the purpose of obtaining the friction coefficient of the flat rope, in order to compare this value with the value of the friction coefficient of the steel rope with a round cross-section in the groove of the friction disc, a device (Figure 2) was prepared in the Research and Testing Laboratory, on which it was possible to measure the values of the rope friction coefficient through experimentation.

![Figure 1. 3D and 2D construction design of device for experimental determination of friction coefficient of flat rope](image)

The device, see Figure 1, is comprised of a frame construction 1, to which an electric drive 2 is attached by screws. The drive unit 2 is comprised of an electric motor 3 (MR90L-4 [13]) and gearbox 4 (CMB903 B5/B14, see p 13/19 [13]). The friction disc 7 (diameter $D_k = 160 \text{ mm}$) is attached to the hollow output shaft of the gearbox 4.

One end of the flat rope 5 (F30 XHP II CONTI POLYFLAT [16]), in the approaching branch of the rope on the friction disc, is attached to an RSCC tensometric load cell 6 [14] (with a maximum load of 1000 kg), which is attached to the frame construction 1 of the described equipment. The flat rope 5 is wrapped (angle $\alpha = 3.14 \text{ rad}$) on the friction disc 7. In the receding branch, the flat rope 5, after passing
through the free pulley 8, is attached to an RSCC load cell 9 [14] (with a maximum load of 500 kg). The load cell 9 is attached to a tension lever 11, which is flexibly mounted on the frame construction 1 using a tensioning bolt 10.

**Figure 2.** Implemented device for experimental determination of friction coefficient of flat rope

During the experimental measurements of the friction coefficient of the rope in the friction disc there was a decrease in the initial value of the force $T_2$ in the device (Figure 2) in the receding branch of the friction disc. The load cell 9 detects the immediate value of this force and its time course is recorded by the DEWESoft X2 SP5 software and stored in a PC. The end of the rope 5 is attached in the receding branch of the friction disc 7 to the frame construction 1 in two ways, see Figure 1, either to the lever 11, which is supported by two compression coil springs 12 [15] with a stiffness $k_p = 20.27$ N·mm⁻¹, or to the threaded parts of a screw 13.

\[
f_j = \frac{1}{\alpha} \cdot \ln \left( \frac{T_1}{T_2} \right)
\]

(2)

According to the validity of the Euler-Eytelwein equation (1) for the transmission of force by friction, when the friction disc 7 is rotating, the initial value of the approaching force $T_1$ increases in the approaching branch of the rope on the friction disc. During the experimental measurement on the device (Figure 2), the immediate value of this force is recorded by the load cell 6.

### 3.1. Laboratory measurement under the assumption of the rope attached by a screw

According to the theory of the transmission of force by friction, relation (3) applies, i.e. the maximum circumferential force $F_{\text{max}}$ can be expressed as the difference between the approaching $T_1$ and receding $T_2$ forces.

\[
F_{\text{max}} = T_1 - T_2 = T_2 \cdot \left( e^{-\alpha} - 1 \right) [N]
\]

(3)

Figure 3 shows the course of the tractive forces $T_1$ and $T_2$ under the assumption that the end of the flat rope 5 is attached to the screw 13 (Figure 4a).

Table 1 shows the measured values of the approaching $T_1$ and receding $T_2$ forces on the friction disc
The value of the friction coefficient \( f_i \) of the flat rope \( 5 \) is given in Table 1 as well as in Table 2 by the calculation pursuant to relation (2), which is obtained by a modification of relation (1) and according to (4), which is obtained by a modification of relation (3).

![Figure 3. The measured traction forces \( T_1 \) and \( T_2 \) in the flat rope in the approaching and receding branches of the friction disc](image)

**Table 1.** Measured values of tractive forces in both branches of the flat rope

| \( i \) | 1    | 2 a | 3   | 4   | 5   |
|-------|------|-----|-----|-----|-----|
| \( T_{1i} \) [N]                  | 924.8 | 1187.2 | 1186.6 | 1224.7 | 1218.4 |
| \( T_{2i} \) [N]                  | 357.0 | 473.4 | 461.6 | 485.8 | 467.2 |
| \( F_{\text{max}} \) [N] (3)      | 597.8 | 713.8 | 725.0 | 738.9 | 751.2 |
| \( f_{1i} \) [-] (2)              | 0.31  | 0.29  | 0.30 | 0.29 | 0.31 |
| \( f_{2i} \) [-] (4)              | 0.31  | 0.29  | 0.30 | 0.29 | 0.31 |

a see Figure 3

\[
f_i = \frac{1}{\alpha} \ln \left( \frac{F_{\text{max}}}{T_2} + 1 \right) [-]
\]

The values of forces \( T_1 \) and \( T_2 \), which were obtained by measuring and were used for the calculation of the friction coefficient in Table 1 (as well as in Table 2), were deducted from the curves of the measurement curves, see Figure 3 (Figure 5). The values of both these tractive forces (which were detected by load cells 6 and 9, recorded by the measuring apparatus in DEWESoft DS-NET and displayed on the PC screen through DEWESoft X2 SP5 software) were deducted right at the moment when the tested flat rope started to slip on the circumference of the friction disc.

3.2 Laboratory measurement under the assumption of the flexible attachment of the end of the rope

Figure 5 shows the course of the tractive forces in both branches of the friction disc 7 under the assumption that the end of the rope 5 is attached to the tension lever 11 (Figure 4b). If both springs 12 (Figure 1) are compressed by a value of \( \Delta L_{pi} \) at the initial moment (before the friction disc 7 starts to rotate) of the experimental measurement, then one of the springs 12 imparts a compressive force of \( F_{pi} \) (5).

\[
F_{pi} = k_p \cdot \Delta L_{pi} [N]
\]

where \( L_{pi} [mm] \) is the compression of the spring (a change, i.e. shortening, the length of the spring
with respect to its initial length $L_0 = 48$ mm).

The value of the friction coefficient $f_{3i}$ of the flat rope 5 is determined in Table 2 by a calculation according to relation (7), which is derived according to Figure 4c. If torque $M_k [N\cdot m]$ is not applied to the circumference of the friction disc, then the size of the normal force $N [N]$ pressing the flat rope 5 into the groove of the friction disc is given by the sum of the tractive forces in both branches of the friction disc 7.

If torque $M_k$ is applied to the circumference of the friction disc, then the friction force $F_T [N]$ is applied in the contact area of the rope and the friction disc (6). At the moment the rope began to slip on the circumference of the friction disc, the force $F_T$ acquires the same size as the circumferential force $F_{\text{max}}$ (3). We get the friction coefficient $f$ by modifying relation (6) and by substituting the expression $F_{\text{max}}$ from relation (3) for $F_T$ (7).

$$\begin{align*}
N &= T_1 + T_2 [N], \quad F_{\text{max}} = T_1 - T_2 [N] \\
F_T &= N \cdot f = \left( T_1 + T_2 \right) \cdot f \Rightarrow f = \frac{F_T}{N} = \frac{F_{\text{max}}}{T_1 - T_2} [-] 
\end{align*}$$

(6)

(7)

Table 2. Measured values of tractive forces by spring compression

|   | 1    | 2$^b$ | 3    | 4    |
|---|------|------|------|------|
| $T_1$ [N] | 1465.7 | 1437.1 | 1490.8 | 1410.5 |
| $T_2$ [N] | 562.1  | 572.0  | 555.2  | 559.5  |
| $F_{\text{max}}$ [N] (3) | 903.6  | 865.1  | 935.6  | 851.0  |
| $\Delta L_{\text{pl}}$ [mm] | 13.9  | 14.1  | 13.7  | 13.8  |
| $f_{1i}$ [-] (2) | 0.31  | 0.29  | 0.31  | 0.29  |
| $f_{2i}$ [-] (4) | 0.31  | 0.29  | 0.31  | 0.29  |
| $f_{3i}$ [-] (7) | 0.45  | 0.43  | 0.46  | 0.43  |

$^b$ see Figure 5

As follows from Figure 3, when experimentally measuring the friction coefficient, there is a decrease in the initial value of force $T_2$ in the receding branch and an increase in the initial value of force $T_1$ in the approaching branch of the rope on the friction disc. It can be assumed, see Figure 4c, that the size of the receding force $T_2 (T_2 = 2 \cdot F_{\text{pl}})$ can be deduced from the compression force $F_{\text{pl}}$ (5) of both compression springs. It is difficult to measure the precise value of the compression $\Delta L_{\text{pl}}$ of a spring at the moment the rope begins to slip along the circumference of the friction disc, though the value of the compression $\Delta L_{\text{pl}}$
of the spring can be calculated from relation (5) (with the known compression force of the spring $F_{pi}$ calculated according to the relation $F_{pi} = T_2/2$).

![Figure 5. Measured tractive forces in approaching and receding branches of a flat rope](image)

4. Results and discussions

In this paper, the values of the measured approaching and receding forces at the moment the synthetic surface of a flat rope slips along the steel surface of the circumference of a driven friction disc are presented in two tables. Figure 3 and Figure 5 present the time recordings of the measured tractive forces in the approaching and receding branches of the flat rope in the DEWESoft X2 SP5 software.

A condition for obtaining the precise values of the measured forces is using calibrated measuring elements, calibrated before the beginning of each measurement by both load cells and the configuration of the proper functions of the measurement apparatus. The friction coefficient in the contact surfaces of the flat rope on the circumference of the friction disc was obtained by a calculation from the mathematically-modified Euler relation.

5. Conclusion

The paper discusses the construction design and important machinery parts that comprise the equipment on which the friction coefficient of the lift ropes in the grooves of a friction disc can be determined experimentally. If the friction disc is equipped with a U, undercut U or V groove and if the corresponding steel rope with a circular cross-section is used for the experiment, then the size of the friction coefficient of the rope in the groove of the friction disc is influenced by these parameters: condition and friction coefficient $\mu$ of the contact surfaces, angle of undercut $\beta$ and angle of wedge $\gamma$.

The paper describes the procedure of a laboratory method that was an “indirect method” for obtaining the value of the friction coefficient of the flat rope against the surface of the circumference of the friction disc. The friction coefficient was determined by a calculation from the measured sizes of the tractive forces in both branches of the rope wrapped around the friction disc. The size of the friction coefficient was obtained by the experimental measurement of the tractive forces on the described equipment in the dry and clean state of both contact surfaces.

The values of the friction coefficient depend on the microstructure of the contact surfaces; the pressure that arises in the area of the contact and in the relative speed of the movement. If the pressure in the contact is very high, there is a danger of seizing. As the relative speeds increase, the values of the friction coefficient decrease, though for high relative speeds they increase again. If the unevenness of the surfaces decreases, the value of the friction coefficient also decreases. If, however, the surface is already very smooth, its values can once again increase. A small amount of lubrication also has a large effect on the value. If the lubrication causes the surfaces of the bodies to not touch, the values of the coefficient drop to very low values.
The size of the friction force of the flat rope along the circumference of the friction disc is directly proportional to the contact force (if it is small, large enough friction is not created and excessive slipping is created), whose size is given by the sum of the sizes of the measured tractive forces in the approaching and receding branches of the friction disc.

The difference between the value of the friction coefficient determined by measuring on the equipment described in the paper and the true value of the friction coefficient depends primarily on the precision of the used load cells and on the precision of the measurement method. According to “error theory”, the “best” estimate of the actual value of the measured values and the estimate of the “absolute” benchmark (standard) errors can be found on the basis of a set of measurements.

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