Motions and forces in the rope system of aerial ropeways during operation

Stephan Liedl [1]

1 Introduction

The proven safe operation and the high availability of aerial ropeways is mainly thanks to their design. This is based on the manufacturer's extensive experience as well as the strict application of the relevant rules and norms.

Higher performance requirements from the customers together with the general pressure of costs determine a change in ropeway design. As a result there is an increase in operating speed, vehicle weight and rope spans of new or renovated installations. Considering all kinds of aerial ropeways the rope system and all other units with it in contact combine to a system, whose state of motion and distribution of loads continuously change during operation. Therefore modern high-powered ropeways underlie an extension of the dynamic part of the movement behavior and component loads.

Today the market requires a great variety of types of aerial ropeways with numerous equipment options which must be recalculated and checked within shortened project times. Fast technical evolution is object to varying national rules in the marketing countries, a mainly conservative set of equations and the small evolution possibilities in theory, in relation to other technical fields. The above general conditions complicate a standardized and efficient computational assessment of a ropeway by the manufacturer or surveyor.

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It can be observed that there is a considerable potential in the calculation of ropeways that is not yet exhausted and is more likely to increase with the market modifications.

2 State of the art

Some scientific publications which take the requirements and the innovations in ropeway design into account have appeared in recent years. The works handle the dynamic behavior of the track, haulage or carrying-hauling rope and / or the vehicles in the case of an individual type of ropeway or a certain type of burden. On monocable circulating ropeways Richter examines the oscillating behavior of rope, vehicles and counterweight due to starting and stopping [3]. Winkler handles in [4] the dynamics of the track rope of reversible bicable ropeways with regard to the longitudinal waves. Beha treats in [1] the motions and forces of the haulage rope and the vehicles of bicable ropeways. The much discussed topic of a break in the haulage rope of a reversible bicable ropeway and subsequent track rope braking is taken up by Kovacs in [2], where he develops a very detailed means for calculating the oscillatory behavior and the dynamic loads of the vehicle.

3 Objective

The purpose of this thesis was to develop a clear and universal means for calculating the movements and forces of the rope system of aerial ropeways during operation considering the static and a part of the dynamic effects. In addition to the track and haulage rope or the carrying-hauling rope, all ropeway units in contact with the ropes were also considered. The procedure is suitable for all usual types and configurations of aerial ropeways. Finally the calculation model was transposed to a simulation program prototype.

In the following, the essential features of the calculation procedure are stated. Most are also implemented in the simulation program.

Suitable for:

- mono- and bicable, circulating and reversible aerial ropeways
- any combination of arrangement of the drive and tensioning device (bottom or top station)

- rope tensioning by counterweight or hydraulic cylinder or also double anchoring
- free input of key data of the installation such as longitudinal sectional view, unit masses and key features of the standard operational cycle
- variable determination of friction at contact points between rope and supports or vehicles
- only 1 ropeway section (line between two stations)

Calculation of:

- geometry of the entire rope system in all states of the operating cycle
- longitudinal and transversal motions of ropes and vehicles
- longitudinal pendulum motion of the vehicles
- displacement of tension sheave
- drive and braking torque

On account of the relatively universal formulation and the required simplifications (see next section), the calculation method is not suitable for specific oscillation computations of individual ropeway units. It should allow a calculation of the entire rope system of an installation with limited dynamics. However, for a detailed dynamic analysis it can be used as a pre- or postprocessor or as a parallel system to define exact initial and boundary values.

4 Mechanical model

The central unit of every ropeway is the rope system consisting of the track and haulage plus counter rope or the carrying-hauling rope with the units in contact with it such as stations (drive, tensioning device), towers and vehicles plus, if applicable slack carriers (= suspended haulage rope supports). The movement behavior and the applied forces can not be computed for individual components without consideration of the overall system. Considering the size and the diversity of the complex mechanical system, the number of degrees of freedom is reduced and some simplifications were made to get a basis for the modeling:

- External influences except ambient temperature are not considered.
- The rope system is handled as a plane problem.

- Dynamic considerations remain limited at relatively slow alterations in load (quasi-static view).
- Contact areas between rope and fixed or moving ropeway units are reduced to coupling points.
- The form of the curve of the moving rope between two coupling points always corresponds qualitatively to the static rope curve.
- All components except the ropes are regarded as non-elastic.
- Ropes are idealized without bending stiffness.

In Fig. 1, the mechanical model of the rope system of a reversible aerial ropeway is exemplary represented as it serves as the basis for the derivation of the mathematical equivalent in the calculating procedure. The track and haulage ropes or the carrying-hauling rope are subdivided by two kinds of coupling points, the fixed supports and the moving contact points, into sections on two levels. Stations and towers subdivide the system into spans with constant distances. A finer subdivision into coupling sections with variable position and length results with the addition of the vehicles and, if applicable the slack carriers. At every coupling point ends at least one span or coupling section.

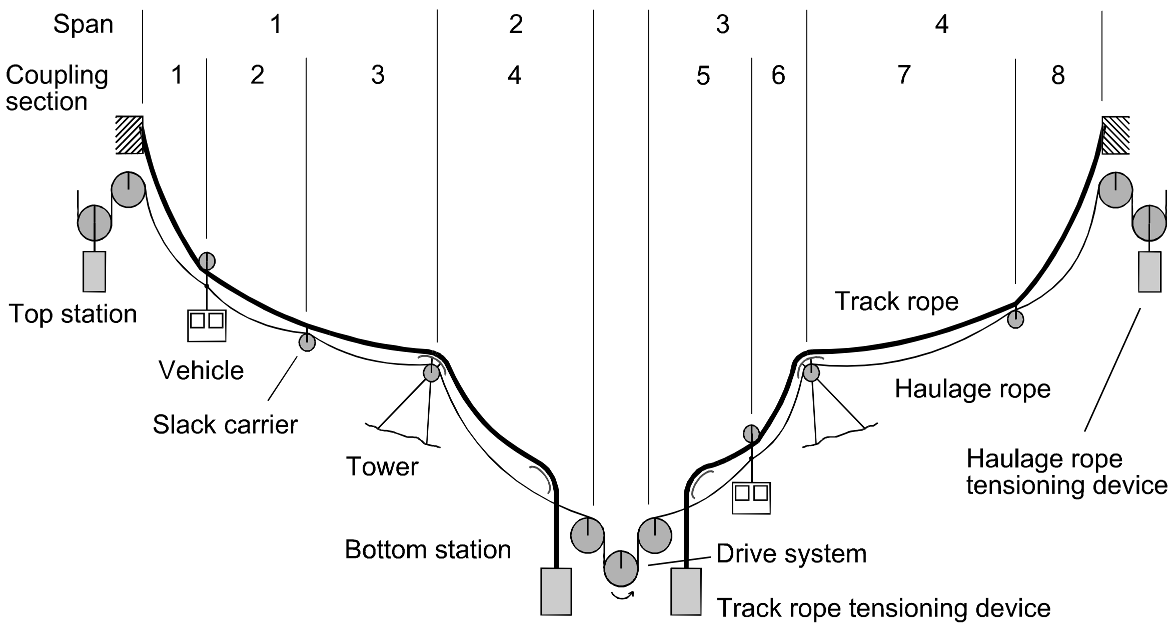

Fig. 1: Substitute model of the rope system of a reversible bicable aerial ropeway

Stations and towers as well as slack carriers are considered as points. For more precise investigations of the tower passage of a reversible bicable aerial ropeway, the specification of the radius of the track rope saddle is provided. At the supports, the mass action of rotating parts like sheaves and bull wheels is replaced by a total moment of inertia. In the drive station this is added to that of the main drive. Movement behavior of the rope sections within both stations is not represented. The distance between track and haulage rope that exists with bicable ropeways is ignored. This last-mentioned simplification also applies to the vehicle.

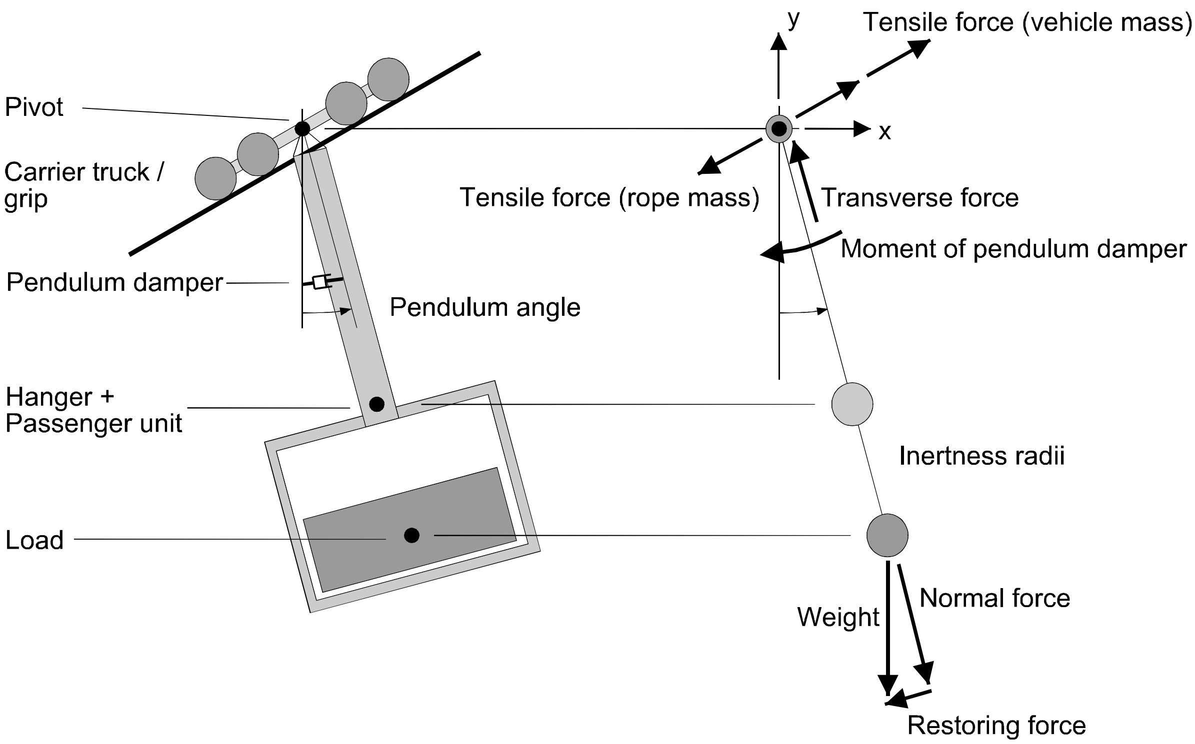

Fig. 2: Substitute model of the vehicle

Due to the division into carrier truck or grip, hanger, passenger unit and load the detailing of the vehicle is relatively precise (see Fig. 2). In addition to the masses, their lever arms and inertness radii must be known. As a choice the entire mass of all vehicles also can be considered as additional mass per unit length to the rope. For monocable circulating ropeways with many, uniformly distributed and lightweight vehicles, this simplification rarely leads to a mistake, but reduces the mathematical complexity and therefore the CPU time enormously. Damping of the longitudinal pendulum motion, which is important for large vehicles, is foreseen. In addition, a displacement of one vehicle of a reversible ropeway on the haulage rope loop can be defined, which guarantees for an installation with the drive system in the bottom station, that a vehicle standing in the top station does not leave the regular stop position while loading.

A rope hanging between two coupling points is regarded in the static state as a uniform and self-weighted element devoid of bending stiffness like a chain. The consideration of longitudinal extensibility is possible. Regarding the dynamics, a rope is modeled in two different ways for the calculation of longitudinal and transversal motions, following [1] (see Fig. 3). Concerning the longitudinal direction, named s in Fig. 3, the whole rope mass in a span is split up into lumped masses on both end points. In the vertical transversal direction, named f in Fig. 3, the continuous mass distribution survives, however, the different sag alteration is replaced by a mean value.

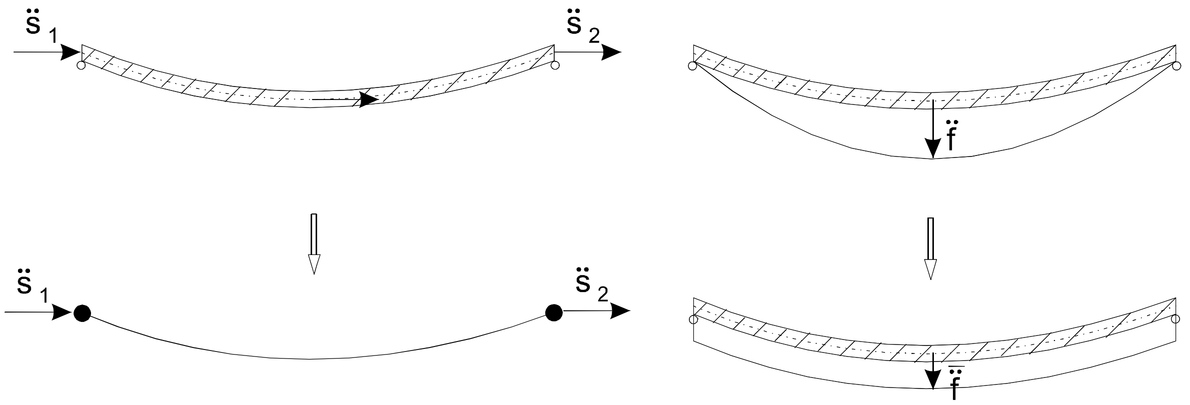

Fig. 3: Modeling of the longitudinal and vertical transversal motions of a rope span

Every contact with relative motion of the rope and another system part is friction afflicted. For the friction of the moving haulage or carrying-hauling rope and the slightly moving track rope, three different models were chosen. At a real installation the track rope of a reversible ropeway slides and sticks alternately on the tower saddle where the movement alternation is subject to a hysteresis. This behavior is represented realistically by an algorithm that switches between a coefficient of adhesion and one of sliding friction. As observations and measurements show (see sect. 7), their absolute values as well as their relation is decisive for the movement behavior of the track rope on a tower. In case of tensioning by a counterweight, for the deflection of the track rope on a roller chain saddle or a similar device, pure sliding friction is assumed. Friction of the moving ropes on bull wheels and sheaves is made up of a constant component and one depending on rope speed.

The correct time sequence of all phases of the standard operational cycle in the computational program is realized similar to the function of the drive control system of an original installation. Rope speed, acceleration and deceleration rates and, if applicable, lower speed for tower passage of a reversible ropeway are given by a way-speed-diagram for the rope on the drive bull wheel, which is automatically generated from input values. All creatable states of operation of the drive and brake device can be represented, also any start-up or braking on the line.

5 Mathematical procedure and computational program

The mathematical counterpart to the mechanical model presented in the above section is included in the calculating procedure as algorithm. The ropeline between two coupling points can be represented optionally as parabola or catenary. In individual cases the latter can supply more exact results as the approximation function usually used in ropeway calculation [4]. Setting up the equilibrium of forces and / or linear and angular momentum equations as well as geometrical constraints at the coupling points and in the spans, results in an extensive, closed mathematical system. Its size depends on the chosen level of detail as well as the number of the ropeway units to be considered. These dependencies are also decisive for the computing time and stability of the numeric solution of the system of equations. Because of the limited dynamics, an explicit difference method with simple handling and in variable form can be used. The transferred version as a simulation program is executable on a i386 and higher PC and requires between one minute and several hours for the calculation of one operating cycle, depending on the size of the installation examined, the level of detailing and on the PC used.

6 Verification and validation

Reference values for the verification and validation of the simulation results come from measurements on a real installation. A reversible bicable ropeway, the type which contains all units considered in the computing model, served for this. Specifically created sensing elements were used due to the lack of products suitable for sale. For measurements on the track rope, rope inclination, rope displacement and relative tension in the rope were registered synchronously in the bottom and top station as well as on a tower. To get information about temperature influences, in particular concerning changes of the coefficients of friction, measurements took place during operation in summer and winter. Fewer corresponding measurements were carried out on the haulage rope.

The calculation method taken as basis for the simulation program is validated, at the moment for this ropeway type, by comparing the computed results with the reference values considering the chosen aim.

Fig. 4 shows the measured and computed displacement of the track rope on the roller chain saddle in the bottom station during an upward travel in dependence on the distance between bottom station and vehicle. In Fig. 5 and Fig. 6 the computed curves of the absolute tensile force in the haulage rope on both sides of the carrier truck during a downward travel are compared with the corresponding measured relative data.

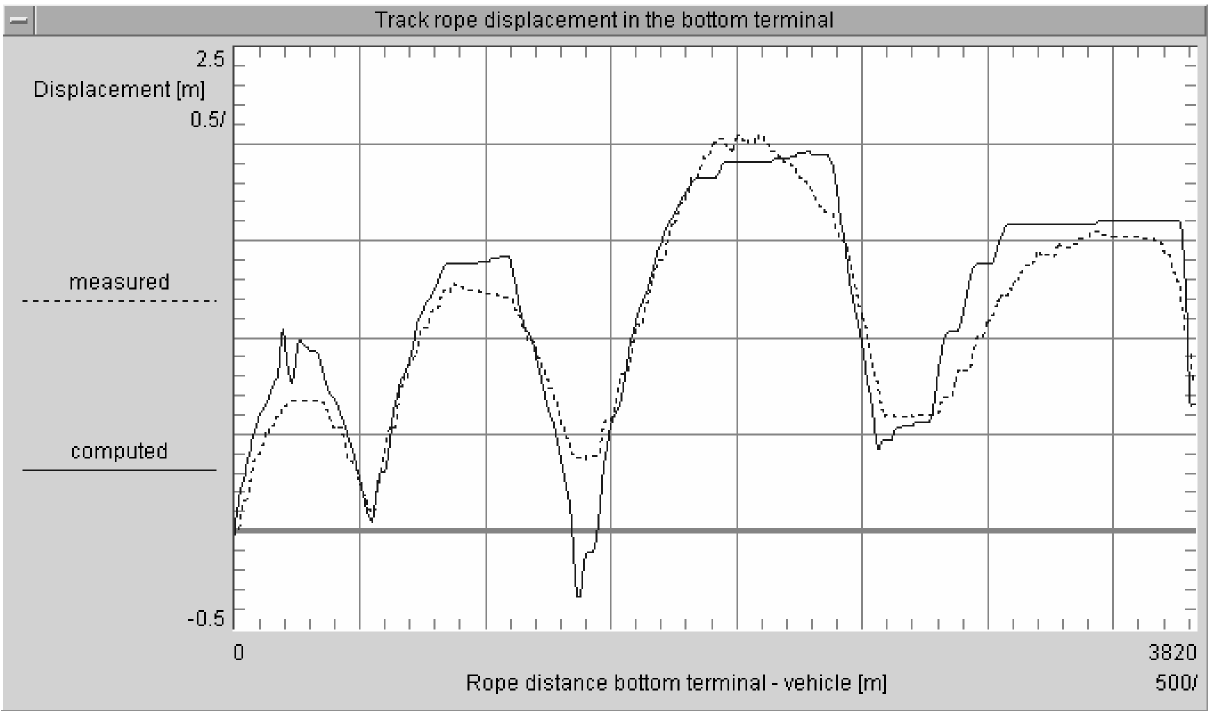

Fig. 4: Measured and computed track rope displacement in the bottom station

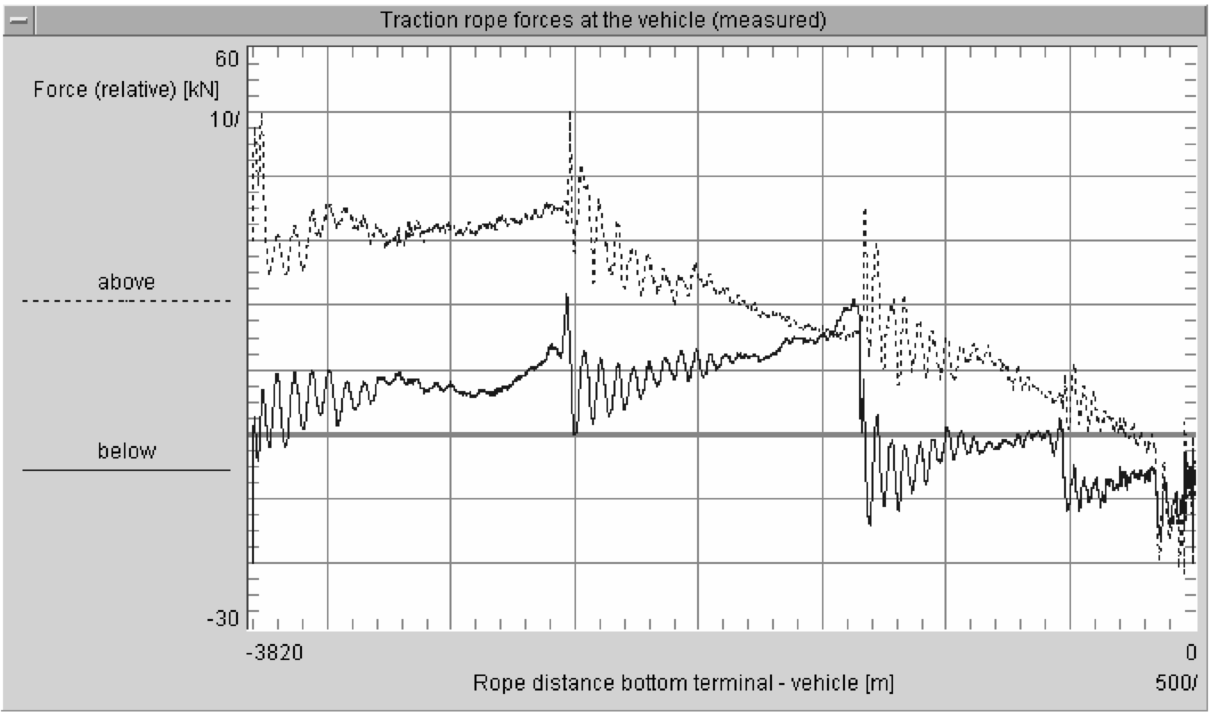

Fig. 5: Measured relative tensile force in the haulage rope on both sides of the carrier truck

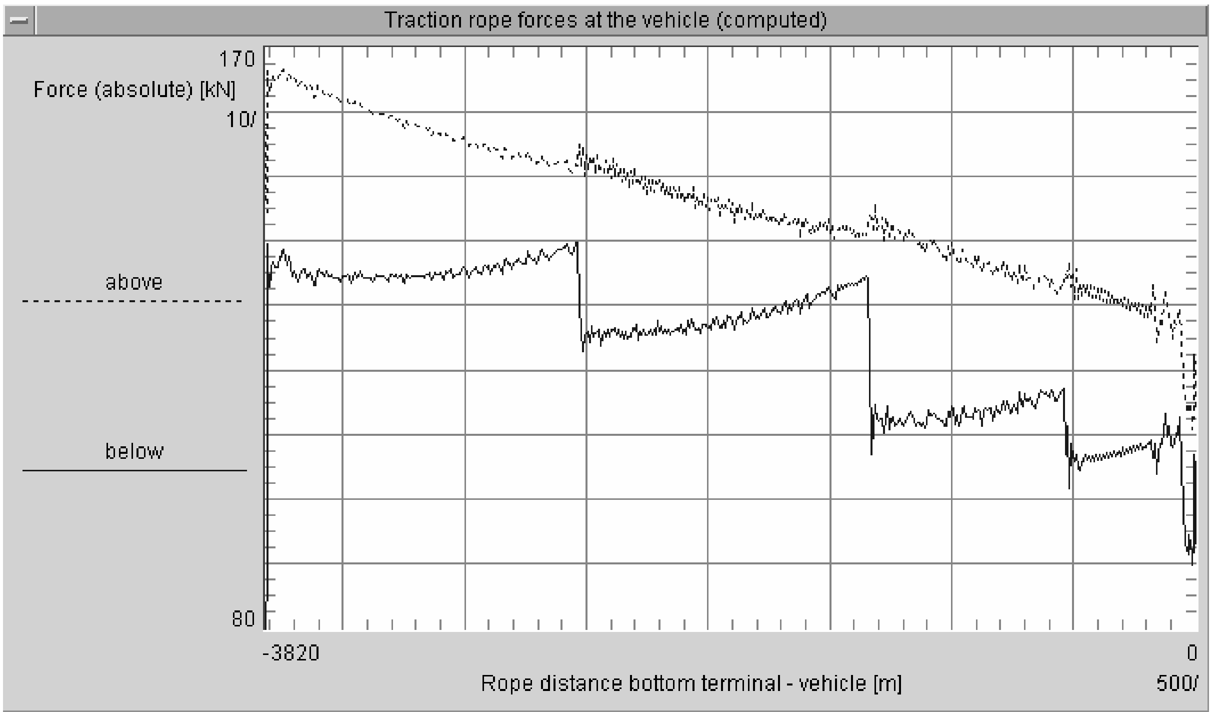

Fig. 6: Computed tensile force in the haulage rope on both sides of the carrier truck

Sample computations also show the suitability of the procedure for all other types of ropeways so that at least it may be regarded as verified here despite the lack of appropriate reference values.

7 Application

The kernel of the simulation program is already provided with an automated input which among other things avoids multiple entries of identical units and transfers riding data to a drive program. The additional use of a graphical user interface makes the operation even easier and provides better error protection on the one hand and guarantees simple data maintenance on the other.

Fig. 7 shows a screenshot of the main input window of the graphical user interface for a circulating monocable ropeway.

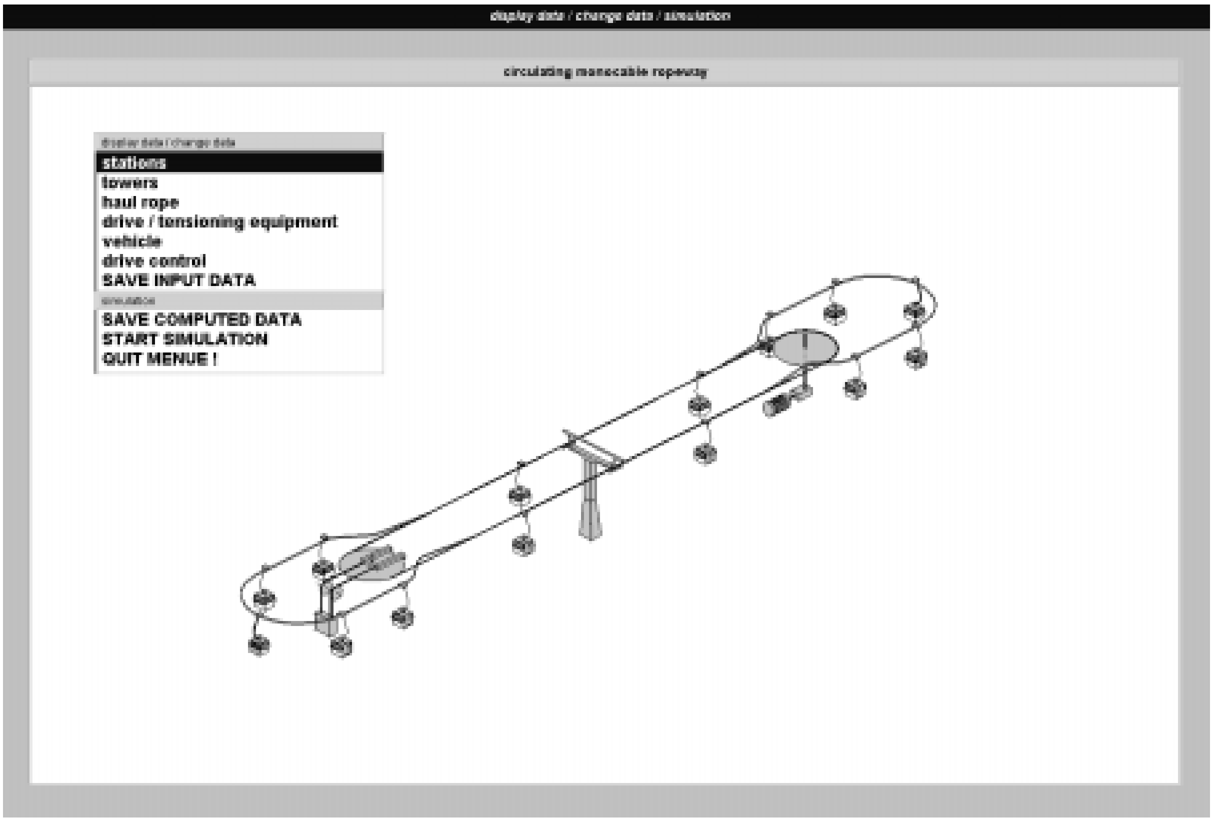

Fig. 7: Screenshot of the main input window for a circulating monocable ropeway

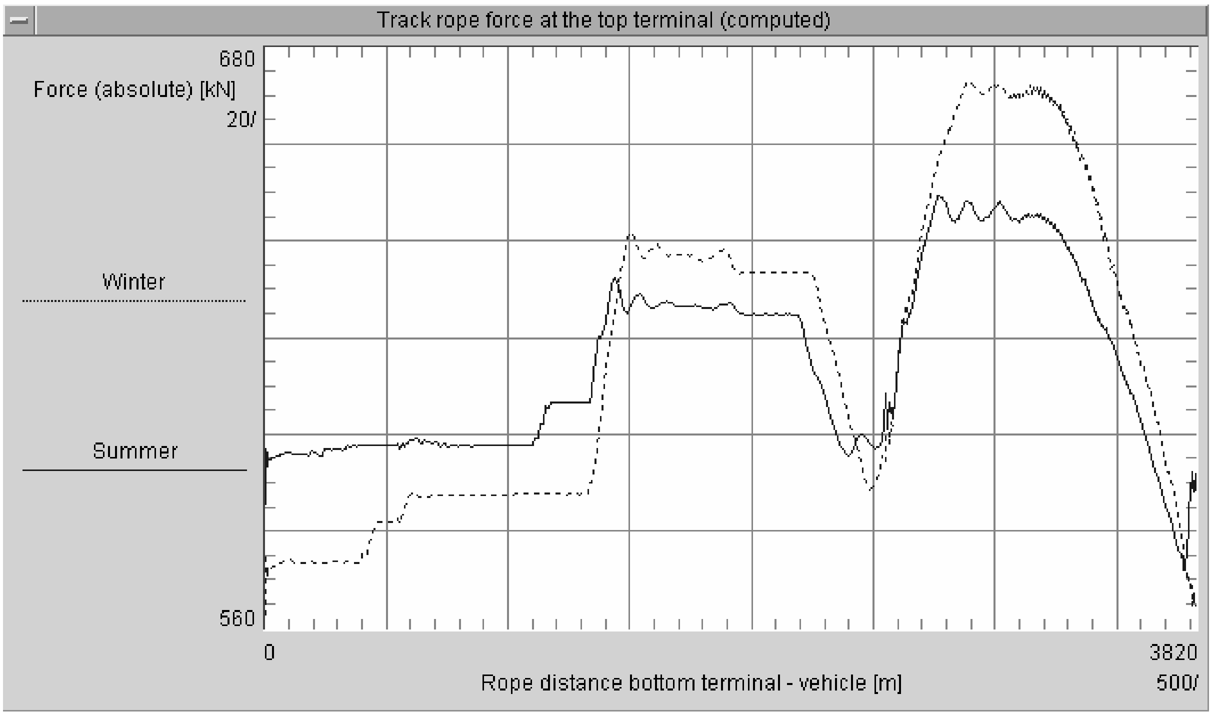

Fig. 8: Comparison of the computed tensile force in the track rope at the top station between high (= winter) and low (= summer) coefficients of friction

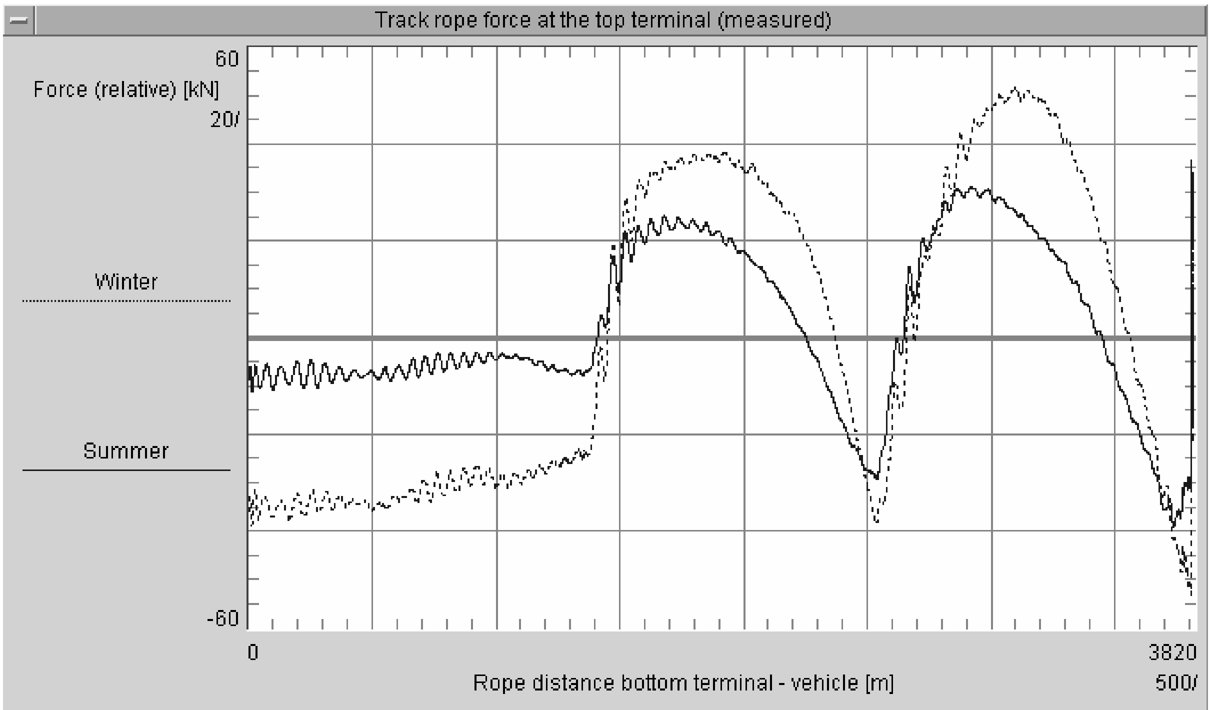

Fig. 9: Comparison of the measured relative tensile force in the track rope at the top station between winter and summer

Exemplary the simulation program was used to analyze the effect of friction between the track rope and the tower saddle of a bicable reversible ropeway on the resulting forces in the rope. Fig. 8 shows the computed tensile force in the track rope at the top station during an upward travel on condition of high (= winter) and low (= summer) coefficients of friction on the track rope saddle. The friction resistance disturbs the balancing of rope lengths between the spans and leads to an increase in rope tension. Operation in summer with well lubricated rope saddles and normal ambient temperatures produces lower friction resistance than operation in winter, when the track ropes can stick on the rope saddles under extreme conditions. Except the coefficients of friction both curves base on the same input data. Comparison measurements in winter and summer led to similar results (see Fig. 9).

8 Summary

With regard to the modifications in the market of aerial ropeways and the small theoretical development capacity on this field, a basic method is worked out for calculating the movements and forces of the rope system of aerial ropeways during operation. The procedure considers the static and a part of the dynamic effects on the ropes and the further main units of a ropeway which stand in contact with the ropes. It is suitable for all usual types and configurations of aerial ropeways. Due to required simplifications of the mechanical and mathematical model, the method is not suitable for detailed dynamic analyses. Based on the calculating method is a simulation program prototype which is equipped with a graphical user interface for easy use. Reference values for the verification and validation of the computed results come from measurements on a real installation. Exemplary the simulation program was used to analyze the effect of friction between the track rope and the tower saddle of a bicable reversible ropeway on the resulting forces in the rope.

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