KINISIS
User-friendly program for calculating the dynamic movements and loads to which aerial cableways are subjected during braking operations on the carrying cable

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Brief description of the computer program developed at the Federal Institute of Technology (ETH), Zurich in collaboration with the Swiss aerial cableway industry (Garaventa and Von Roll) and the Swiss Federal Transport Office (BAV).

1. Introduction

In areas with difficult topographical and meteorological conditions, aerial cableways continue to constitute very reliable transport installations offering the highest possible level of availability. To meet the growing need for high carrying capacities, installations are being produced which have cabins accommodating ever larger numbers of passengers (up to 180 persons) and which travel at higher speeds.
A precondition for reliable operation is the ability for the cablecar to be braked automatically, rapidly and independently of the drive mechanism if a fault occurs (e.g. a crack in the haul rope). This is the task of the carrying cable brake, used on all licensed aerial cableway installations operating in Switzerland.

When the brake is operated, however, oscillations are generated which in extreme cases may cause the cabin to collide with the cableway (carrying cable or tower shoe) or lift the running gear from the carrying cable. Moreover, forces may be generated in the structure of the cablecar which correspond to three to four times the static load.

Up till now, these movements of the cablecar and forces in the suspension tackle generated by braking on the carrying cable have been determined using conservative, sometimes rudimentary computing processes employing computer programs which, although wholly adequate 25 years ago when they were developed, are not particularly user-friendly and are thus suitable only for trained, experienced operators.

This situation created a need for the development of a program employing sophisticated computer models and based on currently standard user interfaces. The program should permit efficient and simple verification of the safety of aerial cableways in the context of carrying cable braking. Due to close cooperation between the two Swiss manufacturers Von Roll and Garaventa and the Federal Transport Office, it has been possible to develop a product which operates to a great extent using standardised input and output formats.

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2. Basic mechanisms

Situations classed as dangerous usually involve braking operations carried out on the carrying cable in connection with a crack on one side of the haul cable. Carrying cable braking is triggered as soon as the force of the haul or countercable falls below a certain threshold. Such situations cause abrupt changes in the forces prevailing at the running gear and consequently violent movements of the cabin and the running gear. Different oscillatory movements of the cabin and cableway may occur, depending on the position and speed of the cablecar and the location of the crack in the cable. Identification of the possible dangers, such as for example:

- overloading of the suspension tackle,
- collision of the cabin with the cableway,
- levels of acceleration which are too high to be tolerated by the passengers,
- lifting of the running gear etc.,

necessitates precise analysis of the dynamic processes occurring. To prevent dangerous situations from arising, suitable structural measures have to be taken. These may involve:

- using suspension tackle which does not transmit compressive forces
- addition of a crumple zone at the leading edge of the cabin
- articulated connection of a braking truck to the running gear.

Such devices, which are crucial to safety, need in turn to be examined for efficiency and reliability. The digitally-based calculation process described below was developed for this very purpose and uses a computer program which is capable of calculating all the loads and movements of the cabin which arise during braking operations on the carrying cable.

In digital processes, only **one** load scenario can generally be analysed with any **one** calculation. All the load scenarios necessary for investigating an entire installation and all operating states are summarised in one of the load scenario categories assigned to the relevant incident. The load scenarios are divided into the following 6 categories:

- lifting of the running gear from the cableway
- turn up the running gear on the cableway
- crushing of the cabin suspension
- suspension tackle loading in the pivots and the cabin suspension points
- collision of the cabin with the cableway
- maximum braking distance of the running gear.

These assist in the examination of the relevant individual incident. On the basis of the results, it is possible to determine the corresponding extreme case from each load scenario category. The cablecar may then be appropriately dimensioned using the loading values from the extreme case in question.

For each load scenario, it is necessary to indicate the

- type of load (passengers, goods, no load)
- location of crack in the haul cable (on the mountain side or valley side of the cablecar)

- initial status of the cablecar (travelling speed, angle of swing, rate of swing),
- maximum free swing angle
- location of incident (tower number or station) and
- local angle of inclination of cableway.

It is usually possible to take a conventional operating state as the basis for the calculations. For greater ease of processing, a load number is assigned to each load scenario.

3. Modelling

3.1 Cableway

The cableway of a bicable reversible aerial cableway consists of one or more carrying cable(s), which form a freely suspended, easy-to-oscillate structure. Exceptions to this are the two end stations and the towers distributed over the course of the cableway, where the cables rest on shoes and thus form a fixed, virtually immovable cableway.
In view of the fact that the cableway exhibits very different characteristics at different points along its length, differentiation of the modelling is imperative. Extensive investigations described in [1] have revealed that, taking into account the operating values standard today, the highest values are obtained for the suspension-tackle loading and swinging movements resulting from carrying cable braking when braking occurs at or in the immediate vicinity of a tower. Under these circumstances, markedly smaller values are to be expected when braking occurs on a section of free span.
In determining the critical loads and movements of the cablecar, the KINISIS program therefore only gives consideration to the elastic tower portion of the cableway. Irrespective of secondary damping mechanisms, the spring characteristic of the tower may be regarded as a variable independent of load alternation frequencies. (However, the bases of and calculation programs for calculation using carrying rope in free span as the track are provided in [1] and are therefore available for study.)

The cable is supported on the tower by the carrying cable shoe. This forms a trough-like rail, which is curved in accordance with the bending radius of the cableway. This carrying cable shoe is attached to the cable saddle and the latter is in turn attached to the outermost end of the tower head. Because of their size, the towers are in most cases lattice structures. The support illustrated in Figure 3.1 consists of 4 structural components:

- foundations,
- tower foot
- tower shaft,
- tower head.

The tower is anchored to the ground, thus transmitting to the ground not only the inherent weight of the tower but also all the external forces acting on the tower. Owing to their slim light-weight construction, the tower foot and shaft are the principle elastic parts of the system. In contrast, the tower head and carrying cable shoe form a fairly rigid element. This means that any general deformation of the tower, caused by external loading of the carrying cable shoe, is a consequence of the relatively non-rigid construction of the tower shaft and foot. The tower, together with the carrying cable shoe, which is located at the outermost ends of the tower head, may thus be regarded as constituting an elastic system influenced by mass.

A thorough examination of the dynamic behaviour of such a structure would be extremely expensive and is not really necessary in the context of carrying cable braking. The desired aim is to achieve the simplest possible modelling, showing the interaction of the cablecar and the tower, the former being viewed as a swinging element and the latter as the cableway.

The different loading, such as longitudinal and vertical forces, lead to corresponding bending and torsional deformation of the tower. All the individual deformations combined result in displacement of the centre of gravity of the cable shoe. In the event of carrying cable braking at the tower, only the deformation of the tower as a result of unilateral vertical loading is of any significance as far as the effect of loading on the cablecar is concerned. The longitudinal movement of the tower has no role to play during the braking procedure (slippage of the brakes), because the maximum expected loading of the cablecar occurs during the final stage of slippage or before the running gear comes to a standstill. It is therefore unnecessary for the longitudinal movement of the tower to be taken into account in the model.

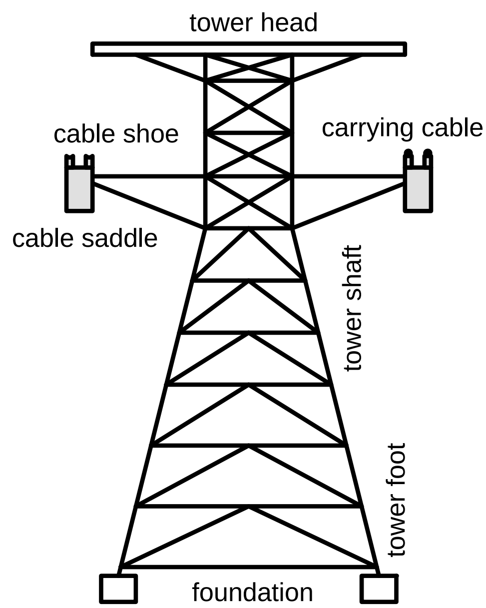

Fig. 3.1 Structure of the tower

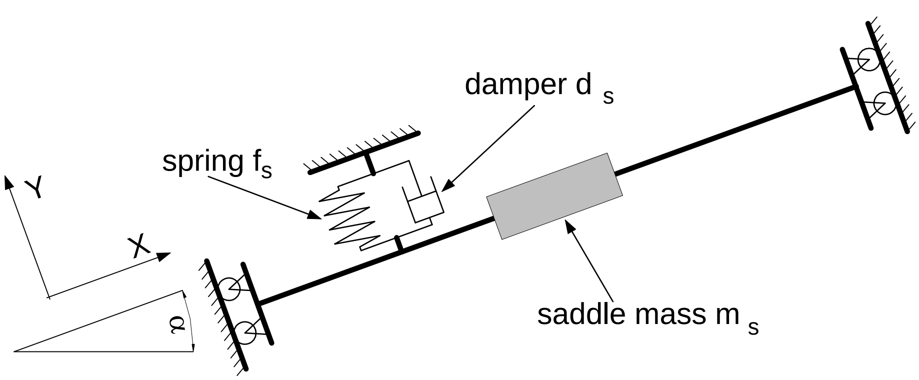

Fig.3.2: Modelling of the tower

The single-mass oscillator shown in Fig. 3.2 is used as the simplest oscillation model for simulating tower movement. This model has only one degree of freedom and may be coupled without difficulty to the cablecar model. As with the suspension tackle of the cablecar, the entire structure of the tower acts as a spring influenced by mass.

In the event of braking on the carrying cable during descent as the result of a crack in the cable on the valley side (or during ascent as the result of a crack in the cable on the mountain side), the braking distance available to the roller running gear is very short (0.5-1m). With a radius of curvature of the tower shoe of approximately 15 – 30m and the limitations imposed by the very short braking distance, the cableway may be regarded as straight for the purpose of the description of the longitudinal running gear movement.

3.2 Cablecar

3.2.1 Modelling of the elastic cablecar structure

Loads that occur suddenly usually apply substantially greater stress to the structure than does the same load in static form. To determine these stresses, it is necessary to undertake a study of the dynamic loading processes. Unlike elastic systems, in the hypothetical ideal rigid model sudden loading processes are always quasi-static. A model has therefore been developed which is provided with elastic elements.

Naturally, it would not be reasonable to use as a model an aerial cablecar exhibiting the full range of, in some cases, high frequency forms of oscillation. Instead, all that is necessary is to study the critical forms of oscillation, i.e. to regard only critical components of the cablecar as oscillatory elements for the purpose of the model. Therefore, the reversible aerial cablecar is divided up into structural components which form the elements of the model. A prerequisite for practical implementation of the calculation is that the individual structural components be connected in as simple a manner as possible. In these connections, forces are passed on from one structural component to the next.

These elements, which are in themselves rigid and are influenced by mass and by mass moment of inertia, are interconnected by spring, damping and driving forces. The cableway structure is greatly stretched by the rapidly changing loads. Dynamically occurring load peaks in the suspension tackle pivot may be calculated with the aid of the analogous spring connections of the model. Fig. 3.3 shows clearly the subdivision of the cablecar structure into the following individual elements:

1. (Roller) running gear
2. Suspension tackle

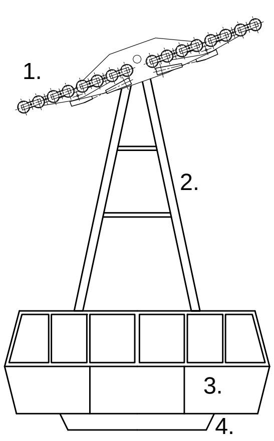

Fig.3.3:
Subdivision of the cablecar into structural components

3. Cabin
4. Load.

It is assumed that the running gear effects only slight rotary motion upon carrying cable braking. It is not therefore assigned any mass moment of inertia.
Because of the slim, easily bendable construction, the greatest proportion of the overall expansion of the cablecar takes place in the suspension tackle (in the case of rigid loading). Under these circumstances, it is expedient for the suspension tackle to be modelled as a spring combined with a mass. The total mass of the suspension tackle is broken down into a portion which oscillates and a portion which does not oscillate. The load (Fig. 3.3, reference numeral 4) may be applied at various locations depending on its type:

- rigid loads such as water tanks and vehicles etc. are suspended underneath from the floor on fastening straps,
- passengers are accommodated in the cabin itself.

Where the load is positioned determines variations in the overall centre of mass of the swinging element. If the load consists of passengers, special attention should, according to [1], be paid to the elasticity and damping values and the co-oscillating mass.

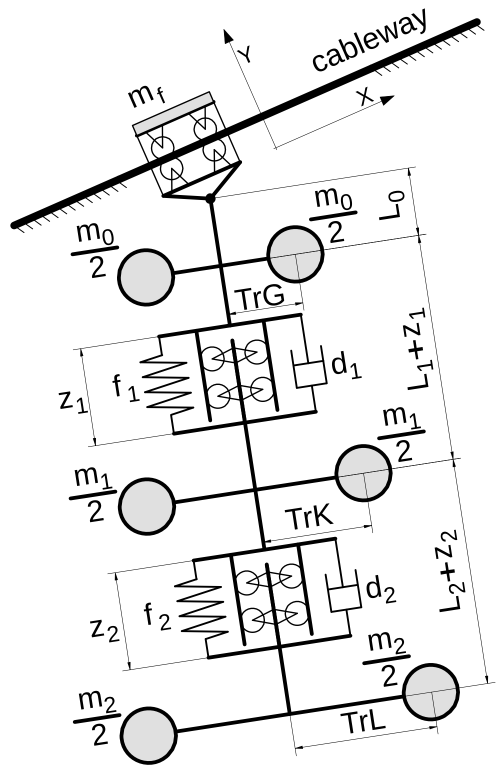

Fig.3.4: Model of the cablecar

Trg: Radius of inertia of the suspension tackle
Trk: Common radius of inertia of the cabin and the elastic part of the suspension tackle
Trl: Radius of inertia of the load
m_0: Mass of the rigid suspension tackle
m_1: Mass of the cabin and of the elastic part of the suspension tackle
m_2: Mass of the load
m_F: Mass of the running gear
f_1: Spring constant of the suspension tackle
f_2: Spring constant of the load
d_1: Damping constant of the suspension tackle
d_2: Damping constant of the load

Each element of the model has a mass assigned to it and, apart from the running gear, a mass moment of inertia (or radius of inertia). These are interconnected together by spring/damper elements to form an imaginary guide rail. The movements of the cablecar take place in only one plane. The transverse swinging movements of the cablecar may be disregarded, since they are not directly generated.

The derivation of the motion equations may be found in [1]. This modelling enables the following scenarios to be described:

- calculation of the maximum suspension tackle load arising
- speed of collision of the cabin with the tower or the carrying cable
- lifting behaviour of the roller running gear
- maximum braking distance.

The cablecar data required for the calculation (e.g. structural elasticity, co-oscillating mass, dimensions) may be determined either from the construction drawing or from measurements carried out on existing installations (see [1]). For example, measurements of the expansion characteristic of the suspension tackle may be taken from existing installations with different-sized cablecars and different modes of construction. From the results of these measurements, the current suspension tackle elasticity may be culated in the form of recommended values as a function of cablecar mass. (Most of these works are already done and the results integrated in the program.)

3.2.2 Modelling of the cablecar structure with pressure-free suspension tackle

The lifting behaviour of the running gear during track rope braking

- on very steep sections of the cableway (on the valley side of the tower),
- during ascent
- and with a crack in the haul rope on the mountain side

has already been discussed in detail in [2]. Under such circumstances, the swinging element is set in rotary motion by the force of the haul rope on the valley side, the instantaneous centre of rotation being very much further down owing to the considerable mass inertia of the cabin (including load), i.e. in the vicinity of the cabin. This results in an instantaneous reduction in the load pressure of the running gear, which may be so marked that the running gear lifts off the cableway and the whole cablecar finds itself in "free flight" for a short time. The cableway itself cannot follow this movement because it is too rigid (in the vicinity of the tower).
In order to prevent the running gear from becoming derailed and/or the carrying cable braking from failing, appropriate constructional measures have been developed, which differ from manufacturer to manufacturer. Garaventa have developed a special suspension tackle design which cannot transmit any compressive forces. The cabin and suspension tackle are connected vertically at the 4 corners of the cabin by chains. Diagonally disposed wire cables are used to absorb shearing forces. The length of the chain, or the distance between the suspension tackle foot and the cabin roof is an important parameter in the prevention of a collision between the two and has to be established at the relevant project stage by means of calculations so that the height of the cablecar and the length of the suspension tackle may be determined. In order to minimise the overall height of the cablecar, the ideal chain length has to be determined by an iterative procedure: a length is proposed by the operator and tested by model computation to see whether the proposed value meets the requirements. If the chain is too short, an undesirable collision occurs. If the distance is too great, the installation becomes uneconomic to run owing to the resultant excessive cablecar height.

Model:
For calculation of the movement of the cabin and the suspension tackle with running gear, the cablecar is subdivided into three structural components, each of them rigid, according to Fig. 3.5:

- running gear
- suspension tackle
- cabin with load.

Connection of the suspension tackle and the cabin is modelled by articulated tension springs, which cannot transmit any compressive forces. This spring-loaded suspension of the cabin serves primarily to establish in what situation the suspension is compressed. To prevent compressive forces from arising in the suspension, the spring constant is set at a relatively very low value (approximately zero). With this method, the same computer model may always be used for simulation of the movements regardless of the momentary status of the cablecar. The spring rigidity of the chain links is optimised without the user being involved, in such a way that on the one hand the springs are not expanded to an unrealistic degree and on the other hand the computing time is not increased unnecessarily owing to the high frequencies.

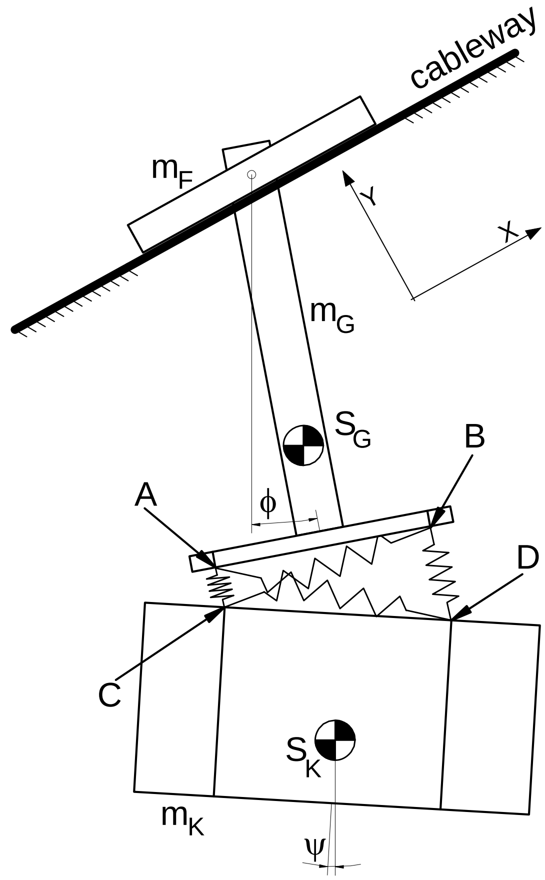

Fig.3.5: Computer model with pressure-free supension tackle

3.2.3 Modelling of the cablecar structure with braking truck

To solve the problems described in section 3.2.2 which may arise during track rope braking

- on a very steep cableway (on the valley side of the tower)
- during ascent
- and when the haul cable has cracked on the mountain side

Von Roll has opted to mount the entire gripping brake system on a braking truck, which is connected to the running gear by means of articulated connecting rods. If relevant lifting of the running gear from the carriageway occurs, the braking truck remains on the cableway. In this way, the carrying cable brake is in a position to act on the carrying cable and brake the cablecar. This design accordingly permits the use of conventional suspension tackle.

The eccentric arrangement of the articulated connection of the braking truck with the running gear produces one-sided application of the braking force and the haul cable tractive force. With this construction it would thus be feasible for the running gear to be tilted up during braking

- on a curved cableway,
- during ascent,
- when a crack has occurred on the valley side,
- and in particular on a countergradient.

To establish whether this scenario can actually happen in an installation, it is necessary to determine the movement cycle of the running gear and the braking truck. For investigation of such a process, the running gear with braking truck according to Fig. 3.6 was modelled. The computer model of the swinging element (suspension tackle, cabin and load) matches that described in section 1.3.
The spring-loaded suspension of the running gear at points A and B serves to establish the time at which the running gear is lifted from the cableway. As soon as the compressive force of one spring reaches or exceeds zero, the spring constant is set at a very much lower value. In this way, the link with the cableway is not broken completely, but the "free-flight movement" of the running gear may nevertheless be modelled with sufficient precision owing to the substantially smaller linkage forces.

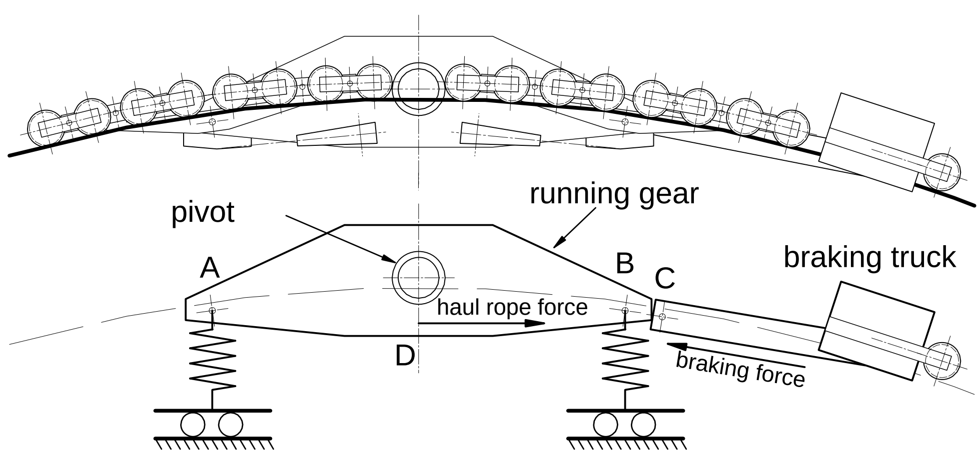

Fig.3.6: Model of the running gear with braking truck

The braking force of the track rope brake is applied at point C and the force of the remaining haul rope is applied at point D.

4. Program

4.1 The structure of the main KINISIS program:

The KINISIS software package consists of a main KINISIS program and 6 calculating programs capable of running independently. The main program serves primarily to process the input data and evaluate the results of the calculations. User involvement is generally restricted to this program. The calculating programs are activated by KINISIS and carry out the following calculations:

- calculation of the suspension tackle loads
- calculation of the maximum height of lift of the running gear with a rigidly suspended cabin (standard design)
- calculation of collision behaviour of the cabin against the tower shoe
- calculation of the positioning behaviour of the running gear with braking truck (Von Roll design)
- calculation of the buckling level of the suspension tackle in the case of cablecars with compressive force-free cabin suspension (Garaventa design)
- calculation of the maximum braking distance.

The calculating programs may also be operated directly, but this is recommended only for experienced users.

4.2 The calculating programs

All 6 calculating programs independently run WINDOWS batch programs which may be activated not only by KINISIS but also directly by the operator. These programs operate in cooperative multitasking mode and are substantially independent of the main KINISIS program. This means that KINISIS may be used to process input data while the computing operations are being carried out.
The main KINISIS program and the calculating programs communicate with each other by transmitting WINDOWS messages to each other. When a computing program is activated, important start information is transmitted to the computing program in question. KINISIS is also informed of the completion of a calculating program. The relevant calculation results relating to **all** load scenarios **in any one** load scenario category are recorded sequentially and continuously in ASCII format on the hard disk. This permits the following to be achieved:

- rapid trouble-shooting in the event of problems
- possibility of evaluating the calculation results in KINISIS (e.g. calculation of extreme values) and using outside products
- once the data has been backed up, all the results remain available for subsequent analysis.

4.3 Operation of KINISIS:

KINISIS is an event-controlled, partly object-oriented WINDOWS application. It is mainly operated by the conventional WINDOWS input devices, i.e. keyboard and mouse. Once the program has started, a program window is automatically generated, which, with the aid of a "guided input procedure" simplifies input of the installation and load scenario data and additionally reduces the risk that an input data group will be left out of consideration due to an oversight. In addition, a push button bar appears below the menu bar and provides quick access to current installation and load scenario data. All the program functions are operated by means of the pulldown menu. Data input is effected in interactive mode. The results of all calculations and maximum values of the extreme scenarios can be observed visually on the screen and on hardcopy.
The KINISIS program package is compatible with all versions of WINDOWS® (WINDOWS 3.1, WINDOWS NT and WINDOWS 95).

Bibliography:

[1] G. Kovacs, "Schwingungsverhalten eines Pendelbahnfahrzeuges bei einseitigem Zugseilriss und anschliessender Tragseilbremsung" [Oscillatory behaviour of a reversible aerial cablecar in the event of cracking of the haul cable on one side and subsequent braking on the carrying cable], report from the *Institut für Leichtbau und Seilbahntechnik*, ETHZ [Swiss Federal Technical University, Zurich], 1994

[2] H. Wettstein, "Die Tragseilbremsung" [Braking on the carrying cable], report from the *Institut für Bau- und Transportmaschinen,* ETHZ [Swiss Federal Technical University, Zurich], 1969