Dynamic Behaviour of the Grip and the Terminal Equipment of a Detachable Monocable Ropeway at the Terminal Entry

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1 Problem Definition

With detachable circulating monocable ropeways (CMR), the vehicles are able to pass from one terminal to the other at higher speeds than with comparable fixed gripped CMR, yet a slower terminal conveying transit speed ensures comfortable loading and unloading of the vehicles inside the terminals.

This is achieved by detaching the carriers in the terminal from the rope and decelerating them to walking speed. As the rope speed of such ropeways is always constant, the uncoupling is effected at full riding speed, which may cause high loads on the grip and hanger structure of the vehicles. The loads on grip and hanger become more critical when the vehicle at the moment of detachment makes a pendulum motion transverse to the direction of travel.

In the interest of increased economy and ride comfort, the trend on modern detachable CMRs is to build even larger carriers (6-seater chairs or 15-seater gondolas) and raise operating speeds. In order to reduce construction costs and avoid excessive interference with nature and environment, terminals become smaller and more compact. Increased operating speed, larger carriers and more compact

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terminals are factors to be taken into account in connection with the additional loads generated at terminal entry.

To make the uncoupling safe, the grips of the vehicles which may undergo a pendulum motion are trapped by a catching device mounted on the terminal entry (trumpet) and adjusted to a horizontal position. Due to the intensive lever action of the vehicle mass, which is a function of the weight of the vehicle, operating speed, type of suspension of the passenger unit and stiffness of the trumpet bearing (springs and dampers), this process of catching the grips generates considerable forces which must be taken into account when dimensioning the component parts affected.

The purpose of this paper is to analyze different terminal entry conditions and consequently different damping processes so that correct assumptions on load levels can be made. A computer program has bean established to determine the ***contact forces*** and the ***kinematic interaction*** between the guide sheave of the grip and the entry trumpet for vehicle and trumpet during terminal entry as a function of the position of the vehicle relative to the damper and of the initial conditions (vehicle speed, transverse pendulum motion) and is based on known design situations.

2 Mechanical Models

The carrier, the hanger including the grip, the entry trumpet and the rope are factors relevant to the motion at terminal entry. Mechanical design models are defined for the components in order to be able to describe their motion mathematically.

2.1 General Modelling Variants of the Carriers

For initial calculations, the carrier is modelled as a point mass. For exact calculations, a more accurate mathematical description of the inertia of the carrier is required, which is accomplished by modelling these carriers as rigid bodies.

Fig. 2-1 shows the arrangement of the masses in the mechanical model.

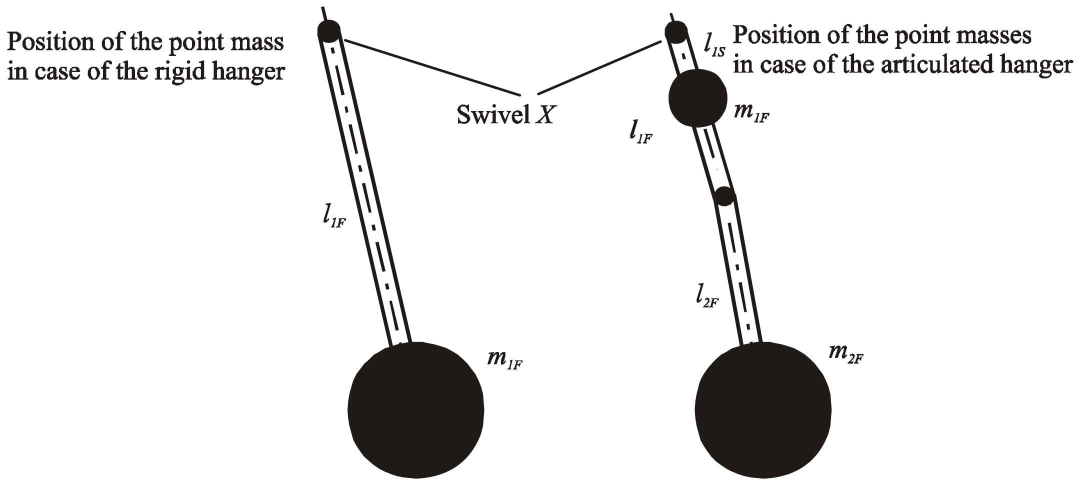


Fig. 2-1: Arrangement of Masses in Mechanical Models

Fig. 2-2 shows possible rigid body models for gondola and chair.

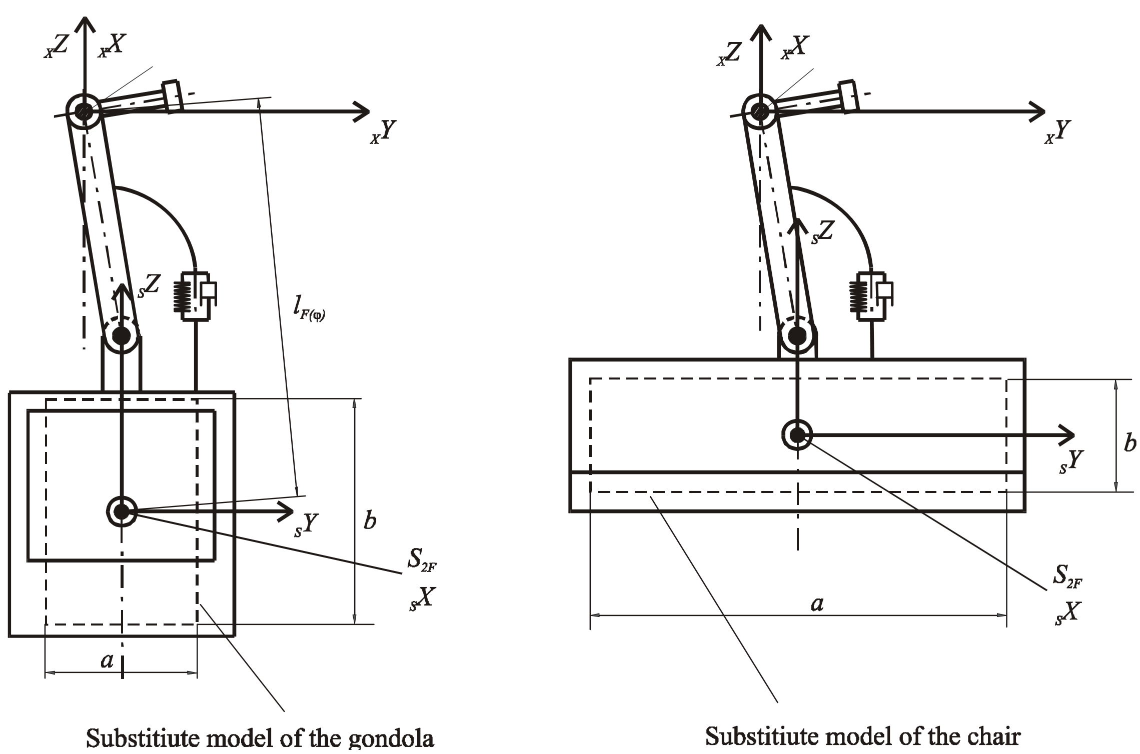


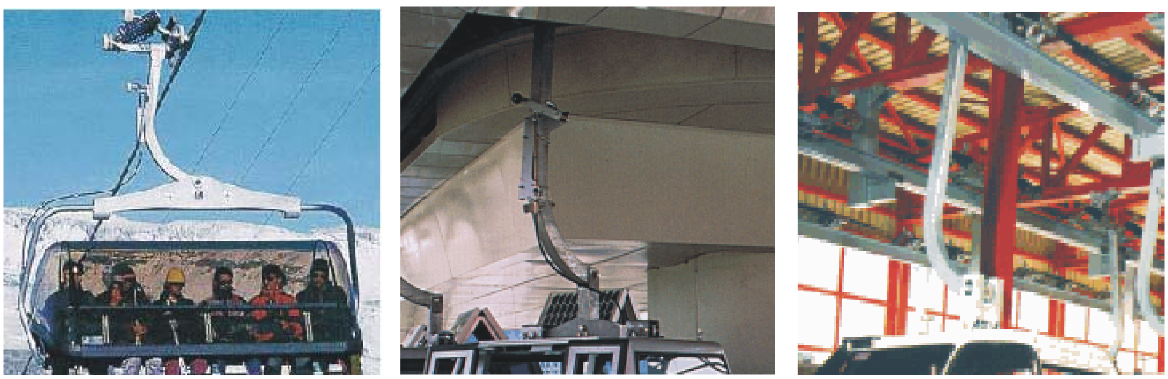
Fig. 2-2: Mechanical Models of Gondola and Chair

2.2 Model Variants of Vehicle Hanger Structure

For the purpose of the mathematical description of the hanger, we distinguish between two types of suspension:

1. The stiff suspension which is primarily used for chair lifts
2. The articulated suspension for vehicles of gondola ropeways

Fig. 2-3 shows photographs of different types of hangers:



Rigid hanger | Simple articulated hanger | Double articulated hanger

Fig. 2-3: Different Vehicle Suspension

Fig. 2-4 shows the mechanical models of various hanger systems.

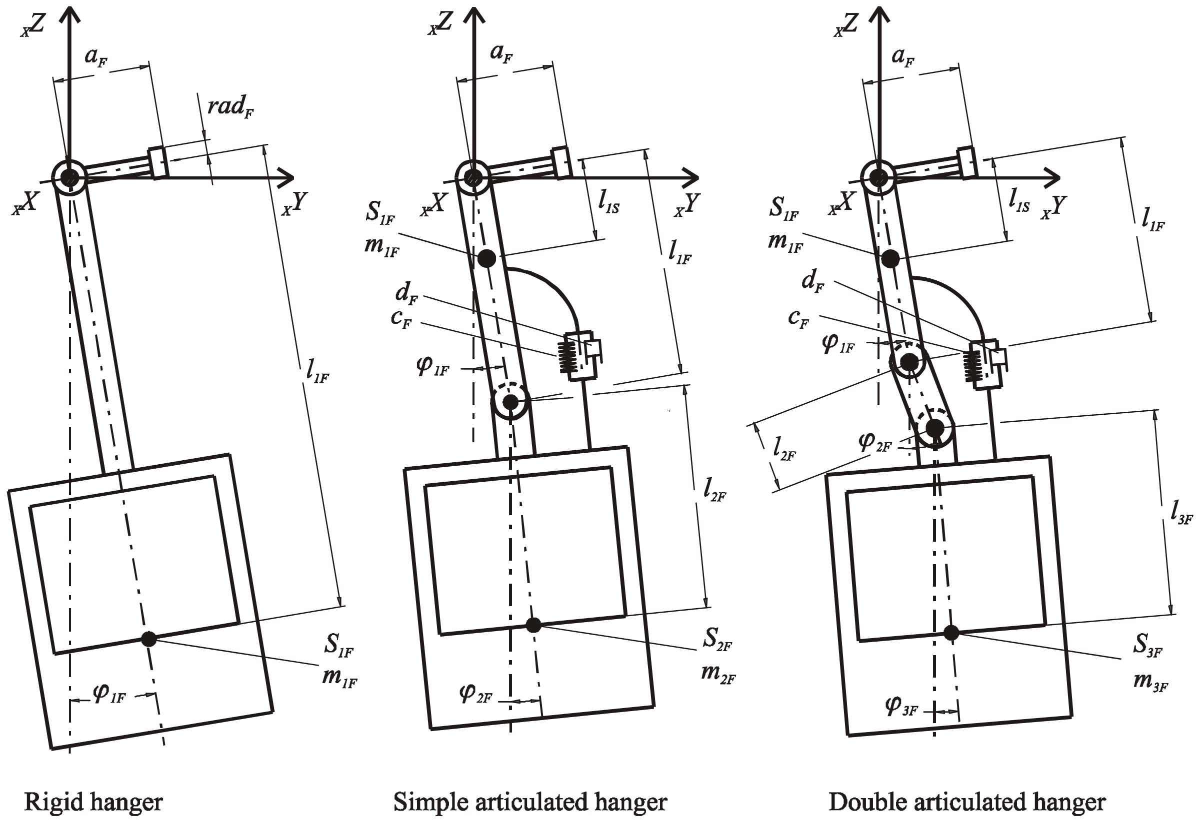


Fig. 2-4: Mechanical Models of Different Vehicle Suspension

In all suspension models explained below, the hanger bodies are modelled as zero-mass connecting rods. Simple masses are attached to the respective centres of gravity (see Fig. 2-1) to account their inertia.

2.2.1 Modelling of a Rigid Suspension

As shown in Fig. 2-4, the rigid hanger is the simplest type of all three designs. The mechanical model for this type of suspension is a rigid pendulum with only one degree of freedom, the pendulum angle φ_{1F}.

Detachable CMR are no longer built with all-rigid suspensions. Due to the high vehicle speeds today, the loads developed during terminal entry and the vibrations created when passing compression towers will be too high with this type of hanger. The suspensions of chairs are also fitted with damping rubber elements, which makes them not completely rigid.

2.2.2 Modelling of a Simple Articulated Suspension

The second design shown in Fig. 2-4 is a simple, articulated suspension. This type is frequently used with gondolas. It has two degrees of freedom, φ_{1F} and φ_{2F}. Its simplest mechanical model is a double pendulum. Due to the shocks acting on the real hangers during terminal entry, this type provides for mutual damping of the two hanger bodies. This avoids excessive and uncomfortable relative movements between carrier and hanger. In the model, this damping effect is achieved by means of a rotary spring / damper system acting at the two pendulum bodies (see Fig. 2-4).

2.2.3 Modelling of a Double Articulated Suspension

A double articulated suspension has three degrees of freedom, φ_{1F}, φ_{2F} and φ_{3F}. Again, this type is frequently used with gondola vehicles. The simplest way of modelling is to use a triple pendulum with three pendulum bodies. In order to avoid excessive relative movements between vehicle and hanger also with this type of hanger, the motion of the triple pendulum is damped. In the mechanical model, this is achieved by means of a rotary spring / damper system.

2.3 Modelling of the Entry Trumpet

The entry trumpet is mounted via a swivel joint, flush with the transit guide rail of the terminal. Outside the terminal, it is elastically suspended by means of a spring / damper system. When displaced from its rest position, the trumpet merely performs a rotary movement about the swivel bearing point *L* (see Fig. 2-6) and thus has only one degree of freedom, the trumpet deflection angle φ_T. Fig. 2-5 shows a real entry trumpet.

Fig. 2-5: Real Entry Trumpet

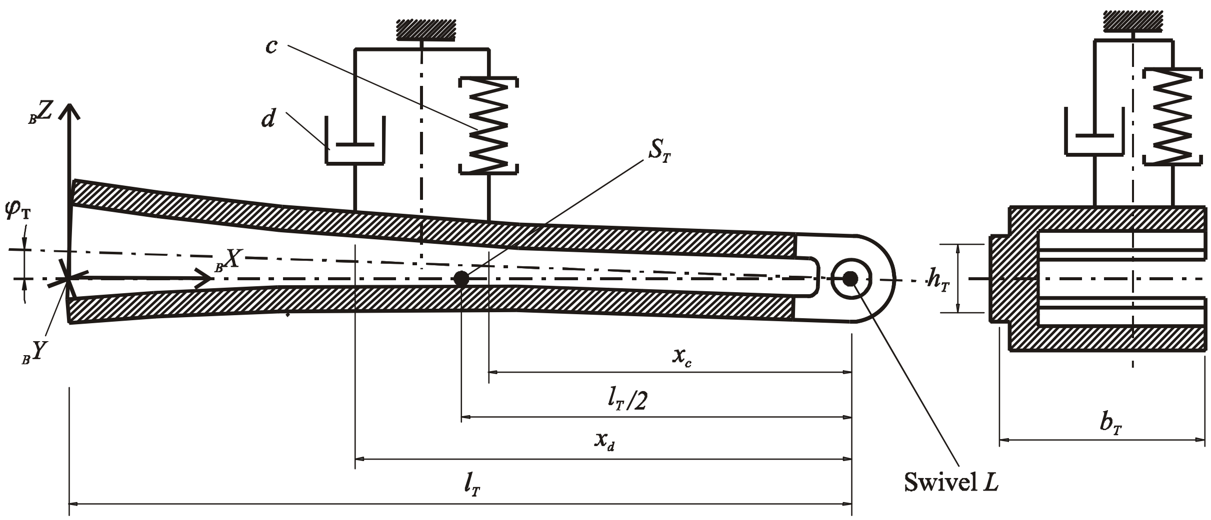


Fig. 2-6: Mechanical Model of the Entry Trumpet

The trumpet profile is approximated by several straight lines. The direction of the shock between guide sheave and trumpet wall is always perpendicular to the slope of the trumpet profile at the point of contact. If the trumpet is modelled with a straight line rather than a constant function, the slope of the trumpet profile changes abruptly at the transitions from one straight line to the next. As a consequence there are irregularities in the results at these points when calculating the constraining force.

2.4 Modelling of the Carrying-hauling Rope

The rope is modelled as a rigid rod. Ropes suspended freely in a rope span are highly complex vibration systems. It is therefore very difficult to generate a mechanical model of similar dynamic behaviour. Close to the trumpet hinge point, the rope rests on sheaves where a rigid rod is sufficient as a model. At the trumpet entry point, the rope sag is relatively large due to the vehicle weight and the approximation of the rope as a rigid rod is therefore a very coarse one.

2.5 Complete Model for Calculation

Fig. 2-7 shows a schematic representation of the complete mechanical model which serves as the base for the terminal entry calculation.

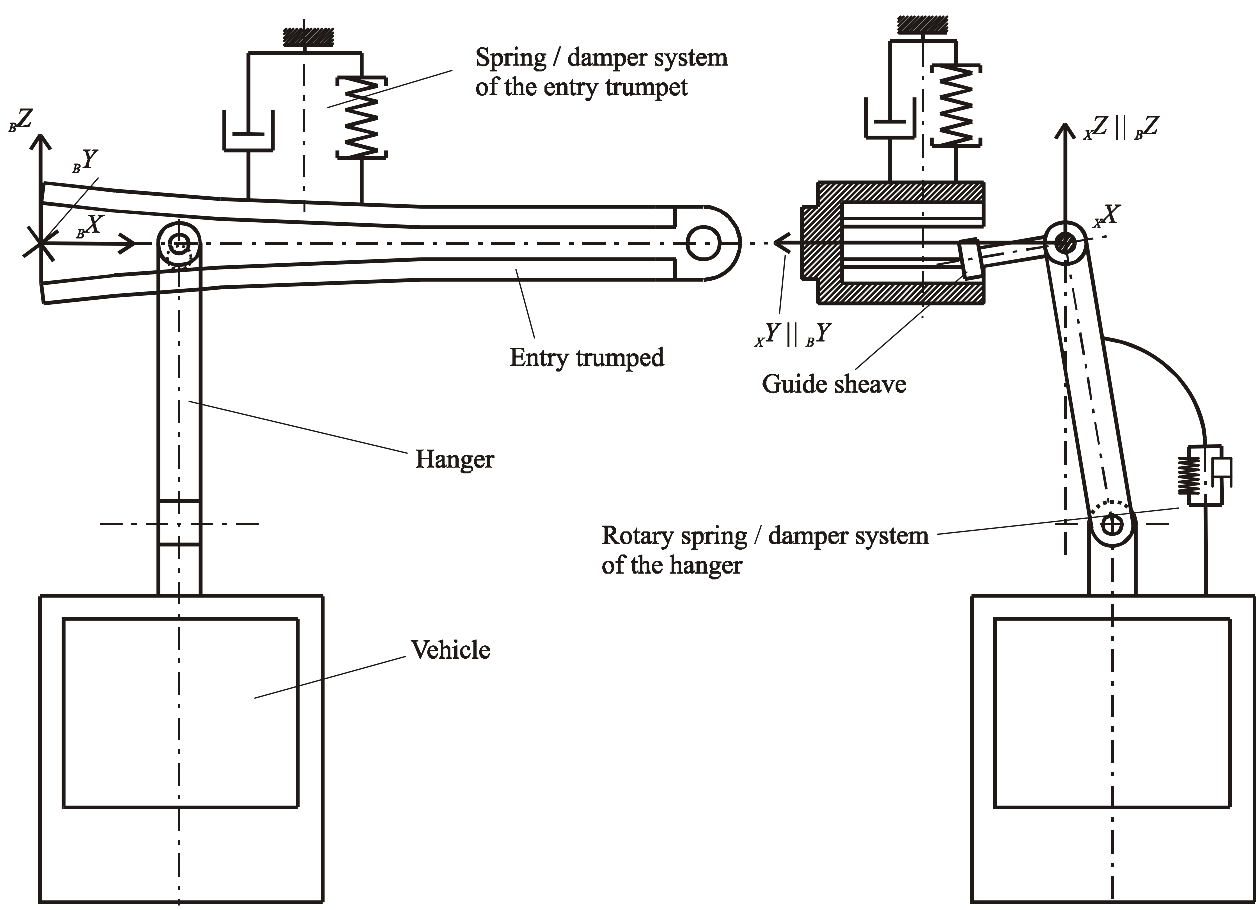


Fig. 2-7: Mechanical Model of the Entire System

3 Derivation of Motion Equations

3.1 Rigid Suspension

The elastic distortion capability of the rope permits a pendulum motion of the vehicle transverse to the direction of travel (*y/z* plane in Fig. 3-1). The twist angle φ_{1F} best describes this motion and is therefore defined as the generalized coordinate.

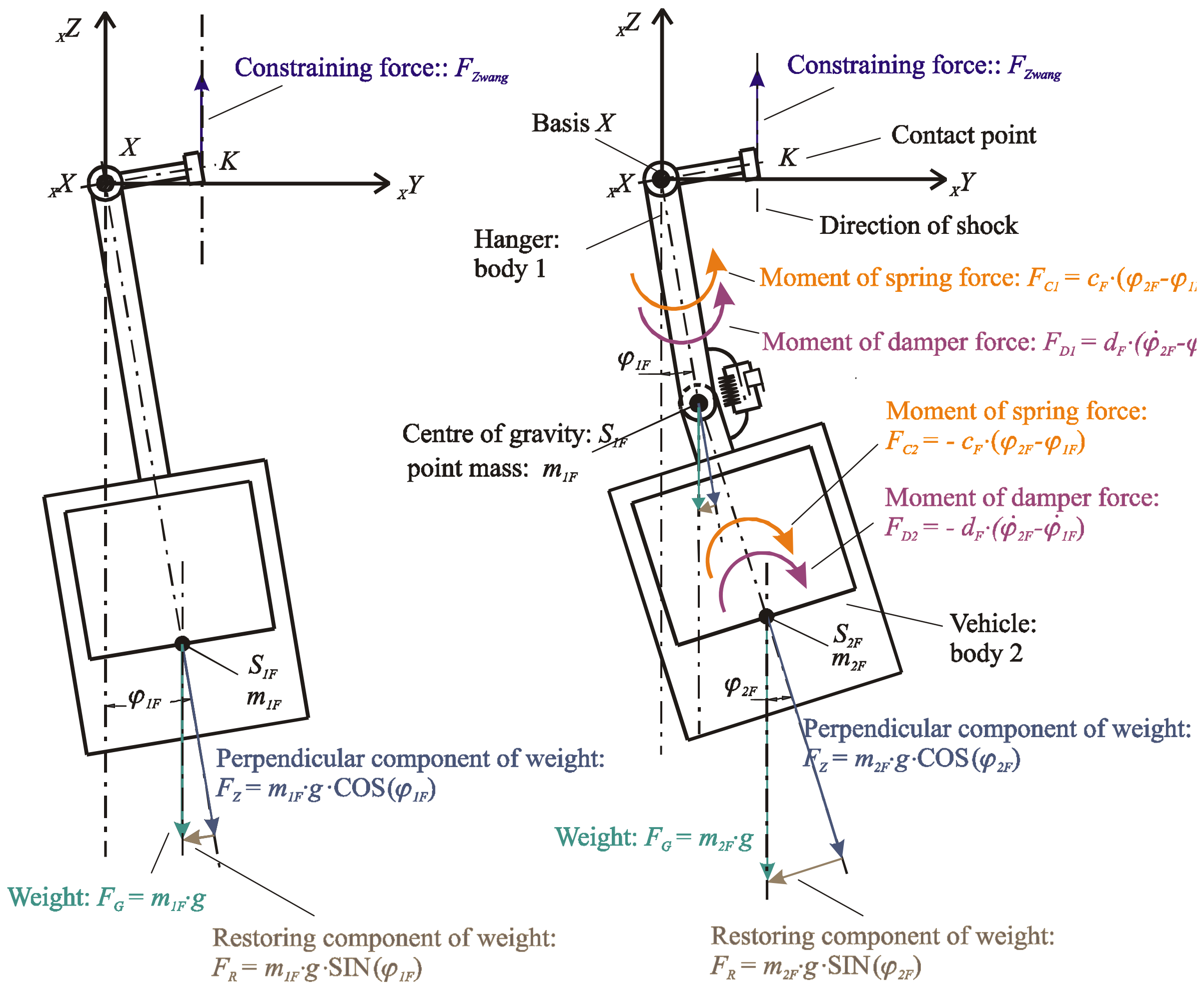


Fig. 3-1: Vehicle Model incl. Forces and Moments

The motion equation of the vehicle with rigid suspension can be derived by means of the momentum equation.

3.2 Simple Articulated Suspension

As described above, the simple articulated suspension has two degrees of freedom. As both bodies (hanger and vehicle) influence each other with this type of suspension, their mathematical description requires two interdependent motion equations which can be derived by means of the Lagrange`s principle (see Fig. 3-1).

3.3 Derivation of the Motion Equation for the Entry Trumpet

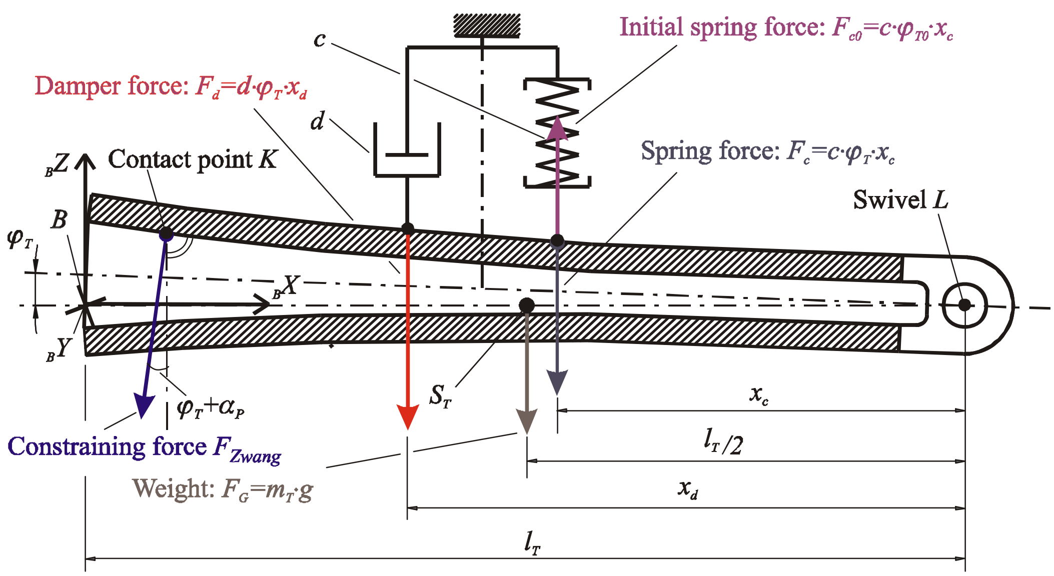


Fig. 3-2: Entry Trumpet incl. Forces and Moments

If the trumpet is displaced from its rest position, the forces $F_C = c \cdot \varphi_T \cdot x_c$ of the spring and $F_D = d \cdot \dot{\varphi}_T \cdot x_d$ of the damper are activated. Additionally, if there is physical contact, the constraining force F_{Zwang} acts upon the contact point. The motion equation of the trumpet is defined by means of the momentum equation.

3.4 Contact Condition and Constraints

As the grip passes through the entry trumpet, there are two different states of motion:

1. Free state of motion
2. Contact condition

<u>Free state of motion:</u>

In the free state of motion, the two bodies are not in contact. They move completely independent of each other. There is no action of any constraining force (= contact force) between guide sheave and entry trumpet.

<u>Contact condition</u>

In the contact condition the guide sheave and entry trumpet are in contact. A constraining force which influences both types of motion now acts between the two bodies. Mathematically, this can be recognized by connecting the equations of motion by a function of constraining force. The equations of the vehicle and entry trumpet now influence each other.

Fig. 3-3 shows the graphical representation of the free state of motion and the contact condition.

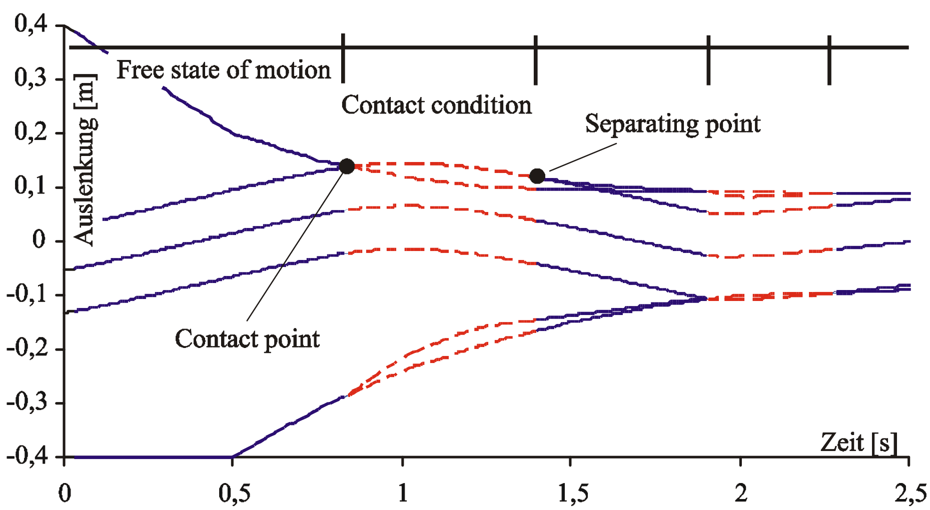


Fig. 3-3: Free State of Motion and Contact Condition

To ensure a correct time sequence of the computer program, it is necessary to define contact conditions and constraints which decide which state of motion prevails at what moment of the computation.

3.4.1 Contact Condition

The contact condition describes the transition from the free state of motion to the contact condition.

3.4.2 Constraint

The constraint determines whether the constraining force in the contact condition is a physically correct value, i.e. whether it is a compressive force. Only compressive forces can be transmitted between guide sheave and entry trumpet. If a tensile force is calculated in the simulation program, the constraint condition is violated and the two bodies separate again. The bodies then continue to move in a free state of motion.

4 Computer Program

Based on the mechanical models in chapter 2 and the equations derived to describe the dynamic motion cycles, a program has been developed to simulate the terminal entry of CMR vehicles. This program was written in ***FORTRAN 77*** and can be installed on PCs and workstations as well. The following is an explanation of the results obtained from various simulation runs, thereby indicating the options available with this computational program.

5 Evaluation of Results

5.1 General

This Section compares different calculations, thereby explaining the physical behaviour of the simulation model. The comparison of different calculations will illustrate the characteristic behaviour of the mechanical model.

The analysis covers the influences of operating speed, vehicle weight and the type of hanger on the load of the guide sheave and kinematic behaviour of the mechanical model. To be able to compare the different simulated entry conditions, the only parameters changed are those that are needed to describe a specific entry situation.

Terminal Entry with Reference Parameters

The following „terminal entry situation with reference parameters“ serves to explain the charts which can be used to better understand the results of the calculations.

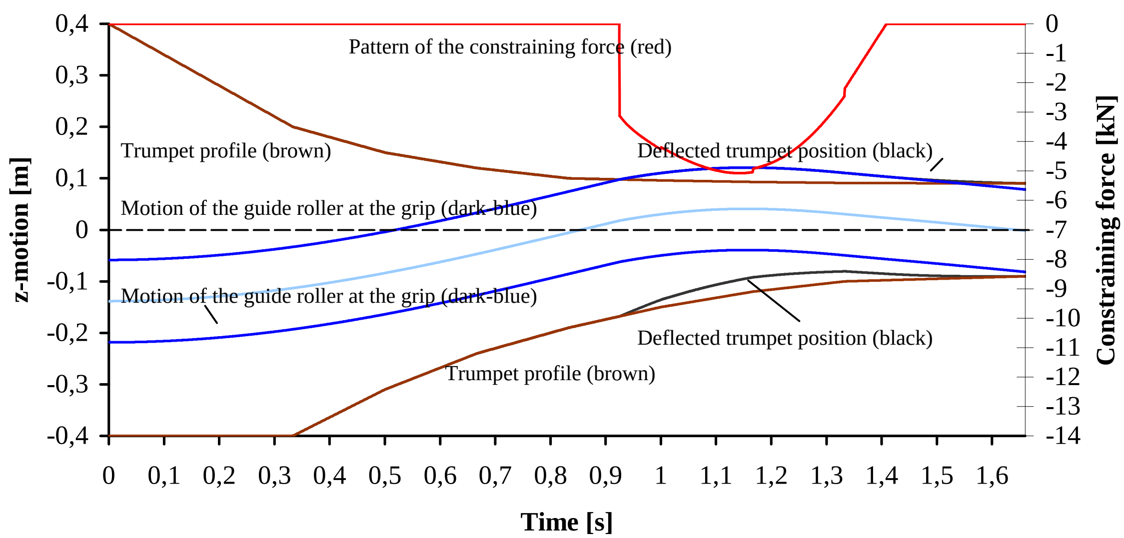


Chart 5-1: Terminal Entry with Reference Parameters

The two brown lines of the trumpet mark the trumpet profile in the non-deflected position. The black lines describe the deflected trumpet position caused by the vehicle. The dark-blue and light-blue lines mark the motion of the guide sheave at the grip. The red line shows the pattern of the constraining force (= contact force) between guide sheave and trumpet wall.

5.2 Influence of Vehicle Speed

When colliding with the guide sheave of the vehicle, the entry trumpet is deflected for two reasons:

1. Due to the speed of the vehicle transverse to the direction of travel (**effect 1**).
2. Due to the motion of the vehicle and the shape of the trumpet which tapers in the direction of travel (**effect 2**).

The faster the vehicle travels the greater and therefore the faster the deflection of the trumpet will be. Large deflections generate high spring forces, fast deflections generate high damper forces. The following charts show and compare two calculations with different entry speeds.

Terminal Entry at Elevated Vehicle Speed: $\dot{x}$ = 6 *m/s*

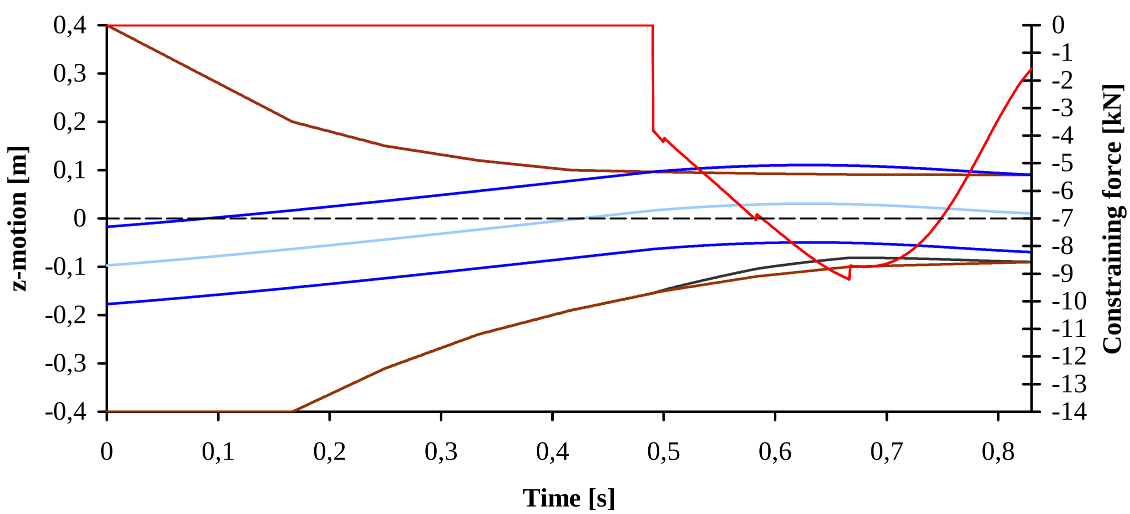


Chart 5-2: Terminal Entry at High Vehicle Speed: $\dot{x}$ = 6 *m/s*

Chart 5-2 shows a terminal entry at a vehicle speed that equals the real operating speed of modern CMR. The guide sheave (blue line) hits the trumpet (brown line) at the top. The cross-pendulum-type motion acts on the trumpet and a contact force is built up (effect 1). The high entry speed additionally deflects the trumpet as a result of effect 2. This causes the trumpet to move more intensively and faster and the contact force rises. The steps in the force characteristic can be explained by the unsteady transition from one straight trumpet profile line to the next.

Terminal Entry at Reduced Vehicle Speed: $\dot{x}$ = 1 *m/s*

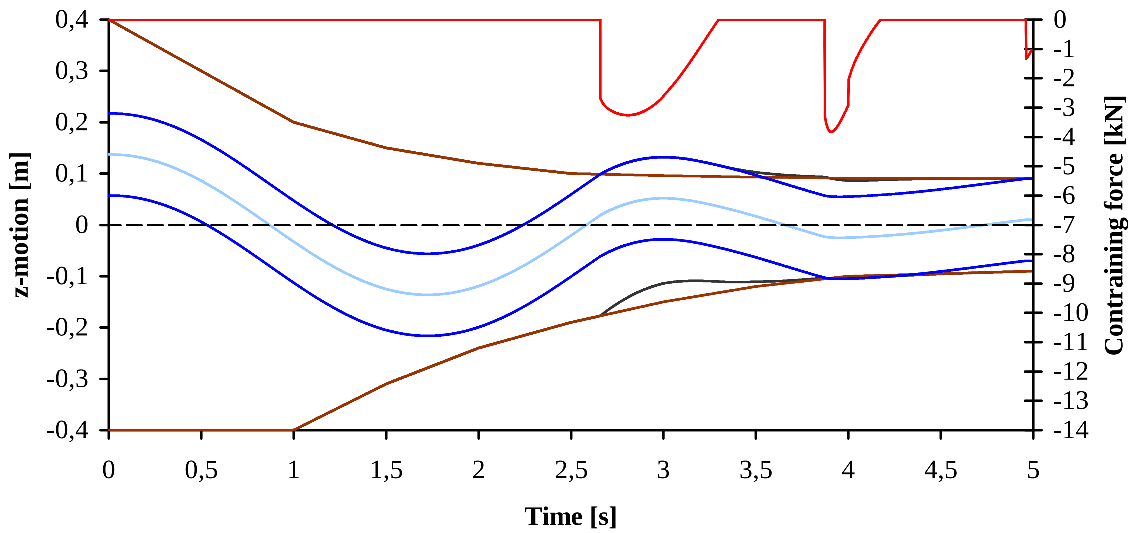


Chart 5-3: Terminal Entry at Reduced Vehicle Speed: $\dot{x}$ = 1 *m/s*

Again, the trumpet is impacted approximately at the same point as in the case of entry at high operating speeds. In this case, the trumpet is deflected almost exclusively by the cross-pendulum effect (effect 1). This causes a relatively slow movement with only little stress on the damper. The trumpet thus returns to the vehicle the energy briefly absorbed by the spring. The consequence is a short time of contact with only little damping of the vehicle pendulum motion. The second contact produces a somewhat greater force which can be explained by the stiffer response of the springs and dampers close to the hinge point.

The simulation of a terminal entry process at reduced vehicle speed helps illustrate the kinematic behaviour of vehicle and trumpet.

5.3 Influence of Vehicle Weight

The vehicle weight is a key factor contributing to the loads acting on the components during terminal entry. More weight means more energy and consequently greater forces resulting from shock loads and deceleration processes. The following analysis covers the influence of changing the weight of the carrier. The hanger weight is left unchanged.

Terminal Entry at Reduced Carrier Weight: m_{2F} = 100 *kg*

Due to the very light vehicle, only a small amount of energy is available, generating relatively small contact forces. Chart 5-4 shows a simulation with reduced carrier weight and an entry speed of 3 *m/s*. The lightweight vehicle is unable to displace the trumpet by a large amount. Compared to the reference entry ($m_{2F} = 400 \cdot kg$), the contact phase in this case is only very short and the resulting forces are small.

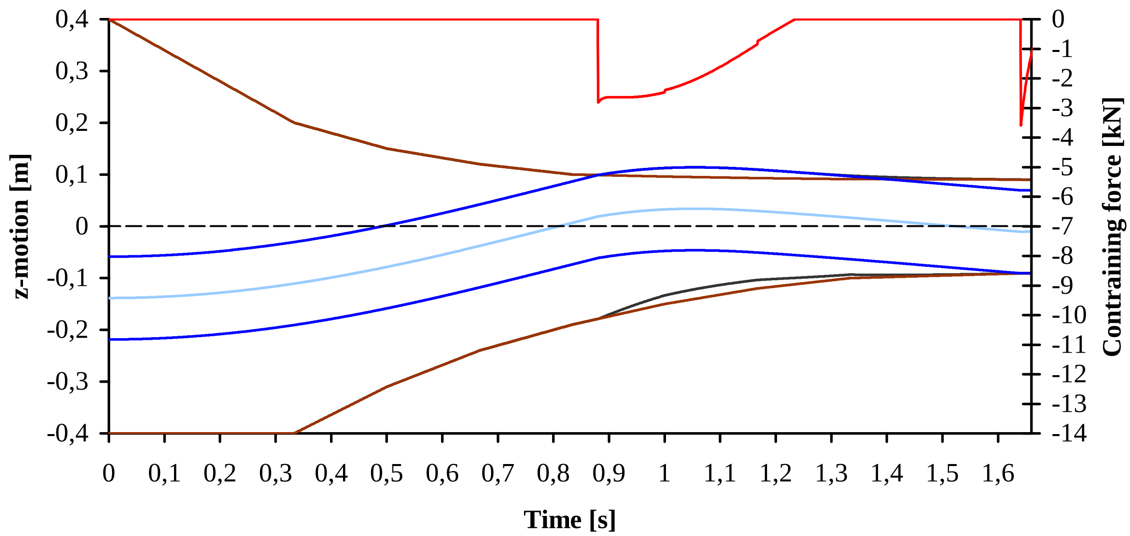


Chart 5-4: Terminal Entry at Reduced Carrier Weight: m_{2F} = 100 *kg*

Terminal Entry at Elevated Carrier Weight: m_{2F} = 700 *kg*

With heavier carriers larger amounts of energy and greater forces must be absorbed by the trumpet mounting to catch the vehicle grip. For the same springs and dampers of the trumpet mounting, this is possible only with greater or faster deflection. The contact phase, compared with the previous entry conditions, is longer and the contact force significantly greater. Even at the relatively small terminal entry speed of 3 *m/s*, the contact forces are similar to those created when entering terminals at high operating speeds (see Chart 5-2).

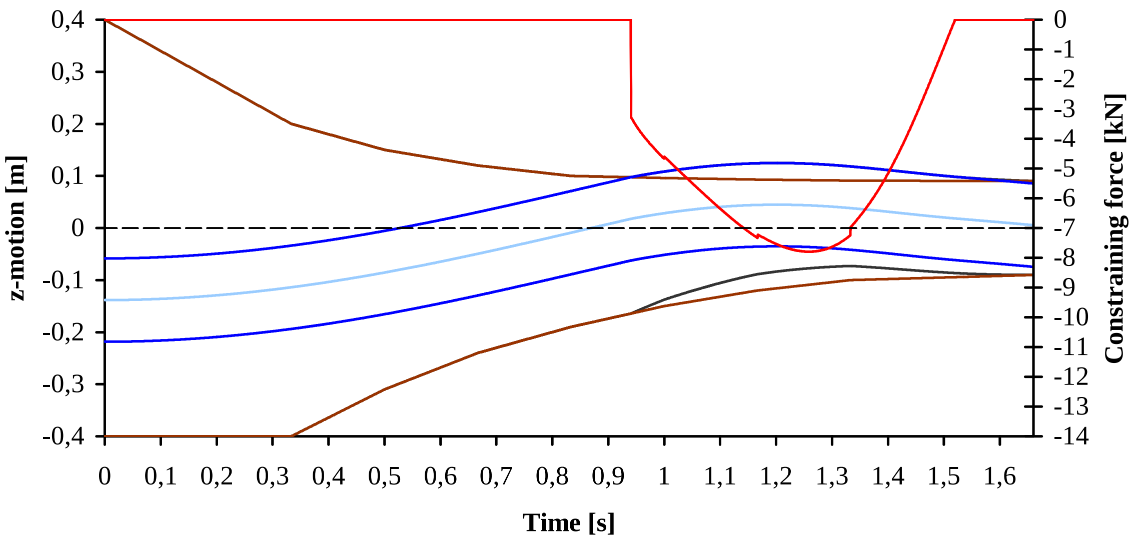


Chart 5-5: Terminal Entry at Elevated Carrier Weight: m_{2F} = 700 *kg*

5.4 Comparison Between Rigid and Simple Articulated Hanger

The articulated hanger is compared to the rigid hanger structure. This is achieved simulating terminal entries with the same initial parameters. The kinematic behaviour as well as the amount of the contact force are compared.

Articulated Vehicle Hanger: Speed 3 *m/s*

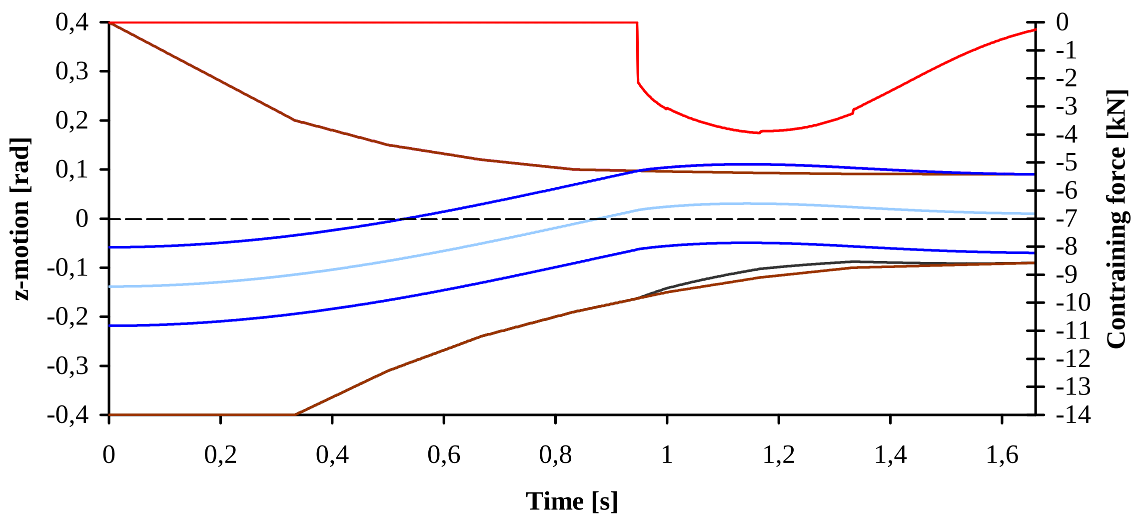


Chart 5-6: Articulated Vehicle Hanger: Speed 3 *m/s*

The articulated pendulum which is subjected to deformation is able to avoid resistance at the guide sheave. The contact force is reduced. Compared to terminal entry conditions with rigid hanger, as described in the following paragraph, the contact phase is relatively long.

The key factor on articulated hangers is how much energy of the swinging cabin mass can be transfered to the trumpet via the grip. If the contact force is too small and the transfer of energy in the area of the entry trumpet is therefore insufficient, this may have adverse effects in the area of the deceleration section, where the vehicle, which is still heavily swinging, is retained by the rigid guide rail, which may cause heavy loads on the component parts. It is therefore necessary to achieve optimized conditions between hanger and trumpet so that the largest possible amount of energy of the vehicle can be transfered to the terminal equipment before the uncoupling.

Rigid Hanger: Speed 3 *m/s*

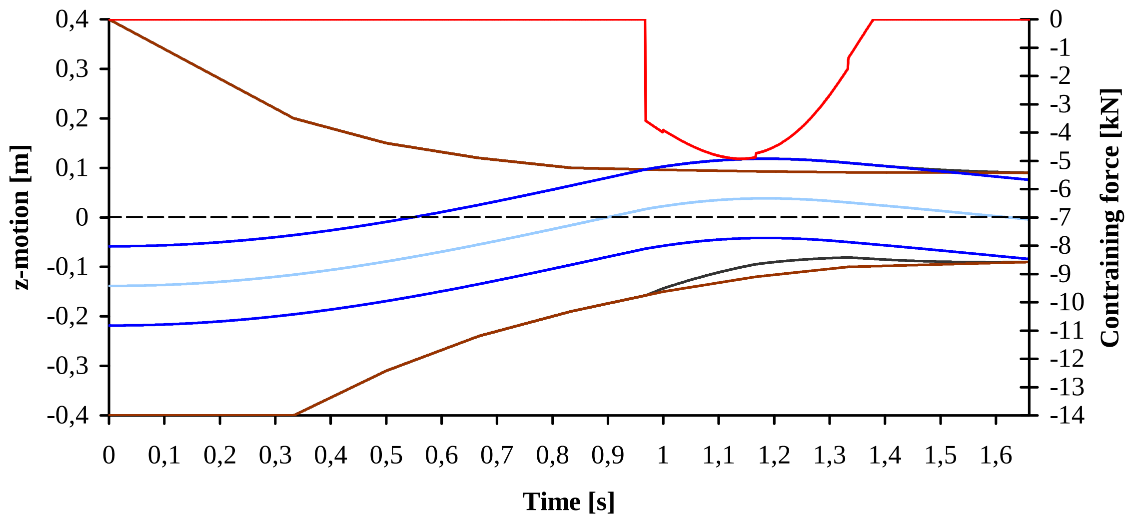


Chart 5-7: Rigid Hanger: Speed 3 *m/s*

The trumpet is deflected to a considerably greater extent in order to balance it against the rigid pendulum. At the same time, however, the contact period is shorter This causes abrupt deceleration of the grip and the rigidly connected hanger and vehicle, which also results in greater contact forces between guide sheave and trumpet. Due to the great deflection of the trumpet, the tapering shape of the trumpet and the forward motion of the vehicle, the guide sheave, hanger and the rigidly mounted cabin are again accelerated inward after passing the reversal point, which increases the pendulum effect. The load on the parts increases and the passengers are exposed to higher g loads.

6 Summary

Modern circulating monocable ropeways are designed for even larger carriers and for continuously increasing operating speeds. Additionally, the terminals become more and more compact to save construction costs on the one hand and to conserve nature and the environment on the other. These three effects, increased operating speed, larger carriers and shorter terminals, result in even greater loads on vehicle components, such as grip, hanger and cabin or chair.

This computer program was created as a tool to simulate terminal entry conditions of the CMRs. It is thus possible to design carrier, hanger and trumpet and to adjust their mountings or damping (hanger damping) in such a manner as to prevent excessive loads on the component parts in critical terminal entry situations (high speed, fully loaded carrier, considerable cross-pendulum motion) and to protect the passengers against excessive g loads. The computer program is not yet verified on the basis of reference data from measurements on a real installation.

For a complete analysis of the entire terminal entry process, the computer program will be further improved, existing inaccuracies of the model will be eliminated and the simulation extended to include the entire entry path (entry trumpet and deceleration section). The additional analysis of the deceleration section will later also provide more accurate information about an „ideal" behaviour of the entry trumpet. Energy studies covering the trumpet area should help to decide how the trumpet mounting must be adjusted in order to absorb a large amount of pendulum energy from the vehicle. A key element in this connection also includes the analysis of various hangers with different pendulum damper setting as a significant factor to transfer to the entry trumpet the energy of the gondola and the payload via the grip.