Instrumenting a cablecar on the Zugspitze to quantify loads during emergency-brake testing

by Heinz Joas

A new cablecar system was built in order to transport skiers faster to ski lifts on the glacier plateau at the top of the Zugspitze-West Germany's highest mountain. The task of the Bavarian Technical Inspection Association was to verify by actual measurement theoretical methods employed in the design of the system and at the same time to determine whether the speed of 5 m/s (984 ft/min) desired by the operator could be approved under prevailing safety regulations. During the course of verification testing, a fully laden car was halted abruptly at predetermined points on the track cables and the resulting force, acceleration, and deflection were measured.

The Zugspitze, at 2966 m (9,731 ft) above sea level, is West Germany's highest mountain and a year-round recreational area. Depending on one's interests, physical endurance, and climbing skill, there are several methods of reaching the summit. For hikers, the climb can involve hours of intense effort. For sightseers and Alpine skiers, the trip can be made easily and quickly either by cog railway or cablecar.

Using the traditional cog railway to travel from the base station (Eibsee) to the summit station (Schneefernerhaus) takes about 25 min. The true summit is accessible in another 10 min by cablecar. Those in more of a hurry can cover the 2000-m (6560-ft) vertical difference with the Eibsee cablecar in only 10 min. From any of the spacious terraces at the top of the mountain there is a glorious view of the peaks and glaciers of four alpine countries — Austria, Italy, Switzerland, and West Germany.

Snow can be found *on* the upper slopes of the Zugspitze year round, and if the weather is favorable up to 8000 skiers per hour sweep along the various runs. In order to transport skiers more quickly from ski lifts on the glacier plateau to the Schneefernerhaus station, the Bavarian Zugspitzbahn Company built a new cablecar system. Its loaded car is shown in **Fig. 1** against the background of the snow-covered Alps.

The cablecar system is of the winch type or so-called cableway system in which a single car is hung on two track cables and hauled via a separate hauling cable and drive winch located at the top station. This is unlike normal bicable systems, in which driving and braking forces can be created in both directions by a hauling cable that forms an endless loop. Instead, the winch provides power for ascent while gravity provides the sole driving force for descent, regulated of course with the winch from above. Because of the steepness in grade, rolling resistance of the car is insignificant.

Fig. 1: The cablecar system, with two track cables and one hauling cable is ideal for short, steep grades such as this one with maximum track grade of about 30 deg

This type of transport system is used primarily for steep, relatively short routes requiring only a single track. The cableway is the first of its type used for passenger transport in West Germany; only in Switzerland, Austria, and France are there a few systems like it in operation. Some of the most essential technical features of the cableway are listed in the Table below.

Unlike bicable systems, a cableway requires no restraining cable, no restraining-cable reversing sheave, no horizontal sheaves, and no constant-tension device. Consequently, the bottom station can be a very simple, relatively inexpensive structure, especially if the track cables are of fixed tension. **Fig. 2** shows a side view of the bottom station in which the twin-leg trestle, trackcable saddle, bracing strut, and platform are seen.

Complexities of hauling-cable systems

Despite the apparent simplicity of the cableway system, there are also several problems connected with this type of construction. As a result, special requirements are necessary for cable-system layout and planning, as well as for the sizing and design of major components.

For example, since the track cables maintain basically all of the tension in cableway systems, a relatively small-diameter cable can be used for hauling. This cable must be capable, however, of withstanding substantial pulsating stress. The maximum fluctuation in haulingcable force is between 35.25 kN and 7.06 kN (7924 lb and 1587 lb), which is 16.7% and 3.3 % respectively of the theoretical breaking load. Considering the size of the cable, its stress fluctuates in the range between 65 N/mm^2 and 322 N/mm^2 (9427 lb/in.^{2} and 46,702 lb/in.^{2}) -a tensile stress range of 257 N/mm^2 (37,274lb/in.^{2}).

In addition to pulsating tensile stress, the cable also undergoes pulsating bending stress as it is wound onto the drum. This stress is normally greater than on the sheaves of bicable systems because drum radii of curvature are often smaller and maximum compression is greater. These two factors tend to reduce fatigue limit and consequently, cable life.

Horizontal length	216.35 m	709.84 ft
Altitude change	76.35 m	250.50 ft
Max. track grade	29.33 deg	
Min. track grade	10.00 deg	
Max. car speed	5 m/s	984 ft/min
Max. car load	64 kN	14,388 lb
No. of passengers	45	
No. of track cables	2	
Track-cable diameter	41 mm	1.6 in.
Hauling-cable diameter	17 mm	0.7 in.

Table: Main technical features of the cableway

Additional mechanical stresses result from winding because as the cable completes one layer, it compresses previously wound layers. Accompanying this compression is the settling of the cable into grooves of the previous layer which creates vibration. Underlayers of cable become deformed because the drum is wound with increasing cable tension as the car rides up the track cables. The combined compression and friction during winding results in damage to the galvanized surface of the cable and eventually leads to corrosion.

Fig. 2: View of bottom station with platform for boarding cablecar reveals its simple and relatively inexpensive design

Since the conditions regarding stress and makeup of the hauling cable differ considerably from those foreseen by the normal regulations, it was necessary for more rigorous standards to be applied in cable sizing and inspection frequency.

Testing and measuring strategy

The purpose of conducting the tests was to verify experimentally the theoretical methods used in design, although a specific objective was to determine whether the maximum speed of 5 m/s (984 ft/min) could be permitted under prevailing safety regulations.

In view of the objectives, the following testing procedure was developed:

- The fully laden car would be stopped suddenly by applying the catch brake at predetermined points along the track cables as it descended at constant speed. Resulting forces, accelerations, and deflections would be measured and analyzed.
- Traveling speed would be increased in stages. Progression to the next step was dependent on the analysis of the results of previous stages.
- Of particular interest was the swinging of the car which, in the extreme case, could result in contact with the track cables.

Planning was conducted by the cablecar manufacturer and specialists in instrumentation and testing. After the various transducers, and measurement and recording equipment had been selected, the whole rig was assembled and tested in the laboratory to reduce the probability of failure and to reduce rigging time at the site.

One of the conditions that at first appeared difficult to satisfy was the simultaneous recording of all measured values. Reason: The monitoring point for the tests was in the car itself, however two essential signals originated at the fixed bottom station. No attempt was made to employ telemetry because previous tests on other cablecar systems has been beset with serious interference problems. Fortunately, the relatively short distance involved and the existing terrain made it possible to trail two 300-m-long signal-transmission cables. Possible effects on the measured signals from changing inductance during the test runs was determined by preliminary tests (zero-point stability, calibration signal). During measurement, movement of the shielded cable produced no noticeable variation in the measured signals.

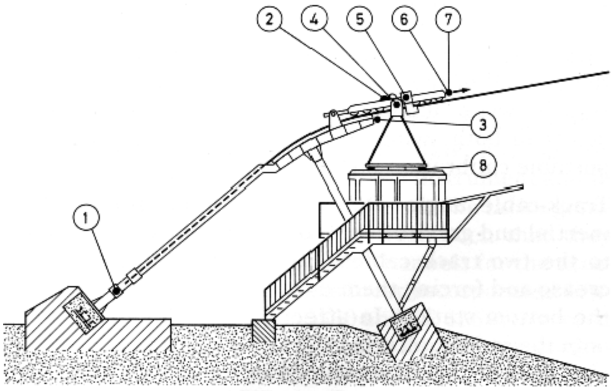

Fig. 3: Two transducers were on fixed parts of the bottom station; the remaining six on the running gear and roof struts of the cablecar

① Pressure transducer for tension in bracing strut
② Strain gages on bridge bar for hauling-cable tension
③ Inductive displacement transducer on saddle for determining track-cable entry angle
④ Inductive angle transducer for swing angle of car
⑤ Accelerometer for measuring car deceleration
⑥ Tacho-generator for car speed on the track cable
⑦ Displacement transducer for measuring distance travelled
⑧ Load cell for determining car load

Parameters and their transducers

Fig. 3 illustrates the position and explains the function of the eight transducers used in the verification test. Two transducers were on fixed parts of the bottom station; the remaining six on running gear and roof struts of the car. Despite much preparation in the laboratory, it still took three days to install the transducers and set up the measuring and recording equipment. Electric power for the instruments was provided by a 14 A-h battery which could be recharged overnight.

Speed. To measure the speed of the cablecar along the two track cables, a tacho-generator was mounted on the ascent side of the running gear. The device has a rotational element which generates a dc signal proportional to the speed of travel. A source of error which had to be taken into account was possible slip between the running wheel and track cable, caused either by high acceleration, high deceleration, or adverse weather conditions. **Fig. 4** shows the underside of the running gear with the tacho-generator on top of the left track cable.

Travel. Measurement of the distance covered along the track cables was performed by attaching a disc-shaped permanent magnet selectively to one side of either of the two running wheels of the tacho-generator. These wheels have a circumference of 0.5 m and 1 m (1.64 ft and 3.28 ft). A cold curing, two-component strain-gage cement (HBM Type X60) was used to attach the magnets. Each revolution of the wheel generates a pulse in a stationary coil mounted nearby. This parameter is vulnerable to error in the same way as speed.

Time. To provide a reliable time reference for analysis of oscillograph traces and tape recording, a frequency generator was installed in the car. This eliminated the possibility analysis errors due to fluctuations in chartfeed speed or tape speed.

Deceleration. Deceleration of the moving system —made up of the car (including staff, equipment, and weights), running gear, and hauling cable— was measured with an accelerometer (HBM Type B12) mounted on top of the running gear. Fig. 5 shows the accelerometer and its mounting immediately next to the pivot axis of the running gear. The longitudinal axis of the accelerometer was aligned with the track cables.

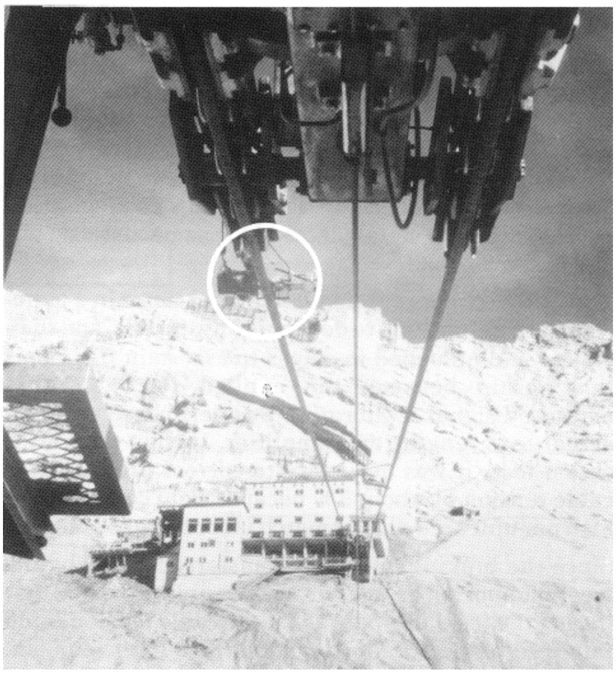

Fig. 4: Encircled on running gear and trackcable is tacho-generator for speed and travel measurement. View is from below looking toward Schneefernerhaus

Cable tension. The hauling cable on this type of cablecar system is not normally attached to the running gear but instead is wound several times around a spring-loaded cable drum and then secured with a clamping device. The torque created and absorbed by the drum reduces the likelihood of cable kinks or overstressing.

Since standard tension transducers could not be used without major modifications, the spring mechanism of the drum was replaced by a bridge bar with strain gages attached to it. The torque resulting from cable tension and drum radius was born by the bridge bar through a stop on the drum. **Fig. 6** shows a top view of the running gear. To the right, adjacent to the cable drum and clamping device are two plates of the cabledrum stop with the bridge bar underneath. The strain gages are also partially visible.

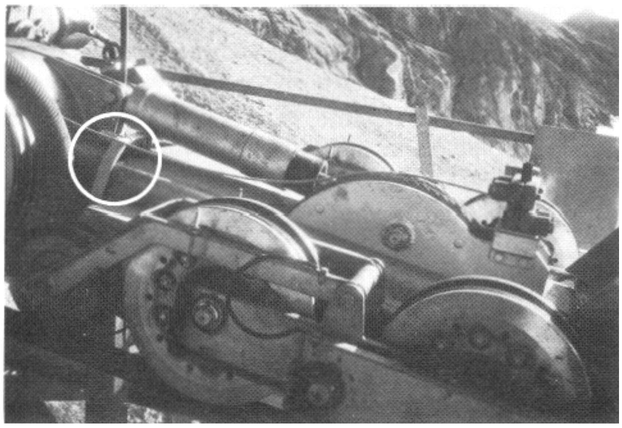

Fig. 5: Accelerometer aligned with track cables was used to measure deceleration of moving system

The bridge bar was sized to create the maximum possible measuring signal without overstepping a sufficient safety factor for the maximum anticipated cable tension. Since the area on the bar around the point of stress was not directly accessible, strain gages were adhered to its underside. Strain gages (HBM Type LY 61) were connected in a full-bridge circuit. Two passive gages needed for temperature compensation were attached to metal plates of the same material but exposed to no load.

The bridge bar was preloaded several times in a materials-testing machine to determine hysteresis, and then loaded and unloaded in stages to ascertain the linear relationship between the applied force and the measured signal. Calibration was performed with the actual lead lengths and amplifier. During the verification tests it was necessary to correct the values of cable tension by about 5 % because field conditions of load per unit area did not match laboratory conditions.

Since the braking force was transferred solely by the freely supported bridge bar, the possibility existed that during the jerkiness of braking the cable tension could fall to zero briefly, allowing the bridge bar to slip out. For this reason the crew on board put a lot of personal value in "loss control".

Angle of swing. When the emergency brake is applied as the fully laden car is descending at maximum speed, the maximum swing deflection is in the direction of travel and comes nearest to track cables during the first oscillation. The measurement of swing angle is important from a safety standpoint because it is imperative to prevent a collision between the car and the cables.

Swing angle for the cablecar is defined as the relative change in angle between the car and track cables. (Note that because of sag in the track cable this angle is not a constant over the length of the track). The inductive transducer used for measuring swing angle was bolted to the running gear by means of a bracket. The swing angle of the car was transferred to the rotational axis of the transducer by means of a tie rod cemented to the journal of the swing bearing. The linear relationship between angle and measured signal, and symmetry in both swing directions, was checked with a portable calibration instrument.

Track-cable angle. During emergency braking, the inertial and gravitational forces of the car are applied to the two track cables, causing their tension to increase and forcing them downward onto the saddle of the bottom station. In effect, the track cable "rolls" onto the saddle, altering the angle of cable entry. This change in angle was measured indirectly with an inductive displacement transducer (HBM Type W 50). **Fig. 7** shows the transducer mounted on the saddle and its probe arm pressed against the underside of the track cable. Correlation of measured signal with cable-entry angle was done by reading from an inclinometer at the saddle while the car stood at different points along the track cable.

Track-cable tension. Since track-cable tension can be adjusted hydraulically from the bottom station, it was possible to determine cable tension by measuring hydraulic pressure with a strain-gage-based pressure transducer (HBM Type P2/1000).

Cablecar load. Measuring load presented no difficulties because standard safety equipment included four strain-gage-based load cells (HBM Type U1-V) incorpo-

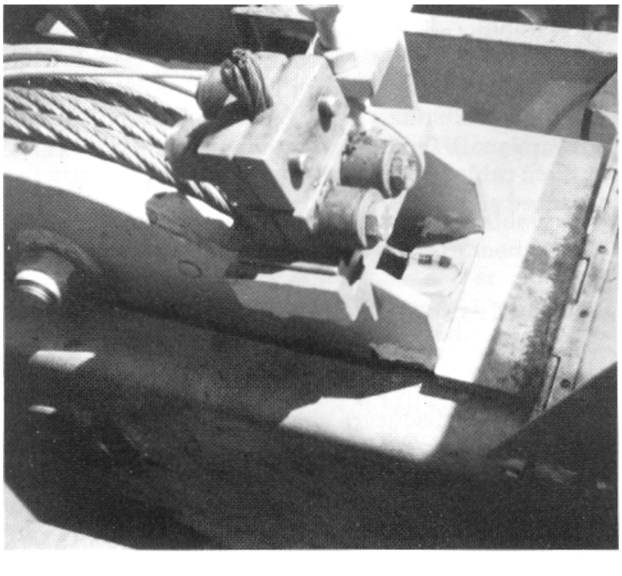

Fig. 6: From above looking on running gear are haulingcable drum and bridge bar with strain gages visible

rated into the car's roof support structure together with an integral instrument amplifier. In the event of overload, the system normally triggers an alarm by means of a limit switch. For the verification tests, the same signal was used to determine the change in the car's apparent load when braking.

Conditioning, amplification, monitoring, and recording of the eight transducer signals and frequency-generator signals were performed by two three-channel 5-kHz carrier-frequency instrument amplifiers with digital display (HBM Type KWS 382.D8), a 14-channel UV-lightbeam oscillograph recorder, and a 14-channel analog tape recorder. **Fig. 8** shows the equipment in the cablecar, strapped down for safety during emergency-brake testing.

The signals for track-cable tension, hauling-cable tension, cable-entry angle, swing angle, and deceleration had to be fed through the two instrument amplifiers for recording. The signal levels of the tacho-generator and frequency generator were such that they could be recorded unamplified. Channels for the accelerometer and pressure transducer incorporated lowpass filters (HBM Type TP 3550 and TP 3551) to screen out high-frequency interference. Transducer assignments and circuitry for the measuring and recording system are illustrated in the block diagram of **Fig. 9.**

Actual testing and data analysis

Each test run started from the top station with the car descending at as constant a speed as possible. The load, including instrumentation, gear, and staff, was 25 % above the permitted maximum. As the car reached a point along the track where prior analysis had indicated that the swinging, force variations, and operating conditions would be least favorable for braking, the catch brake was triggered. After swinging had died away, one of the crew had to climb through the roof and up the ladder to the running gear in order to release the brake.

An analysis and extrapolation of the results performed immediately after each run was used to determine if

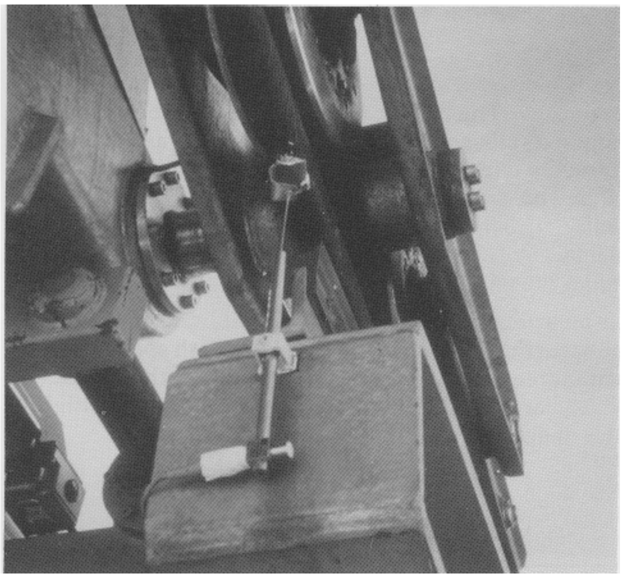

Fig. 7: At bottom station, track-cable entry angle is measured with inductive displacement transducer

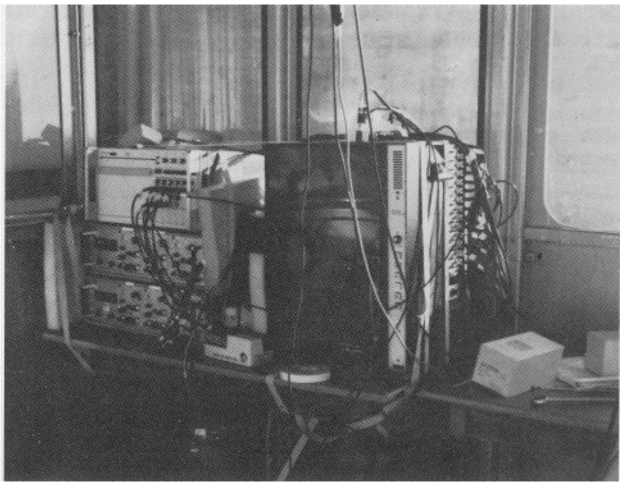

Fig. 8: Monitoring center: Seen here are tape recorder, two three-channel carrier-frequency instrument amplifiers and UV oscillograph

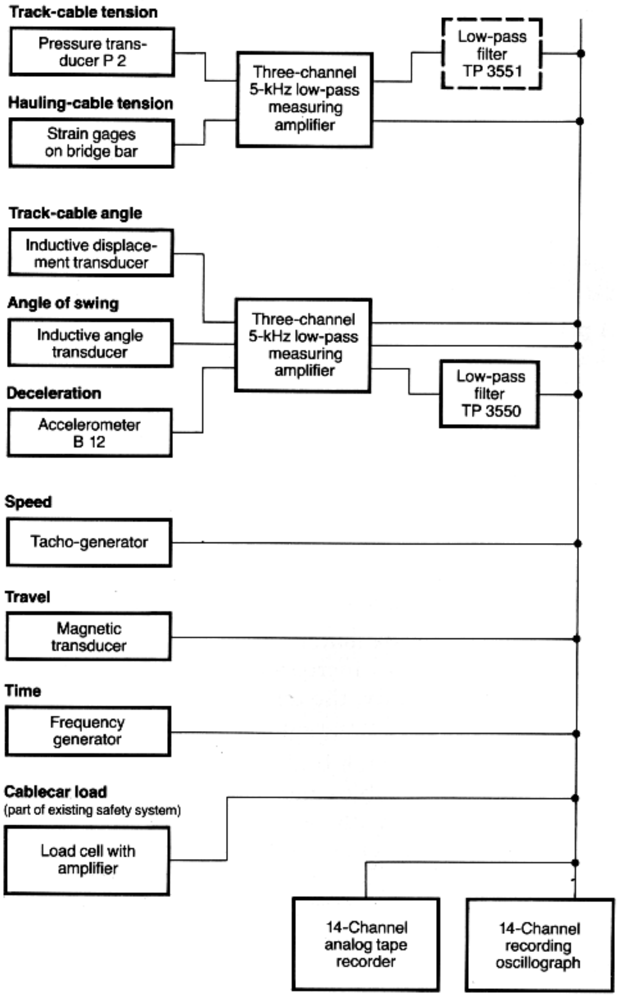

Fig. 9: Transducer assignments and simplified circuitry for the measuring and recording system

a higher speed could be attempted without risk. This made it possible to complete the constant-speed tests and braking tests in half a day.

The scales for the traces on the strip-chart recorder were created so that measured values could be read in the proper units without conversion. This made the decision of whether or not to go on to the next testing stage faster and easier. **Fig. 10** shows a typical stripchart recording for an "emergency braking event". Recording of the signals on magnetic tape also allowed analysis of the braking events by stretching time scales or combining traces.

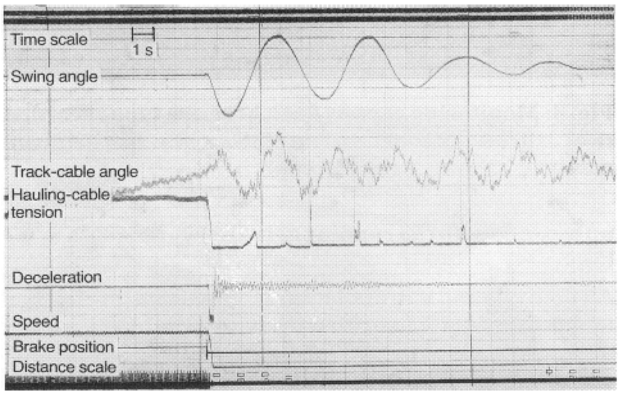

Fig. 10: UV-oscillograph trace shows sudden change in measured values caused by abrupt deceleration

One aspect of the analysis worth special note is the problem of describing the motion of the cablecar, which moves in space and has no fixed reference point with respect to the ground. This is an important consideration in the measurement of swing angle.

A profile drawing of the cableway in **Fig. 11** illustrates the variation in apparent swing angle with location on the track cables. Above is a graph of the variation in angle with time during a descent, indicating the wide swing after the catch brake is applied.

The following is a description of the influences on swing-angle measurement at the points A, B, and C along the track cables:

Point A: The car has left the top station to descend. Change in swing angle is still practically zero.

Point B: At approximately midway between both stations rope sag has increased. This means with the car hanging vertically, the angle between the car and the track ropes has increased.

Point C: Here the catch brake is operated. The angle between the track cables and car has increased by the angle γ compared with reference point A. Braking causes inertial forces tangent to the curve of the ropes. The horizontal component causes most of the swing, whereas the vertical component increases the sag of the cables and therefore the cable reference angle by the increment β.

Since the swing-angle transducer is only able to measure the relative change in angle α_1 between the car and the track cables, the additional angle of swing β, with respect to the vertical, is not detected because it is the angle through which the car and track ropes move simultaneously in the same direction. In **Fig. 11**, this movement is shown to be clockwise.

The actual maximum angle of swing with respect to the vertical, which is needed for comparison with the theoretical data, is not only α_1 as shown by the trace, but α_1 plus β or α. This angle can be calculated from the equation for the curve of the cable, substituting the changes in angle which occur at point D.

On the other hand, the track-cable angle measured simultaneously at point D can be used to construct an instantaneous reference line of the angle in order to obtain β. The relationship between the increase in angle α_1 measured on the running gear and the simultaneous change at point D was determined during a slow run down the track with the car hanging vertically. This enabled the angle β, which cannot be detected by the swing-angle transducer, to be estimated from the angle which occurs during braking.

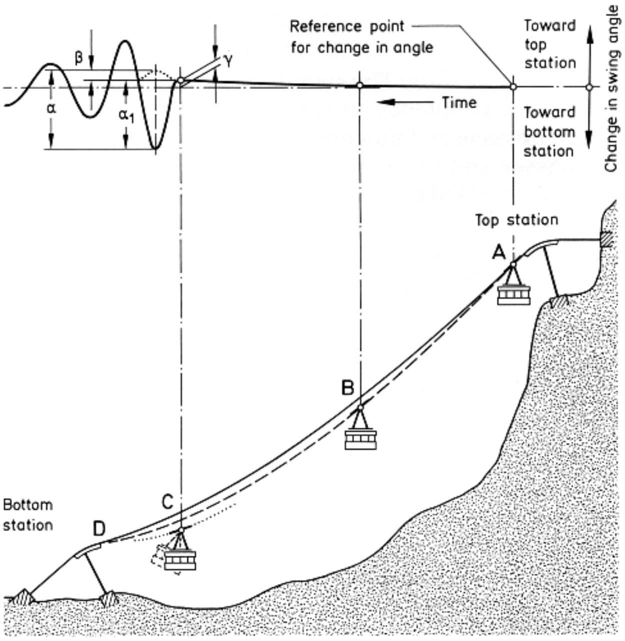

Fig. 11: Cableway profile shows variation in apparent swing angle with cable location. Above is graph of timebased variation in angle during descent with catchbrake operation at point C

If no attention is paid to the additional swing angle β, measuring errors increase steadily with speed, causing an increasingly dangerous situation. In this particular case, swing angle error would have been as high as 1.5 degrees.

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