Analysis of a Partly Sprung Drive

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Abstract — **During the operation of trams in cities the bogies and drives are dynamically loaded through acceleration, deceleration, passaging curves and evidently by the roughness of the tram track. These added dynamic loads can significantly increase the wearing of tram drive components. The aim of this analysis is the investigation of stress state and motions of the gearbox hinge (support). For this purpose, strain gauges and optical system Qualisys are used. Special type of the strain gauges arrangement for measuring tension and bend together is designed. Acquired data are processed in the software Matlab and in the user interface of the Qualisys software.**

Keywords — Tram drive, tram bogie, induction motor, axle gearbox, gearbox hinge, strain gauges, Qualisys, Matlab.

I. Introduction

During working of a tram the bogies are dynamically loaded through acceleration, deceleration, passaging curves and evidently by the roughness of the tram or train track [5]. These added dynamic loads can significantly increase the wearing of the bogie and drive components or they can cause damage of some parts. Thus all the components have to be designed with respect to the given conditions. In this case, problems with bearing mounting into gearbox occurred after relatively small number of driven kilometres in almost all gearboxes. One of the hypotheses, which can explain this problem, is too rigid support of the gearbox. The hinge (support) does not allow sufficient movements of the gearbox and generated reaction forces are transferred to the bearings of the output shaft as an additional load. Therefore testing of the gearbox hinge was suggested. The aim of the measurement is to analyse behaviour of the tram gearbox and its hinge during the real driving conditions.

A. Partly Sprung Drives with the Vertical Hinge

In case of partly sprung drives with axle gearbox, it is necessary to catch reaction moment of the gearbox. For this purpose the hinges are used. The reaction force in the hinge differs according to the type of the gearbox. The simplest design uses one-stage gearbox (two gears), see Fig. 1.

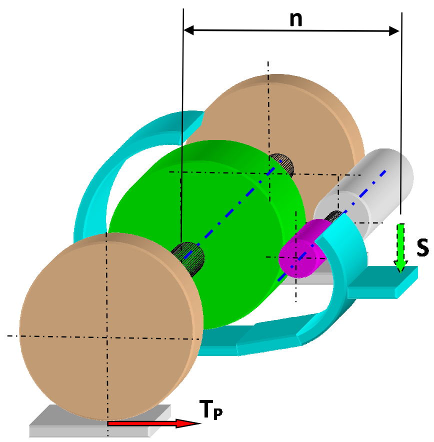

Fig. 1. Drive with one-stage gearbox [7].

The reaction force in the hinge S, considering the drive on the imperfect rail track and swinging of the gearbox on the axle, can be calculated according to [6] as follows

$$S = \frac{(T_R + T_L)r + M_M - J\ddot{\psi}}{n} = \frac{M_M(i_c + 1) - J\ddot{\psi}}{n} \quad (1)$$

where T_R and T_L are the driving forces on the right and left wheels, r is the nominal radius of the wheel, M_M is the torque of the induction motor, J is the moment of inertia of the gearbox without the big gear, $\ddot{\psi}$ is the angular acceleration of the gearbox sway around the wheelset axle (i.e. the second derivative of the rotation angle of the gearbox around the axle of the wheelset), n is the distance from the hinge axis to the axle (output shaft axis) and i_c is the total gear ratio of the gearbox defined as

$$i_c = \frac{r_2}{r_1}. \quad (2)$$

The notation r_i defines the radius of the appropriate spur gear pitch circle.

The second variant uses the gearbox with inserted gear (three gears), see Fig. 2. The reaction force in the hinge can be written analogically

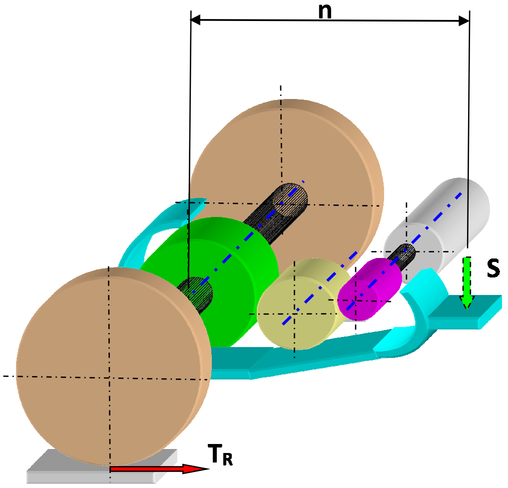

Fig. 2. Drive with gearbox with inserted gear [7].

$$S = \frac{(T_R + T_L)r - M_M - J\ddot{\psi}}{n} = \frac{M_M(i_c - 1) - J\ddot{\psi}}{n}, \qquad (3)$$

where the total gear ratio of the gearbox i_c is defined as

$$i_c = \frac{r_3}{r_1}. \qquad (4)$$

The last design variant uses the two stage gearbox (four gears), see Fig. 3.

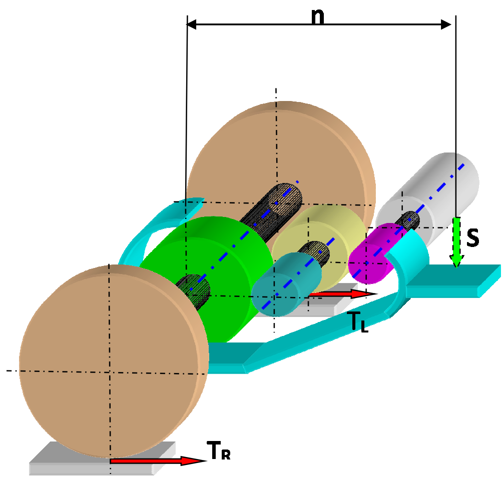

Fig. 3. Drive with two stage gearbox [7].

The reaction force in the hinge can be written analogically as

$$S = \frac{(T_R + T_L)r - M_M - J\ddot{\psi}}{n} = \frac{M_M(i_c - 1) - J\ddot{\psi}}{n}, \qquad (5)$$

where the total gear ratio of the gearbox i_c is defined as

$$i_c = \frac{r_4}{r_3}\frac{r_2}{r_1}. \qquad (6)$$

From (1), (3) and (5) follows, that the axle gearbox with three and four gears induces significantly lower value of the force *S*, considering the same value of the driving torque of an induction motor M_M, the same value of the total gear ratio i_c and the same value of the distance *n*.

B. Tram and its Drive

Tested tram is partially low-storeyed tram. It has three two-axle drive bogies (Fig. 4.) and it can reach the maximum speed of 60 km/h. Each bogie has two wheelsets, which are driven by partly sprung drive. That consists of an induction motor of power 90 ÷ 110 kW and two-stage axle gearbox connected with claw coupling. The big gear of the gearbox is pressed on the axle of the wheelset, which is imbedded into bearing units. Their connection with the frame is providing four rubber-metal cone springs; those create the primary springing of the tram bogie.

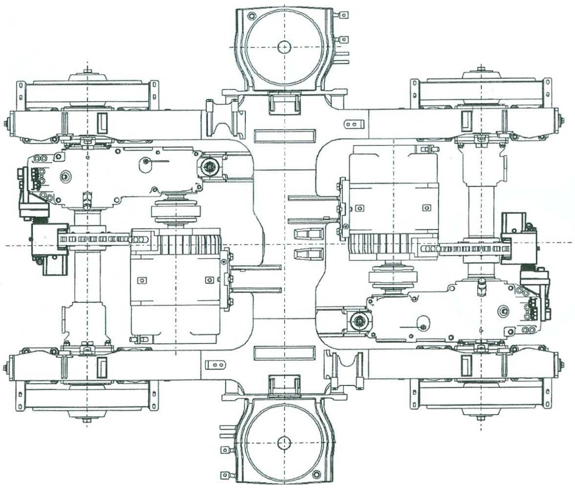

Fig. 4. Design of tram bogie with partly sprung drive [2].

II. HYPOTHESIS

The axle gearbox is furthermore connected to the bogie frame through the vertical hinge of the gearbox. The hinge catches reaction force generated by the rotation torque of the wheelset, but it has to allow some specific movements of the gearbox – swinging round longitudinal, lateral and vertical axes. The maximum tensile force in the hinge for the two stage gearbox considering quasi-statics with respect to the good quality of the rail track (i.e. without respect to the inertial forces of the gearbox) can be calculated as

$$S = \frac{M_M(i_c - 1)}{n}, \qquad (7)$$

where M_M is the maximum torque of the induction motor.

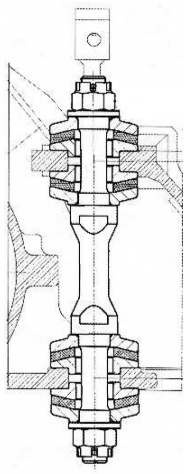

Fig. 5. Gearbox hinge design [2].

The hinge of the axle gearbox of the tested tram is designed as a round bar of a 28 mm diameter. It is imbedded into rubber supports as it is shown in Fig. 5. These should behave nearly as ideal spherical joints so the hinge can catch only tensile or pressure forces. Any bending stress in the hinge is parasitic, because it is caused by lateral forces which produce undesirable additional radial and axial loading forces for bearings of the output gearbox shaft.

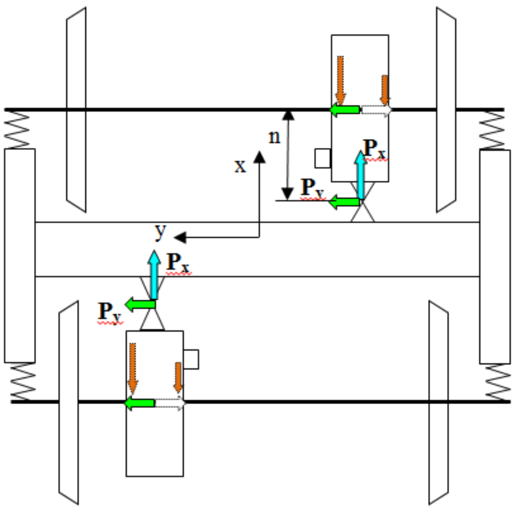

Fig. 6. Parasitic force in gearbox hinge.

Disabling swinging of the hinge around the *y* axis, i.e. limit sliding of the gear in the *x* direction, exerts a longitudinal reaction force P_x. This parasitic force represents the additional loading of the radial bearings on the output shaft.

The disabling swinging around the *x* axis, i.e. limit sliding of the gear unit in the *y* direction, exerts a transverse force P_y. This parasitic force operating on the distance *n* creates an additional bending moment M_z, see Figure 6.

Moment M_z together with additional parasitic effects of radial and axial forces aggravate the life time of the roller bearings on the output shaft.

The increase of the axial and radial forces (due to the inner friction in the bearing) is causing the torque on the outer ring, which tends to spin the outer ring of the roller bearing.

III. INSTRUMENTATION

The hinge should transfer only tension or pressure forces. It is desirable to investigate its stress state. Specifically tension or pressure which are expected and bending stress which is undesirable can confirm the above mentioned hypothesis. For this purpose strain gauges are used. For the verification and better description of gearbox suspension behaviour the system Qualisys for capturing and evaluating motion is also used.

A. Strain Gauges

Foil strain gauges are used to investigate stress state of the hinge. It is desirable to measure tension – pressure and bend simultaneously. Moreover the bend has to be found out in two perpendicular planes to obtain complete knowledge of the bend and the resultant including its orientation. The first plane is coincident with the tram drive direction (longitudinal plane) and the second one is perpendicular and lies in the lateral plane of the tram. For measuring tension and pressure Wheatstone half-bridge arrangement has to be used due to the bend compensation (i.e. two strain gauges). For the bend measuring also the Wheatstone half-bridge arrangement has to be used due to tension-pressure compensation (i.e. four strain gauges for measuring in two planes). To decrease quantity of strain gauges a new arrangement is designed (Fig. 7). Only four strain gauges are connected into four independent Wheatstone quarter-bridges with time synchronization. This arrangement is very convenient because it is possible to measure tension and pressure and simultaneously measure bending in two perpendicular planes. Thanks to this improvement only four strain gauges has to be used, which spares not only the number of used strain gauges but also space and makes the connection of strain gauges easier. Acquired signals are obtained as strain from each strain gauge and they can be assembled after measurement according to following formulas. The tension or pressure stresses can be calculated from (8). The bending stresses in two planes are a consequence of (9), (10) according to [3].

$$\sigma_t = \frac{E}{4}(\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4) \quad (8)$$

$$\sigma_{b1} = \frac{E}{4}(\varepsilon_1 - \varepsilon_3) \quad (9)$$

$$\sigma_{b2} = \frac{E}{4}\left(\varepsilon_2 - \varepsilon_4\right) \quad (10)$$

Foil strain gauges are installed in the middle of the cylinder surface of the new unused hinge precisely after 90 ° as it is shown in Fig. 7. For this application self-compensative strain gauges with nominal resistance 120 Ω are used. Moreover there is installed a semiconductor thermal sensor for monitoring changes of temperature during test drives. As the hinge is located in the chassis without any cover it is necessary to protect installed strain gauges against outside actions, e.g. water, dust or oil. It has to be protected also during mounting to the bogie frame. For this purpose short part of plastic tube is used together with flexible putty which creates big enough chamber for strain gauges between the hinge and plastic tube and also wires can pass through it. Thus adapted hinge is prepared for mounting into bogie of the tested tram.

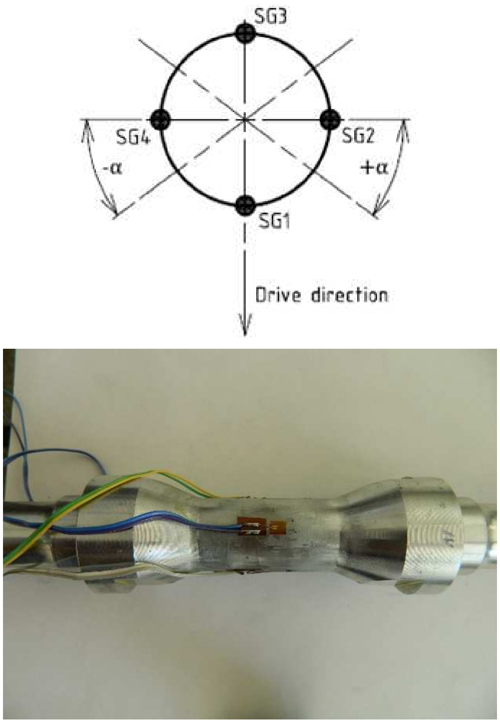

Fig. 7. Measuring arrangement of the strain gauges on the gearbox hinge [2].

B. Qualisys System

In addition to measurement of the stress state of the hinge it is convenient to monitor relative motions of the gearbox connected with the wheelset to the frame of the bogie and to the induction motor. Then it is possible to evaluate relative shifts and rotations of the output shaft of the induction motor to the input shaft of the gearbox and required range of motions of a claw coupling. For this purpose the optical Qualisys system for continual capturing and evaluating motions is used. For tracking motions of the object it is necessary to use three cameras and three markers creating the reference plane on the monitoring object. In this case six spherical markers are used. Three are placed on the gearbox and three remaining are placed on the induction motor. In each object (gearbox and induction motor) local Cartesian coordinate system is thus created (see Fig. 8). Furthermore another marker is placed on the axle of the wheelset to sample revolutions so the covered distance and current speed can be calculated.

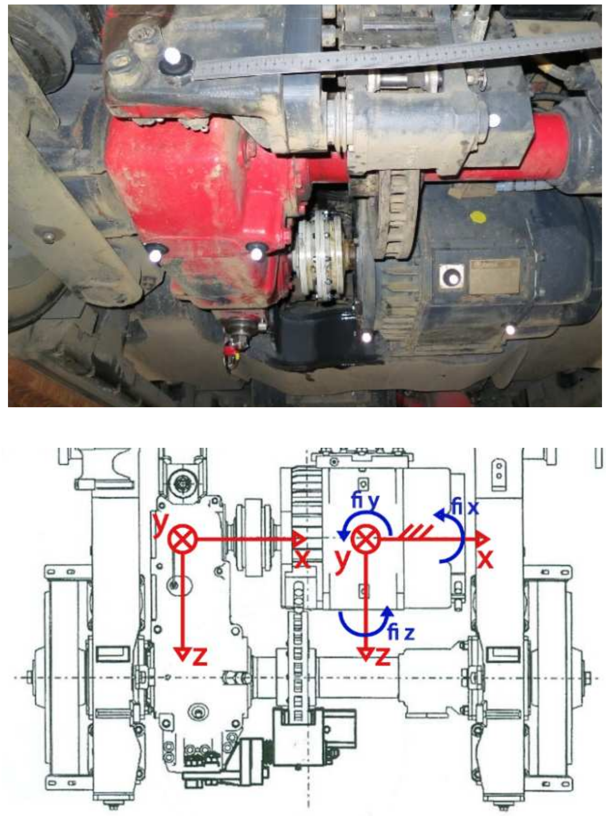

Fig. 8. Markers of the Qualisys system and Cartesian coordinate systems of the gearbox and the induction motor [3].

Altogether six cameras are used; they are divided into two subsystems – moving subsystem and stationary one. The first one is mounted on a special holder which is bolted to the car body of the tram so it moves with the tram. The second one is placed in the floor pit.

Fig. 9. The distribution of the Qualisys system six cameras.

The stationary system of cameras is there to verify accuracy of the moving system which could be influenced by the tram car body vibration. Both systems are calibrated together and time synchronized.

IV. Data Acquisition, Processing and Evaluation

The test drive was divided into three regimes – maximum acceleration, maximum deceleration and common drive. Testing of maximum acceleration and deceleration was carried out inside the depot above the floor pit so the accuracy of the moving camera subsystem could be verified by the stationary subsystem. It has to be noticed that maximum deceleration was reached only by electric-dynamic breaking. Common drive was carried out on the loop inside and around the depot in total length of 721 m (Fig. 10).

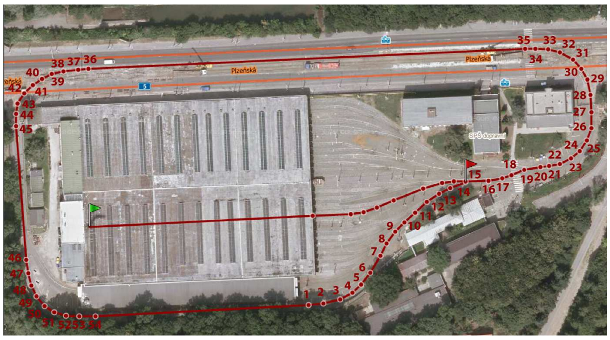

Fig. 10. Testing loop for common drive measurement [2]

The hinge with installed strain gauges and thermal sensor was mounted into rear wheelset of the tested tram rear bogie (Fig. 11).

Fig. 11. Mounted and connected gearbox hinge [2]

In addition to stress and motion measurements, the torque of two induction motors mounted to the bogie was recorded from the tram control unit. Data acquired by the strain gauges contained lot of noise. That´s why a low-pass linear filter with Hamming´s window was applied to reduce it. Script calculates tension, bend in two perpendicular planes and resultant with its orientation from data acquired from four independent Wheatstone quarter-bridges. Data captured by the Qualisys system were processed in an user interface of the Qualisys software. The main aim of this experiment is to detect a bend presence in the hinge during test drive regimes. Tensile stress can be used as verification with analytical tensile stress in the hinge which can be calculated according to Eq. (7).

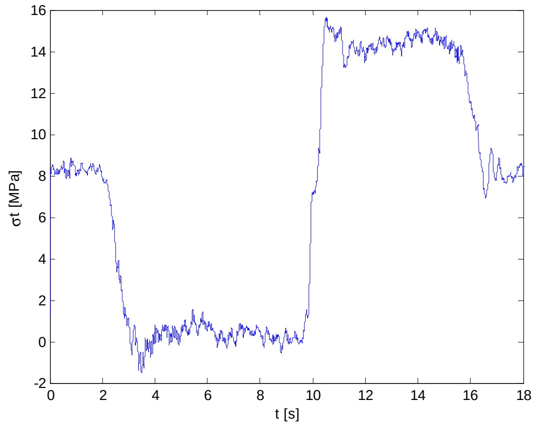

Fig. 12. Tensile stress in the hinge for the acceleration regime [2]

The measured tensile stress (Fig. 12) is in very good agreement with the analytically calculated value. Following graphs prove the presence of the bend in the hinge. There is also shown behaviour of the torque of one pair of the induction motors mounted to the bogie.

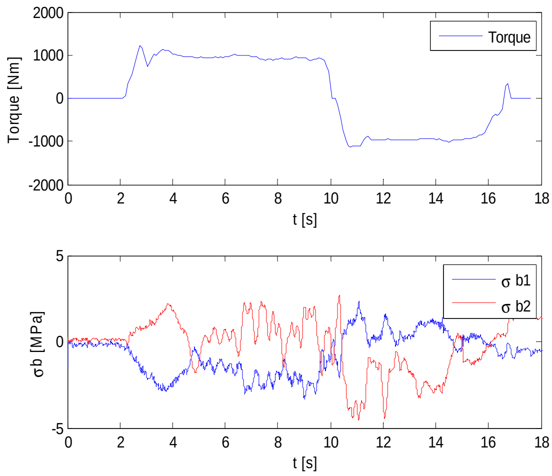

Fig. 13. Torque of the induction motor pair and bending stress in two perpendicular planes for the acceleration regime [2]

In Fig. 14 there is shown the rotation of the gearbox round the tram longitudinal axis during the acceleration regime. For a better transparency red line is added into raw signal. It is a representation of the mean value during the time. The average deviation of the angle Φ_z during the acceleration (time between 2 s – 9 s) is 5 °.

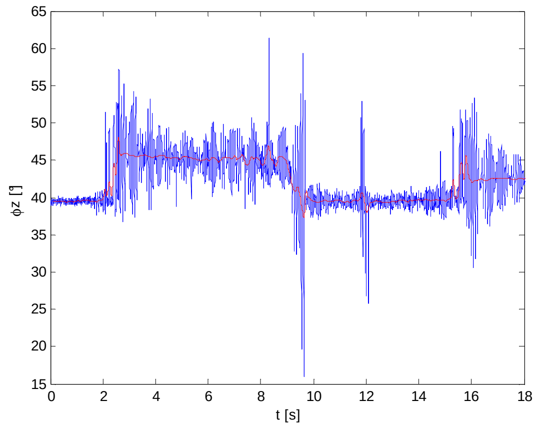

Fig. 14. Relative rotation of the gearbox to the induction motor round the longitudinal axis *z* [2].

V. Results and Conclusion

The measurement proved the hypothesis that the gearbox hinge doesn´t catch only tensile and pressure forces, vice versa it is also stressed by bending. But the measured values of the bending stress are quite low. This can be caused by low dynamic effect. The tested tram was empty and the quality of the tram track in the depot was quite good. Another reason could be that the gearbox hinge was mounted exactly with specified pretension so the rubber bedding is not so rigid and the hinge allows bigger movements. This hypothesis is proved by data measured by the Qualisys system. Presented graph shows that the movements are higher than admissible values for the claw coupling.

The measured relative movements of the gearbox to the induction motor obtained from the Qualisys system are relatively considerable. Even in case of a slow drive across the railroad switches and crossings. The relative movements can significantly shorten the life of the coupling between the traction motor and input shaft of the axle gearbox.

When driving fully loaded tram on a real tram track, which has the vertical and transverse unevenness, it has to be expected that the time required to accelerate the vehicle is longer.

The acceleration time with maximum driving force or deceleration with maximum braking force significantly extends the time of the parasitic forces S_x and S_y effect. These effects increase the loading of the axle gearbox bearing. It can be assumed that the magnitude of the parasitic forces S_x and S_y is in normal operation larger than those which were measured during the drive with an empty tram.

The used design of the gearbox hinge is not convenient, because it does not allow required compensation of the assembling deviations. More convenient solution could be the hinge with rubber-metal joints and adjustable length. Thus the assembling deviations could be compensated.

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