Applied and Computational Mechanics 1 (2007) 165 - 174

Control rod drive WWER 1000 – tuning of input parameters

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Received 7 September 2007; received in revised form 27 September 2007

Abstract

The article picks up on the contributions presented at the conferences Computational Mechanics 2005 and 2006, in which a calculational model of an upgraded control rod linear stepping drive for the reactors WWER 1000 (LKP-M/3) was described and results of analysis of dynamical response of its individual parts when moving up- and downwards were included. The contribution deals with the tuning of input parameters of the 3rd generation drive with the objective of reaching its running as smooth as possible so as to get a minimum wear of its parts as a result and hence to achieve maximum life-time.

Keywords: control assembly drive, finite element method, linear and nonlinear springs, geometric non-linearity, linear stepping drive, frequency-modal analysis, dynamical motion, stress state

1. Introduction

A linear stepping drive is a major element of WWER 1000 reactor safety actuating control system. It is placed on reactor head nozzle in a containment. It is used for inserting into the reactor core a suspension bar provided with a control element or for pulling it out of it, for keeping the control element in extreme and intermediate positions, and for indicating the control rod position. It also makes possible for the control organ to fall down into the core at emergency operation. If the drive housing is leaking it prevents the control element sliding out of the core as a result of a pressure gradient.

The reactor always-safe operation at normal service operation modes as well as the safe shutdown on all levels of the accident protection system interventions depends largely on the drives service reliability. The third modernized series of linear stepping drives (LKP-M/3) is being developed in ŠKODA JS a.s. at present time.

The contribution deals with the tuning of input parameters of the 3rd generation drive with the objective of reaching its running as smooth as possible so as to get a minimum wear of its parts as a result and hence to achieve maximum life-time (cf. [5]).

2. Brief description of the LKP-M/3 drive and the calculational model

2.1. Description of the LKP-M/3 linear stepping drive

The LKP-M/3 drive consists of five basic parts:

The *drive housing* is a pressure barrier between the primary circuit and the space above the reactor head. It holds other parts of the drive. There is a flange in the bottom part with which the drive housing is fastened to the reactor head nozzle by six prestrained studs.

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From the above, *a system of electromagnets* is slipped over the drive housing. Its bottom end rests against the thickened portion of the drive housing finding itself above its lower flange and is thrusted against this support by springs in the upper part. It consists of pulling, retaining and holding electromagnets. Through their magnetic field, the magnets govern the armatures, which ensure the function of the lifting system mechanisms and hence even the motion of the suspended bar.

Lifting system is placed inside the drive housing and ensures a straight reversible motion, emergency drop and standstill of the suspension bar with the control element. It furthermore prevents its unprompted pushing out when the drive housing gets leaky. It is composed of a pulling and a retaining system.

Main parts of the pulling system are a tractive armature, a holding armature, a holder of holding pawls and a tractive armature shock absorber with a dead stop. The holder of holding pawls is operated by the tractive armature through a tubular draw bar that ensures lifting or dropping of the suspension bar by one step 20 mm long. A housing connected with the holding armature by a tubular draw bar closes or opens the pawls. Lifting of the tractive armature is damped by a spring shock absorber with a stop face after 10 mm while after next 10 mm the travel of the armature is limited by the dead stop.

Main parts of the retaining system are a retaining armature with a retaining pawls holder. A housing connected through a tubular draw bar with the retaining armature controls the retaining pawls, which are placed in the retaining pawls holder.

The lifting system is attached to the drive housing by a spring suspension in the upper part and by a spring in the lower part.

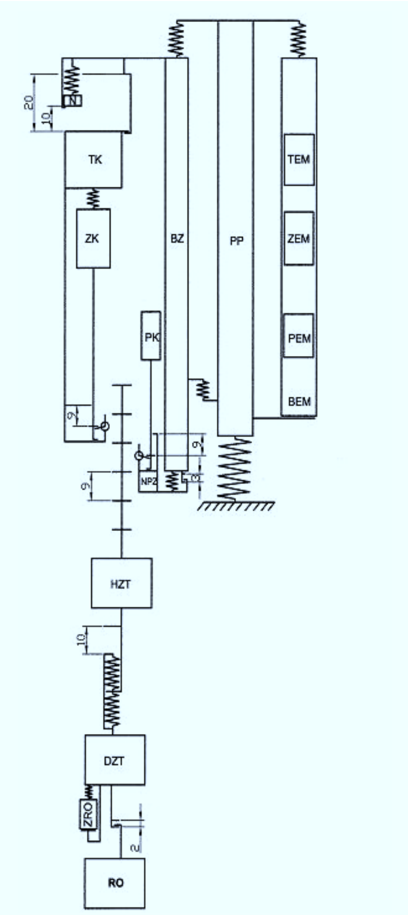

Fig. 1. Kinematical scheme.

The *suspension bar* is a connection between the control element and the lifting system pawls. It is divided into an upper and a lower part. The upper suspension bar is provided with shoulders with a pitch equal to the step length (20 mm). At the lower end, lower suspension bar is provided with a bayonet joint for connecting the control element. A square safety pin to prevent disconnection of the bayonet is situated also at the lower end. There is an elastic mounting between the upper and the lower suspension bar. The upper part of the suspension bar is a tube-like body with shoulders. The rest of the bar is made up of tube-like and cylindrical bodies.

The *position indicator* (UP-3) indicates the position of the suspension bar with control element. It extends through the lifting system and the upper suspension bar.

Description of the upgraded LKP-M/3 drive together with the schematic drawing of its major parts is presented in [1]-[3].

2.2. Principle of the drive performance

Fig. 1 shows a kinematical scheme of the LKP-M/3 drive.

The motion of the suspension bar together with the control element is serviced by the lifting system through the pulling and retaining system by means of coordinated switching on and off the current supplying the pulling, holding and retaining electromagnet. In the course of one step of the lifting or dropping, magnetic field of varying intensity given by the amount of current passing through the electromagnets acts on the tractive, holding and retaining armature. The armatures govern the pawls holders and pawls closing housing by pipe-like drawing bars.

Gradual closing, opening and axial displacement of the pawls system leads to a stepping, reversible motion of the suspension bar with the control element. A single step upwards and downwards takes approximately 1 s.

2.3. Calculational model

Calculational model was set up using the GEOSTAR module of the COSMOS/M program.

The goal of dynamical analysis is determining the drive behaviour during its normal operation, and establishing the displacements, velocities, accelerations and stressing due to dynamical forces of separate drive elements. Theoretically (neglecting the manufacturing tolerance, resulting magnetic forces direction deviations and others), the excitation forces are only vertical. However the model has been turned out more generally in 3D space so as to have the disposition of being used even for calculations considering some other loads (seismic e.g.).

The geometry of the calculational model was transferred from the CAD model created in I-DEAS that also served for generating the manufacturing drawings and the manufacturing of the drive prototype.

The following assumptions were accepted when setting up the calculational model:

- the model is axi-symmetric,
- the flange of the reactor head is stiff,
- the coolant inside the drive housing and system is defined by its static mass only,
- the friction is not considered (practically, all friction areas are “lubricated” by the coolant, and moreover, the parts in motion are guided by plastic rings),
- the lock of the control element was included in the lower suspension bar because of its very low mass as compared with the masses around. Its compression spring was omitted,
- the UP-3 position indicator is firmly bolted to the drive. That’s why these parts form the whole even in the model.

There are two kinds of non-linearities introduced in the calculational model of the LKP-M/3, namely geometrical (dead stops) and force type (influence of electromagnets on the armatures).

The *dead stops* are single-ended or double-sided and some of them are combined with springs (upper spring suspension connecting the lifting system with the drive housing, elastic mounting between lower and upper suspension rod). The stops were modelled using non-linear spring elements.

The *forces* acting on the structure are volumetric, i.e. they act on the whole volume of the structure (gravity), and concentrated forces acting in respective nodes. The weight due to the gravitational field of our planet is specified by the acceleration of gravity $g = 9.81$ m/s^2. It works in the negative direction of the calculational model global axis y.

The *concentrated forces* are partly steady (spring pre-stressing) and partly variable. In this case, the variable forces are either linearly dependent on the drive parts relative displacement (compression of the springs) or non-linearly dependent on the distance of armature from the corresponding electromagnet antipole (attraction of the electromagnet armatures).

In the COSMOS/M, the *forces* that are *non-linearly dependent* on the relative displacement of two nodes can’t be specified directly. We therefore made the decision to get rid of the problem by specifying constant attractive forces in the nodes in question and, simultaneously, we inter-connected the nodes with help of a two-node non-linear element (NONLINEAR SPRING), the characteristic of which is opposite to the so called static characteristic of electromagnet. The latter is measured in a testing laboratory and it specifies the attractive force varying dependent on the armature displacement. In the course of a lifting or dropping step, currents of varying intensity excite the individual magnets. Consequently, we use two or three static characteristics for each magnet. Then the specific constant force corresponds to any of them according to the current intensity for which this characteristic applies.

Masses. Length and cross-sectional characteristics of the calculational model exactly agree with the CAD model according to which the actual drive was manufactured. Some differences could be however found in the details that the calculational model focused on the dynamical calculation cannot cover (bolted joints, shoulders, grooved recess, holes in the walls and so on.) The greatest difference in mass of the model as compared with reality has been identified at the drive housing and amounts to 3.08 %.

The masses of the cluster are 17 kg, 27 kg, or 43 kg. One single beam element is put in place of the cluster in this calculational model.

Materials. All principal parts of the LKP-M/3 were manufactured of 08CH18N10T stabilized austenitic stainless steel. Its material properties as dependent on temperature are shown in Tab. 1.

Temperature [°C]	**20.0**	**100.0**	**200.0**	**300.0**	**350.0**
E [Pa]	$2.05.10^{11}$	$2.00.10^{11}$	$1.90.10^{11}$	$1.80.10^{11}$	$1.75.10^{11}$
α [K^{-1}]	$1.64.10^{-5}$	$1.66.10^{-5}$	$1.70.10^{-5}$	$1.74.10^{-5}$	$1.76.10^{-5}$
ν [-]	0.3	0.3	0.3	0.3	0.3
ρ [kg.m^{-3}]	7900	7900	7900	7900	7900
Z [%]	40	40	40	40	40
$R_{p0.2}$ [MPa]	196	186	177	167	157
R_m [MPa]	491	461	422	392	353

Tab. 1. Material properties of 08CH18N10T steel against temperature.

It is very difficult to establish the *damping* of the system as a whole. That's why a number of calculations were carried out following the aim of establishing the influence of damping rise on the variation of individual parts motion during the lifting and the damping. The results of the calculations were compared with the measurements presented in [6].

3. Introducing calculations

3.1. Modal analysis

The individual parts of the LKP-M/3 drive move relatively to each other in the vertical direction (axis y). Their relative motion is limited by dead stops. Some parts are interconnected with springs, some others move slidingly with minimal friction. This is neglected in the calculations.

As first, modal analysis of seven particular parts calculational models was performed for determining dynamical properties of individual parts of the drive and for establishing time constants of the non-linear, dynamical calculation. Results of this analysis are in [1], [2] and [4].

3.2. Non-linear calculations

A method of direct integration of the equation of motion included in the solver of COSMOS/M module NSTAR was used for computing the step size of the lifting and the dropping. The solver offers the possibility to consider all kinds of non-linearities in the calculation that are incorporated in the model.

Preparatory phase. First the stabilisation of the motion due to the sudden inception of the acceleration of a gravity effect and to pulling-in the holding magnet armature in the initial position was calculated. Subsequently the currents in magnets begin to change according to the corresponding diagram for the lifting or the dropping. We chose the time of one second for the stabilisation. At this stage the lower suspension bar together with the control element vibrates under the influence of sudden inception of the acceleration of gravity effect. The other parts vibrate minimally. At the end of the preparatory phase the whole model stays practically at rest and the lifting or the dropping of the control element can be simulated.

The lifting or the dropping step can be calculated after the preparatory step went through or it can reassume the lifting or the dropping step just evaluated.

One lifting and dropping step of the LKP-M/3 takes 1 s. We divided it into 12 time intervals. They differ in the specification of the electromagnet static characteristics (depending on the current intensity) and initial conditions and constants that determine the NONLINEAR SPRING element properties. The elements are the fixation of the upper suspension bar to the holding pawls holder and retaining pawls holder in turns.

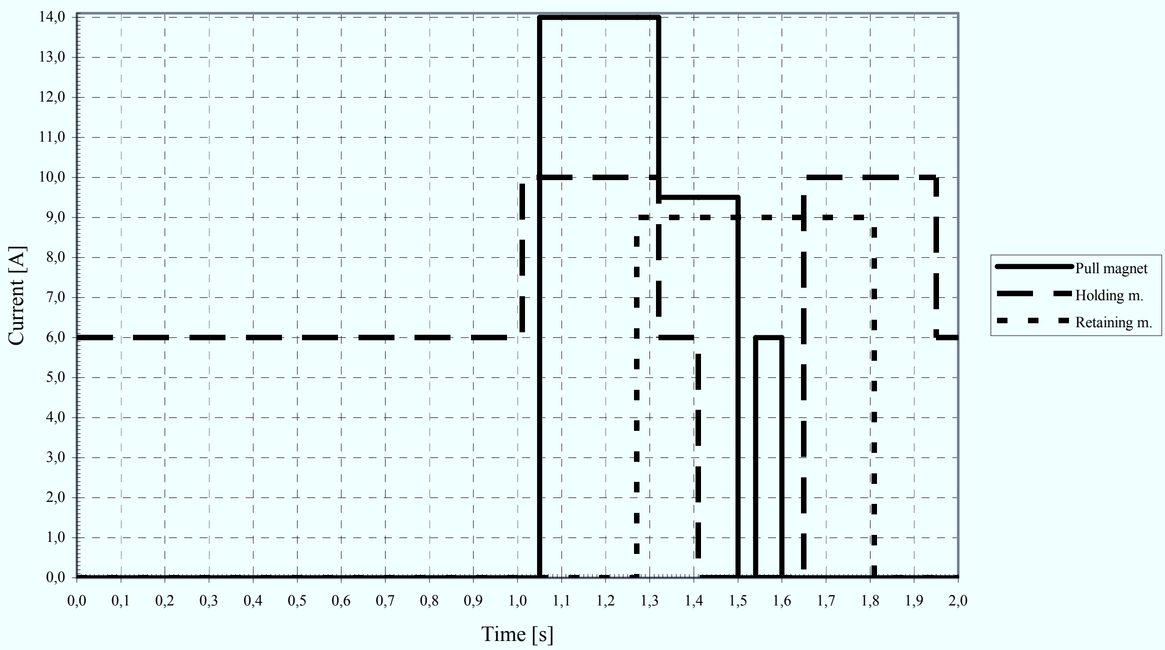

Fig. 2. Succession of switching the current on and off into the coils of electromagnets – step of lifting.

The length of the time intervals as well as the static characteristics used in the calculation were set using the diagram visualising the succession of switching the electromagnets on and off. As for the lifting step. Fig. 2 shows the respective succession.

Initial conditions at the beginning of the lifting are given by the vectors of deformations, velocities and accelerations at the end of the preparatory phase, and in every next time interval they equal to such vectors evaluated for the end of the previous interval.

The properties of dead stops were modelled using the elements NONLINEAR SPRING. The size of the clearance and the stop stiffness are defined by the given parameters.

3.3. Results of calculations

There were a number of calculations run through the damping 5 %, 10 %, 15 %, and 20 %. As a result we obtained time history of displacements, velocities, and accelerations of the calculational model nodes. The stiffness of the main load bearing and movable parts in the y-axis direction is great in comparison with the stiffness of the springs. That's why the knowledge of the nodes motion allows conclusions as to the motion of the whole movable parts. The outermost nodes of the main movable parts were chosen for investigating their motions because they also follow the components vibration at basic natural frequencies.
Fig. 3 presents the course of the main parts motion for damping D = 20 %.

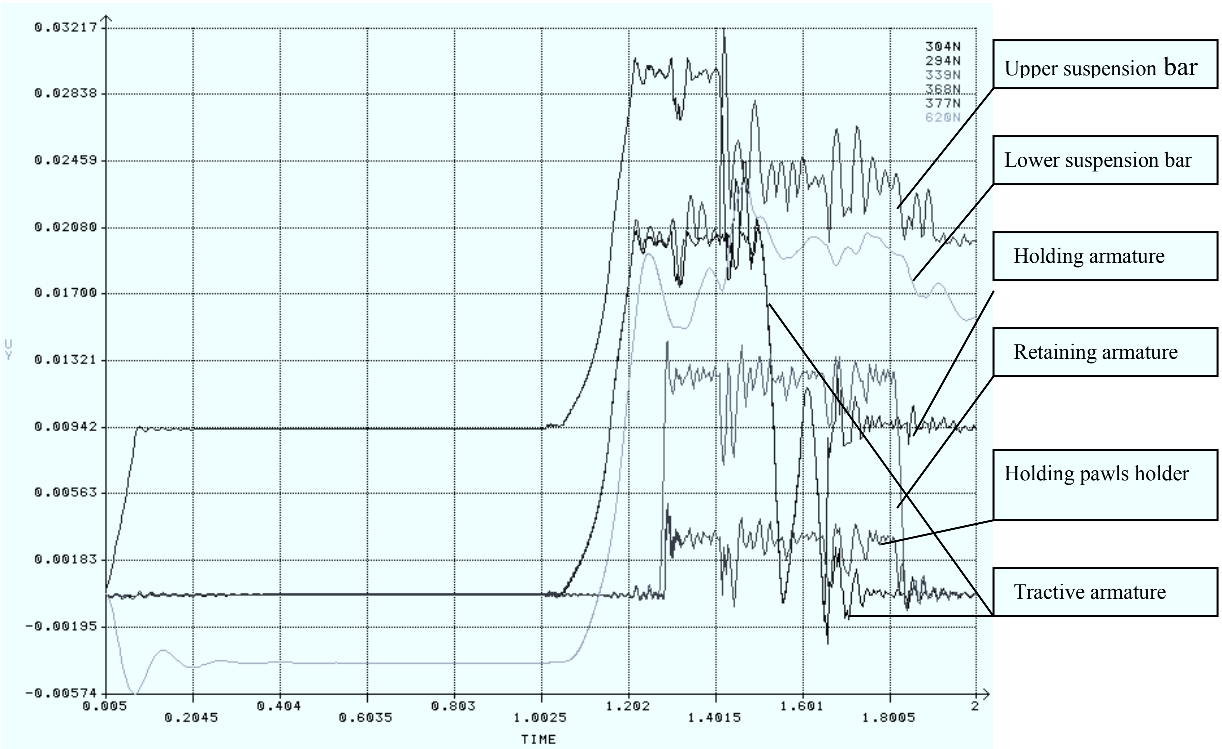

Fig. 3. Example of computed motion of main parts LKP-M/3 for damping D = 20.%.

The results of the calculations were compared with the measurements presented in [6] and the damping was fixed to be D = 5 % resp. D = 20 % at preparatory phase resp. at the lifting and the dropping phase.

4. Improving input data

Increased wearing of the retaining pawl was detected in the latest variant of the upgraded LKP-M/3. In order to enhance the possibility of comparing the measured values with calculations, the input data were made more precise so as to bring them near to the values determined by means of the measurement referred to in [6]:

- intensities of currents were modified to correspond to the values actually measured,
- static characteristics were substituted by the improved trends in behaviour measured for the electromagnets used in the experiments,
- time history of the current intensities in the electromagnets was substituted by improved trends in behaviour actually measured,
- in order to receive a better compliance with the experiment, the impulse of force was put at the end of the preparatory step to bring the lower suspension bar in motion which would be very near to the state present in the initial stage of the experiment.

The subsequent text deals with the lifting step only because it showed much greater dynamical forces.

Fig. 4 gives a look into the record of current intensity changes provided by the measurements in the lifting step. Only one step exactly one second long is depicted but the lifting step begins at the time point 3.675 s in the diagram.

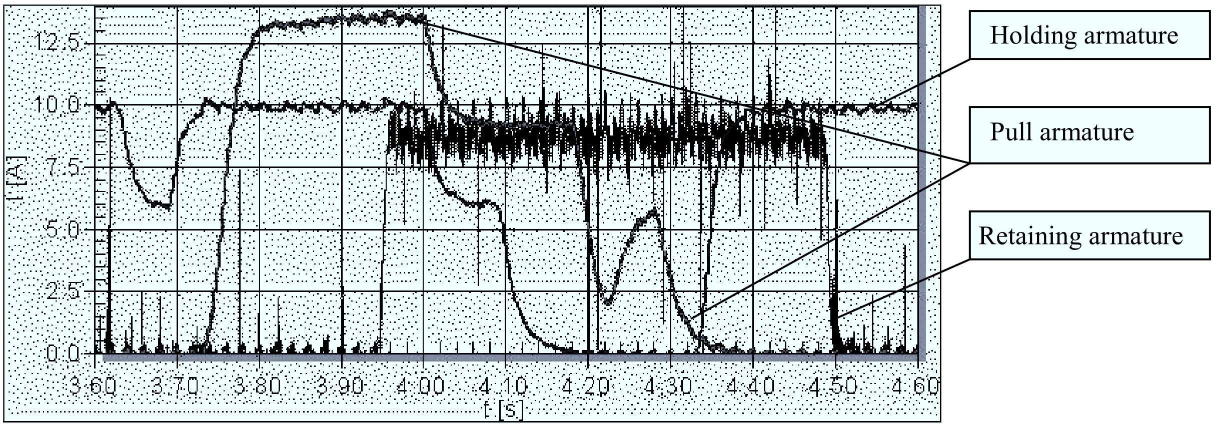

Fig. 4. Record of current development received from the lifting step measurement.

Approximate time-delay of the beginning of the current intensity growth in the electromagnets and the gradients of the linearized rise time of currents were set using the records of current development.

Fig. 5 shows the currents development for the lifting step modified by measurement.

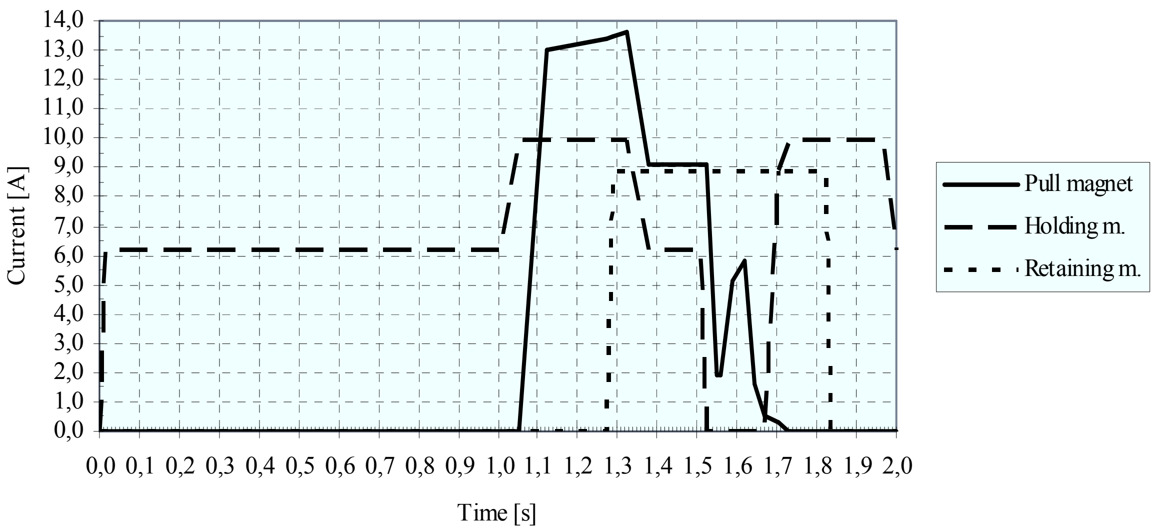

Fig. 5. Development of currents in the electromagnets for lifting step modified by measurement.

5. Searching the optimal contact-making of the retaining magnet to reduce the pawls wear

The forces in the upper suspension bar are the deciding factor for the pawls stressing. The report [6] suggests that a steep rise in forces in the upper suspension bar occurs at the time point 1.323 s in our calculations. It is the point at which the current intensity in pulling and retaining electromagnet decreases. The dynamical forces are proportional to the acceleration of the upper suspension bar. We have concluded that it would be possible to affect the magnitude of the upper suspension bar acceleration by shifting the moment of switching on the current into the retaining magnet.

Fig. 6 shows the development of the upper suspension bar acceleration for switching on the retaining electromagnet at the time point 1.273 s (original setting - see Fig. 4).

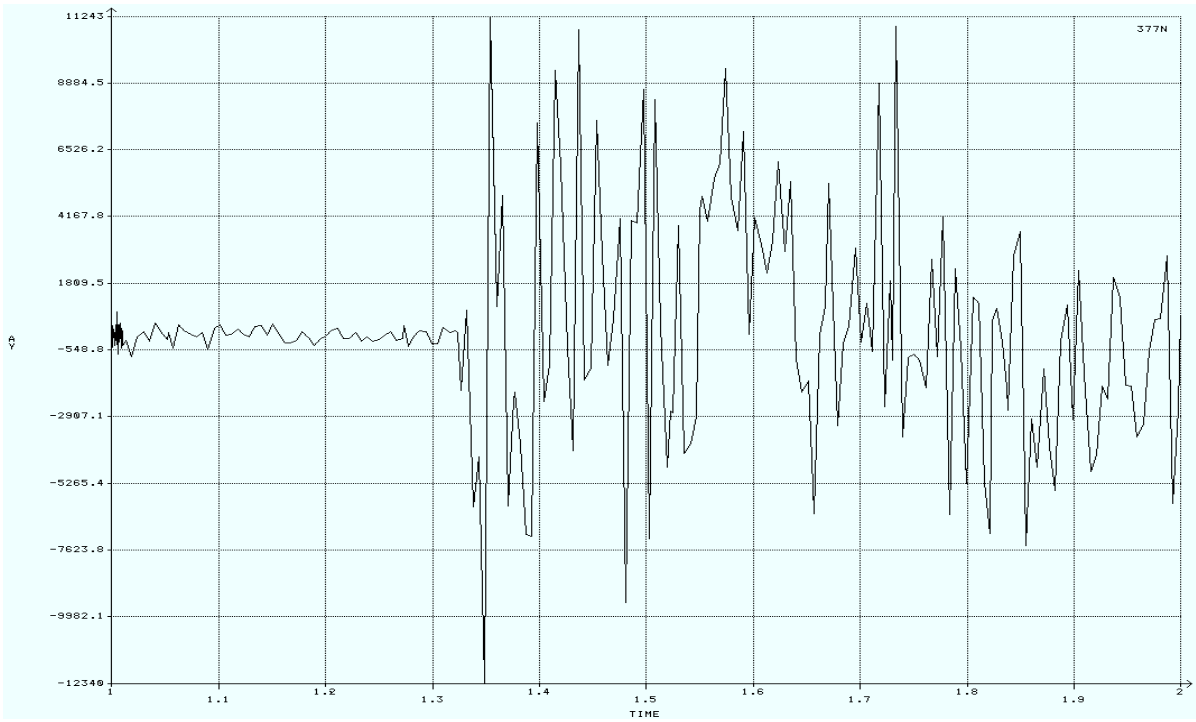

Fig. 6. Development of the upper suspension bar acceleration for original setting of the retaining electromagnet switch on.

Maximum acceleration in the upper suspension bar occurs at the time points 1.3486 s and 1.3541 s and reached the value of 12340 m/s^2. At these moments the maximum stresses in the upper suspension bar range as high as 27.1 and -33.5 MPa.

Analogous computations were performed for the shifts of the moment of retaining electromagnet actuation by -0.075 s, -0.05 s, -0.025 s, +0.025 s, +0.05 s and +0.075 s.

The computations considering the early switch-on moment (negative shift) disclosed that the acceleration peaks at approximately equal values and the stresses in the upper suspension bar are comparable with the basic calculation, too.

A substantial change occurs when the retaining magnet switches-on lately (positive shift). At the shift by 0.025 s maximum acceleration is 2200m/s^2 and the maximum stresses in the upper suspension bar reach 6.2 and –8.9 MPa. Shifting the retaining magnet switch-on by +0.05 s provides slightly more favourable values for the upper suspension bar but the retaining armature acceleration peaks increase. This trend still continues with the shift of

+0.075 s. Moreover, from the point of view of its function, the contact-making of the retaining electromagnet can be shifted by +0.05 s at most.

In such a way it was found that a convenient interval for the shifting of the retaining magnet switch-on lays in the interval +0.025 s-+0.05 s. Based on the measurements and above-said calculations we propose the shift of the magnet contact-making moment to be +0.04 s.

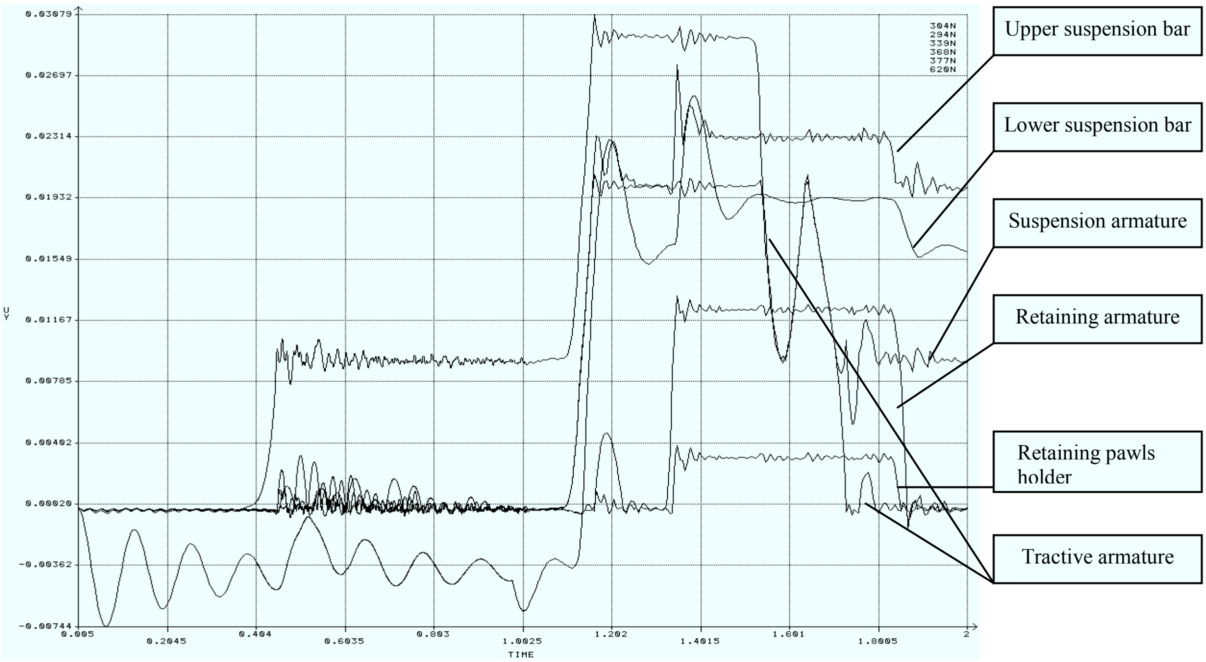

Fig. 7. Motion of LKP-M/3 major parts in the lifting step when the contact-making moment has been shifted by +0.04 s.

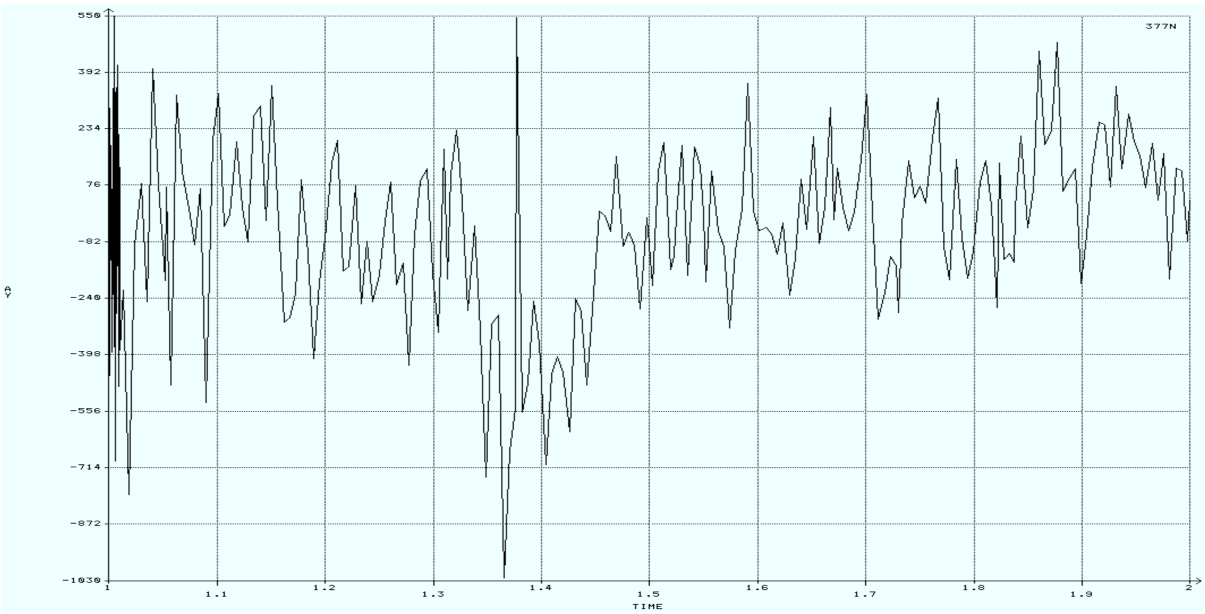

Fig. 8. Development of acceleration in the upper suspension bar when the contact-making moment has been shifted by +0.04 s.

Fig. 7 presents the development of the main parts motion with damping D = 5 % in the preparatory step and D = 20 % in the lifting step. Further, before the beginning of the lifting step, the impulse of force moves the initial conditions at the start of the lifting closer to the measured experiment. This calculation considers the moment of the retaining electromagnet contact-making to be 1.273+0.04 = 1.313 s.

In Fig. 8 the development of the upper suspension bar acceleration is plotted at the same computation.

Maximum acceleration in the upper suspension bar occurs at the time-points 1.3651 s and 1.377 s and takes the values not exceeding –1023 and 544 m/s^2. The stress peaks in the upper suspension bar are then 14.9 and –9.5 MPa.

The shift of the retaining electromagnet switch-on moment by +0.04 s reduced substantially the acceleration of the upper suspension bar and its stress state. The loading and wear of the pawls, on which the bar is suspended, would reduce in the corresponding fashion.

6. Conclusion

Satisfying the assignment of the task, we have found a possible cause of the excessive wear of retaining pawls in the upgraded LKP-M/3drive.

The calculational model was taken from [1] and a convenient combination of damping for both the preparatory step and the lifting step with respect to the results of the measurement [6] were established. Next the static characteristics of the electromagnets were modified according to the measurements carried out, and actual rise- and decay time at switching on and off and at the electromagnets current intensity changes (see [6]) was taken into account. When calculating the development of drive parts displacements in the lifting step, the introduction of the changes into the calculational model input data led to results that were very close to the measurement [6].

The study results in the following conclusions:

- negative shift of the contact-making moment does not bring the requested improving,
- positive shift of the contact making moment brings the requested improving,
- feasible interval for the contact-making moment shift was found between +0.025 s and +0.05 s against the initial setting on,
- shift of the contact of the retaining magnet +0.04 s proposed on the basis of the measurement [6] and our calculations, and it is feasible as it gives very low stressing of all the LKP-M/3 parts,
- in particular, the peaks of the control element upper suspension bar acceleration are lower with this shift. This leads to decreasing the wear of the retaining pawls that bear the suspension bar with the control element in the course of the lifting step.

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