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USE OF THE FINITE ELEMENTS METHOD FOR MODELLING THE DYNAMIC LOAD IMPACT ON HYDRAULIC LEG VYUŽITÍ METODY KONEČNÝCH PRVKŮ PŘI MODELOVÁNÍ DYNAMICKÉHO ZATÍŽENÍ NA HYDRAULICKÝCH STOJKÁCH

Abstrakt.

Příspěvek se zabývá modelováním velmi složitého mechanizmu obsahujícího jak části hydraulické tak i pneumatické a to při dynamickém zatížení. V článku je proveden podrobný popis přípravy numerického řešení, které vychází ze vzájemného působení tří různých materiálů a to oceli, kapaliny a plynu a ukazuje způsob modelování počatečního statického zatížení celého systému.Na základě software fy MS Softwer je pak provedena počitačová simulace působení dynamického zatížení na hydraulickou stojku a skutečného zatížení hydraulické stojky před přetížením pomoci plynového akumulatoru.

Abstract.

Modelling of a complex mechanical system, which contains hydraulic and pneumatic components and undergoes dynamic load action was presented. Especially procedures of preparation of numerical analysis, consisting in a simulation of cooperation of three different media: steel, liquid and gas as well as modelling of the initial static load of the mechanical system were discussed. By using the MSC.Software products the following exemplary computer simulations were made: dynamic load impact on the hydraulic leg as well as effectiveness of the hydraulic leg protection against overload with help of gas accumulator.

1 Introduction

Operational safety of the power roof support depends mainly on reliability of hydraulic legs. Thus, the process of legs designing and especially their protection against results of the load caused by rock mass dynamic action, is of great importance as regards operational safety of roof support. The hydraulic legs are the parts of roof support that most frequently can be damaged in a result of rock bursts. From the accident files including 63 rock burst cases (reported in the Polish part of Upper Silesian Coal Basin within 1978-1995), in which roof support was damaged, it results that hydraulic legs damage made 54% of all recorded damages of roof supports [3].

According to the PN-EN-1804-2-2004 Standard the hydraulic legs undergo compulsory testing on test rigs for static and dynamic loads [11]. The tests are very expensive and that is why it is reasonable to replace the stand tests of new prototype or at least part of tests, by numerical testing, made on hydraulic leg models, especially in case of designing a new model of the leg or new device protecting the leg against overload. At present the finite elements method (FEM) is the most reliable method for modelling of quickly changeable dynamic processes and strongly nonlinear processes occurring in solids, mechanical systems or fluids. Due to the computer simulation, it is possible to carry out much more virtual tests, what enables to understand more precisely the mechanism and to design better the energy absorption devices. There are many applications on the market as well as big commercial packages which enable the users to solve nonlinear dynamics problems. The software such as *PAM-Crash*, *LS-Dyna*, *MSC.Dytran*, developed to carry out the analyses of such a type, has strong and well-deserved position on the market [2].

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Computer simulation of dynamic load impact on the hydraulic leg requires a solution of many problems associated with use of FEM method to model the complex mechanical systems. The following belongs to most important problems:

- □ modelling the load, transferred by the metal parts of the leg and by working medium,
- □ interaction of moving metal parts and fluid including the changeable contact surface between working medium and cylinder walls,
- \Box modelling an initial setting of the leg.

The proper solution of the above mentioned problems is especially important when modelling the devices protecting the leg against dynamic overload – especially gas accumulators.

Process of preparation of the numerical analysis to model the hydraulic leg as well as results of calculations, made by MSC.Software package, will be discussed below.

2 Preparation of the numerical analysis

The preparation of numerical analysis, which aims at modelling the dynamic impact on hydraulic leg, can be divided into the following stages:

- □ creation of the geometric model,
- □ partition of the geometric model into finite elements and volumes,
- □ defining of the material properties,
- □ determination of load and boundary conditions,
- □ attributing the physical properties to finite elements,
- □ preparation and generation of the input file.

Geometric model of the hydraulic leg, discussed in the paper, was built on the basis of technical documentation of the Ø200 hydraulic leg used in the FAZOS-12/28-Oz powered roof support. Geometric model of the hydraulic leg, presented in Fig. 1, was developed with a help of CAD (Autodesk Inventor) software, which enables to create parameterized spatial models.



Fig.1. Geometric model of the hydraulic leg [4]

Parameters of geometric model of the hydraulic leg, after loading it to the MSC.Patran (preprocessor) software, enable a creation of the model made of finite elements and volumes. Partition of the geometric model into finite elements and volumes has been shown in Fig. 2.



Fig.2. Partition of the geometric model into finite elements and volumes [4]

In the hydraulic legs, an external load is transferred by steel tubes and by liquid, closed in an annular compartment. Simulation of the system operation, in case of dynamic load, requires a recreation of both types of bodies in a numerical model.

Finite elements method (*FEM*) was used to recreate the steel subassemblies (upper prop and lower prop). The subassemblies were divided into uniform finite elements using the solid elements of *CHEXA* type and the material model of the following properties: *Young modulus* E=2E+11 Pa, density $\rho=7850$ kg/m³, *Poisson coefficient* v=0.3 and yield point $R_e=7.8E+8$ Pa, was attributed to them.

Flow of liquid was described by Euler's method, that is part of the space, in which the movement and state of material inside it can be tracked, is defined. The space is divided into cells – finite volumes, and in a rough approximation we can assume that they are motionless. Continuous medium i.e. liquid, passes through the cell walls. The software calculates the state variables like: pressure, mass, momentum, internal energy of material in the cells as well as forces acting on material in the cells and resulting changes of momentum [1]. The liquid filling the annular chamber of leg was modelled using the elements of *CHEXA* type. The following properties of material (liquid) were attributed to those elements: density $\rho =$ 1000 kg/m³ as well as modulus of volume elasticity $a_1 = 1.65E+9$ Pa.

In some way, we can say that the algorithms analyzing the finite elements and finite volumes operate independently. The forces transferred by the finite elements do not act directly on a material in cells of Eulerian space. Coupling of the solid body model with liquid model is possible due to the *ALE Coupling* option. The method consists in implementation of additional object (coupling surface, called "the skins", modelled by surface finite elements of *CQUAD4* type), which in both cases uses the mechanism of entering the boundary conditions. Coupling surface enables a transfer of the pressure which acts on the finite elements nods due to the liquid neighborhood. The surface is also a boundary for the liquid, and its relocation causes a change in liquid boundary position and forces its flow. Due to that fact, it is possible to recreate the liquid flow in a leg's cylinder, the walls of which can relocate or deform [1]. Fig. 3 shows the method for defining the coupling surface between solid bodies and liquid.



Fig.3. Defining the coupling surface between solid bodies and liquid [7, 9]

When modelling a dynamic load action on the hydraulic leg, installed in the support, which was set in the workings, we have to include not only the external load, but also the initial load of leg. Diagram of load and support of discussed mechanical system is presented in Fig. 4.



Fig.4. Diagram of analyzed mechanical system

To obtain the most disadvantageous variant of leg's load, it was assumed that initially there is a nominal static pressure in annular chamber equal to 35 MPa, i.e. the pressure at which the leg's lowering starts due to an action of operational valve. In a discussed problem the nominal pressure of working medium was included to a dynamical analysis by defining the initial liquid density ρ_0 . *EO-SPOL* balance equation, which is a polynomial density function, is used to calculate ρ_0 value. In case of (liquid) compression, it has the following form [7]:

$$\mathbf{p} = a_I \, m \,, \, [\mathrm{Pa}] \tag{1}$$

where: $m = \frac{p_o}{p} - 1$ p - pressure [Pa] $\rho - material density$ [kgm⁻³] $\rho_o - wanted material density$ [kgm⁻³] $a_1 - volume elasticity modulus$ [Pa]

When preparing the analysis, it was assumed that during the first 20 ms of analysis the pressure of working medium will increase from 0 to 35 MPa and will stabilize on this level. To protect upper prop against coming out from the cylinder, due to increasing pressure of working medium, additional surface (a limiting wall against which the upper prop is leaning – Fig.4) was modelled. Additionally, not to allow for reciprocal penetration of upper prop components and wall, the proper type of contact should be defined (e.g. *Master-Slave Surface*).

External load of hydraulic leg was defined in a form of forcing the leg's head movement (Fig. 4). Time process of dynamic load was selected in such a way to achieve dynamic overload – pressure increase in annular chamber equals 1.7 times of the nominal pressure, after stabilization of working medium pressure, on the level of nominal pressure $p_n=35$ MPa . Time of dynamic load increase and drop, for the time process given in Fig. 5, was accepted basing on time processes of dynamic load realized on a test stand by ignition of explosives [12].



Fig.5. Time process of dynamic load [4]

The final stage of analysis preparation included a generation of the input file, basing on the following parameters of analysis:

- \Box time of analysis (0.085 s),
- \Box starting time interval (1E-7 s),
- \Box minimal time interval (1E-8 s),
- □ file of results (pressure, dislocation, deformation, stress).

The generated input file, which included information about geometry, loads, boundary conditions and parameters of analysis, was loaded to *MSC.Dytran* (solver). *MSC.Dytran* calculation process verifies the following in the first step:

- □ geometrical correctness of the system,
- □ correctness of boundary conditions,
- correctness of defined contacts between the neighboring elements.

In the next step, the file is analyzed numerically. The software has to read the required values every 0.0001 s and to save them in proper *ARC* or *THS* results files.

Analyzed system was built from 54757 finite elements (flat and solid) and resulting 50113 nods. Numerical analysis of leg's dynamic load phenomenon, lasting 85 ms, was carried out in *MSC.Dytran* within 17 hours.

3 Results of numerical calculations

Time processes of liquid pressure in a leg caused by dynamic load were recorded in selected measurement points marked with P.0 \div P.5 symbols in Fig. 6.



Fig.6. Arrangement of measurement points on the model of hydraulic leg [5]

Time processes of pressure, upper prop yielding and stress on a cylinder surface, obtained in a result of numerical calculation, were smoothed using a special coefficient called progressive mean, due to an imperfection of the process of achieving the initial static state. Time processes were given in Fig. 7 and 8.



Fig. 7. Time processes of pressure in the model of liquid [5]





Fig. 9 shows a distribution of reduced stress in steel subassemblies of hydraulic leg (upper prop, lower prop) which occurs in a result of dynamic load and working pressure of liquid in the selected time intervals (from 0.02 s to 0.027 s).



Fig. 9. Distribution of reduced stress in steel subassemblies of hydraulic leg, time interval: a) 0.02 s – beginning of dynamic force action, b) 0.024 s – maximal dynamic force, c) 0.027 s –pressure drop to the initial value [5] According to standard regulations, the leg's dynamic overload can not result in a presence of permanent deformations. From the map of permanent deformations of steel components of the hydraulic leg, at the moment (0.044s) of maximal load, presented in Fig.10, it results that the permanent deformation did not occur.



Fig. 10. Map of plastic strains in steel subassemblies of the hydraulic leg [5]

4. Analysis of interaction between steel components, liquid and gas on an example of gas accumulator installed in the hydraulic leg

Application of gas accumulator is one of the methods for protecting the hydraulic leg against results of dynamic action of rock mass. That device is especially suitable to be used in conditions of dynamic load characterized by a very short time of load increase, due to its small inertia and little possibility of rigidity changes in a wide range. Principle of operation of such a device consists in a significant compression of gas closed in the accumulator during dynamic load action on the leg and return back to the initial dimension by accumulator and leg when dynamic load stops.

The hydraulic leg, equipped with gas accumulator (designed by KOMAG) (A), installed in the upper prop (B) of the leg, consists of cylinder (1) and piston (2) (equipped with sealing and guiding rings), installed inside the upper prop (B) (Fig. 11). In the leg's head (8) there is a gas valve (4), which supplies accumulator's gas chamber (3) through channels and a pipe (7). Liquid (5) is in a space confined by the piston and cylinder walls (9) and the leg's foot (10).



Fig. 11. Diagram of hydraulic leg equipped with gas accumulator [6]

A simplified geometrical model of the hydraulic leg, equipped with gas accumulator, was created to show possibilities of operation of three technical media (steel, liquid, gas) together. Geometrical model of the hydraulic leg, presented in Fig. 12, consists of cylinder (1) and upper prop (2) protected by a limiting wall against coming out (3). In the cylinder (1) there is a hydraulic liquid (4) which presses a piston (6) of accumulator filled with gas (5). Both liquid (4) and gas (5) are under suitable pressure.



Fig. 12. Computer model of analyzed system: 1 – cylinder, 2 – upper prop with a pneumatic accumulator installed, 3 – limiting wall, 4 – hydraulic liquid, 5 – gas, 6 – piston of gas accumulator [6]

Numerical analysis of dynamic load of the leg with gas accumulator, containing information about geometry, load cases, boundary conditions and parameters of analysis, was prepared similarly to the numerical analysis discussed in a previous chapter of the paper. Additionally, properties of gas, which fills the chamber, were defined. The gas was modeled using the elements of *CHEXA* type. The following material properties were attributed to those elements (which characterize the ideal gas): density $\rho = 1.2887$ kg/m³, material constant $\gamma = 1.4$, internal energy in a temperature 293 K, e = 1.94E+5 J/kg. Assumed working pressures of liquid (35 MPa) and gas (40 MPa) in leg's annular chambers and gas accumulator were entered to the numerical analysis by defining the initial densities of both media. In the case of gas accumulator, the *EOSGAM* balance equation, being the polynomial density function, is used to calculate the initial gas density ρ_0 [7]:

$$\mathbf{p} = (\gamma - l) \,\rho_0 \,\boldsymbol{e} \tag{2}$$

where: p - pressure [Pa] $\rho_o - wanted material density$ [kgm⁻³] γ - material constant, e - internal energy [Jkg⁻¹].

Time processes of momentary pressure in Eulerian parts in the leg loaded dynamically, were recorded in selected "measurement points" marked in Fig. 13. Cells of liquid were marked with red color: P1 – measurement of pressure under piston and P2 – in lower prop's bottom, and cells of gas were marked with blue color: P3 – measurement of pressure under accumulator's piston and P4 – in accumulator's bottom.



Fig. 13. Arrangement of "measurement points" [6]

Calculated time processes of medium's working pressure in an annular compartment of the leg loaded dynamically, were presented in Fig. 14.



Fig.14. Time processes of pressure in a model of liquid (P1, P2) [6]

Calculated time processes of gas pressure in gas accumulator chamber loaded dynamically, were presented in Fig. 15.



Fig. 15. Time processes of pressure in a model of gas (P3, P4) [6]

In Fig. 16, pressure distribution in liquid and gas models – resulting from a dynamic load exerted on the initially set hydraulic leg, were presented in selected time intervals (from 0.01 s to 0.0175 s).



Fig. 16. Phases of pressure distribution in liquid and gas w models a) 0.01 s start of dynamic force action,

b) 0.015 s - maximal pressure value, c) 0.0175 s - pressure drop to the initial value [6]

Maps of reduced stresses in steel components of leg and gas accumulator in selected time intervals (from 0.01 to 0.018 s) were given in Fig. 17. Deformation of models and dislocation of gas accumulator piston were considered.





Map of plastic strains at the moment (0.015 s) of maximal load exerted on the leg, by a dynamic force, was presented in Fig.18a. During an analysis in time interval from 0 s to 17 ms, there were no plastic strains in the leg.



Fig. 18. Map of plastic strains in leg: a) zero plastic strains at the moment of maximal dynamic load, b) plastic strains resulting from accumulator's piston impact on protecting flange after gas decompression [6]

By analyzing the next time intervals, it was found that after disappearance of external dynamic load and gas decompression, accumulator's piston causes permanent deformations by hitting the protecting flange, showed in Fig.18b. On the basis of presented initial results obtained from stereo mechanical analysis of accumulator, its design was modernized.

5. Summary

Problems that condition application of finite elements method for modelling the action of dynamic load on hydraulic leg were the subject of the paper.

Modelling of interaction between three different media – steel components, liquid and gas is the main problem. In the FEM method each of these media is described in a different way: steel leg's components by finite elements of Lagrange type, and fluid by finite elements of Euler type. Mutual interaction of those media were modelled by entering boundary conditions on coupling surface – so called "skins", made by surface finite elements (Lagrange elements).

The other problem is how to include an initial static setting of the leg to the dynamic load calculations. Initial static load was modelled by assuming the initial density of liquid and gas, which depend on initial static pressure and physical properties of media. Besides, the leg dislocation, in a direction of its longitudinal axis, was one-sidedly limited assuming a rigid resistance plane as well as assuming a proper type of its contact with leg's head. In an analysis of dynamic load it was assumed that time indispensable to reach the accepted leg's static load is 20 ms. Besides, during analysis of dynamic load simulation – pressure time processes in selected cells, reduced stresses and dislocations in pointed finite elements and leg's nods – it was found that there is a necessity to smooth the obtained time processes using a progressive mean coefficient. Other method of elimination of imperfections of initial leg's static load modelling process, would consist in a preparation of special procedures for users and thorough interference in the structure of input file of the MSC.Dytran calculation software.

Use of finite elements method to the simulation of dynamic load in hydraulic leg equipped with gas accumulator has enabled a correction of design model of gas accumulator already at the designing stage due to more detailed recognition of phenomena accompanying the dynamic loads.

Necessity for continuation of the studies on leg simulations, results from carried out initial numerical analyses. On the basis of the studies, it is possible to determine gas accumulators range of application and it is possible to select technical parameters of accumulator which depend on the characteristics of expected dynamic load exerted on the leg.

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