Numerical modelling of interaction between mechanical system and fluid

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Abstract. Using the gas accumulator is one of the methods for protection of hydraulic leg against dynamic load caused by bumps. The structure of numerical model of the hydraulic leg with gas accumulator, intended for computer simulations aiding the selection of technical parameters of gas accumulator, is presented. It is used to protect hydraulic leg against dynamic overload. Features of the method for modelling the interactions between solid and fluid, used in dedicated MSC.Dytran software tools are discussed. Mathematical model of the leg with gas accumulator was validated by comparison with the stand test measurements. Impact of gas accumulator on pressure in working area at set external load is given.

1. Introduction
The problem of designing the systems protecting the hydraulic leg against damages from rock bursts is under investigation in many scientific centres [1, 2, 3, 4]. Computer simulations of dynamic effects occurring in a hydraulic leg subjected to a dynamic load [5, 6] are known. Their focus is mainly on analysis of the flow of working medium in the aspect of system efficiency and the possibility of limiting the pressure in work space of the hydraulic leg [6, 7]. Because these computer simulations are conducted using the finite volume method (e.g.: FLUENT, ANSYS CFX) [7, 8], the interaction between the fluid and the elastic wall of the hydraulic leg is not taken into account in the calculations. The prototype method of passive protection of hydraulic leg by use of gas accumulator in leg’s upper prop has been developed in the KOMAG Institute of Mining Technology. The hydraulic leg with gas accumulator, designed in KOMAG, is presented in figure 1.

The gas accumulator consists of a cylinder, a piston (equipped with sealing and guiding rings) and a collar protecting the accumulator components against entering the under-piston area. Gas valve, used to feed accumulator chamber and a pressure transformer used to control gas condition are installed in the accumulator’s bottom.

Besides the necessity of solving the problems associated with current maintenance of gas accumulator, also the problem of proper selection of the device’s technical parameters is very important. Rational selection of gas accumulator technical parameters requires assistance of computer simulations. Modelling the interactions between the solid and fluid is especially important in creation of the model of hydraulic leg with gas accumulator. The interaction consists in changes of fluid volume during movement of solid, what results in changes of fluid pressure acting on the solid. The phenomenon can be found for example, when describing the movement of piston in a cylinder filled with a fluid.
The problem of interaction between solid and fluid is especially important in the case of exertion of impulse load to the discussed system. Impulse load causes the wave of elastic deformations resulting in significant vibrations of points far from the place of force exertion [10]. The described dynamic effects can be found, for example, during modelling the explosion of explosives [11] or during computer simulation of dynamic load from bumping [9], acting on a hydraulic cylinder.

Resolution of the problems requires using dedicated software environment. The characteristic features of the methods for numerical modelling of interaction between solid and fluid illustrated by the problems being solved in the KOMAG Institute of Mining Technology in Gliwice, Poland, are presented.

2. Methods for modelling the interaction between solid and fluid

The main difficulty that appears during building the model, which includes cooperating areas covering fluid and solid, consists in coupling the boundary conditions in the contact area [12]. Pressure on the wall of finite volume depends on the parameters of fluid in the cell (e.g. stress tensor components). Appearance of pressure does not result in dislocation of finite elements nodes. Due to this, the nodes, which belong to the finite elements modelling the solid, which have a contact with the finite volume wall, would also have zero dislocation. Pressure on the wall of finite volume cell does not affect the stress condition in the finite element, because stress tensor components in the finite element depend on dislocations of nodes. Analogically, dislocations of finite element nodes, resulting from stress condition in the finite element, do not change the parameters characterizing condition of fluid in the finite volume neighbouring the finite element.

Solving this problem requires using the special numerical methods enabling transformation of boundary conditions between the areas modelled by Lagrange elements and Euler volumes. The following two methods for coupling the boundary conditions between the model of solid and the model of fluid are described in the literature [13]: General Coupling method and Arbitrary Lagrange Euler Coupling (ALE) method.

These methods consist in using the additional coupling surfaces called “skins”. They are used to inter-transfer the boundary conditions – i.e. conditions formulated in the area modelled by Lagrange elements and in the area modelled by Euler volumes.

General Coupling method consists in surrounding the solid area, modelled by the finite elements (of Lagrange type), and moving in the area modelled by the finite volumes (of Euler type), with the coupling surface. The coupling surface can be of any closed form, while the area confined by this surface requires nonzero initial volume. Coulomb friction on the coupling surface can be assumed in defining the surface properties. It is also planned to use the model of solid porosity.

The coupling surface, schematically presented in figure 2, is built of coating finite elements, which nodes overlap only the nodes on the edge of the area modelled by Lagrange elements.
The coupling surface is forced to be dislocated by dislocations of the structure modelled by Lagrange elements. At same time, moving coupling surface creates geometric constraints to the movement of fluid between finite volumes (i.e. Euler cells). In General Coupling method the grid of Euler cells is constant and thus moving coupling surface divides the finite volumes into two smaller cells.

Computational procedures of the software programme check the penetration of coupling surface and Euler cells in each time interval. Then, adequately to the calculations, the procedures modify their shape and fluid flow between the cells at the same time as well as equations of state. As, according to the Courant criterion, accepted time interval for integration of equations of motion depends on the size of the smallest finite volume in the model, in the computational procedures of the software programme the fusion of the finite volumes, size of which is smaller than the size set by the programme user, with the neighbouring cells, is planned. In the case of such combined cells, their volumes are summed as well as their weight, energy and momentum of fluid.

At the same time, the coupling surface is used to load the structure, modelled by Lagrange elements by action of fluid in Euler cells. Load generated by fluid on the coupling surface is reduced to the form of collected forces applied to the nodes of this surface. Nodes of Lagrange finite elements, overlapping the coupling surface, are loaded with these forces treated as the external load.

General Coupling method is especially useful in the case of modelling the solid dislocation in the fluid – in the medium modelled by Euler elements. Relatively long time of calculations, resulting from the need of calculations of penetration of coupling surface and cells of finite volumes in the whole area modelled by Euler elements for each time interval, is a disadvantage of this method. It is possible to shorten the time of calculations even by 50 ÷ 90 % after using the Fast Coupling Technique algorithm. Algorithms for control of penetration of coupling surface and cells of finite volumes as well as algorithms for fusion of neighbouring cells are the same as in General Coupling method, while significant limitations to the shape of the grid of Euler elements. The grid has to be orthogonal and defined in a general coordinate system.

Arbitrary Lagrange Euler Coupling method, called ALE, consists in a creation of two coupling surfaces – one surface limiting the fluid and the other modelled by the finite elements (figure 3). Nodes of elements creating the coupling surfaces and referring nodes of the finite volumes cells and Lagrange elements require the same coordinates. However, they cannot be treated as joint nodes. Similarly to General Coupling method, the coupling surfaces can have any closed shape. ALE method consists in forcing dislocation of grid of cells of Euler area by deforming coupling surface (skin), surrounding the grid of finite elements. Due to this the ALE method can be used only in the case of small dislocations of the structure of Lagrange elements (in relation to the amounts characterizing the size of finite element) to enable “adaptation” of changes of grid of Euler elements to deforming coupling surface.
The ALE procedure consists of the following two, consecutive steps: recreation – consisting in
determination of dislocations of finite elements nodes in realized time interval, and advection – realized
on Euler cells and consisting of the following operations [15]:

- determination of nodes of finite volumes grid that should be displaced,
- determination of dislocations of nodes on the edge of area modelled by finite volumes,
- recalculation of all variables referring to the cells of finite volumes, while the speed of
  dislocation of finite volumes grid is not the same as the speed of fluid,
- calculation of fluid momentum and updating the fluid speed.

Determination of variables in each cell of finite volumes consumes most of time of calculations made
within the advection step. Parameters of fluid state depend on fluid movement between cells as well as
on changes in finite volume cells position induced by movement of coupling surface. Moreover, the
principles of conservation of mass, momentum and energy of fluid should be met in the whole area
modelled by the finite volumes [15].

Maintaining constant topology of finite volumes grid, as the nodes of this grid always dislocate
towards the centres of neighbouring cells, is additional advantage of ALE procedure. Therefore, areas
filled with fluid can be modelled by relatively dense grid of finite volumes. Unlike General Coupling
method, the calculations in each time interval for the whole grid of finite volumes are not required in
ALE procedure, so the method enables obtaining the calculation results faster and better.

Apart from limiting the analyses only to small dislocations of finite elements grid, the necessity of
maintaining the same density of finite elements grid and finite volumes grid at the contact between fluid
and solid is the ALE method disadvantage. Modelling the fluid compressibility is also impossible.

The ALE method can be used in solving many complex problems referring to dynamics of continuous
media, e.g.: simulations of crash tests, designing the energy absorbers, simulations of hammering,
extruding and fluid waving in containers, etc. The examples of using the ALE method for modelling
detonation of explosives and designing the gas accumulator for protection of hydraulic leg against
overload are presented below.

3. Modelling of gas accumulator protecting the hydraulic leg against dynamic overload

Computer simulations with use of FEM model of the leg with gas accumulator can support designing
process and laboratory tests by determining the most advantageous technical parameters of accumulator
regarding the criterion of required yielding of the leg and can reduce scope of expensive stand tests.

Presented example of modelling the interaction between solid and gas was developed with use of the
tool of Patran – Dytran software environment of MSC.Software. This software environment is not the
only product available on the market, which is dedicated to solve such problems. The problem of
interaction between solid and fluid in conditions of dynamic load can also be solved with use of such
software programmes as Pam–Crash, LS–Dyna or ANSYS.
The mathematical model of the leg, given in figure 4, was developed to select the most favourable accumulator’s technical parameters as regards minimization of pressure in under-piston area.

Metal elements of the leg: upper prop, lower prop and gas accumulator’s piston were modelled by homogenous solid finite element of CHEXA type, which were assigned to a model elastic-and-plastic material of the following material properties:

- Young modulus: $E = 2.1 \cdot 10^{11}$ Pa,
- density: $\rho = 7850$ kg·m$^{-3}$,
- Poisson ratio: $\nu = 0.3$,
- yield point: $Re = 4.0 \cdot 10^8$ Pa.

Coupling the model of solid with the model of working medium and the model of gas is defined by ALE Coupling method. Coupling surfaces between fluid and solid (figure 2) were modelled with use of hull finite elements of CQUAD4 type. Model of linearly elastic material – steel, was assigned to these elements.

Finite elements (cells) of CHEXA type and properly defined model of liquid as well as model of ideal gas were used to model working medium, filling the under-piston area of the leg, and gas in a chamber of gas accumulator.

Model of operational medium has the following parameters:

- density: $\rho = 1000$ kg·m$^{-3}$,
- bulk modulus of elasticity: $a_1 = 2.2 \cdot 10^9$ Pa.

When modelling the kinematic excitation of the leg, installed in a support set to load, both external dynamic loads as well as initial static pressure of working medium, filling the under-piston area, should be taken into account. In numerical analysis, the value of working medium pressure is defined as $p_o –$ initial density of the material (fluid) filling the under-piston area of the leg model. It is determined from EOSPOL equation, which is a polynomial function of density. In the case of compression, this equation has the following form [13]:

$$p_e(t = 0) = \left( \frac{\rho_o}{\rho} - 1 \right) a_1$$

where:

- $p_e$ – pressure of working medium [Pa],
- $\rho$ – density of working medium [kg·m$^{-3}$],
- $\rho_o$ – density of working medium [kg·m$^{-3}$],
- $a_1$ – bulk modulus of elasticity of working medium.

Model of ideal gas is characterized by the following material parameters:

- density: $\rho = 1.25$ kg·m$^{-3}$,
- adiabatic curve exponent: $\gamma = 1.4$,
- material constant: $R = 8.314472$ J·mol$^{-1}$·K$^{-1}$,
- specific internal energy: $e = 1.94 \cdot 10^5$ J·kg$^{-1}$.
Initial pressure of compressed air in the accumulator chamber was defined as in the case of working medium, using EOSGAM [14] equation, by determination of density of the material (gas) filling the gas accumulator – \( \rho \), referring to the initial static pressure of the gas \( p_g \):

\[
p_g(t=0)=\left(\gamma-1\right)\rho_0 \cdot e
\]

where:
- \( p_g \) – initial pressure of the gas; [Pa],
- \( \rho_0 \) – initial density of the material; [kg\( \cdot \)m\(^{-3}\)],
- \( \gamma \) – adiabatic curve exponent,
- \( e \) – specific internal energy of gas; [J\( \cdot \)kg\(^{-1}\)].

At sequential times, the pressure of fluid filling the finite volumes is determined using calculation algorithm depending on momentary density of the fluid in the discussed cell.

Modelling the interactions between upper prop and lower prop requires a separate approach as well as in the case of modelling interactions between accumulator piston and chamber walls of the leg with gas accumulator. In the real object, space filled with working medium is closed by a pack of sealing installed on leg and accumulator pistons. In the case of FEM model of the leg, space of finite volumes was closed assuming the additional limiting surfaces, presented schematically in figure 5.

![Figure 5. Discretization of limiting surfaces by the surface elements [9].](image)

So-called “artificial” model of material, parameters of which (\( E \) and \( \rho \)) have significantly lower value than analogical material parameters used in material model of steel, was defined to minimize the impact of material properties of limiting surfaces used in the model on the result of calculations.

The simulation of the computerized hydraulic operation of the pneumo-hydraulic accumulator, was considered [16], where the hydraulic system consisting of the hydraulic accumulator actuator and hydraulic lines was modeled using the MSC Easy5 software. In the considerations, elastic deformation of the accumulator walls was omitted.

4. Validation of FEM model of the hydraulic leg with gas accumulator
Validation of FEM model, consisting in assessment of conformity of parameters characterizing model response with the parameters characterizing time functions, determined experimentally, is the main condition determining the possibility of using the FEM model in designing process of a machine. The tests, in which dynamic action of rock mass on the leg was generated by the energy from burning the explosives, were carried out at KOMAG to verify the FEM models of the leg with gas accumulator [17].

During tests time curves of working medium pressure and pressure of gas as well as a displacement of the piston of dynamic load generator were recorded. Measurements of displacement of the piston of
dynamic load generator were used in computer simulations for modelling the external load. It was assumed that during action of dynamic load, the piston of generator does not detach from the leg’s head, thus, it means that its displacement is equal to the yield of tested leg.

Time curves of working medium pressure (in leg’s under-piston area) and pressure of gas (in the accumulator’s chamber) in the analyzed models of the leg loaded dynamically were read out from the selected cells of “Euler space” marked out in figure 6.

![Figure 6](image)

**Figure 6.** Spacing of finite volumes, from which the pressure was read out [9].

Time curves of physical amounts recorded during the tests and time curves of the same physical amounts determined in computer simulation, were the subject of validation. Comparison of time curves recorded during stand tests with analogical time curves determined with use of the model described above, is presented in figure 7 ÷ 9.

![Figure 7](image)

**Figure 7.** Time curve of working medium pressure in under piston area of the leg with gas accumulator [17].

It results from diagrams presented in figure 7 ÷ 9 that the FEM model of the leg with gas accumulator enables generation of time curves, which are similar to the curves recorded during stand tests of the legs.

Coefficient of correlation between the measured value and the value determined numerically is a general measure of conformity of the results, obtained from computer simulation, to the real time curves.
Figure 8. Time curves of gas pressure in the accumulator chamber [17].

Figure 9. Time curves of yield of the leg with gas accumulator [17].

In figure 10, the correlation between pressure of working medium in FEM model of the leg with gas accumulator and the pressure in the leg recorded during stand tests are given.

Linear correlation between those amounts for the discussed 132-elements test is characterized by correlation coefficient, which is 0.981. Critical value of the correlation coefficient for 132 degrees of freedom and confidence level 95% is 0.144. Assuming the confidence level 95% it was proved that also in general population correlation coefficient is significantly greater than 0.977. Thus, the discussed linear correlation is very strong. This is described by a regression line in the following equation:

$$ p_{c,b} = 0.97 \cdot p_{c,s} + 2.06 \text{ [MPa]} \quad (3) $$

where:
- $p_{c,b}$ – pressure in under-piston area measured during stand tests,
- $p_{c,s}$ – pressure in under-piston area obtained in numerical calculations.
In Figure 10, regression line, confidence curves for the regression lines, determined on the confidence level 95% as well as – resulting from the Tchebyshev inequality – interval \( \pm 3\sigma \) (where \( \sigma \) – standard deviation from the test), covering the most probable pressures of working medium, obtained in tests.

In the result of above, the leg’s cylinder should be designed assuming the pressure \( p_{c,obl} \) in under-piston area according to the equation:

\[
p_{c,obl} = p_{c,b} + 3\sigma = 0.97p_{c,s} + 4.62 \text{ [MPa]}
\]

(4)

Considering the upper border of most probable values of pressure of the working medium, measured during stand tests, resulting from the relationship (3), it was found that error of conformity of FEM model of the leg equipped with gas accumulator to the real object, in relation to maximal values of pressure in under-piston area is below 4.31%.

Taking into account the maximal pressures both of working medium in under-piston area and pressure of gas, the maximal percentage error of conformity is below 4.5%. Thus, it has been proved that the following FEM models: leg in standard manufacture and the leg with gas accumulator, developed in this project conform enough to the real objects. Thus, they can be used in analyses of impact of accumulator technical parameters on the leg response at given excitation as well as in selection of gas accumulator parameters for the given leg.

4. Summary
Numerical modelling of interaction between solid and fluid requires the use of dedicated software tools enabling transformation of boundary conditions between the finite elements and cells of finite volumes. The problem of use of these software tools for modelling of mechanical systems is presented on the example of model of action of dynamic load on the hydraulic leg with gas accumulator, which was developed and experimentally verified at the KOMAG Institute of Mining Technology in Gliwice.

Validated numerical model was used in designing the leg for selection of technical parameters of gas accumulator by experiment planning method. It was found [9] that gas accumulator of initial chamber capacity \( V_0=12.5 \text{ dm}^3\) has the most advantageous technical parameters, due to criterion of required leg yielding. In figure 11 the curve presenting the pressure of operational medium in under-piston compartment of the model of leg with gas accumulator (\( V_0=12.5 \text{ dm}^3\)) in time is compared with the...
curve presenting the pressure of operational medium in the model of leg in standard manufacture, where both curves were obtained in the result of acting of the same dynamic load on the legs.

Besides reduction of maximal pressure of operational medium, the use of gas accumulator caused reduction of average rate of pressure increase. In a result, the mechanical system hydraulic leg – gas accumulator has better elastic properties at pressure higher than the operational pressure.

![Graph](image)

**Figure 11.** Comparison of time curves of working medium pressure of the following models: leg with gas accumulator (V₀=12.5 l) and standard version of the leg [9].

### 5. References

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