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Računalniško modeliranje gibanja goriva in njegov vpliv na konstrukcijo rezervoarja

Computational Modelling of Fuel Motion and Its Interaction with the Reservoir Structure

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Računalniški modeli vozil za simuliranje trkov vedno natančneje opisujejo obnašanje resničnih vozil. Rezervoar za gorivo je eden izmed elementov vozil, katerega računalniški modeli so bili do sedaj zelo poenostavljeni. Takšni modeli upoštevajo le vztrajnost mase goriva, ki je z masnimi točkami pritrjena na steno rezervoarja, vendar pa je vpliv gibanja goriva v rezervoarju popolnoma zanemarjen.

Prispevek opisuje nove računalniške modele, s katerimi je mogoče simulirati deformacijo rezervoarja za gorivo ob upoštevanju gibanja goriva pri trku vozila. V ta namen so bile vrednotene štiri metode simuliranje gibanja tekočine (Lagrange, Euler, poljubnostna Lagrange-Eulerjeva metoda - PLE in hidrodinamika zglajenih delcev - HZD) v rezervoarju preproste oblike, analizirane z eksplicitnim programom LS-DYNA. Računalniški rezultati so bili primerjani s poprej objavljenimi preizkusnimi opazovanji, pri čemer je bila ugotovljena zelo dobra primerljivost med rezultati.

Najprimernejši metodi (HZD in PLE) sta bili kasneje uporabljeni v dinamičnih simulacijah dejanskega rezervoarja za gorivo. Simulacije so pokazale, da predstavljeni modeli rezervoarja ob upoštevanju gibanja goriva zagotavljajo mnogo natančnejše rezultate v primerjavi z znanimi poenostavljenimi modeli.

(Ključne besede: gibanje goriva, Lagrangev opis, Eulerjev opis, ALE, SPH, vplivi tekočina - trdnina)

Computational models of vehicles for crash simulations are ever more precisely describing the behaviour of real vehicles. A fuel-tank is a typical vehicle element that has been very simplified in the computational models used so far. Such models have considered only the influence of the fuel mass inertia, which was point-wise connected to the tank walls, with total neglect of the fuel motion in the tank.

This paper describes new computational models that allow for a simulation of the fuel-tank deformation considering the fuel motion during a vehicle crash. For this purpose four different methods for describing fluid motion (Lagrangian, Eulerian, Arbitrary Lagrange-Eulerian description - ALE, SPH) were evaluated on a simple reservoir problem, analysed with the explicit dynamic code LS-DYNA. The computational results were compared with previously published experimental observations and a good correlation of the results was observed.

The most appropriate methods, SPH and ALE, were afterwards used in dynamic simulations of a real fuel-tank. The simulations showed that by also taking into consideration the fuel motion, the proposed computational models provide more accurate results in comparison with the previously used, simplified models.

(Keywords: fuel motion, Lagrangian description, Eulerian description, ALE, SPH, fluid structure interaction)

0 UVOD

V zadnjem času postajajo numerične simulacije v avtomobilizmu vse pomembnejše. Njihov cilj ni več zgolj določitev globalnega obnašanja vozil, temveč tudi natančnejše obnašanje posameznih

0 INTRODUCTION

In recent years numerical simulations in automotive engineering have gained in importance. Their aim is not only the determination of the global vehicle behaviour but also the behaviour of single

sestavnih delov. Pri razvoju konstrukcije novega vozila ali izboljšavi konstrukcije že znanega vozila so za računalniško simuliranje komponent najpogosteje uporabljene analize po metodi končnih elementov. V mnogih primerih simuliranje posameznih komponent ni zadostno, zato morajo biti v analizo vključene komponente oziroma celotni sklopi, ki vplivajo drug na drugega. Reševanje problemov postane zahtevnejše, kadar so sestavni elementi sklopa iz dveh ali več fizikalnih sistemov, ki medsebojno vplivajo. Kadar medsebojno vplivata dva ali več fizikalnih sistemov in je rešitev posameznega brez upoštevanja ostalih nemogoča, govorimo o vezanih problemih [20].

Eden izmed delov vozila, pri katerem vplivata dva fizikalna sistema, je rezervoar za gorivo. V preteklih simulacijah je bilo simuliranje rezervoarjev zelo poenostavljeno, saj vpliv gibanja tekočine na obnašanje rezervoarja ni bil obravnavan. Upoštevana je bila le masa goriva, ki je bila porazdeljena po posameznih vozliščih sten rezervoarja zaradi upoštevanja vztrajnostnih sil. Gibanje goriva pri trku vozila, ki ima velik vpliv tako na deformacijo rezervoarja kakor tudi njegovih nosilnih elementov, pa je bilo popolnoma zanemarjeno. Omenjene poenostavitve so bile neizogibne zaradi omejene uporabe simulacijskih programskih paketov, vendar pa novejši programski paketi omogočajo tudi učinkovito reševanje več fizikalnih sistemov hkrati. V prispevku so opisani in vrednoteni različni numerični modeli, s katerimi je mogoče opisati gibanje in vpliv tekočine na trdnino s programskim sistemom LS-DYNA [10]. LS-DYNA temelji na metodi končnih elementov in je bila prvotno namenjena reševanju dinamičnih problemov v mehaniki trdnin. Modeliranje odzivov v dinamiki trdnin je zato zelo dobro razvito. Modeliranje vezanih problemov med tekočino in trdnino pa še vedno ostaja izziv. Primerjava metod in njihova uporabnost je ponazorjena na praktičnem primeru gibanja tekočine v rezervoarju s preprosto geometrijo. Z eksperimentalnimi meritvami pa so primerjani tudi rezultati analiz [11].

1 MEDSEBOJNI VPLIV TEKOČINE IN TRDNINE

Eden izmed najpogosteje obravnavanih vezanih problemov v inženirski praksi je medsebojni vpliv tekočine in trdnine, zaradi česar so se razvili različni postopki reševanja teh problemov. K razvoju algoritmov za računanje vezanih problemov je pripomogel tudi silovit razvoj

components. In the case of computational component simulation, during the designing phase of a new vehicle structure or during the design improvements of existing vehicle designs, finite-element method analyses are most often used. In many cases, however, simulating separate components is not sufficient. Therefore, other components or assemblies that interact with each other have to be included in the analysis. The solution process becomes more sophisticated when the assembly components consist of two or more different physical systems that interact. When two or more physical systems interact with each other and an independent solution of one system is impossible without a simultaneous solution of the others, such systems are known as coupled [20].

One of the vehicle components where two physical systems interact is the fuel-tank. In previous simulations the model of the tank was very simplified, since the fluid motion's influence on the tank's behaviour was not considered. Only the fuel mass was taken into account, which was distributed at discrete nodes along the tank walls to account for the fuel inertia forces. The fuel motion during a vehicle crash, which has a large influence on tank deformation and its supporting elements, was thus completely neglected. Such simplifications were necessary due to the limitations of the simulation software used. However, some recent releases of simulation software already allow for an effective solution of several physical systems simultaneously. In this paper different computational models that allow for consideration of the fluid motion and its influence on the structure are described and evaluated with the software LS-DYNA [10]. LS-DYNA is based on the finite-element method and it was originally designed for solving structural dynamic problems. Therefore, its ability to model structural responses in general is well defined. However, the modelling of a coupled fluid-structure interaction is still quite challenging. A comparison of the methods and their applicability is illustrated on a practical example, describing the fuel motion in a reservoir with simple geometry. The computational results are further compared with the experimental measurements [11].

1 FLUID-STRUCTURE INTERACTION

One of the most popular coupled problems in engineering is the interaction between the fluid and the structure, which consequently results in different approaches to solving such a problem. The development of coupled problems solution algorithms was also influenced by the rapid develop-

računalniške opreme, saj so tovrstne analize računsko zelo zahtevne. Vezane probleme je z uporabo različnih programskih paketov mogoče reševati na dva načina:

- z uporabo dveh programskih paketov: eden za določitev območja tekočin in eden za ločeno določitev rešitve območja trdnine. Takšni programski paketi (npr. CFX in Nastran) so po navadi povezani z vmesnikom, ki nadzoruje izmenjavo potrebnih podatkov o robnih pogojih ([4] in [19]);
- z uporabo programskega paketa, ki omogoča hkratno reševanje dveh ali več vezanih fizikalnih sistemov (npr. ADINA, ANSYS, LS-DYNA).

Programski paket LS-DYNA omogoča dinamično ugotavljanje medsebojnega vpliva med tekočino in trdnino z eksplicitno integracijsko shemo. V LS-DYNI je vpliv tekočine mogoče opisati in simulirati na dva načina: (i) s stičnimi silami (uporabno pri Lagrangevem in SPH modelu) in (ii) s kriterijem poroznosti snovi, ki v vsakem opazovanem elementu določi silo, ki je potrebna za vzpostavitev ravnotežja med tekočino in trdnino (uporabno pri Eulerjevem in modelu PLE) ([1], [6], [10] in [12]).

2 RAZLIČNI OPISI DOMEN

2.1 Lagrangev opis

Lagrangev opis se običajno uporablja za opis problemov v mehaniki trdnin. Problem se opiše z velikim številom masnih delcev, pri čemer se opazuje gibanje vsakega posameznega delca v prostoru in času (sl. 1). Problem je natančno določen, kadar poznamo gibanje vseh delcev [17].

ment of computer hardware, because such simulations are computationally very intensive. Coupled problems can be solved in two ways, by using commercial software:

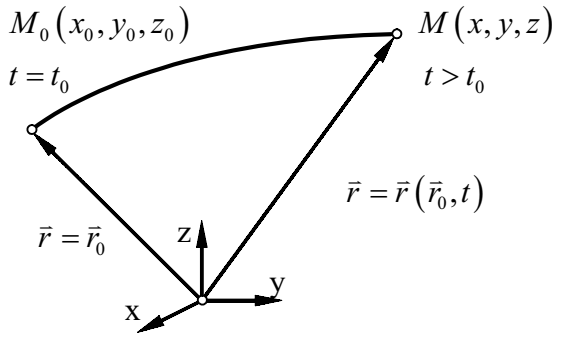
- with the use of two commercial codes: one for solving the fluid domain and one to separately determine the solid-domain solution. Such codes (e.g., CFX and Nastran) are usually connected via an interface that controls the necessary boundary conditions' data exchange ([4] and [19]);
- with use of a commercial software that simultaneously solves a multi-physics problem (e.g., ADINA, LS-DYNA, ANSYS).

The LS-DYNA code is capable of establishing a dynamic interaction between the fluid and the structure with an explicit integration scheme. In LS-DYNA it is possible to describe and simulate the influence of the fluid on the structure, and vice versa, in two ways: (i) with contact forces (applicable for Lagrangian and SPH model) and (ii) with a leakage criteria, which in each observed element determinates the force that is necessary to establish equilibrium conditions between the fluid and the structure (applicable for Eulerian and ALE model) ([1], [6], [10] and [12]).

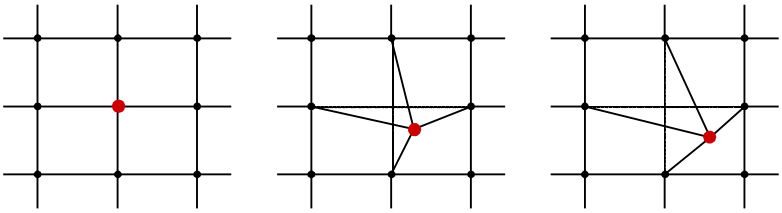
2 DIFFERENT DOMAIN DESCRIPTIONS

2.1 Lagrangian description

The Lagrangian formulation is usually used for describing solid mechanics problems. The problem is described with a large number of mass particles, where the motion of every single particle is observed in space and time (Fig. 1). The problem is exactly defined when the motion of all the particles is known [17].



Sl. 1. *Lagrangev opis [17]*
Fig. 1. *Lagrangian formulation [17]*



Sl. 2. *Deformacija mreže pri Lagrangevem opisu*
Fig. 2. *Mesh deformation in the Lagrangian formulation*

Lagrangev način opisa gibanja je preprost in nezahteven za uporabo, dokler gre za posamezni masni delec. V primeru proučevanja problema z velikim številom masnih delcev pa postane izredno zahteven in zapleten [17].

Pri Lagrangevem opisu predstavlja en končni element isti delež materiala celoten potek analize. Mreža končnih elementov je pritrjena na material med celotnim računskim postopkom, zaradi česar se pomika z materialom. Slika 2 prikazuje način reševanja preprostega primera tekočine z Lagrangevim opisom. Predpostavljeno je, da obremenitev deluje le na sredinsko vozlišče. Rezultat te obremenitve je pomik vozlišča v računskem časovnem koraku. Če vpliv obremenitve ne preneha, oz. se spremeni, vozlišče v naslednjem časovnem koraku ponovno zavzame novo lego in mreža se vedno bolj deformira, saj sledi toku materiala.

Ker mreža končnih elementov sledi materialu, ima relativen pomik medsebojno povezanih vozlišč izrazit vpliv na deformacijo končnih elementov. S premikom elementov se prenašajo tudi masa, gibalna količina in energija [2]. Enačba o ohranitvi mase se lahko v Lagrangevem opisu v parcialni diferencialni obliki zapiše kot:

$$\frac{\partial \rho}{\partial t} + \rho \cdot \frac{\partial v_i}{\partial x_i} = 0 \qquad (1),$$

kjer sta ρ gostota in v hitrost materiala (mreže). Za nestisljiv material je znano, da je div(v) = 0. Lagrangev opis ohranitve mase se lahko zapiše tudi v obliki algebrajske enačbe kot:

$$\rho \cdot J = \rho_0 \qquad (2),$$

kjer je J Jacobijeva matrika med trenutno in referenčno obliko. Ohranitev gibalne količine je v Lagrangevem opisu podana kot:

$$\rho \cdot \frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{i,j}}{\partial x_i} + \rho \cdot b_i \qquad (3),$$

The Lagrangian formulation is very simple and easy to use for one or only a few mass particles. However, the method becomes very complicated and complex for a description of large number of mass particles [17].

In the Lagrangian formulation, one finite element represents the same part of the material throughout the course of the analysis. The finite-element mesh is fixed to the material during the entire computational process and therefore moves with the material. Figure 2 illustrates the solution process of a simple fluid problem using the Lagrangian formulation. It is presumed that the loading influences only the central node. The result of the loading is the shift of that node in a computational time step. If the influence of the loading does not stop or change, the node takes a new position in the next time step and the mesh deforms even more, since the mesh follows the material flow.

Since the mesh follows the material, the relative movement of connecting nodes can result in a significant deformation of the finite elements. Mass, momentum and the energy are transported with the movement of the elements [2]. The mass conservation equation can be, in partial differential equation form, written for the Lagrangian description as:

where ρ is the density and v is the velocity of the material (mesh). For an incompressible material it is known that div(v) = 0. The Lagrangian description for the mass conservation can also be written in an algebraic equation as:

where J is the Jacobian between the current and reference configuration. Conservation of momentum in terms of the Lagrangian description gives:

kjer sta σ Cauchy-jeva napetost in b masna sila (sila na enoto mase). Tretja enačba predstavlja ohranitev energije in se lahko v primeru izključno mehanskega postopka zapiše kot:

where σ is the Cauchy stress and b is the body force (a force per unit mass). The third equation represents the energy conservation and can be, in a purely mechanical process, written as:

$$\rho \cdot \frac{\partial u}{\partial t} = \sigma_{i,j} \cdot \frac{\partial v_i}{\partial x_i} \tag{4},$$

kjer je u notranja energija na enoto mase.

Pomanjkljivost Lagrangevega opisa postane razvidna v primerih s skrajno popačeno mrežo, saj njihov opis vedno temelji na mreži. Popačenost mreže vpliva na natančnost metode in zato na rezultat analize. Sprejemljiva možnost za izboljšanje Lagrangevega modela je ponovno mreženje domene problema.

where u is the internal energy per unit mass.

The disadvantage of the Lagrangian description becomes evident in cases of an extremely distorted mesh, because their formulation is always based on mesh. When the mesh is heavily distorted, the accuracy of the formulation and hence the solution will be severely affected. A possible option to enhance the Lagrangian model is to re-mesh the problem domain.

2.2 Eulerjev opis

Pri Eulerjevem opisu, ki se navadno uporablja za reševanja problemov računalniške dinamike tekočin, se problem opazuje v določeni prostorski točki in ne sledi gibanju posameznega delca (sl. 3). V enem časovnem koraku Δt gredo skozi točko številni masni delci, katerih gibanje je v trenutku prehoda natančno določeno. V opazovani točki se veličine polja spreminjajo s časom.

Ohranitev mase je v Eulerjevem opisu zapisana kot:

2.2 Eulerian description

In the Eulerian formulation, which is commonly used for solving computational fluid dynamic problems, the problem is being observed at separate points in space that do not follow the particles motion (Fig. 3). In one time step, Δt, several mass particles can pass through the observed point. Their motion is exactly determined at the moment of passing through that point. The field variables at the observed point are time dependent.

In the Eulerian formulation the mass conservation is written as:

$$\frac{D\rho}{Dt} + \rho \cdot \frac{\partial v_i}{\partial x_i} = 0 \tag{5},$$

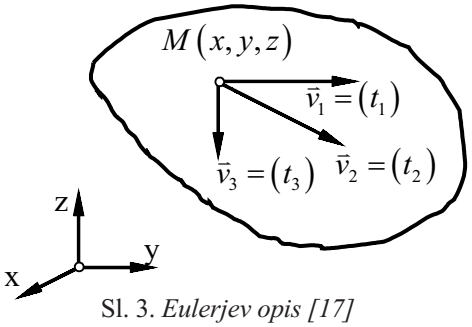
kjer je $\frac{D}{Dt} = \frac{\partial}{\partial t} + v_i \cdot \frac{\partial}{\partial x_i}$ snovski oziroma hitrostni odvod, ki podaja časovno spremembo veličine in prostorsko spremembo veličine zaradi nehomogenosti hitrostnega polja (vsota lokalnega in konvektivnega odvoda).

Ohranitev gibalne količine je izražena:

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + v_i \cdot \frac{\partial}{\partial x_i}$ is the total time derivative that is physically the time rate of the change following a moving material element (sum of the local and the convective derivative).

The conservation of momentum can be expressed as:

$$\rho \cdot \frac{Dv_i}{Dt} = \frac{\partial \sigma_{i,j}}{\partial x_i} + \rho \cdot b_i \tag{6}.$$



Sl. 3. *Eulerjev opis [17]*
Fig. 3. *Eulerian formulation [17]*

In ohranitev energije se lahko zapiše:

$$\rho \cdot \frac{Du}{Dt} = \sigma_{i,j} \cdot \frac{\partial v_i}{\partial x_i} \quad (7).$$

Temeljna razlika med Lagrangevim in Eulerjevim postopkom je v tem, da so pri Lagrangevem opisu veličine *x*, *y* in *z* spremenljive koordinate gibljivega delca. Pri Eulerjevem opisu pa te koordinate pomenijo mirujoče koordinate določene točke polja [17].

Kljub temu da se Eulerjeva mreža med analizo v LS-DYNI navidezno ne premika ali deformira, se dejansko spreminjata njena lega in oblika, vendar le v posameznem časovnem koraku ([13], [14] in [16]). Razlog za to je uporaba Lagrangevega opisa v posameznih časovnih korakih, ki je naprednejša v LS-DYNI. Eulerjeva mreža je v LS-DYNI obravnavana na poseben način (sl. 4). Uporaba Eulerjeve mreže je ponazorjena na enakem primeru, ki je bil uporabljen pri Lagrangevem opisu. Zaradi obremenitev na sredinsko vozlišče opazovano vozlišče spremeni lego v enem računalniškem časovnem koraku (mreža se deformira). Po časovnem koraku se analiza ustavi in izvedeta se naslednji dva približka [5]:

- premik vozlišč: vsem vozliščem Eulerjeve mreže, ki so zaradi obremenitev spremenila svojo lego, se ponovno določi izhodiščna lega;
- interpolacija vmesnih rezultatov: vse notranje veličine (napetost, tokovna polja, hitrostno polje), ki se nanašajo na vozlišča s spremenjeno lego, so interpolirane tako, da imajo ustrezno prostorsko porazdelitev kakor pred premikom vozlišč. Tako premik vozlišč ne vpliva na porazdelitev notranjih veličin.

Opisani postopek se ponavlja v vseh časovnih korakih celotne analize in ponuja uporabniku nepremično in nedeformirano Eulerjevo mrežo.

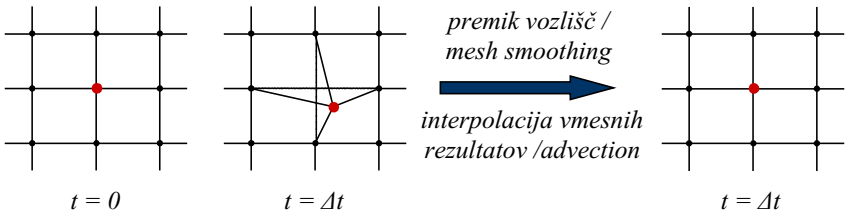
And the conservation of the energy can be written as:

The basic difference between the Lagrangian and the Eulerian formulations is that in the Lagrangian formulation the magnitudes *x*, *y* and *z* are variable coordinates of a moving particle; in the Eulerian formulation those coordinates represent the steady coordinates of the defined field point [17].

Although the Eulerian mesh in LS-DYNA appears not to move or deform during the analysis, it does actually change its position and form, but only within a single time step ([13], [14] and [16]). The reason for this is the use of the Lagrangian formulation in single time steps, which is much more advanced in the LS-DYNA. The Eulerian mesh in LS-DYNA is treated in a special way (Fig. 4). To illustrate the use of an Eulerian mesh the same example is used as at the Lagrangian formulation. Because of the central node loading, the observed node changes its position during one computational time step (mesh deforms). After the time step the analysis stops and the following two approximations are performed [5]:

- mesh smoothing: all the nodes of the Eulerian mesh that have been displaced due to loading are moved to their original position;
- advection: the internal variables (stresses, flow fields, velocity field) for all the nodes that have been moved are recomputed (interpolated) so that they have the same spatial distribution as before the mesh smoothing. In this way the mesh smoothing does not affect the internal variable distribution.

The described procedure is repeated for each time step of the analysis and provides the analyst with a non-movable and undeformable Eulerian mesh.



Sl. 4. *Deformacija mreže pri Eulerjevem opisu*
Fig. 4. *Mesh deformation in the Eulerian formulation*

2.3 Poljubnostni Lagrange-Eulerjev opis (PLE)

Značilnosti Lagrangevega in Eulerjevega opisa napovedujejo, da bi bilo računalniško ustrezno združiti omenjena opisa in poudariti njune prednosti ter se izogniti njunim pomanjkljivostim. Ta zamisel je vodila do razvoja poljubnostnega Lagrange-Eulerjevega opisa (PLE). V tem opisu se mreža lahko deloma premika in deformira, ker sledi materialu (Lagrangev opis), hkrati pa dopušča, da material teče skozi mrežo (Eulerjev opis).

Povezava med konvektivno hitrostjo c_i, hitrostjo materiala v_i in hitrostjo mreže $\hat{v}_i$ je definirana kot:

$$c_i = v_i - \hat{v}_i \tag{8}.$$

Glede na gibanje materiala in mreže se ohranitvene enačbe mase, gibalne količine in energije zapišejo kot:

$$\frac{\partial \rho}{\partial t} + c_i \cdot \frac{\partial \rho}{\partial x_i} + \rho \cdot \frac{\partial v_i}{\partial x_i} = 0 \tag{9}$$

$$\rho \cdot \frac{\partial v_i}{\partial t} + \rho \cdot c_i \cdot \frac{\partial v_i}{\partial x_i} = \frac{\partial \sigma_{i,j}}{\partial x_i} + \rho \cdot b_i \tag{10}$$

$$\rho \cdot \frac{\partial u}{\partial t} + \rho \cdot c_i \cdot \frac{\partial u}{\partial x_i} = \sigma_{i,j} \cdot \frac{\partial v_i}{\partial x_i} \tag{11}.$$

Iz zgornjih enačb je razvidno, da v primeru, ko sta hitrost mreže in hitrost materiala enaka, izpeljemo Lagrangev opis. Kadar se material premika in mreža miruje (hitrost mreže je enaka konvektivni hitrosti), pa izpeljemo Eulerjev opis (preglednica 1) [2].

Računalniški algoritem reševanja opisa ALE v LS-DYNI je podoben opisanemu postopku Eulerjevega opisa ([13], [14] in [16]). Razlikuje se le v premiku vozlišč. V Eulerjevem opisu so vozlišča premaknjena nazaj na izhodiščne lege, pri čemer se

2.3 Arbitrary Lagrange-Eulerian description (ALE)

The features of the Lagrangian and Eulerian descriptions suggest that it would be computationally beneficial to combine these two descriptions so as to strengthen their advantages and to avoid their disadvantages. This idea led to the development of the Arbitrary Lagrange-Eulerian formulation. In this formulation the mesh partly moves and deforms because it follows the material (Lagrangian formulation), while at the same time the material can also flow through the mesh (Eulerian formulation).

The relationship between the convected velocity, c_i, the material velocity, v_i, and the mesh velocity, $\hat{v}_i$, is defined as:

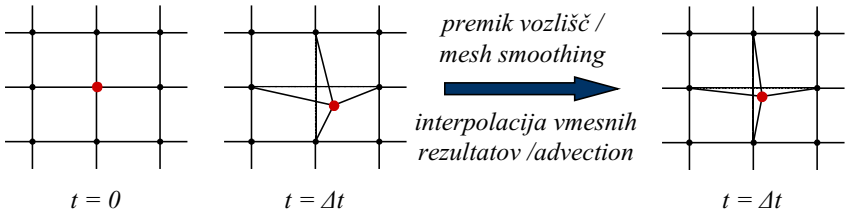
Regarding the material and the mesh movement, the mass, the momentum and the energy conservation equations can be written as:

From the above equations it is obvious that if the mesh and material velocity are equal this would give the Lagrangian description, and if the material moves and the mesh remains steady (the mesh velocity is equal to convected velocity) this would give the Eulerian description (Table 1) [2].

The ALE algorithm in LS-DYNA is similar to the described Eulerian computational procedure ([13], [14] and [16]). The only difference is the mesh smoothing. In the Eulerian formulation the nodes are moved back to their original positions, while in

Preglednica 1. *Primerjava kinematike PLE, Lagrangevega in Eulerjevega opisa*
Table 1. *Comparison of the kinematics for the ALE, Lagrangian and Eulerian formulations*

		PLE ALE	Lagrange	Euler
pomik / displacement	material mreža / mesh	u_i $\hat{u}_i$	u_i $\hat{u}_i = u_i$	u_i $\hat{u}_i = 0$
hitrost / velocity	material mreža / mesh	v_i $\hat{v}_i$	v_i $\hat{v}_i = v_i$	v_i $\hat{v}_i = 0$
pospešek / acceleration	material mreža / mesh	a_i $\hat{a}_i$	a_i $\hat{a}_i = a_i$	a_i $\hat{a}_i = 0$



Sl. 5. *Deformacija mreže pri PLE opisu*
Fig. 5. *Mesh deformation in the ALE formulation*

pri opisu PLE nova lega premaknjenih vozlišč izračuna glede na povprečno oddaljenost do sosednjih vozlišč (sl. 5).

Podobna numerična shema je uporabljena v drugih primerljivih programskih sistemih (npr. MSC/Dytran).

Prednost Lagrange-Eulerjevega opisa se pokaže, kadar želimo slediti določeni napetosti in se mora mreža samodejno zgoščevati. Drug primer je analiza rezervoarjev s tekočino, pri kateri je upoštevano gibanje tekočine v rezervoarju, mejna ploskev pa se zaradi vpliva med trdnino in tekočino ves čas spreminja (sl. 6).

Kljub temu pa lahko uporaba PLE opisa povzroči popačenost elementov, kar lahko vpelje nevarne napake v numeričnih simulacijah. V določenih primerih PLE opis povzroči nepričakovano ustavitev računskega postopka. To se običajno zgodi zaradi zelo majhnih časovnih korakov, kot posledica zelo majhnih deformiranih Lagrangevih elementov ali celo negativne prostornine končnih elementov.

2.4 Metoda hidrodinamike zglajenih delcev (MHZD)

Stanje sistema je pri metodi hidrodinamike zglajenih delcev (MHZD) opisano z določenim

the ALE formulation the positions of the moved nodes are calculated according to the average distance to the neighbouring nodes (Fig. 5).

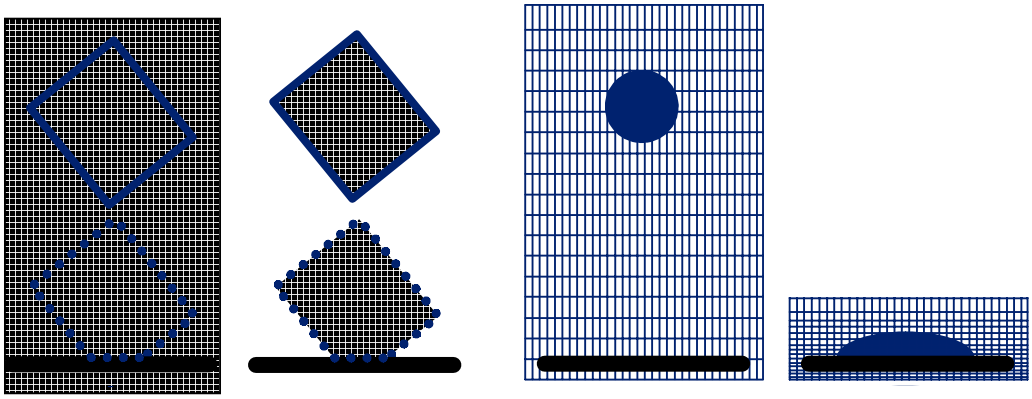
A similar calculation scheme is also used in other comparable codes (e.g., MSC/Dytran).

The advantage of the ALE formulation is evident when a stress front needs to be followed and the mesh is automatically refined. Another example is the analysis of fluid tanks, where the fluid's movement inside the tank is of interest and the boundary surface is continuously changing due to the interaction between the fluid and tank surfaces (Fig. 6).

However, using the ALE formulation can also result in a highly distorted mesh, which can introduce large errors in numerical simulations. In some cases the ALE formulation can encounter unexpected terminations in the computational process, usually due to very small time steps following from very small, deformed Lagrangian elements or even negative element volumes.

2.4 Smoothed Particle Hydrodynamics (SPH)

In the SPH method, the state of the system is represented by a set of particles (Fig. 7) that pos-



Sl. 6. *Uporaba PLE opisa*
Fig. 6. *Applications of the ALE formulation*

številom delcev. Le-ti posamezno vsebujejo materialne lastnosti in se gibljejo na osnovi temeljnih ohranitvenih enačb. MHZD je brezmrežna Lagrangeva metoda delcev, ki so jo razvili Lucy, Gingold in Monaghan z začetnim namenom simulirati astro-fizikalne probleme ([5], [7] do [9] in [15]). Kasneje je bila MHZD obsežno preučena in razširjena za reševanje dinamičnih odzivov trdnih materialov pa tudi za simuliranje toka tekočine z velikimi deformacijami. MHZD ima pred običajnimi brezmrežnimi metodami določene prednosti. Najpomembnejša prednost je prilagodljivost, ki je dosežena v začetnem koraku približka spremenljivih veličin (npr. gostote, hitrosti, energij). Le-ta je izvedena v vsakem časovnem koraku in temelji na trenutni krajevni porazdelitvi delcev s poljubno lego. Zaradi prilagodljivosti približka metoda HZD ni odvisna od poljubne porazdelitve delcev. Zaradi tega lahko obravnava zelo dobro probleme z izrednimi deformacijami. Naslednja prednost metode HZD je kombinacija Lagrangevega opisa in približka delcev.

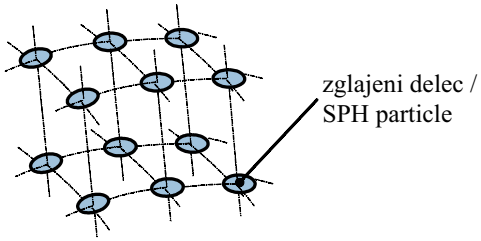
V nasprotju z drugimi brezmrežnimi metodami, pri katerih so brezmrežna vozlišča uporabljena le kot interpolacijske točke, vsebujejo zglajeni delci tudi materialne lastnosti in so tako namenjeni kot aproksimacijske točke ter materialni elementi. Ti delci so se zmožni gibati v prostoru, prenašati vse računalniške podatke in dodatno oblikovati računalniški sistem za reševanje parcialnih diferencialnih enačb, ki opisujejo ohranitvene zakone. Metoda HZD je razdeljena na dva ključna dela. Prvi del je predstavitev integrala funkcij polja, drugi del pa predstavlja aproksimacijo delcev. Omenjeni postopek je uporabljen za izpeljavo parcialnih diferencialnih enačb v navadne diferencialne enačbe v diskretizirani obliki v odvisnosti le od časa [9].

Ohranitvene enačbe mase, gibalne količine in energije MHZD lahko zapišemo kot:

sess individual material properties and move according to the governing conservation equations. SPH as a meshfree, Lagrangian, particle method was developed by Lucy, Gingold and Monaghan, initially to simulate astrophysical problems ([5], [7] to [9] and [15]). Later the SPH method was extensively studied and extended to the dynamic response with material strength as well as dynamic fluid flows with large deformations. It has some special advantages over the traditional mesh-based numerical methods. The most significant is the adaptive nature of the SPH method, which is achieved at the very early stage of the field variable (i.e., density, velocity, energy) approximation that is performed at each time step based on a current local set of arbitrarily distributed particles. Because of the adaptive nature of the SPH approximation, the formulation of the SPH is not affected by the arbitrariness of the particle distribution. Therefore, it can handle problems with extremely large deformations very well. Another advantage of the SPH method is the combination of the Lagrangian formulation and the particle approximation.

Unlike the mesh-free nodes in other mesh-free methods, which are only used as interpolation points, the SPH particles also carry material properties, functioning as both approximation points and material components. These particles are capable of moving in space, carry all the computational information, and thus form the computational frame for solving the partial differential equations describing the conservation laws. The SPH formulation is divided into two key steps. The first step is the integral representation (kernel approximation) of the field function, and the second is the particle approximation (discretization). This procedure is applied to the particle differential equations to produce a set of ordinary differential equations in a discretized form with respect only to time [9].

The SPH equations for the conservation of mass, momentum and energy can be written as:



Sl. 7. *Model po MHZD*
Fig. 7. *SPH model*

$$\frac{\partial \rho_i}{\partial t} = \sum_{j=1}^{N} m_j \cdot v_{ij} \cdot \frac{\partial W_{ij}}{\partial x_i} \tag{12}$$

$$\frac{\partial v_i}{\partial t} = \sum_{j=1}^{N} m_j \cdot \left(\frac{\sigma_i}{\rho_i^2} + \frac{\sigma_j}{\rho_j^2} \right) \cdot \frac{\partial W_{ij}}{\partial x_i} \tag{13}$$

$$\frac{\partial u_i}{\partial t} = \sum_{j=1}^{N} m_j \cdot \frac{\sigma_i \cdot \sigma_j}{\rho_i \cdot \rho_j} \cdot v_{ij} \cdot \frac{\partial W_{ij}}{\partial x_i} \tag{14},$$

kjer je N število delcev v območju vpliva delca i; W_{ij} predstavlja gladilno funkcijo delca i, izvrednoteno v delcu j, in je tesno povezana z gladilno razdaljo; v_{ij} pa je relativna hitrost med delcem i in delcem j [9].

Glavna možna prednost MHZD je v tem, da ne potrebuje medsebojno povezane prostorske mreže in se s tem izogne problemu popačenosti elementov pri velikih deformacijah. V primerjavi z Eulerjevim opisom je učinkovitejša, saj je treba modelirati le materialna območja in ne vseh območij, kjer bi material lahko obstajal. Kljub vsem obetom pa je metoda HZD razmeroma nova, v primerjavi z običajnim Lagrangevim in Eulerjevim opisom z mrežo elementov, z znanimi problemi na področju stabilnosti, zveznosti in izpolnjevanju ohranitvenih enačb [15].

3 PRIMERJALNA ŠTUDIJA RAZLIČNIH POSTOPKOV REŠEVANJA PRAKTIČNEGA PRIMERA

3.1 Opis problema in računalniški model

Analizirani problem sestoji iz zaprtega rezervoarja iz poliakrilnega stekla (PMMA), v začetnem mirujočem stanju, napolnjen s 60% vode in 40% zraka (sl. 8). Rezervoar je pritrjen na sani (pritrjen v navpični smeri) in pospešen z vzdolžnim časovno odvisnim pospeškom z največjo vrednostjo približno 30 g v času t = 40 ms. Časovno odvisna sprememba proste površine vode in tlak v točki 1, v rezervoarju iz polikarilnega stekla z debelino sten 30 mm, sta bila predhodno določena s preizkusom [11].

Rezervoar je modeliran z lupinskimi Belytschko-Tsayevimi lupinskimi elementi s štirimi vozlišči in tremi integracijskimi točkami po debelini elementa [3]. Za rezervoar je bil uporabljen elastičen materialni model s podatki, ki ustrezajo poliakrilnemu steklu (ρ = 1180 kg/m^3, E = 3000 MPa in ν = 0,35). Spodnja ploskev rezervoarja je bila modelirana kot toga. Za modeliranje vode in zraka so bili, odvisno od uporabljene metode, uporabljeni prostorninski

where N is the number of particles in the support domain of the particle i; W_{ij} is the smoothing function of the particle i evaluated at the particle j, and is closely related to the smoothing length; and v_{ij} is the relative velocity between the particles i and j [9].

The main potential advantage of the SPH technique is that it does not require an interconnected spatial mesh and thus avoids the problem of mesh distortion during large deformations. Compared with the Eulerian description, it is more effective, since only the material's regions of interest need to be modelled, and not all the regions where the material might exist. With all this promise, however, the SPH technology is relatively new, compared to standard mesh-based Lagrangian and Eulerian descriptions, with remaining known problems in the areas of the stability, consistency and conservation [15].

3 COMPARATIVE STUDY OF DIFFERENT APPROACHES TO SOLVING A PRACTICAL EXAMPLE

3.1 Problem description and computational model

The analysed problem consists of a closed container reservoir at rest, 60% filled with water and 40% with air (Fig. 8). The reservoir was attached to a sled (fixed in the vertical direction) and subjected to a longitudinal time-dependent acceleration with a peak acceleration of approximately 30 g at time t = 40 ms. The time-dependent variation of the water surface shape and water pressure at point 1 was previously measured in experimental testing of a reservoir made of PMMA plates with 30-mm thickness [11].

The reservoir was modelled with four-noded Belytschko-Tsay shell elements with three integration points through the thickness [3]. The elastic material model is used for the reservoir container, with the material data corresponding to the PMMA material (ρ = 1180 kg/m^3, E = 3000 MPa and ν = 0.35). Only the bottom surface of the reservoir was modelled as rigid. For the water and air solid elements and SPH particles were used, depending on the ap-

elementi in zglajeni delci. Za modeliranje vode (ρ = 1000 kg/m^3 pri 293 K) in zraka (ρ = 1 kg/m^3 pri 293 K) je bil uporabljen konstitutivni model Null (Type 9) [6]. Domena tekočine je opisana z materialnim modelom, ki zanemari strižne napetosti. Z uporabo nizke meje tečenja se doseže hiter prehod v plastično območje (npr. le z upoštevanjem gravitacije). Ob uporabi visokih dinamičnih obremenitev so strižne sile tako zanemarljive v primerjavi z vztrajnostnimi silami tekočine. Zrak je bil upoštevan le pri Eulerjevem in modelu po PLE.

Uporabljeni sta bili Mie-Gruneisenova enačba stanja (voda in zrak) in enačba stanja idealnega plina (le za zrak). Celoten model je bil izpostavljen nespremenljivem težnostnem pospešku (g = 9,81 m/s^2). V Lagrangevem in MHZD modelu je bil uporabljen avtomatski algoritem za določevanje stičnih sil, v Eulerjevem in modelu po PLE pa je bil stik med tekočino in strukturo definiran z uporabo posebnega algoritma ([6] in [10]).

3.2 Podatki računalniške simulacije

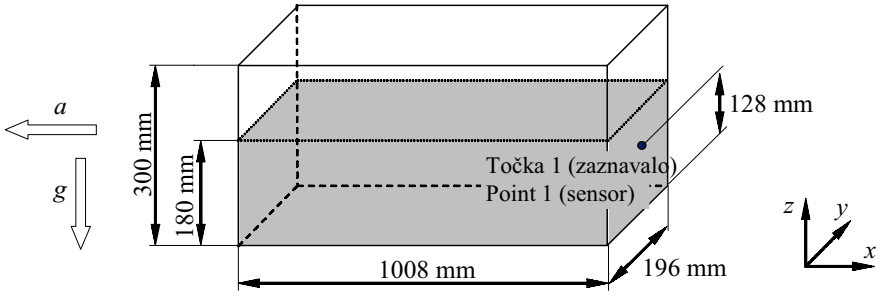
Izvedene so bile eksplicitne dinamične analize z uporabo štirih različnih modelov simuliranja tekočine: Lagrangev, Eulerjev, PLE in MHZD. Za izvedbo analiz je bil uporabljen program LS-DYNA Linux Version 970. Opazovani časovni interval je znašal 80 ms, časovni korak simulacije pa je bil določen glede na najnižjo resonančno frekvenco strukture in je znašal 0,01 ms.

plied method. The material model Null (Type 9) [6] was used for the water (ρ = 1000 kg/m^3 at 293 K) and the air (ρ = 1 kg/m^3 at 293 K) modelling. The fluid domain was described with a material model that neglects the deviatoric stresses. By defining a low yield stress, a rapid transition to plasticity can be achieved (e.g., by only considering the gravitation). Under high dynamic loading, the shear forces become negligible in comparison with the inertial forces of the fluid. The air was considered only in the Eulerian and ALE models.

The Mie-Gruneisen (water and air) and Ideal Gas (only for air) equations of states have been used. The model was also loaded with the constant gravitational acceleration (g = 9.81 m/s^2). In the Lagrangian and SPH model the automatic nodes to surface contact were used, and in the Eulerian and ALE models the contact between fluid and structure was defined with the keyword Constrained Lagrange in Solid ([6] and [10]).

3.2 Computational simulation data

Explicit dynamic analyses were carried out by using all four different fluid model approaches: Lagrangian, Eulerian, ALE and SPH. The models were solved with LS-DYNA Linux Version 970. The computational time frame was set to 80 ms and the time step of the simulation was defined according to the lowest resonant frequency of the structure and was equal to 0.01 ms.



Sl. 8. *Izmere in začetne razmere analiziranega rezervoarja iz poliakrilnega stekla*
Fig. 8. *Dimensions and initial conditions of the analysed PMMA box*

3.3 Računalniški rezultati

Rezultati predvidene oblike proste površine za vse štiri simulacije so pri času $t = 38$ ms prikazane na sliki 9. Črtkana črta pomeni opazovano obliko proste površine v omenjenem trenutku pri preizkusu.

S slike 9 je razvidno, da sta Lagrangeva in MHZD formulacija na desni strani modela ustrezni le za približek gibanja tekočine, saj v resnici tekočina ne bi obdržala oblike posode, kar je razvidno iz simulacij na levi strani modela. Kljub temu pa se morajo omenjene omejitve vrednotiti glede na zahtevane računalniške rezultate. V primeru, kadar je iskan le udarec tekočine na steno rezervoarja, so deformacije in pomiki na nasprotni strani lahko zanemarljivi. Eulerjeva in PLE formulacija opišeta lego in obliko proste površine vode mnogo bolje, kar pa je odvisno od daljšega računskega časa (preglednica 2), kar ni vedno sprejemljivo. Potek gibanja tekočine v rezervoarju ponazarja slika 10. Pomembno je poudariti, da se z uporabo Lagrangevega modela pri zelo velikih deformacijah pojavijo zelo popačeni elementi in posledično velike numerične napake. Omenjeno ponovno potrjuje, da Lagrangeva zapis ni primeren za zelo velike deformacije.

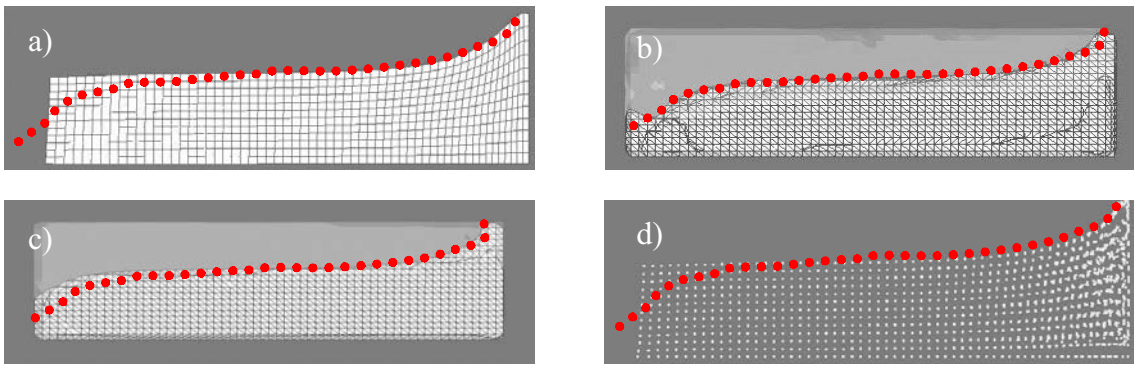
Časovno spreminjanje tlaka vode v točki 1 je prikazano na sliki 11. Rezultati so bili določeni na dva različna načina. V Lagrangevem in MHZD modelu je bil tlak, ki se je pojavil v točki 1, merjen s stičnimi silami. Tlak pri Eulerjevem in PLE modelu pa je bil določen z merili poroznosti snovi in z določitvijo sile, ki je potrebna za vzpostavitev ravnotežja na vsakem opazovanem elementu na meji med tekočino in steno rezervoarja.

3.3 Computational results

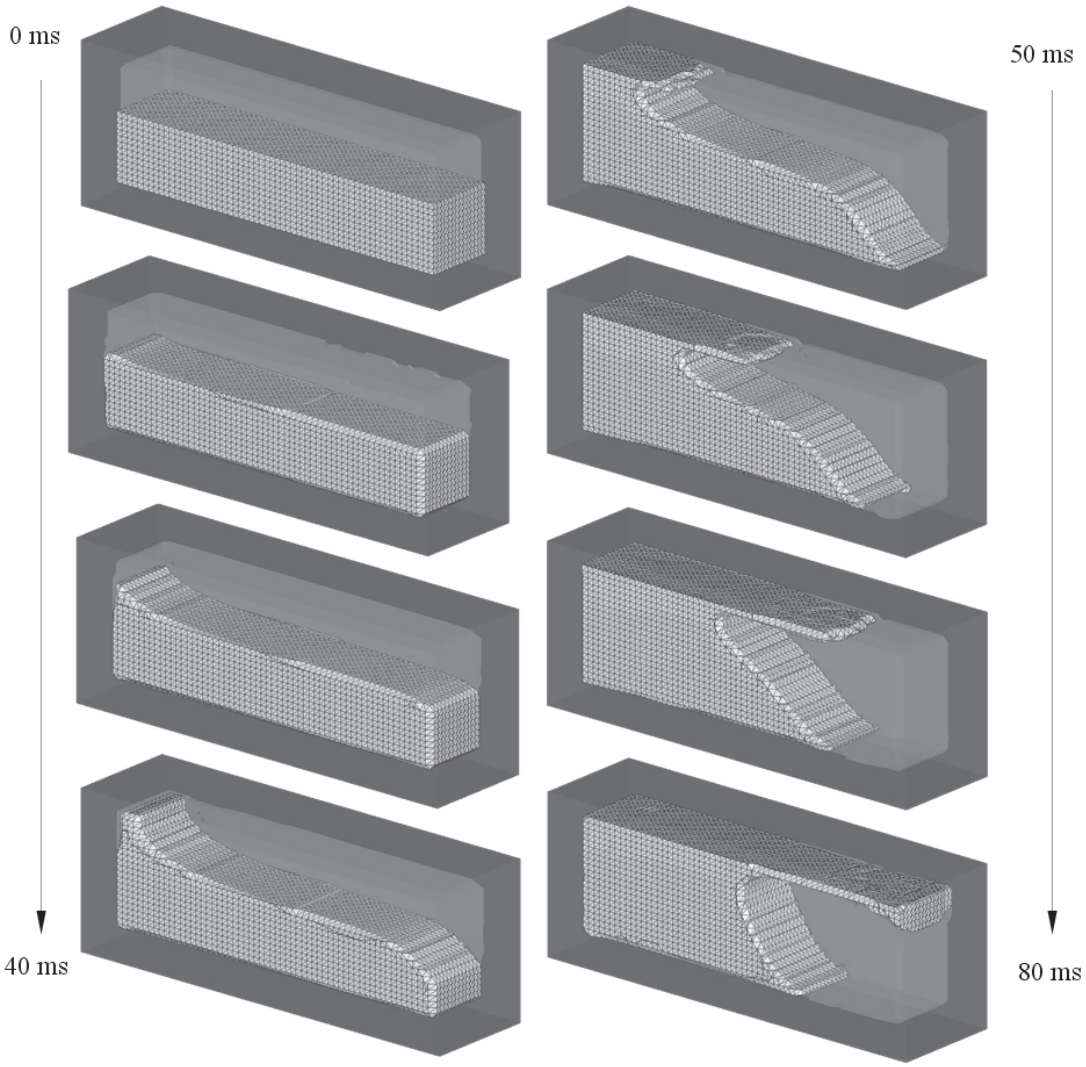
The free-surface shape-prediction results of all four dynamic simulations at the time $t = 38$ ms are represented in Figure 9. The dotted line represents the free-surface shape observed in the experiment at the same time instance.

From Figure 9 it is obvious that the Lagrangian and SPH models are only good for approximations of the fluid motion at the right-hand side wall, since in reality the fluid would not retain the form of the container, which is the case observed in simulations at the left-hand side wall. However, this observation must be considered in view of the required computational results. In the case where only the impulse of the fluid towards the tank wall is needed, the deformations and deflections on the opposite side could be neglected. The Eulerian and ALE formulations perform much better when describing the position and the form of the water's free surface. However, this is only achieved by a dramatic increase of the calculation times, which is not always acceptable. Figure 10 represents the fluid motion in a reservoir during the calculation time. It is important to observe that using the Lagrangian formulation results in very distorted elements and, consequently, large computational errors. This again confirms the fact that the Lagrangian formulation is unsuitable for huge deformations.

The time variation of water pressure at point 1 is shown in Figure 11. The results have been determined by two different approaches. In the Lagrangian and SPH models the pressure at point 1 was measured with contact forces that appeared at the observed point. For the Eulerian and ALE model the pressure was determined by the leakage control, i.e., by determining the force that is needed to establish equilibrium in every observed element at the boundary between the fluid and the reservoir wall.



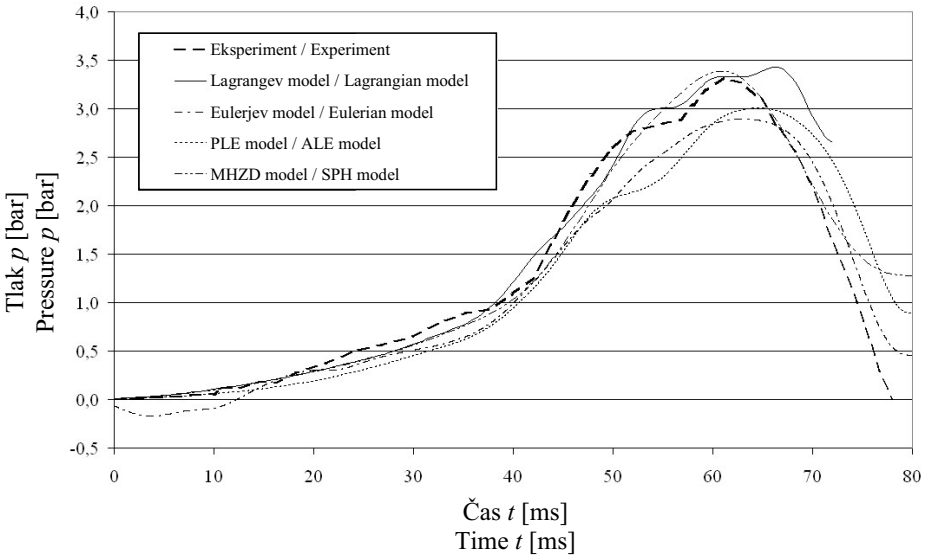
Sl. 9. *Oblika proste površine: a) Lagrangev model; b) Eulerjev model; c) PLE model; d) MHZD model*
Fig. 9. *Shape of the free surface: a) Lagrangian model; b) Eulerian model; c) ALE model; d) SPH model*



Sl. 10. *Gibanje tekočine, modelirane s PLE opisom*
Fig. 10. *Fluid motion modelled with ALE formulation*

Zelo dobro ujemanje z rezultati preizkusa je bilo doseženo z uporabo vseh štirih modelov. MHZD model zagotavlja zelo dobre rezultate, še posebej, če upoštevamo, da uporaba te metode omogoča zelo hitro in nezahtevno analizo (mreža sestoji le iz zglajenih delcev). Rezultati Lagrangevega modela so zelo dobri, kljub temu da se simulacija predčasno prekine zaradi velike popačenosti elementov. Razlog za nizek izmerjen tlak pri PLE modelu in Eulerjevem modelu se lahko pripiše vplivu zraka v rezervoarju, ki deluje kot dušilnik. Razlog za padec tlaka pri Eulerjevem zapisu pa je uporaba drugačnega modela zraka (drugačna enačba stanja), ki je potrebna za vzpostavitev stabilne analize.

Very good agreement with the experimental results was achieved by using all four formulations. The SPH formulation provided very good results, especially when taking into account that using this formulation results in a very quick and uncomplicated analysis (the mesh consists only of SPH particles). The results of the Lagrangian formulation are very good, although the simulation terminates because of the high element distortion. The reason for a lower pressure during the ALE and Eulerian models can be attributed to the air's influence inside the reservoir, where it acts like a damper. The drop in the pressure, observed for the Eulerian formulation, is also attributed to the need for a different air model (a different equation of state), which is necessary to ensure a stable analysis.



Sl. 11. *Primerjava časovne spremembe tlaka v točki 1*
Fig. 11. *Comparison of the pressure time-variation at point 1*

Velikost modelov in njihovi računski časi za posamezne analize so prikazani v preglednici 2, ki prikazuje zahtevane računske sposobnosti za rešitev izbranega problema z različnimi pristopi.

Deformacije samega rezervoarja so zaradi velike debeline njegovih sten zanemarljive. Za nazoren prikaz zmožnosti stika med tekočino in trdnino LS-DYNE je bila izvedena ponovna analiza z istim problemom, vendar je bila debelina sten rezervoarja zmanjšana na 10 odstotkov prvotne debeline, tj. 3 mm [6]. Deformacije sten rezervoarja, kot rezultat stika med tekočino in trdnino pri različnih časovnih korakih, so prikazane na sliki 12.

Iz opisanih simulacij je razvidno, da različni pristopi ponujajo alternativne možnosti za modeliranje toka tekočin in njihovega vpliva na strukturo. Prednost uporabe Lagrangevega in

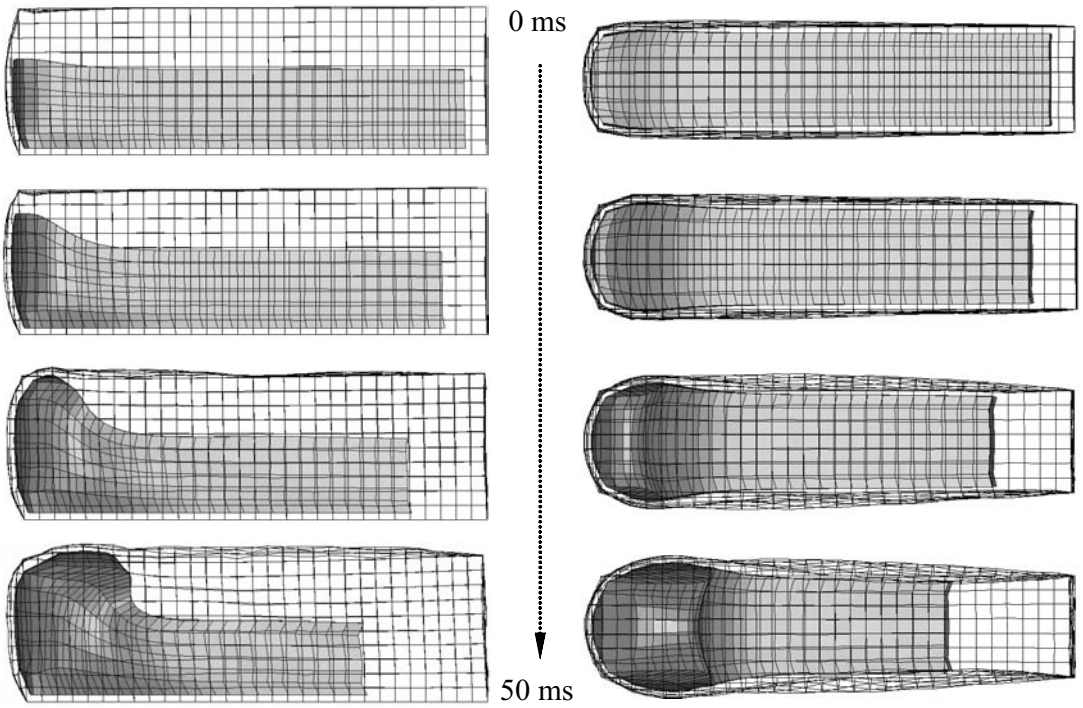
The model size and the required CPU times for each analysis are listed in Table 2, to illustrate the required computational effort to solve the chosen problem with different approaches.

The deformation of the reservoir container is negligible, due to the thickness of the reservoir walls. To clearly illustrate the fluid-structure interaction capabilities of LS-DYNA, another analysis of the same problem was carried with reduced container reservoir walls to only 10% of the original thickness, i.e., 3 mm [6]. The resulting deformations of the container reservoir due to fluid-structure interaction at different time instances can be observed in Figure 12.

Following from the reported simulations it is obvious that these approaches offer an alternative means of fluid-flow modelling and its interaction with the structure. The advantage of using the SPH and

Preglednica 2. *Primerjava računskega časa*
Table 2. *CPU-time comparison*

Model	**Skupno število / Total number**		**Računski čas / CPU time**
	Vozlišča / Nodes	**Elementi / Elements**	min
Lagrangev / Lagrangian	2898	2420	16
Eulerjev / Eulerian	10162	8706	225
PLE / ALE	7462	6396	260
MHZD / SPH	2898	2896	13



Sl. 12. *Medsebojni vpliv tekočine in trdnine*
Fig. 12. *Fluid-structure interaction*

MHZD modela je kratek čas za pripravo modela in sprejemljivi računski čas, medtem ko Eulerjev in PLE model opišeta gibanje tekočine natančneje. Kljub temu pa je bilo začetni udarec tekočine ob stene rezervoarja mogoče natančno simulirati z vsemi štirimi modeli tekočine, ki so vključeni v LS-DYNI.

4 SKLEP

V prispevku so predstavljeni štirje postopki modeliranja toka tekočine v LS-DYNI. Različne metode (Lagrangeova, Eulerjeva, PLE in MHZD) so bile uporabljene za analizo gibanja tekočine v deformabilnem rezervoarju, z namenom, da bi potrdili rezultate v primerjavi z znanimi preizkusnimi opazovanji. Računalniške simulacije so pokazale, da sta gibanje tekočine in medsebojni vpliv tekočine in trdnine natančno opisana z uporabo različnih izbirnih zapisov v LS-DYNI.

Predstavljeni modeli so osnova za komercialne računalniške modele, uporabljene za analizo zapletenejših problemov. Rezultati dejanskega rezervoarja za gorivo z zelo zahtevno geometrijsko obliko ob upoštevanju vpliva gibanja tekočine s PLE in MHZD formulacijami, so pokazali zelo dobro ujemanje s preizkusi [18].

Lagrangian models is a short pre-processing and a reasonable computational time, while the ALE and Eulerian models can describe the fluid motion more accurately. Nevertheless, the initial impact of the fluid on the reservoir wall could be simulated accurately with all four fluid models incorporated in LS-DYNA.

4 CONCLUSION

Four approaches to fluid-flow modelling in LS-DYNA have been presented in the paper. Different formulations (Lagrangian, Eulerian, ALE and SPH) were used to analyse the fluid motion in a deformable reservoir, with the purpose to validate the results in comparison with existing experimental observations. Computational simulations showed that the fluid motion and the fluid-structure interaction can be accurately described by applying different alternative formulations in the LS-DYNA.

The applied models provide a basis for economical computational models that can be used for analysing more complex problems. The results of the real fuel-tank with a very complex geometry, where the fluid motion's influence was considered with the ALE and SPH descriptions, showed a very good agreement with the experiments [18].

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