EXPLICIT DYNAMIC SYMULATION OF THE FLUID BEHAVIOR IN MANIPULATED BOTTLES CONSIDERING AN ACCIDENTAL STOP OF THE COVEIOR

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The study consists in modeling and simulation techniques of the sloshing phaenomenon when semi-filled bottles are manipulated in an industrial robotic cell environment. The preparation of the 3D model of the plastic bottle by simplifying the complex surfaces, in order to obtain simulation results as close as possible to reality, as well as the stopper design from a simple rectangular sketch, and the liquid definition inside the bottle were the first steps of the study. The proper choice of the material properties, model parametrization and mesh generation followed the attempt. A brief description of the analysis, the formulae used as theory background and the explicit dynamic simulation where the main targets of the research. The results were validated by experiments and personal conclusions were drawn.

1. Introduction

The studied robotic cell (Fig. 1.1) integrates an articulated arm type robot with 6 numerically controlled axes. This cell is a virtual copy of an industrial application found in [1]. The red border highlights the area considered in the research.

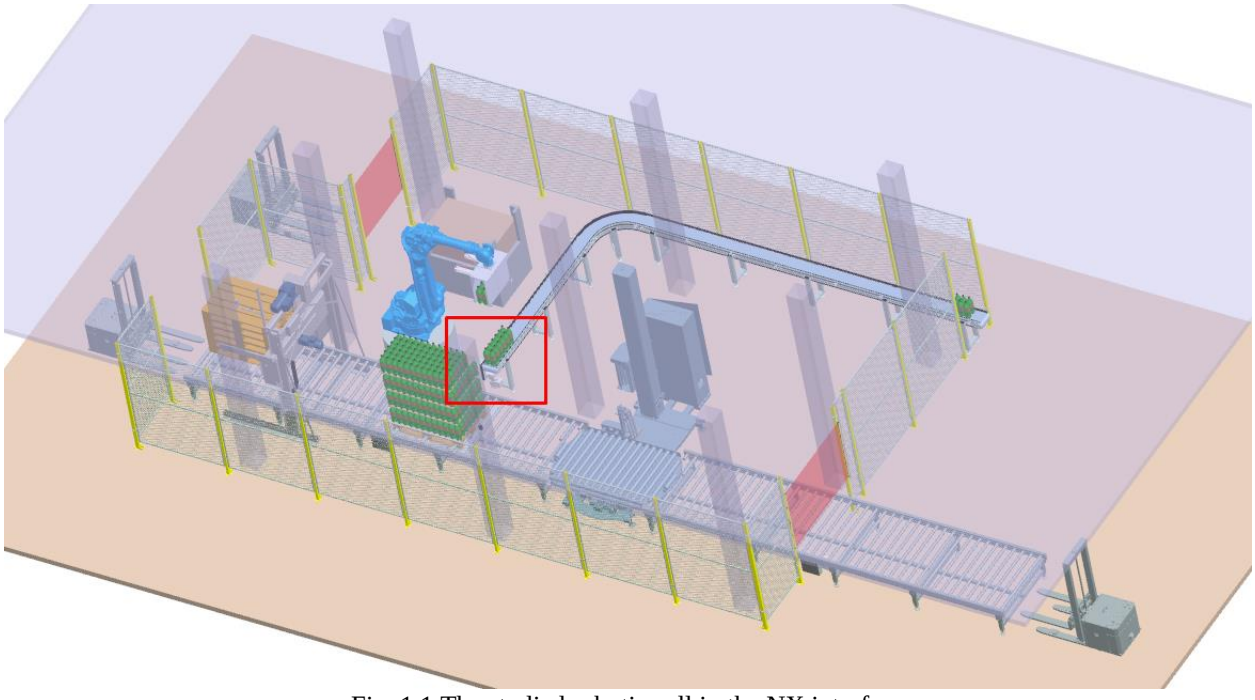


Fig. 1.1 The studied robotic cell in the NX interface

The paper consists in explicit dynamics simulation studies of the fluid behavior of the manipulated bottles (Fig. 1.2), considering an accidental sudden stop of the conveior in ANSYS Workbench 19.0 environment.

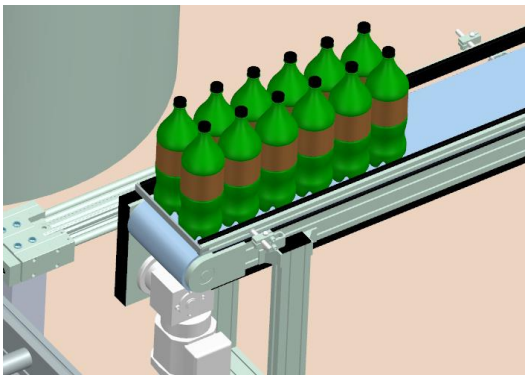


Fig. 1.2 The bottle package assembly in the NX interface: belt conveyor → plastic bottle boxes → stopper

The objective was to emphasize the fluid behaviour and the sloshing phenomenon, which are advanced simulation targets. The liquid energy, the total velocity, as well as main structural response results regarding the bottle behavior were processed and conclusion were summarized. The simulation results were verified experimentally, in the Faculty laboratory employing a color liquid and a transparent bottle. In order to obtain accurate and fast analysis results the computational model was simplified, and only a sigle plastic bottle and the stopper were considered.

2. State of art regarding the sloshing prenomenon

Many published papers investigate the finite element formulation of the liquid sloshing in partially filled rigid tanks of different shapes [2], [3], [4]. For exemplification purposes one of the research articles [4] was chosen to describe the mathematical model of the phaenomenon, where the liquid domain is divided into two-dimensional four-node rectangular elements with the liquid velocity potential representing the nodal degrees of freedom. The sloshing effects induced were studied in terms of the slosh frequencies, liquid velocity field, free surface displacement and hydrodynamic forces acting on the tank walls. In this regard, the model is employed to study the effects of inserting a bottom-mounted vertical rigid baffle, as well as side-mounted horizontal baffles that are wholly immersed in the liquid region, in an attempt to investigate their viability in acting as slosh suppression devices.

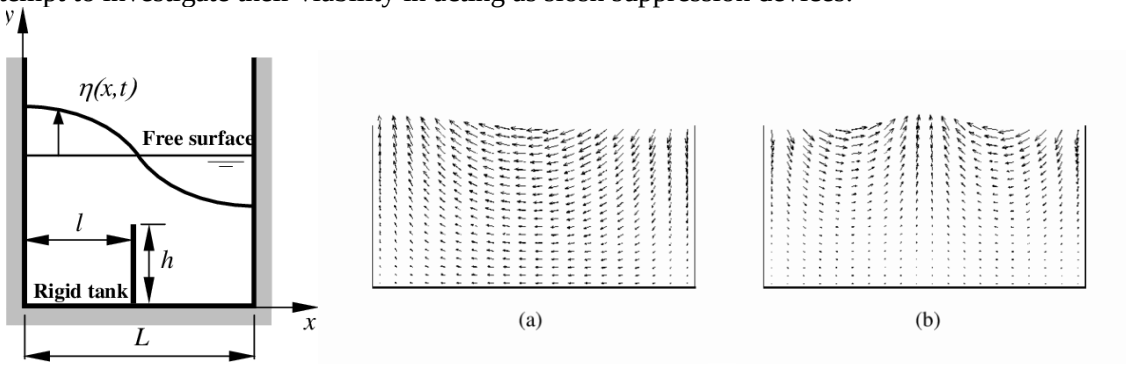


Fig. 2.2 Rigid rectangular tank. Liquid velocity field at the (a) first and (b) second slosh mode [4]

Although most of the research describe the mathematical model and experimental investigation of the liquid sloshing few papers assess the dynamics from a computational dynamics perspective, due to the numerical and modeling issues. On the other hand, recent advances in the FEM solvers surpass the numerical problems. That is why a combination Lagrange-Euler approach was chosen and the

investigation of the liquid sloshing phenomenon was carried out employing explicit dynamics functionalities.

3. Preparation of the computational model

The plastic bottle model was imported from NX in a neutral STEP format. Therefore a “cleaning” attempt for geometry was needed, and defeaturing commands were performed. The stopper was created in ANSYS Workbench because a simplified geometry was required. This stage of "cleaning" the model is done because we want to get the most realistic results.

The steps of "cleaning" the geometry represent the simplification of the model, All the details that ae not relevant for the explicit dynamics simulation were deleted and a high quality mesh was prepared by merging or face splits, as well as projections and slice commands. All the model praparation stages are illustrated in Fig.3.1 and 3.2.

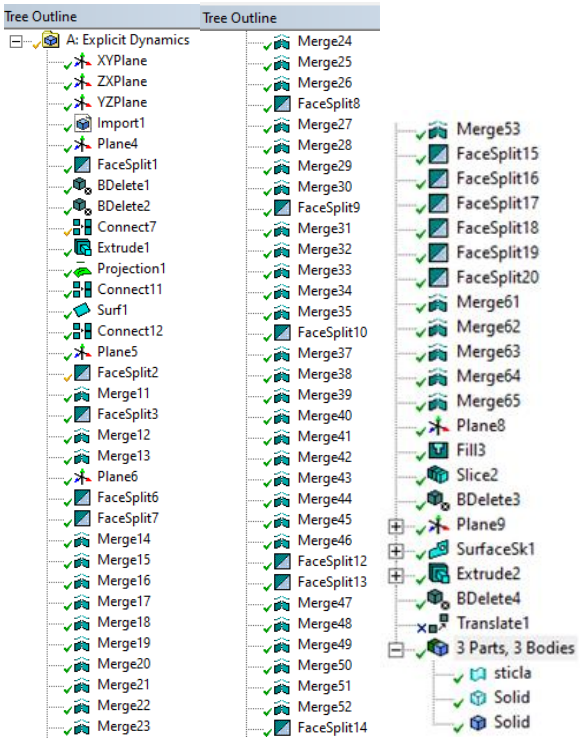


Fig. 3.1 Model preparation stages in DesignModeler

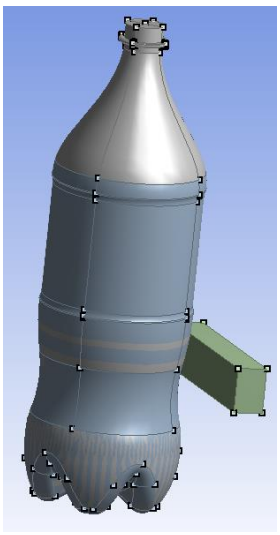


Fig. 3.2 Final geometry

Material description was done in the Engineering Data interface (Fig. 3.3). In addition to the default material used for the stopper – structural steel, plastic and a water-like material were included for the bottle and the bottle content.

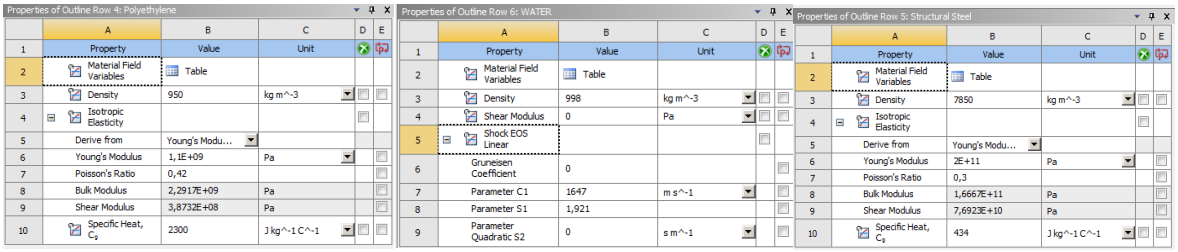


Fig. 3.3 Material properties denied in Engineering database

A controlled mesh was generated (Fig. 3.4) and multiple quality criteria checks were completed

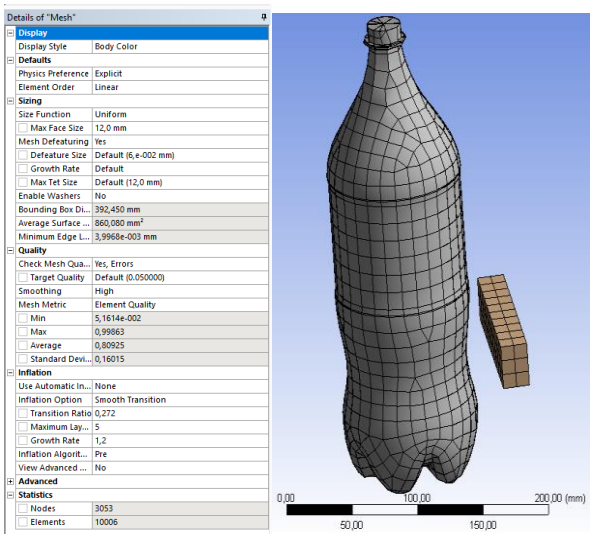


Fig. 3.4 The mesh settings and mesh quality checks

4. Explicit dynamics simulation

Explicit dynamic is employed for transient phenomena with short time duration and extreme nonlinearities [2]. This includes: extremely large deformations, rupture, destruction of the materials and structures, very nonlinear material behavior. The result is a permanent deformation of the assemblies, loose of structural stability or severe fluid flow phenomena. Some of the peculiarities of the explicit dynamics analysis are:

- Time is sampled in very small time steps and the solution is direcly solved for each time increment.
- During the simulation the solution depends only on the results from the previous time step;
- It involves a very short end-time (microseconds) - so the duration of the simulated phenomenon is very short;
- The time step size depends on the mesh;
- Can solve problems with severe nonlinearities.

The explicit algorithm has the advantage that it does not calculate the stiffness matrix. This significantly reduces the computation time for transient dynamic regimes. Nowadays the explicit algorithm allows the control of calculation errors. The main differences between implicit and explicit solvers are, in fact, how the equilibrium equations are solved. Some other pecularities of the algorithm are:

- Just like the default implicit solver it considers mass/inertia and damping, but uses a different solver;
- Iterations are not required. Results are calculated directly (or explicitly) for each time step;
- During coputation it does not matrix invertion;
- There is no inherent limit to the size of the time step;
- The time step must be less than the Courrant time step.

A brief description of the computation algorithms is: → accelerations are calculated $\{\ddot{x}\}$ at time n, velocities $\{\dot{x}\}$ at time n + ½ and deformations {x} at time n+1. Based on displacements {x}, the strains {ε} are assessed. Then the stress vector is determined {σ}. And the cycle is repeated for the next time step.

The Explicit Dynamics solver uses a differential time integration scheme called the Leapfrog method [5]. After calculating the forces in the nodes (resulting from internal stresses, contact or boundary conditions), the nodal accelerations are obtained by dividing the force to the mass:

$$\ddot{x}_i = b_i + \frac{F_i}{m} \quad (1)$$

where $\ddot{x}_i$ are the components of nodal acceleration (i = 1,2,3), F_i are the forces acting in the nodes, *bi* are the components of the acceleration of the body and *m* is the nodal mass.

With the accelerations at the time n - ½ the speeds are calculated at the time n + 1/2:

$$\dot{x}_i^{n+1/2} = \dot{x}_i^{n-1/2} + \ddot{x}_i^n \Delta t^n \quad (2)$$

Finally, the node positions are updated at time n + 1 by integrating the speeds:

$$x_i^{n+1} = x_i^n + \dot{x}_i^{n+1/2} \Delta t^{n+1/2} \quad (3)$$

For each time step these equations are explicitly solved for each element in the model, based on the input values at the end of the previous step. In the first the solution is computed based on the initial conditions. When solving the equations only the conservation of mass and momentum is applied. However, in explicit simulations, mass, momentum and energy should be conserved. That is why energy conservation is constantly monitored during computation on the graph, which also illustrates the quality of the results.

Solution settings were configured as illustrated in Fig. 4.1. The stopper was considered rigid. The simulation regime was considered: the conveior velocity: 500 mm/s; total duration of the analysis 0.2s, the duration until the impact: 0.06 s

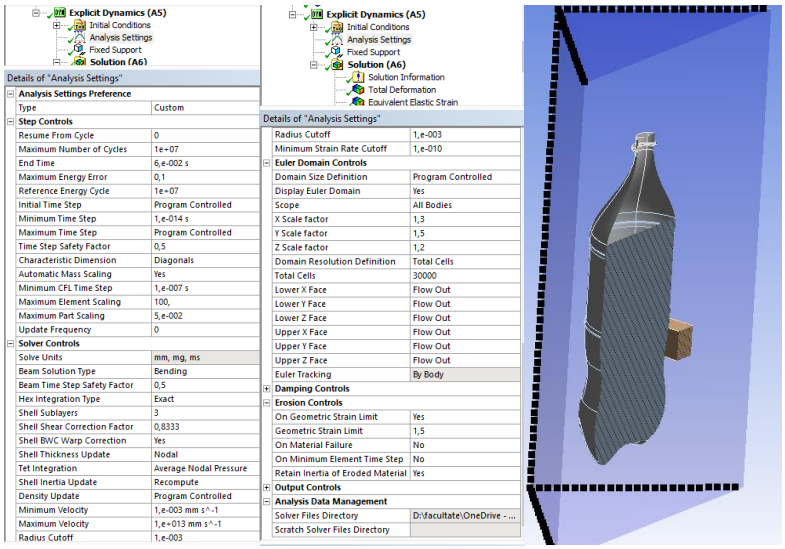
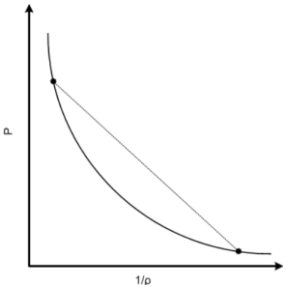
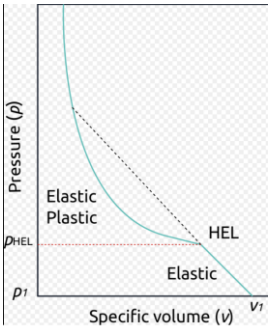


Fig. 4.1 Analysis settings

5. Results discussion

In an explicit dynamics analysis the model encompasses not only the equations of motion but also the propagation of shock waves phenomenon throughout the material. Un example of shock waves modeling is the Equation of state for the Hugoniot shock (Fig. 5.1), that allows the sloshing waves to occur on the results. This model was chosen for the liquid behavior.





a. Hugoniot and Rayleigh shock line in p-v plane for weak shock

b. Hugoniot elastic limit in the p-v plane for shock in the elasto-plastic field

Fig. 5.1 The Hugoniot shock description [6]

The Hugoniot shock describes the location of all possible thermodynamic states in which there may be a material behind a shock, projected on a two-dimensional state plane [6]. Therefore, it is a set of equilibrium states and does not specifically represent the way in which a material undergoes transformations. Weak shocks are isentropic (the entropy is constant) - the material is charged from the initial state to the final state by a compression wave with converging characteristics (Fig. 5.1.a). When a severe shock occurs these simplifications can no longer be assumed. However, for engineering calculations, the isentropic is considered to be close enough to Hugoniot that it can be considered a linear approximation (Fig. 5.1.b). If between the initial state and the final state the charge is given by Hugoniot's law for an "equivalent" compression wave, then the shock conditions can be modeled by a straight line between the initial and final state. This line is called the Rayleigh-Hugoniot line and has the following equation:

$$p_2 - p_1 = u_s^2 \left(\rho_1 - \frac{\rho_1^2}{\rho_2} \right) \tag{4}$$

The solution was monitored employing the kinetic and internal and contact energy and the hourglass energy whici gives a measure of the mesh quality and model behaviour (Fig. 5.2).

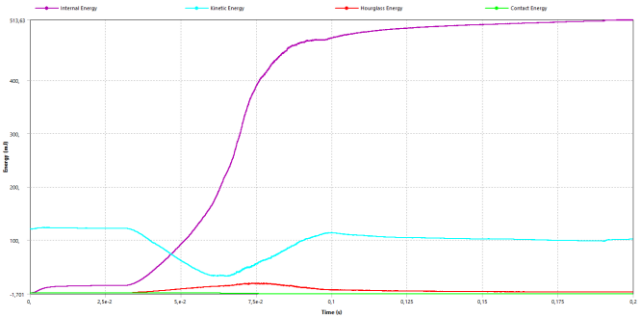


Fig. 5.2 Energy summary during computation.

During the simulation the kinetic energy (light blue) decreases when the impact occurs, the internal energy (purple) increases being influenced by the model displacement and strain in the model and the hourglass energy (red) helps to identify mesh errors, if the values reach a maximum allowable limit, which did not happen in our case.

Figures 5.3 to 5.6 summarize the main simulation results.

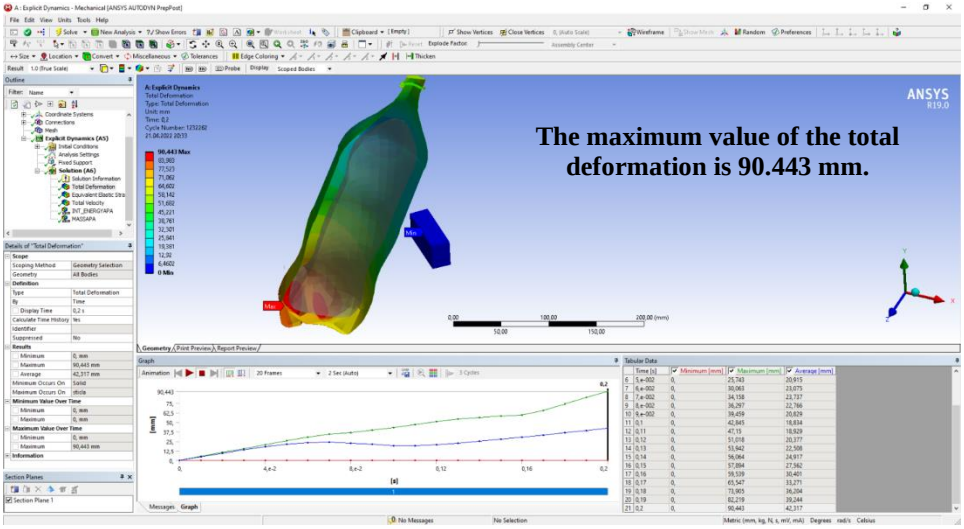


Fig. 5.3 Total deformation of the model

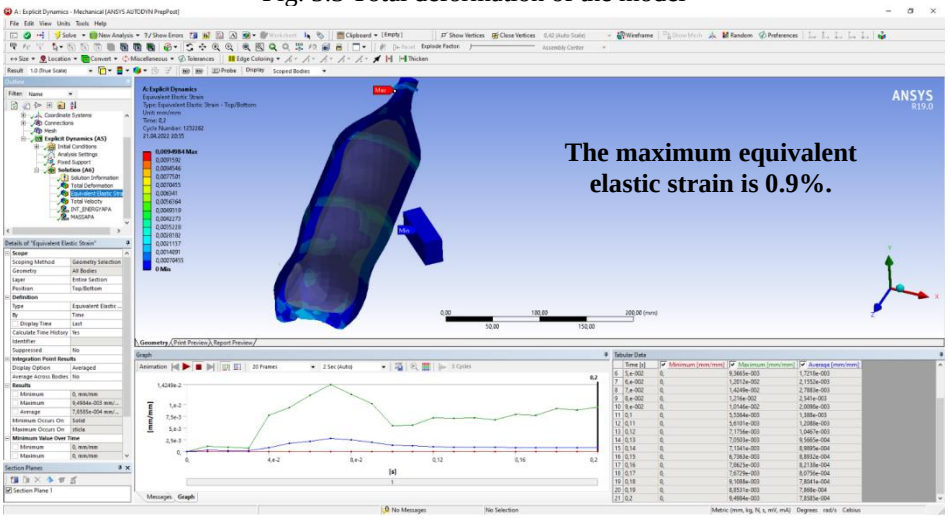


Fig. 5.4 The equivalent elastic strain

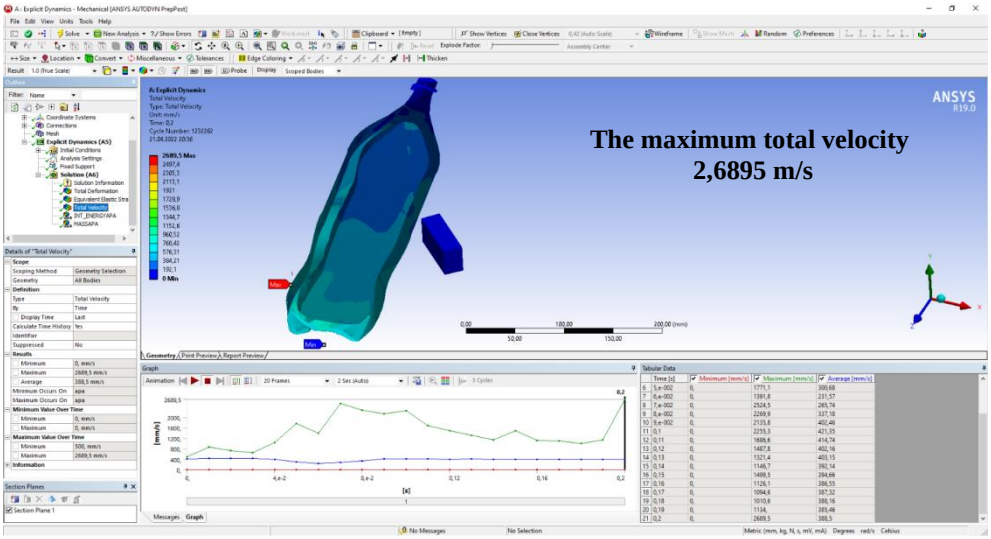


Fig. 5.5 Total velocity

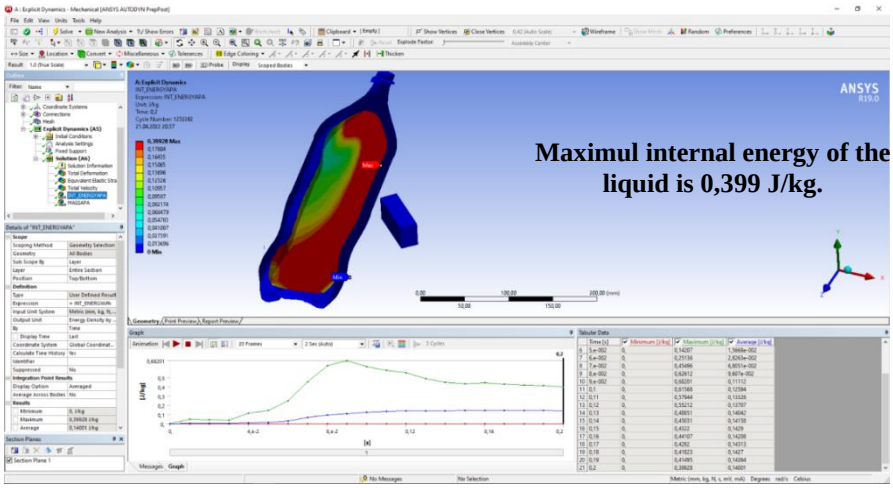


Fig. 5.6 The results obtained from the processing of water energy

The simulation results were validated by experimental tests in the faculty Logistics laboratory (Fig. 5.7). The same behaviour of the liquid was observed.


Fig. 5.7 Laboratory experiments

6. Conclusion

The simulation was successfully completed in 19.5 hours on a laptop. The model was initially generated by many complex surfaces, A detailed and manual simplification of the polyethilene botlle model was needed in order to obtain accurate results. The solution was attained using two solvers: Lagrange solver for the structural components and the Euler solver was activated for the liquid behaviour, which allowed the visualization of the sloshing phenomenon. The visual effect was diminished by the fact that the bottle was considered almost fully filled. Future work may focus on a liquid mixture and bubbles effect.

7. Bibliography

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