Simulation of the Forming Process of Liquid Filled Packages Using Coupled Eulerian-Lagrangian Approach

Mattias Olsson and Anders Magnusson

Tetra Pak Packaging Solutions AB, Ruben Rausings Gata, SE-221 86 Lund, Sweden

Sharat C. Prasad

Dassault Systemes Simulia Corp., 166 Valley Street, Providence, Rhode Island, USA 02909

Abstract: *This study concerns simulation of the forming process of a carton-based package for liquid food (for example, milk or juice), and how the packaging material interacts with the fluid during the forming. The carton-based package is formed inside a filling machine while the fluid is being filled into the package. The carton-based package is thin with low bending stiffness and is thus deformed significantly at small loading. This implies that the forming of the package to a large extent depends on the dynamics of the fluid inside the package. In the filling machine, the filling pipe enters the tube where the carton-based web is partly shaped into a longitudinally sealed tube. The package is formed and transversally sealed below the fluid surface. When forming the transversal seal of the package, the cross-section of the tube changes from open circular to closed in a short period of time, which causes considerable pressure waves inside the package. In order to control the pressure waves and thereby the forming of the package, a pressure flange is mounted on the filling pipe inside the carton-based tube. A coupled Eulerian-Lagrangian approach in Abaqus/Explicit is used in order to study both the deformation of the packaging material and the fluid and the interaction between them entirely within a single finite element model.*

Keywords: Packages, Forming, Coupled Eulerian-Lagrangian, Fluid-Structure Interaction and General contact.

1. Introduction

Carton-based packages are increasingly becoming common to store, transport and distribute liquid food such as milk or juice. Such packages are durable and lightweight and offer the advantage of an efficient and economical distribution – from the manufacture of compact cartons to the distribution and handling of fluid filled packages all the way to the consumer's waste recycle bin.

Carton-based packages are formed inside a filling machine. Packaging material is fed into the filling machine where it is formed into a tube. The packaging material can be sterilized before being fed into the filling and forming section if aseptic packages are to be formed and filled. In the filling machine, a filling pipe, which supplies the fluid, enters the tube where the carton-based web is partly shaped into a longitudinally sealed tube. A folding system then folds and transversely seals the package below the fluid surface. Once the package is formed into the desired shape, it is cut into individual packages. Figure 1 shows a schematic of the filling process in the filling machine.

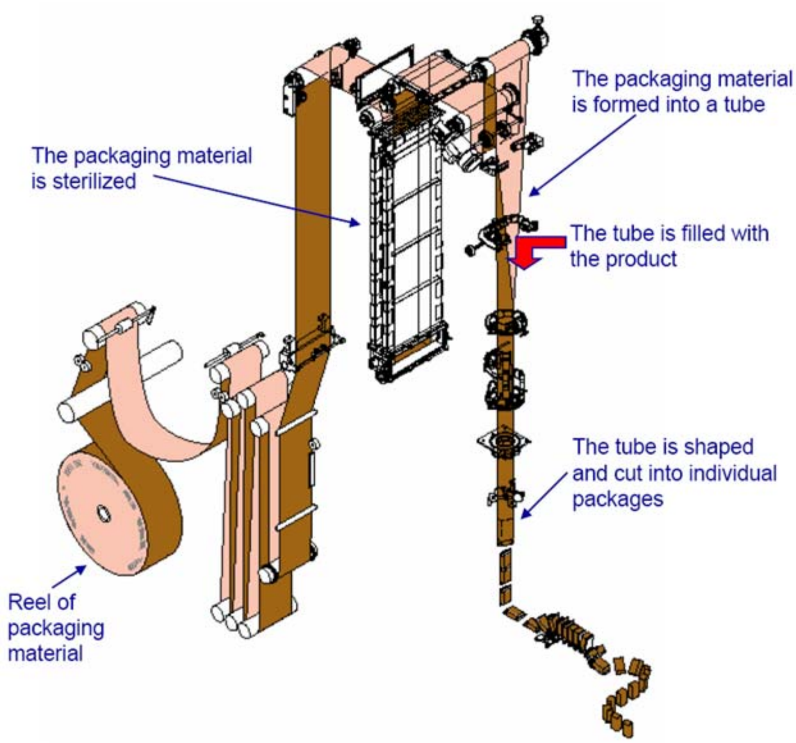

Figure 1. Schematic of the filling process in the filling machine.

The current study focuses on simulation of the forming process of a carton-based package and how the packaging material interacts with the fluid during the forming. The simulation is carried out using a coupled Eulerian-Lagrangian (CEL) approach in Abaqus/Explicit in order to study both the deformation of the packaging material and the fluid and the interaction between them entirely within a single finite element model. The filling machine that we are studying forms packages with a very thin and soft carton layer which necessitates taking into account, the strong fluid-structure interaction. The carton material has a very low bending stiffness. The package is deformed heavily during the forming process and thus its shape and durability largely depends on the dynamics of the fluid inside the package. The forming also changes the cross-section of the tube from open circular to closed in a very short period of time. This causes considerable pressure waves in the fluid thus making the simulation of the fluid and its interaction with the rapidly deforming package an especially difficult interaction to model. Figure 2 shows a formed package (Tetra Fino Aseptic 500 ml, TFA500) which is the subject of the current simulation. This package is quite complex to model since it uses one of the most flexible of the packaging materials available at Tetra Pak.

Figure 2. Package (Tetra Fino Aseptic 500 ml, TFA500).

2. Model setup

The model setup used in the current simulation is shown in Figure 3. A half-symmetry model is used to carry out the simulations.

The model consists of following components:

1. Carton tube: Packaging material is pre-formed into a tubular shape before it is fed to the package forming section. The packaging material is moving vertically downwards at a constant velocity. The folding system at the bottom continuously forms new packages as the packaging material is being fed.
2. Inlet system: The inlet system consists of a cylindrical fill-pipe through which the fluid is supplied.
3. Floater: A floatation device is placed over the fluid surface.

4. Pressure flange: The pressure flange device is mounted in order to control the pressure waves inside the package in the fluid which are caused by sudden change in the tube shape due to forming.

5. Folding system: The folding system folds the packaging material into a package shape.

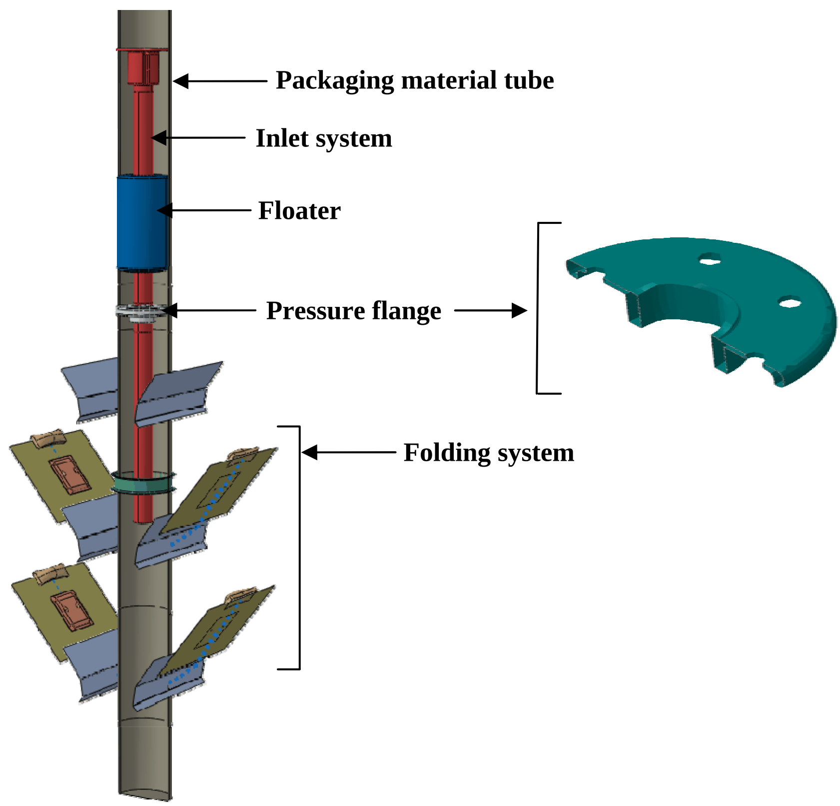

Figure 3. Model setup.

The packaging material tube is the only deformable component in the simulation. Inlet system, floater, pressure flange and folding systems are modeled as rigid. The fluid is modeled using an Eulerian approach while the structural components are modeled in a Lagrangian framework.

An Eulerian mesh is built around the structural components to represent the volume which the fluid can occupy. The Eulerian domain is large enough to permit the downward motion of the fluid filled packages during the filling and forming process. The Eulerian region is initialized by a volume fraction which represents the appropriate fluid distribution at the beginning of the analysis. Fluid volume fraction distribution is calculated using Abaqus/CAE volume fraction tool. This tool let users calculate the volume fraction of the fluid by performing a Boolean operation between the Eulerian region and a reference part representing the volume occupied by the fluid initially. Figure 4 shows the entire Eulerian domain and the initial volume fraction representing the initial fluid distribution.

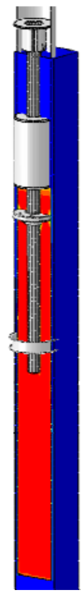

Figure 4. Eulerian domain and initial fluid distribution (red region is fluid filled while blue region is void).

The simulation involves Lagrangian-to-Lagrangian contact between structural components and Eulerian-to-Lagrangian contact between the fluid and Lagrangian structural components. Such complex contact interactions are easily modeled in Abaqus/Explicit using penalty-based general contact approach. This merely requires specifying **`*CONTACT`** and **`*CONTACT INCLUSIONS, ALL EXTERIOR`** options.

3. Material Properties

The packaging material is very thin and has low stiffness. The packaging material also exhibits different yield behavior in different directions. It is thus modeled as an elastic-plastic material with isotropic elasticity using the Hill anisotropic yield criterion for the plasticity. The material model requires specifying the yield stress ratios that are applied to the Hill's potential function.

Water is typically used as a test fluid in package forming trials and experiments, so the current simulation models water. Water behaves as an incompressible viscous fluid. Modeling incompressible viscous fluid in Abaqus/Explicit requires using the linear USUP Hugoniot form of the Mie-Gruneisen equation of state model. The bulk modulus can be appropriately chosen in order to induce the right amount of compressibility to the water. In an Abaqus/Explicit dynamic procedure, a small amount of compressibility has to be introduced to ramp up the explicit time increment and speed up the simulation.

4. Loading, boundary conditions and simulation steps

A gravity load is applied to the entire model through acceleration due to gravity of 9.8 m/s^2 in the vertical direction. Also, in order to prevent crimping of the packaging material during the forming process, the packaging material tube is kept under tension. This is modeled by applying a tensile load to the top end of the packaging material tube through a distributing coupling. Adequate tensile load is critical in order to prevent breakage or crimping of the packaging material.

The simulation is carried out in two steps. The first step involves applying a tensile load to the packaging material tube to provide the required pre-stress. The forming and fluid injection processes are carried out in the second step. During the second step, the packaging material tube moves with a constant velocity while the fluid is also injected through the inlet system. The folding system activates and forms the package. The packaging material tube movement, fluid injection and the folding process is coordinated in time through the use of boundary conditions with amplitude curves. Adequate coordination of the filling and forming process is a pre-requisite to form the package of right shape and volume.

The simulation models a half-symmetry model of the forming process. Appropriate boundary conditions are applied at the symmetry plane for both the Eulerian and structural elements. The fluid injection into the Eulerian domain is achieved through a velocity boundary condition. Applying an inlet velocity at the boundary of the Eulerian domain when fluid is also present at the boundary causes more fluid to be injected with the desired velocity. The inlet velocity boundary condition is applied to those Eulerian nodes at inlet which are completely contained within the cylindrical fill-pipe of the inlet system. The inlet velocity boundary condition specified in the current study amounts to a net volumetric flow rate of 500 ml/sec.

5. Results

The simulations are carried out in Abaqus/Explicit version V6.9PR4. Two sets of simulations are carried out. The first simulation is of the complete system which includes the pressure flange. In the second simulation, the pressure flange is excluded. The second simulation emphasizes the role the pressure flange plays in maintaining the level of fluid and avoiding sudden and rapid bulk motion of the fluid during the forming. Abaqus/Explicit finite element models used in this study comprise of a total of 216,882 elements of which 192,500 elements are Eulerian elements. The packaging material tube is modeled with shell elements. While a significantly larger number of elements are needed to adequately resolve the flow around the pressure flange if a typical computational fluid dynamics (CFD) analysis is performed, our study indicates that the current Eulerian mesh refinement level is adequate to capture the fluid-structure interaction and understand the design parameters of the forming process.

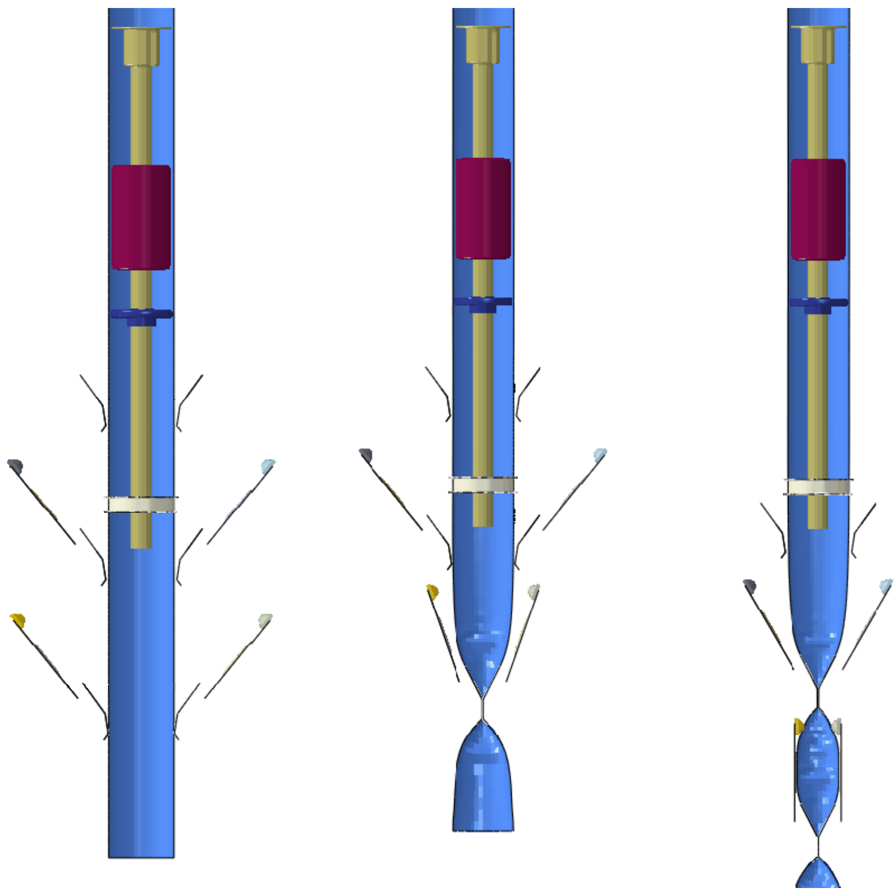

Figure 5. Folding action of the folding system and deformation of the packaging material tube at t = 0.0, t = 0.46 and t = 0.9 sec.

The motion of the folding system and the corresponding deformation of the packaging material are depicted in Figure 5. As can be seen from the figure, the folding system folds and closes the packaging material at two ends while the packaging material tube is moving vertically downwards. While the figure shows a second set of folding arms which can form a second package with subsequent folding action, the current study has been limited to forming just one package.

The formed package shape is shown in Figure 6. As can be seen in the figure, the package shape closely resembles the shape of the desired package shown in Figure 2.

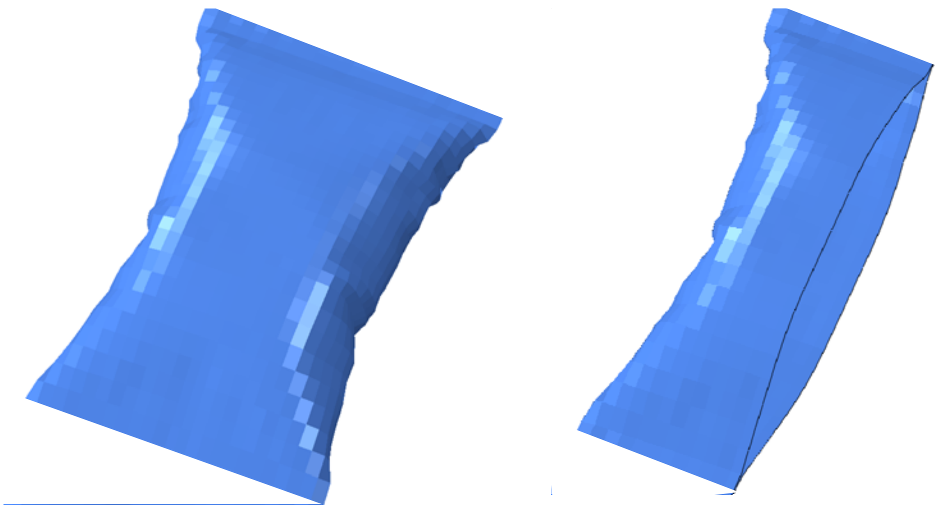

Figure 6. Formed package shape (full and half-symmetry views).

As mentioned earlier, the pressure flange plays an important role in controlling the overall forming process. Figure 7 depicts the vertical displacement of the Floater which floats above the fluid free surface. The pressure flange only offers small conduits (see Figure 3) for upward fluid motion while offering significant resistance to the sudden upward flow of the fluid which is caused by the rapid slamming of the folding system on to the packaging material tube. As is evident from Figure 7, the Floater displacement is significantly reduced when the pressure flange is present. Figure 8 shows the velocity contours at $t = 0.2$ sec.   The velocity contours verify significant bulk motion of the fluid due to the forming process in the absence of the pressure flange.

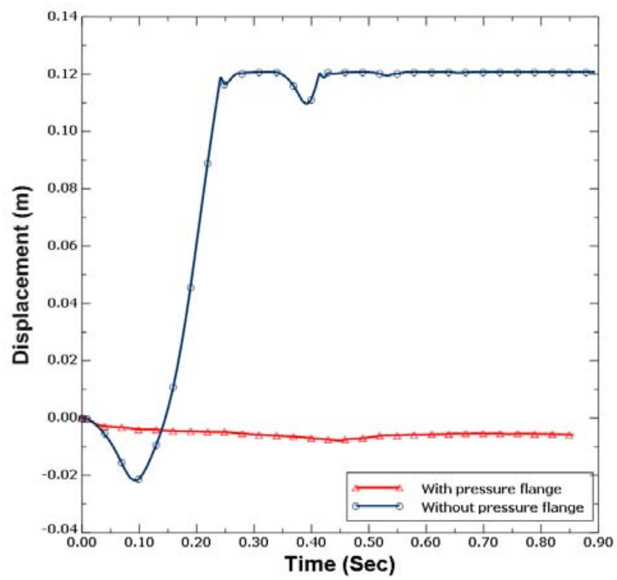

Figure 7. Floater displacement with and without the pressure flange.

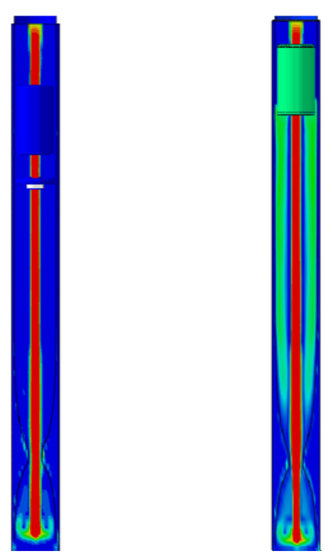

Figure 8. Velocity contours with and without the pressure flange at t = 0.2 sec.

The initial stress applied to the packaging material through a tensile load is shown in Figure 9. While we start with a reasonable value of tensile load in the current simulation, the pre-stress is an important design parameter to set in order to prevent packaging materials from breakage or crimping. The initial stress due to pre-forming of the packaging material into a tubular shape is not included in this simulation. The simulation can be extended to include this effect.

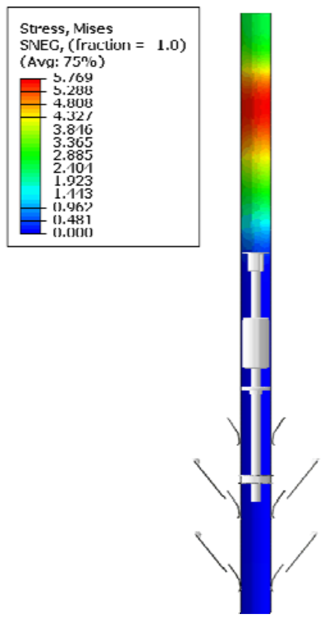

Figure 9. Stress (MPa) in the packaging material due to tensile load.

Couped Eulerian-Lagrangian analyses let users visualize the fluid distribution through Eulerian element volume fraction (EVF) output. Figure 10 shows the fluid distribution in the Eulerian domain initially, and at the times when the bottom and the top of the package are closed. It can be seen that fluid interface mostly conforms to the deformation of the packaging material tube. However, some penetration and minor leakage of the fluid is seen especially at locations where kinks are formed in the packaging material tube due to extreme deformation. Contact between an Eulerian material and a Lagrangian interface is enforced using a penalty-based general contact approach in Abaqus/Explicit. Seeds are created on Lagrangian edges and faces while anchor points are created on the Eulerian material surface. Contact is then enforced between these seeds and anchor points with a fictitious “spring” with a penalty stiffness that depends on both the Eulerian material and underlying Lagrangian material properties. The penalty-based approach allows for small penetrations of one interface into another which is often aggravated at sharp corners and kinks. Mesh refinement should reduce contact penetration. Alternatively, penalty stiffness can often be ramped up to decrease the penetration but has an adverse side effect of decreasing the size of explicit time increments. The current analysis uses the Abaqus/Explicit default general contact settings.

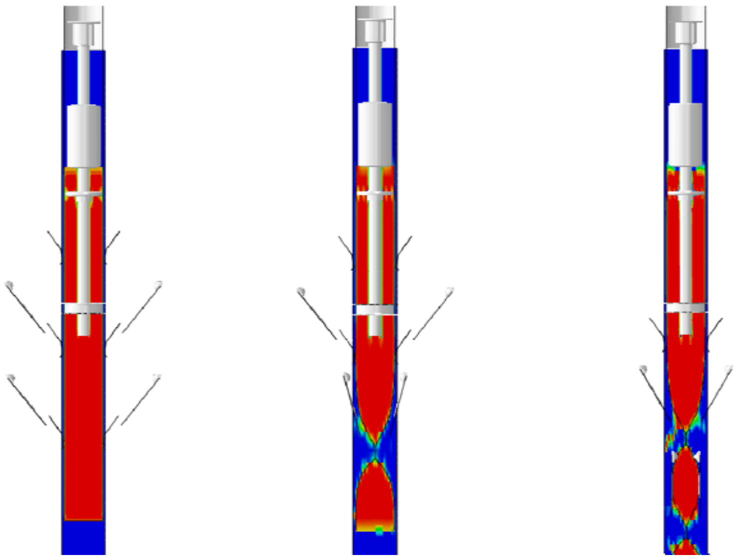

Figure 10. Eulerian element volume fraction (EVF) at t = 0.0, t = 0.46 and t = 0.9 sec (red region with EVF = 1.0 indicates fluid-filled zone while blue region indicates void).

6. Conclusion

This paper presents a methodology to simulate the forming process of a carton-based package using coupled Eulerian-Lagrangian approach in Abaqus/Explicit. Eulerian-Lagrangian approach enables the simulation of both the deformation of the packaging material and the fluid and the interaction between them entirely within a single finite element model. Such an integrated methodology can be used to conveniently simulate the carton-based package forming process in order to understand and set a variety of design parameters such as

a. Sequencing of the folding system action with deformation of the packaging material

b. Choice and suitability of packaging material

c. Correlation between fluid injection rate and formed package volume

d. Tensile load applied to the packaging material to prevent packaging material breakage or crimping

The paper shows that including the fluid in the simulation is important to account for the fluid-structural dynamical interaction in order to get the right shape and volume of the package. The study also corroborates the efficacy of the pressure flange device to control the gross bulk motion of the fluid and somewhat reduce the dynamical interaction between the fluid and the packaging material.

7. References

1. Abaqus Analysis User's Manual, Version 6.8, Dassault Systemes Simulia Corp., Providence, USA, 2008.