Fluid Structure Interaction (FSI) Applications to Consumer Products

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Abstract

Manufacturing consumer products and among them disposable absorbent products is very complex, not only due to the number of components that are assembled together, modified and packed but also because it has to be done at very high speed in order to compete in the ever more competitive disposable absorbent products industry. Creating models to represent such complex processes is very challenging for the above reasons and others like the very small thickness of the materials and their particular properties. Representing these processes using Finite Element Analysis (FEA) has been a growing practice at The Procter & Gamble Co. (P&G) for quite some time and in recent years complexity has been added to the models by including fluid representations, therefore developing Fluid Structure Interaction (FSI) models which in many cases are needed to better represent the processes we want to model.

*In this paper some basic settings of FSI models are described. By using the *Constrained_Lagrange_In_Solid keyword and other necessary keywords it is possible to simulate the interaction of the flimsy structures representing the disposable absorbent products materials with the air that surrounds them, while traveling at high speed. Then the paper goes on to showcase some of the models that have been successfully developed and validated (trim removal, folding and component ribbon handling), all of these models involve the interaction between flimsy structures and air. Validation of the models has been very important to gain confidence in the capabilities and some of the validation data is shared in this paper which shows great agreement between the models' predictions and the data collected during the experiments.*

This paper demonstrates how FSI models developed using LS-DYNA® successfully represented manufacturing processes of disposable absorbent consumer products involving flimsy structures and fluids interacting at high speed.

Introduction

Staying competitive in the disposable absorbent products business is very challenging due to the complexity of manufacturing the products (high number of parts modified and assembled, high speed rate of manufacturing, flimsiness of the materials, etc) and the number of product changes and innovation that are brought to the market on a regular basis, both need to be done under financial constraints to ensure that it can be done in a competitive manner so more consumers are able to afford these products and their benefits. Modeling the manufacturing of these products is not an easy task. Complexity is present, not only in the physics that need to be represented but also the properties of the materials (very thin and flimsy) and the high speed at which these materials are processed (modeling very thin and compliant materials interacting with rigid parts at high speed).

At the Procter & Gamble Co. we have been using modeling to evaluate new manufacturing processes for consumer products including the manufacturing of new disposable absorbent products as part of our process and product development process as a way to evaluate new ideas faster and cheaper than if we were to use experiments. Although validation of our models is done routinely by using physical experiments we have been able to accomplish substantial savings in time and development cost during process and product development and also managed to discard ideas that would not have succeeded in experimental trials earlier, therefore accomplishing two very desirable outcomes during the development process: “fail early” and develop our products and manufacturing processes “better, cheaper and faster”.

Over the past twenty years of evolving efforts in modeling our manufacturing processes, the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) became common. In recent years, modeling more complex physics and multi-physics effects became the next frontier. Fluid Structure Interaction (FSI) emerged as one of those areas that would substantially improve our modeling capabilities and accuracy of our predictions. LS-DYNA has proven to be a very good tool to accomplish this.

In the following sections the different components of typical FSI models for manufacturing disposable absorbent products are described including some considerations that need to be kept in mind when modeling these types of products and processes.

Model Components

Structures Modeling:

When the priority is to model the manufacturing of the disposable absorbent products it is common to simplify the model by assuming that the equipment interacting with the product is rigid. For example the nonwoven material that interacts with an idler, conveyor belt or folding equipment is considerably flimsier than those pieces of equipment so we model the equipment as rigid parts.

For most of the applications of our models to our manufacturing processes, we represent the structures using shell elements with three integration points. This has been sufficient to represent the flimsy structures.

Then the focus is on properly representing the behavior of the flimsy structure, commonly nonwovens, films, or a laminate or patchwork of both. This is not trivial especially when both tensile and bending behaviors are important and need to be represented simultaneously. We have developed some techniques to do this using shell elements which allow us to reduce computational needs of the model but the important aspect to keep in mind regardless the technique used is that the method should be validated as an accurate method to represent both the bending and tensile behavior of the structure.

One commonly used keyword to represent the flimsy materials is the **MAT_ORTHOTROPIC_ELASTIC_TITLE* (using the title option is very helpful to keep track of the different parts with different properties representing the many components of the product). This keyword allows us to represent the flimsy materials which undergo very small elastic deformations properly representing both the bending and the tension responses.

Fluids Modeling:

When we look at most manufacturing processes for disposable absorbent products they happen either exposed to ambient air or use process air as part of the process (for example trim removal, where air is used to transport the trim material away from the manufacturing line). Clearly when air is part of the process it cannot be ignored. But in many instances when air is simply surrounding the product being manufactured the air is interacting and affecting the flimsy structure (for example when diaper ears are folded backwards due to their interaction with air while traveling through the manufacturing equipment) and should be included in the model to adequately represent the forces acting on these product components. Including only the machine parts would be an idealistic and insufficient representation of the control these have on the motion of the product or the relative motion of the product components.

There are several "types" of bodies of air commonly used to represent the different conditions. When air is used to transport a structure we use three different types of air parts: One feeding the model with air (source), another one removing air from the system (sink) and one in between them (mid air). The source and sink with the mid air creates a continuum which allows a flow of air from the source to the sink which when interacting with a flimsy structure is capable of transporting the flimsy structure though the air. The easiest way is to illustrate with an example, Figure 1 shows the multiple bodies of air (in this case for a Trim Removal model), on it one can appreciate the 3 bodies described earlier:

- **Source**: Volume of solid elements at constant pressure higher than the sink (i.e. ambient pressure). These elements surround the Mid Air as a way to provide, feed, air to the Main Volume.
- **Sink**: Volume of solid elements at constant pressure lower than the source.
- **Mid Air**: Volume of solid elements representing air at an initial pressure (i.e. ambient pressure).

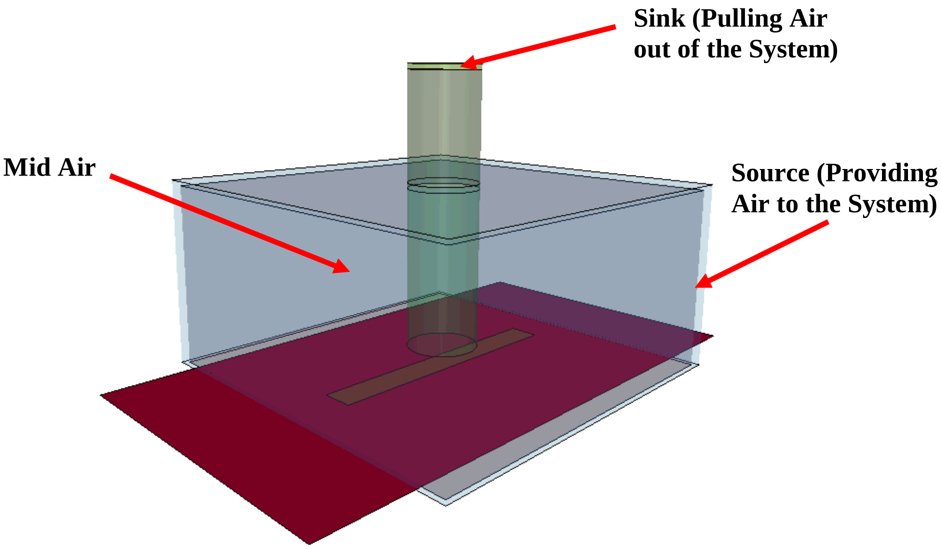

Figure 1: Multiple Bodies of Air in an FSI Model (Trim Removal)

When air is simply surrounding the flimsy structures and therefore interacting with such as the structures travel through the air at least two bodies of air are used: One source providing air constantly at ambient pressure and one main volume where the air elements pressure could change depending on the interaction with the structures.

The material type used for the volumes of air is **MAT_NULL_TITLE* where the density of the air is the most important variable that could change depending on the pressure of the air. It is important also to properly define the **SECTION_SOLID_TITLE* for the part representing the volumes of air, for parts where the pressure on the elements is to be constant (source and sink) the “aet” variable on this keyword should be set to 4, for the part where the pressure on the elements can vary the “aet” variable should be left blank.

To define the pressure on the volumes representing the bodies of air we use the **EOS_LINEAR_POLYNOMIAL_TITLE* keyword where the variable “e0” enable us to define the pressure on the elements.

Coupling Between Fluid and Structures:

When modeling FSI physics using the Arbitrary Lagrange-Eulerian (ALE) method with LS-DYNA the coupling between the structures and fluids can be defined using the **CONSTRAINED_LAGRANGE_IN_SOLID* keyword where the variables “pfac” and “pleak” can be used to tune the interaction between the structures and the fluids. These options are used in our methods.

FSI Applications

In this section we describe three different FSI models that have been successfully developed, validated and reused multiple times. This has allowed several new product development projects to achieve their goals faster while saving resources that otherwise would be used in experimental work.

Trim Removal Model:

Figure 2 provides a description of a typical geometry and the basic components of the model. In this case the trim is transported by a roll towards the nozzle.

The model design can be broken into 6 basic parts:

- *Air Source*: Body of air which acts as a source of air for the model
- *Air Sink*: Body of air representing the lower pressure - vacuum – for example induced by a fan
- *Mid Air*: Body of air between the Air source and Air sink
- *Trim*: Soft, fabric or film like, material which will be removed from the system
- *Nozzle*: Rigid structure, impermeable to air, through which the trim is removed
- *Carrier*: Rigid structure representing the device transporting the trim towards the nozzle. This is either a flat table for a conveyor or a cylinder for a roll

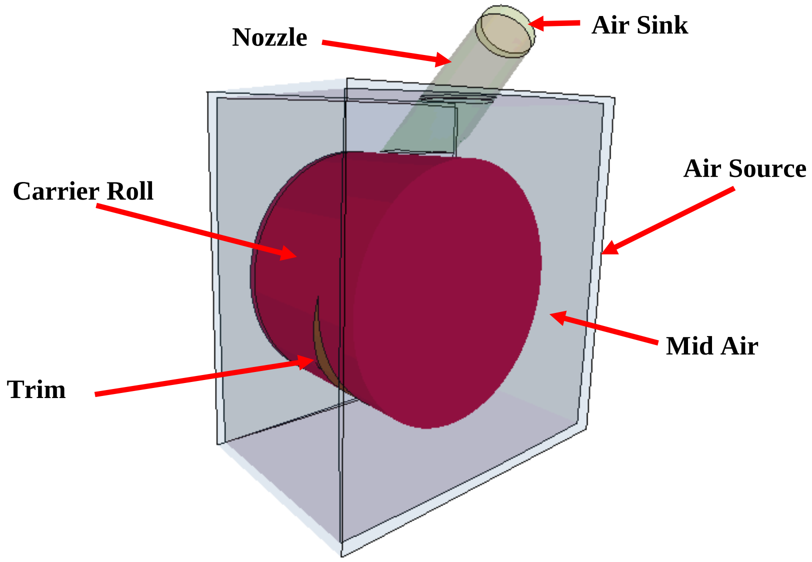

Figure 2: Trim Removal Model

Figure 3 shows an example of the application of this model where the displacement of the trim on the carrier is shown in images 1 and 2. When the trim is released from the carrier, it is sucked into the nozzle due to the interaction with the air that is being pulled into the nozzle. This is shown in images 3 and 4.

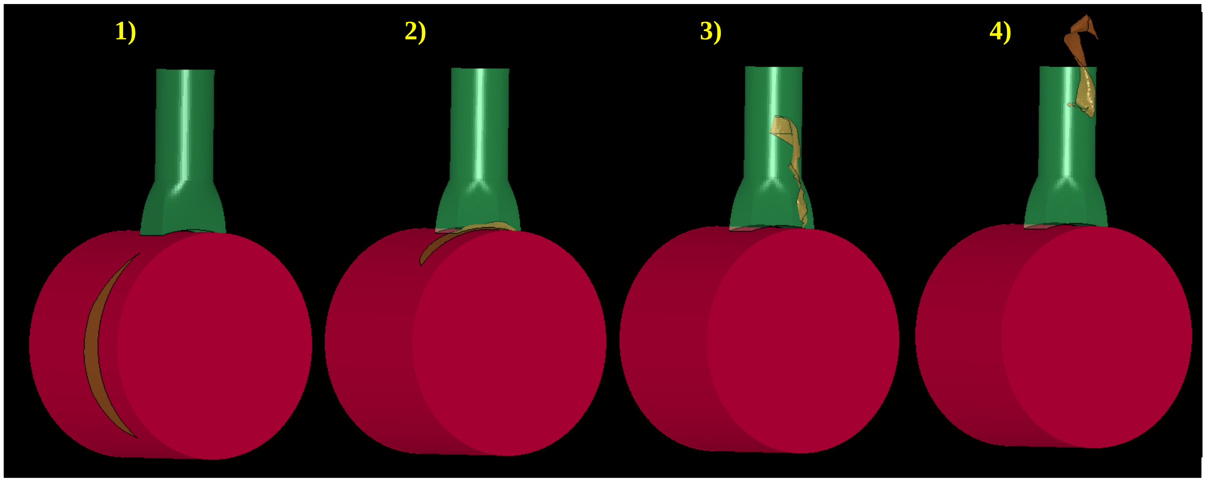

Figure 3: Trim Removal Model – Trim Progression

Several activities were carried out to validate the results from this model, Figure 4 shows some of the validation work where we can see good agreement between the trim behavior in the model and the experiment.

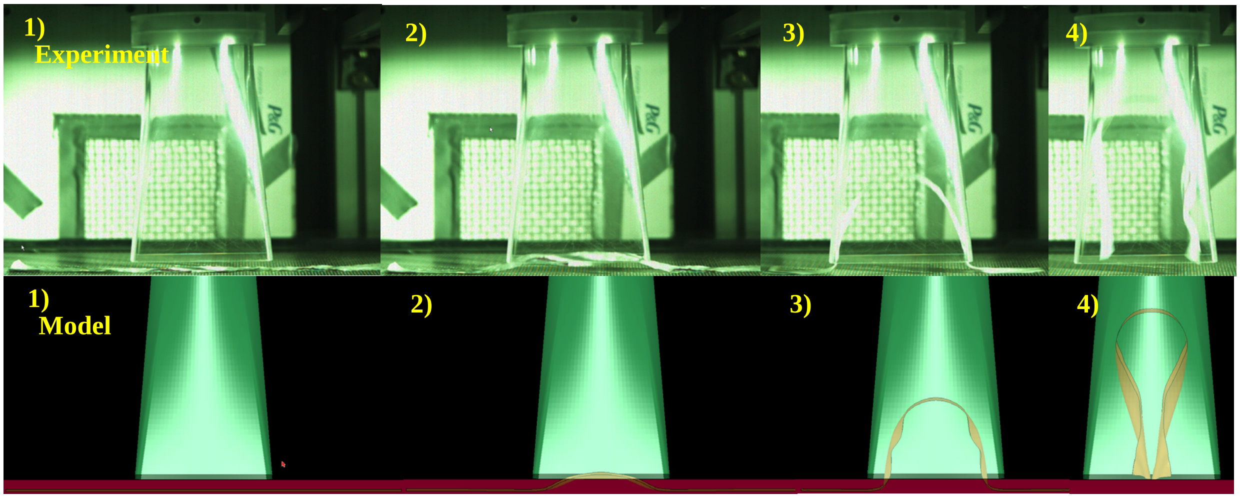

Figure 4: Trim Removal Model – Validation Experiment (Experiment-Top, Model-Bottom)

Folding Model:

The Folding Model simulates the interaction between flimsy structures and equipment which is used to fold the flimsy structure onto itself. Figure 5 illustrates this model applied to folding a disposable diaper and in this case one of the focus areas was to evaluate the effect of the interaction between the ears of the diaper with the air. The model consists of 3 basic parts:

- *Diaper, Ears*: Representing the product to be folded.
- *Air*: Air volume surrounding product and equipment.
- *Folding Board*: Device used to fold the product as the product goes through it.

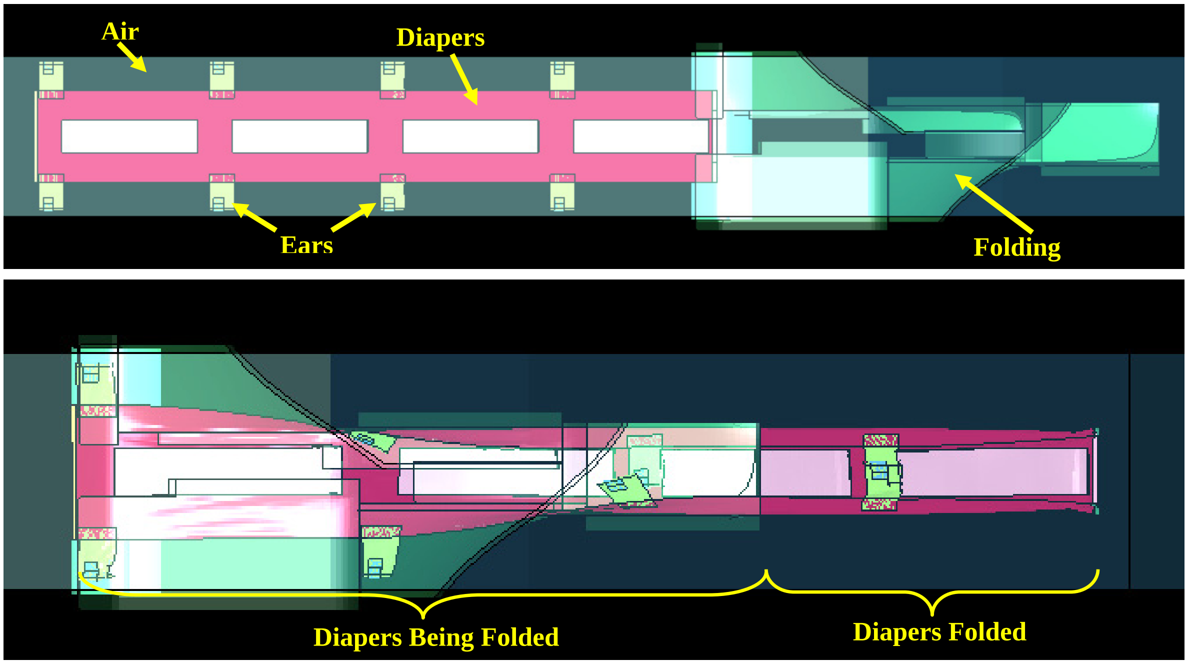

Figure 5: Folding Model – Representing Disposable Diapers

Some results from the validation experiments are shown in Figure 6 (note that in the photographs of the experiment the edges of the ears are highlighted by a yellow line for clarity).

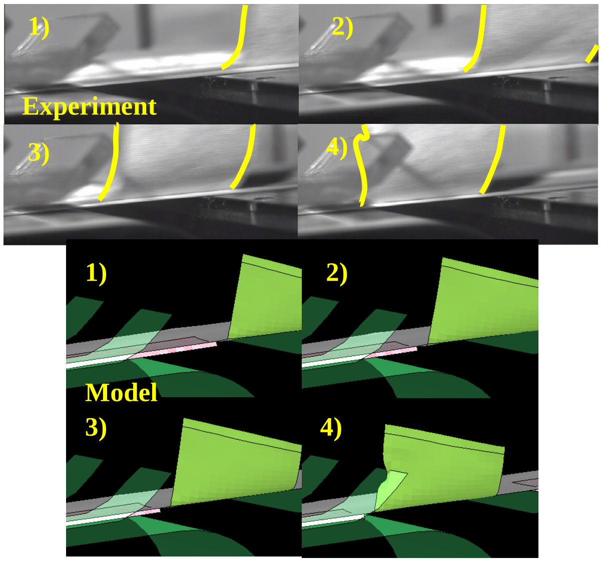

Figure 6: Folding Model – Validation Experiment (Experiment-Top, Model-Bottom)

Ear Ribbon Model:

This model represents a continuous web which will later be cut into discrete pieces which will become the “ears” of the diapers. The model intends to capture the behavior of the material due to the tension through converting but also the bending of the “free hanging” end of the material which could result in undesirable folds of the material and ultimate in defects that will be rejected.

Figure 7 provides a description of the model which consists of the following parts:

Ear Ribbon: This represents the ears before they are cut into discrete pieces.

Air Source: Body of air which acts as a source of air for the model.

Mid Air: Body of air surrounding the equipment and ear ribbon and considered in parts of the model where we wish to study the interaction between the ribbon and the air that may be important.

Equipment: Slitters, dead plates, 45 degree turning bars and other equipment needed for the processing of the material which interacts with the material are represented. The proper coefficient of friction must also be included.

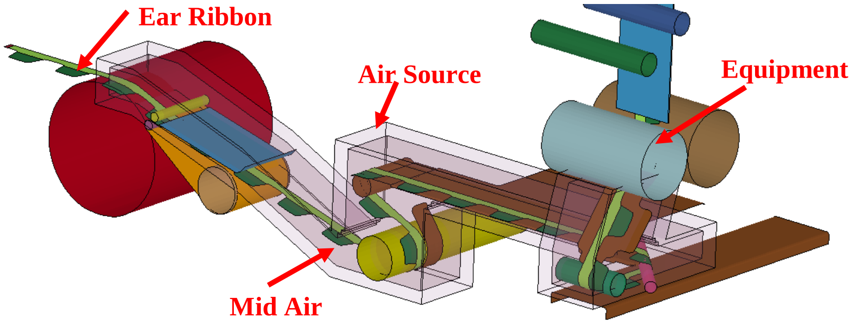

Figure 7: Ear Ribbon Model

Figure 8 shows a comparison of some of the model results with some of the validation data collected. We can appreciate how the behavior of the material is similar in the experiment and the model.

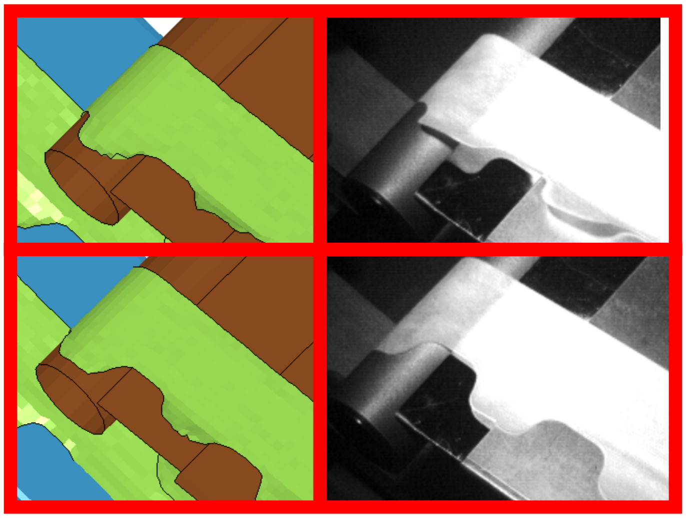

Figure 8: Ear Ribbon Model – Validation Experiment (Model-Left, Experiment-Right)

Concluding Remarks

- Complex manufacturing processes involving flimsy structures and fluids can be successfully modeled using LS-DYNA.
- The models can be used to compare different designs, materials, processing concepts, etc. in a virtual manner avoiding the manufacturing of prototypes that will be discarded after testing and avoiding the execution of many tests, resulting, in the end, in considerable savings of time and resources.