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Dynamic Stability Simulation of a Bottle Pallet in Consumer Packaging

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Dynamic Stability Simulation of a Bottle Pallet in Consumer Packaging

Abstract

The bottles used to fill beverages in the consumer-packaged goods industry are designed with significant consideration. Many design parameters are included to achieve the optimum filling and packaging experience of the bottles. In this study, we elaborate a few of these design constraints and use the SIMULIA Abaqus *solver in the* **3D**EXPERIENCE® *platform by Dassault Systemes to simulate the stability of bottles using the multi body dynamics method. Using Abaqus for multi-body dynamics is a non-trivial approach but it is a preferred way to solve such problems for an FEA engineer who is not a multi body dynamics expert.*

Introduction

The conventional wine bottles that you see in your favorite store require considerable engineering expertise to earn their final shape. These bottles are subjected to several design constraints. The bottles are always in motion at the filling station. Their center of gravity should not be high enough to make them topple during motion. As the packed beverage is sold as per its volume, the bottle inner volume should not deviate from a specified value. After filling, these bottles are packaged and transported. They are usually packed in a pallet of few bottles and the pallets are stacked one over the other during transport. The bottles should have enough strength to withstand the weight of pallets on the top both under static and dynamic conditions. The bottles should also be able to withstand the dynamic stresses developed because of vibrations during transportation. There are aesthetic constraints as well. A design and color that is appealing to a human eye can be more attractive on the shelf and sell quickly. The objective of such problems usually is to produce a bottle design that is as light in weight as possible to save cost within the constraints mentioned above.

Each of the aforementioned constraints requires different physics. The strength estimation of a bottle is a static structural mechanics problem in which the stress distribution plays a significant role. The dynamic strength requires simulation in frequency domain to account for the structural response of the bottle pallets subjected to vibration loads during transport. The dynamic stability computation, considered in this study, requires simulation in explicit dynamics space where velocities and accelerations are the primary concern. As each body is defined as rigid, the stresses are not of much concern.

In this study, a pallet of bottles is modeled and simulated to check their dynamic stability at the filling station. The entire modeling and simulation are done on the **3D**EXPERIENCE platform offered by Dassault Systemes. The design is then modified to increase the stability within the design constraints.

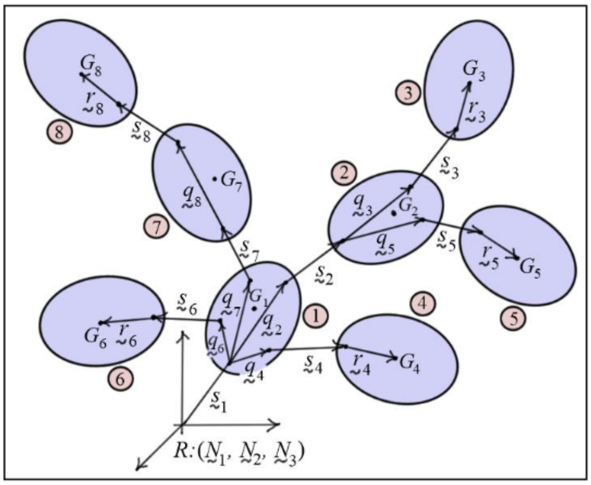
BACKGROUND RESEARCH ON METHODS

The approach used in the study is a hybrid of explicit dynamics of SIMULIA Abaqus and the multi body dynamics. All the parts in the bottling assembly are considered as rigids with six degrees of freedom at the reference node. Hence, a finite element model has been degenerated into a classical rigid bodies model with series of connections and contact constraints.

A rigid body is considerably less expensive than its equivalent finite element model in terms of computation cost. A finite element model of a part may have hundreds of thousands of degrees of freedoms depending on the mesh density. Each node of a solid element contributes six degrees of freedom if its fully unconstrained. The corresponding stiffness matrix has exceptionally large dimensions because of deformable meshes in the system. Solving such a large system of equations using either the implicit or explicit approach is a big computational cost.

In the given study, the focus is on dynamic stability instead of deformation. Hence, it is viable to fully constrain the motion of all the nodes of a mesh to a single reference point governed by dynamics of motion. The contact constraints computation between different bodies remains in effect.

Consider a multi body system with eight rigid bodies as shown above. Each body has its local coordinate system fixed at its centre of gravity G. Euler parameters $\dot{\varepsilon}(Ki)$ are used to measure orientations of the body relative to inertial frame. Translation variables s(Ki) are used to measure displacement of bodies relative to their adjacent lower-numbered bodies. Absolute angular velocity components ω(Ki) are used to measure angular velocities of the bodies relative to the inertial frame R(N1, N2, N3). Here K=1,....N and i=1,2,3. N is the number of bodies. The explicit form of equations of motion of a multibody system depends on the following:



Multibody System with Eight Bodies

- ➢ Choice of Generalized coordinates.
- ➢ Choice of generalized speed.
- ➢ Method used to formulate the equations.
- ➢ Constraints on system motion.

Using the generalized coordinates and speeds defined above, the following system state vectors can be defined.

$$\{\varepsilon\}_{4N\times 1} = [\varepsilon_{11,}\varepsilon_{12}, \varepsilon_{13}, \ldots\ldots \varepsilon_{K1,}\varepsilon_{K2}, \varepsilon_{K3},, \varepsilon_{K4} \ldots\ldots. \varepsilon_{N1,}\varepsilon_{N2}, \varepsilon_{N3},, \varepsilon_{N4}]^T$$
$$\{s\}_{3N\times 1} = [s_{11,}s_{12}, s_{13}, \ldots\ldots s_{K1,}s_{K2}, s_{K3} \ldots\ldots. s_{N1,}s_{N2}, s_{N3}]^T$$
$$\{\omega\}_{3N\times 1} = [\omega_{11,}\omega_{12}, \omega_{13}, \ldots\ldots \omega_{K1,}\omega_{K2}, \omega_{K3} \ldots\ldots. \omega_{N1,}\omega_{N2}, \omega_{N3}]^T$$

The transformation matrix can be written in terms of the Euler parameters associated with body K as follows:

$$[R_k] = \begin{bmatrix} \varepsilon_{k_1}^2 - \varepsilon_{k_2}^2 - \varepsilon_{k_3}^2 + \varepsilon_{k_4}^2 & 2(\varepsilon_{K_1}\varepsilon_{k_2} + \varepsilon_{k_3}\varepsilon_{k_4}) & 2(\varepsilon_{K_1}\varepsilon_{k_3} - \varepsilon_{k_2}\varepsilon_{k_4}) \\ 2(\varepsilon_{K_1}\varepsilon_{k_2} - \varepsilon_{k_3}\varepsilon_{k_4}) & -\varepsilon_{k_1}^2 + \varepsilon_{k_2}^2 - \varepsilon_{k_3}^2 + \varepsilon_{k_4}^2 & 2(\varepsilon_{K_2}\varepsilon_{k_3} + \varepsilon_{k_1}\varepsilon_{k_4}) \\ 2(\varepsilon_{K_1}\varepsilon_{k_3} + \varepsilon_{k_2}\varepsilon_{k_4}) & 2(\varepsilon_{K_2}\varepsilon_{k_3} - \varepsilon_{k_1}\varepsilon_{k_4}) & -\varepsilon_{k_1}^2 - \varepsilon_{k_2}^2 + \varepsilon_{k_3}^2 + \varepsilon_{k_4}^2 \end{bmatrix}$$

The model in study, as discussed later, has a pallet of eighteen bottles and fourteen conveyors along with two guard rails. There are a total of thirty-four rigid bodies. Hence the value of K is thirty-four. Accordingly, there are thirty-four transformation matrices in this system each having a 3x3 dimension. There are additional matrices for contact constraints. But, it is still a computational manageable dynamic system.

The explicit finite element approach for deformable bodies consists of equations of dynamics for each node of the model. The central difference method to solve general dynamic problem with non-linearities is as follows:

$$\dot{u}^{n+1} = u^n + \Delta t\dot{u}_n + \frac{\Delta t^2}{2}\ddot{u}_n$$

If all the system variables at state n are known, then system variables at state n+1 can be calculated without any matrix inversion. That makes a single explicit iteration very economical. However, the system of equations cannot travel fast enough in time as the solution is conditionally stable. There is an upper threshold on time step beyond which the solution becomes unstable. The number of equations to be solved is a function of number of nodes instead of number of bodies if the mesh is deformable.

The model in the study has eighteen bottles with 35,000 nodes on each bottle. That's a total of 630,000 nodes. The bottles are made of glass in which the speed of wave is 5000 m/sec. Assuming average element edge length of 1mm, the critical time step is 2e-4 sec beyond which the explicit solution is unstable. The motion of bottles on conveyors is a long event of about 25 seconds. That makes a total of 125,000 computations of central difference scheme at each node, resulting in 78,750 million equations only for the pallet of bottles. There are additional equations for contact constraints. It's a tremendous computation cost even for a high-performance cluster.

If each bottle is defined as rigid body with a reference point, the motion of 35,000 nodes per bottle are governed by the motion of single reference node with six degrees of freedom. The entire model, including bottles, conveyors and guide rails has only rigid bodies. Subsequently, a full-blown explicit FEA model is transformed into a multi body rigid system model that can be solved in much less time. We used SIMULIA Abaqus explicit on the **3D**EXPERIENCE platform to build and solve this model.

Problem Description

The motion of bottles on the belts are shown below in Image 1. There are total of fourteen belts, and they are grouped together in multiple color codes. The color codes are based on the length of belts which is irrelevant from simulation's perspective. The top guide rail is inclined at 10 degrees. Each belt has a width, speed, and coefficient of friction of its own. These values are shown in Table 1 below. The coefficient of friction between bottles themselves is 0.9 and the interaction between bottles and guide rails is considered frictionless due to very little reaction force. The whole model is subjected to the gravity load of 9.8 m per second squared. The dimensions of the bottle's assembly are defined in inches while the speeds of belts are defined in ft per minute. Hence, there is a mixed system of units to be considered.

Two design iterations of bottles are considered. The first one, coded as 4866026 is relatively slender compared to the second one coded as 5727026. The scope of simulation is to compute which bottle is more stable. There are eighteen bottles in the pallet. Due to variation in speeds of belts, the bottles eventually align themselves in a straight line along the inclined guide rail. A design is accepted if all the bottles can reach the filler belt one by one without toppling on the assembly. The motion of belts is considered smooth without any jerks.

Image 1

Belt #	Force Min (lbf)	Force Max (lbf)	Force Avg (lbf)	FN (weight in oz)	CoF	Belt Speed Min (ft/min)	Belt Speed Max (ft/min)	Belt Speed Avg (ft/min)	Belt Width (in)
Incoming	0.06	0.08	0.070	1.000	0.070	17.90	20.40	19.150	24
1	0.06	0.08	0.070	1.000	0.070	54.3	60.9	57.600	3.25
2	0.06	0.07	0.065	1.000	0.065	64.40	73.10	68.750	3.25
3	0.06	0.08	0.070	1.000	0.070	78.80	88.90	83.850	3.25
4	0.08	0.11	0.095	1.000	0.095	99.80	111.00	105.400	3.25
5	0.06	0.09	0.075	1.000	0.075	119.30	128.40	123.850	3.25
6	0.07	0.09	0.080	1.000	0.080	152.20	167.10	159.650	3.25
7	0.07	0.09	0.080	1.000	0.080	178.20	197.00	187.600	3.25
8	0.06	0.09	0.075	1.000	0.075	198.10	218.20	208.150	3.25
9	0.07	0.10	0.085	1.000	0.085	215.40	214.10	214.750	3.25
10	0.09	0.13	0.110	1.000	0.110	200.80	220.30	210.550	7.50
11	0.10	0.13	0.115	1.000	0.115	227.70	253.10	240.400	7.50
12	0.10	0.13	0.115	1.000	0.115	227.60	253.90	240.750	7.50
To Filler	0.10	0.13	0.115	1.000	0.115	214.60	237.20	225.900	4.50

Table 1

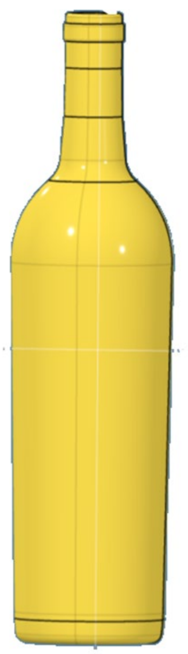
Proposed Solution

The problem could have been pre-processed and solved in conventional stand-alone tools as well. However, one of the objectives of this study is to stress test the **3D**EXPERIENCE platform simulation capabilities on real life use cases. We went a step further to highlight a few features of the platform that make modeling and simulation work easier for this project. The **3D**EXPERIENCE platform brings the native CATIA CAD modeling tools and the SIMULIA Abaqus physics based realistic simulation tools into a single environment. This helps CAD designers and FEA analysts work in collaboration within the same environment, helping to automate repetitive tasks and fostering innovation.

The Structural Generative Engineer role of the **3D**EXPERIENCE platform is used for this study. However, other roles can be used as well.
The Apps used are:

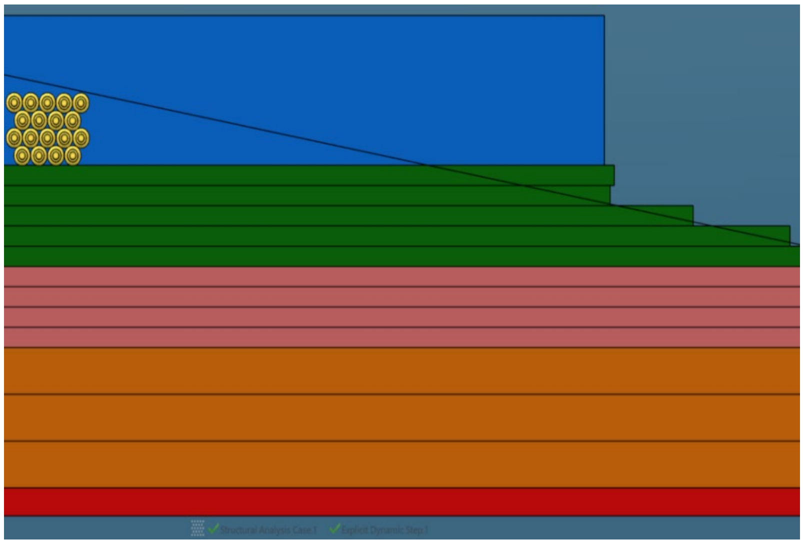
- **Part Design Essentials** for CAD part design
- **Assembly Design** to correctly orient the bottles and conveyors.
- **Structural Model Creation** to create FEM Reps and meshes.
- **Mechanical Scenario Creation** to define contacts, velocities, and gravity.
- **Physics Results Explorer** to visualize results.

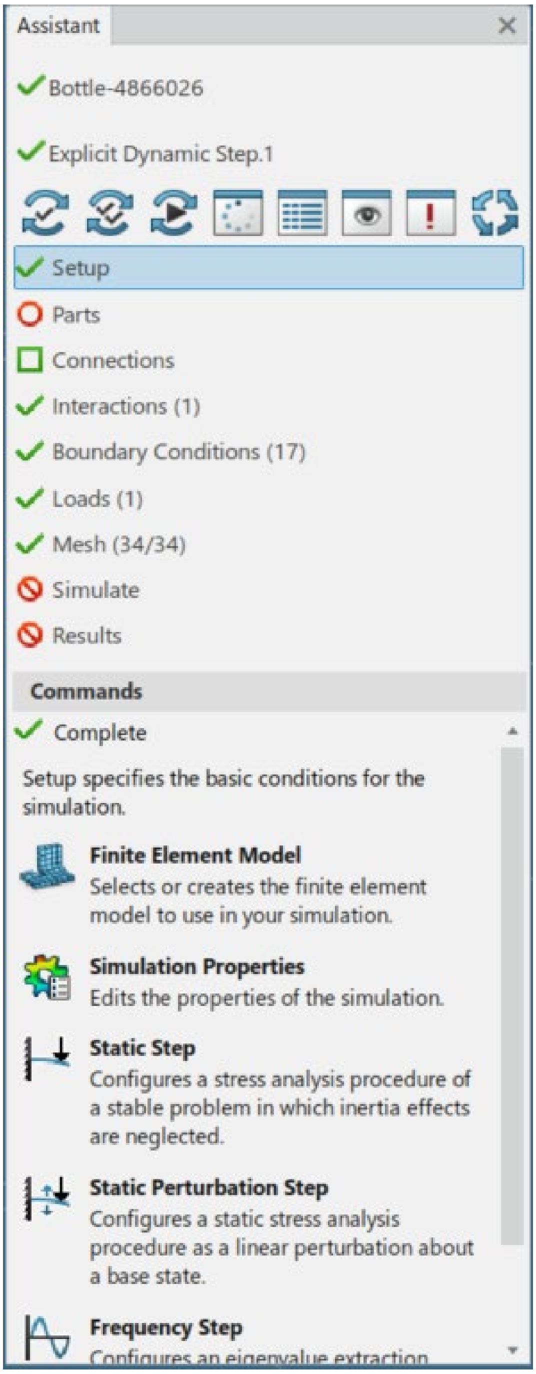
The two design variations, bottle A and bottle B, appear below. The dimensions are confidential; however, one can visually spot the difference.



Bottle A

Bottle B





The Assistant Panel

A great feature to highlight is the Assistant panel of the Mechanical Scenario App within the **3D**EXPERIENCE platform that helps to build models faster. It is a step-by-step navigator for model building. Once the given step definition is complete, the checker associated with it changes from a red circle to a green tick mark. Each step is associated with its corresponding common commands at the bottom. For example, the setup step has commands to define the applicable Abaqus physical step definition as well as to select the associated FEM Rep. The interaction step has commands to define the contact properties, the general contact, the contact pairs as well as contact detection tools.

Each command has a brief description. This makes it easier for a non-Abaqus knowledgeable analyst to understand the main function of the command. The detailed description is just a click away. Hover the mouse on the command and press F1. The search will navigate the user to the exact location of the documentation where the command is explained in detail.

The tools shown at the top of the Assistant panel are used for data check, job submission, selective visualization, and job diagnostic purposes. In summary, the Assistant panel is a one stop shop to define most of the features of the model with ease.

There are distinct benefits of using **3D**EXPERIENCE Simulation depending on the user background. The benefits are more evident if the solution is used by a designer with little knowledge of simulation or an analyst who has a non-Abaqus simulation background. In context of this study, we discovered the following benefits of **3D**EXPERIENCE vs. a simulation point tool.

Functionality	3DEXPERIENCE® Platform Simulation	Standalone Point Solution Simulation
Mixed Unit System	Data can be entered in any system of units. **3D**EXPERIENCE internally converts data as per specified system of units for SIMULIA Abaqus.	These tools do not understand units. It is the user responsibility to enter data in a consistent system of units.
Ease of Data Transfer	Data can be transferred from CATIA V5 (and a large number of other CAD formats) to **3D**EXPERIENCE platform without converting to any neutral file.	Most tools only accept the neutral file formats in which parametric information is lost.
Ease of Building Assembly	Multiple instances can be created by copying and pasting data from the Parts Design App to the Assembly Design App. The instances can be positioned by dragging in space using a robot tool.	Instance positioning is difficult in the absence of smart interactive tools. Most positioning features require CAD support or numerical data entry.
Speed of Iterations	The model once ready can be re-evaluated for a design change without rework from scratch. This is possible using the power of parameters and publications.	A major design change almost always requires re-work from scratch or advanced scripting that needs programming.
Advanced On-Cloud Clusters	Model can be solved on cloud using as high as 192 cores. The results can be stored on cloud as well or downloaded in traditional odb format. This model solved on 144 core cloud cluster in 3 hours.	A third-party cloud service would be required at an additional cost. The same model solved on local eight cores in 12 hours.
Results Collaboration	The results data can be stored in a lightweight visualization format that can be shared with non-simulation stakeholders using a web browser.	Results can be shared with non-simulation stakeholders only through images and movie files.
Fast and Realistic Visualization	The results can be quickly rendered and animated using multiple cores either from local machine or from cloud resources.	These post processing tools usually cause a delay in preparing visuals of large data files.
Simulation Democratization	The simulation prepared by an expert can be templatized for re-use by another user with limited simulation knowledge.	These tools are meant for expert simulation analysts only.

Results and Conclusions

The animation movies below compare the stability of two versions of these bottles. The design A is clearly an unstable one. These bottles fall within a few minutes of motion on the bottling line thereby blocking the filler exit. The design B is a little better but even this design fails as per defined stability. The scope of this study is only to compare the dynamic stability of two design iterations. The design should be further modified to achieve full stability. Moreover, there are more tests required for structural response during packaging and transportation. The weight and aesthetic constraints should also be considered.

The first iteration output is from the **3D**EXPERIENCE Simulation's Physics Results Explorer App, while the second iteration output is from standalone tools to highlight the difference in rendering.

Video 1: 4866026 isometric

Video 2: 4866026 topview

Video 3: 4866026 camera

Video 4: 5727056 isometric

Video 5: 5727026 topview

Video 6: 5727026 camera

The comparison of two designs is a concept study to highlight the capabilities of a robust SIMULIA Abaqus solver and robust CATIA design in a single environment which is **3D**EXPERIENCE platform. The bottles were not defined within the platform so the parametric approach could not be leveraged. Further scope would be to templatize the model using publications to test multiple iterations of a non-parametrized design. We encourage you to go through references below to see work done on other types of models.

References

1. A collaborative and integrated way of design and simulation. Part I. Link to the MODSIM Webinar I
2. A collaborative and integrated way of design and simulation part II. Link to the MODSIM webinar II
3. The blog series on Simulation topics with the latest and greatest about SIMULIA product updates. Link to Blog Posts

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