Simulation of Fluid Sloshing in a Tank

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***Abstract*— Sloshing has widespread applications in many industries including automotive, aerospace, ship building and motorcycle manufacturing. The goal of sloshing simulation is to first study the sloshing pattern and then improve the tank design to reduce noise levels, stresses on the structure and optimize the baffle arrangements.**

In this project simulation of the fluid in tank is studied and the design modification with baffle plate is considered to minimize the sloshing phenomena using ALE method. Also it is explained that there is need to analyze the sloshing phenomena in detail. Arbitrary Langrangian Eulerian finite element methods gain interest for the capability to control mesh geometry independently from material geometry, the ALE methods are used to create a new undistorted mesh for the fluid domain. In this paper we use the ALE technique to solve fuel slosh problem. Fuel slosh is an important design consideration not only for the fuel tank, but also for the structure supporting the fuel tank. Fuel slosh can be generated by many ways: abrupt changes in acceleration (braking), as well as abrupt changes in direction (highway exit-ramp). Repetitive motion can also be involved if a sloshing resonance is generated. These sloshing events can in turn affect the overall performance of the parent structure. A finite element analysis method has been developed to analyze this complex event. A new ALE formulation for the fluid mesh can be used to keep the fluid mesh integrity during the motion of the tank. This paper explains the analysis capabilities on a technical level.

***Index Terms*—Sloshing, ALE, Eulerian mesh, Langrangian mesh**

I. INTRODUCTION

Sloshing is the Periodic Motion of the Free Surface of a Liquid in Partially Filled Tank or Container Can be Caused by Several Factors. Sloshing Viewed in Many Industry Applications

Analysis of the sloshing motion of a contained liquid is of great practical importance. Motion of a fluid can persist beyond application of a direct load to the container; the inertial load exerted by the fluid is time-dependent and can be greater than the load exerted by a solid of the same mass. This makes analysis of sloshing especially important for transportation and storage tanks. Due to its dynamic nature, sloshing can strongly affect performance and behavior of transportation vehicles, especially tankers filled with oil. In fact, a significant amount of research has gone into developing numerical models for predicting fluid behavior under various loads.

Liquid in an arbitrary shaped container under external excitations, results in surface and bulk turbulence. The nature of such turbulence is quite complex due to several effects such as sloshing, pressure gradient etc. Amongst these, sloshing makes the liquid container more vulnerable to structural damages. Depending on the type of disturbance and container shape, the free liquid surface may experience different types of motion including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic. However, the amplitude of slosh depends on the amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. The resonance in the case of horizontal excitation occurs when the external forcing frequency is close to the natural frequency of the liquid. Hence liquid sloshing is a practical problem with regard to the safety of transportation systems, such as oil tankers on highways, liquid tank cars on railroads, oceangoing vessels with liquid cargo, propellant tank used in satellites and other spacecraft vehicles, and several others.

II. THEORY

As it is taken that the problem of partially filled tank there is necessity that we have to take the combination of fluid and structure in which it is filled. So this problem is purely of Fluid and structure interaction. This type of problem can be modeled in basic four approaches which are used for fluid structure interaction problem

1) Lagrangian approach
2) Euler approach
3) Euler and Langrangian approach
4) SPH

Different Formulations Of System Physical State Description:

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

In the Eulerian formulation (Fig.2) the problem is being observed at one point in space which does not follow the motion of the single particle. In one time step *t* several mass

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particles may pass the observed point. Their motion is exactly determined in the moment of passing through that point. In the observed point the field variables are time dependent.

The basic difference between the Lagrangian and the Eulerian formulation is that at the Lagrangian formulation the magnitudes *x* , *y* and *z* are variable coordinates of a moving particle. At the Eulerian formulation those coordinates represent steady coordinates of the defined field point

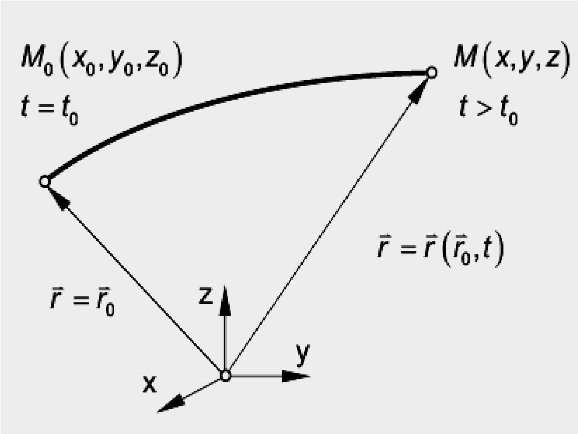

Fig.1 Langrangian Formulation

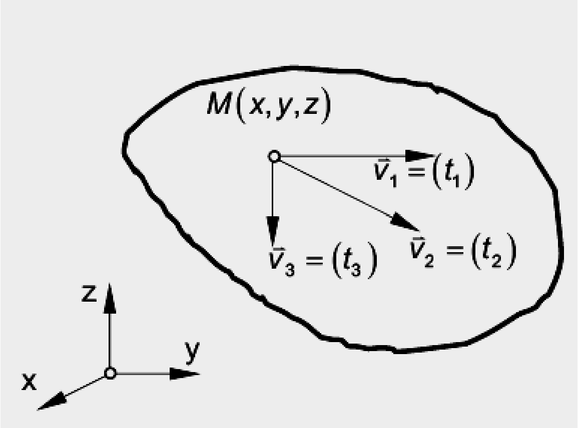

Fig.2 Eulerian Formulation

1. Lagrangian Formulation:

- Finite Element Formulation
  - The Lagrangian processor of MSC.Dytran uses the same finite element based technology.
- Structural Dynamics
  - A Lagrangian mesh should be used to model structural parts of a problem.
- Elements of constant mass

In the Lagrangian formulation (Fig.3) one finite element represents the same part of the material throughout the course of the analysis. The fluid domain can be described with a material model which skips the calculation of deviatoric stresses. By defining a low bulk modulus for fluids such as water, the elastic shear forces become negligible, and by using a low yield stress, fast transition to plasticity can be achieved (e.g. by only considering the gravitation). Under high dynamic loading, the shear forces and any unreal introduced forces become negligible in comparison to the inertial forces of the fluid (Fig.3) 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.

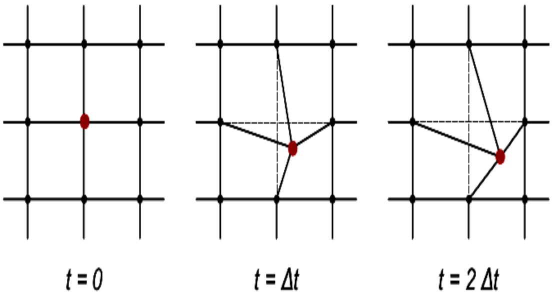

Fig.3 Mesh Deformation In Langrangian Formulation

2.Eulerian Formulation:

It is also possible to apply the Eulerian formulation for fluid flow analyses, where the fluid flow through the fixed mesh in a space is observed. The material point moves from one finite element to another and the finite element mesh does not move or deform. Although the Eulerian mesh in appears not to move or deform during the analysis, it does actually change its position and form only within the single time step. The reason for this is the use of Lagrangian formulation in single time steps, which is much more advanced in. The Eulerian mesh is treated in a special way (Fig.4). To illustrate the use of an Eulerian mesh the same example is used as in the previous chapter. 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:

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

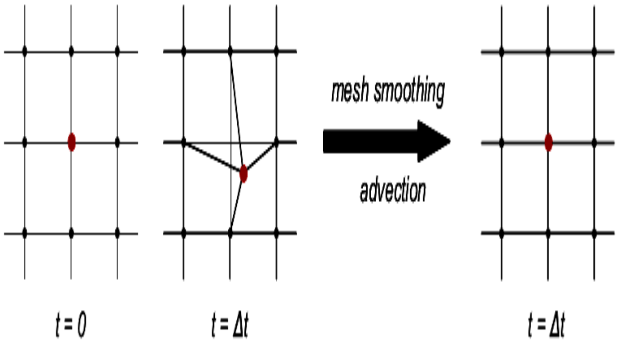

Fig.4 Mesh Deformation In Eulerian Formulation

3. Arbitrary Lagrangian-Eulerian Formulation (ALE)(Fig.5)

General Coupling

- Fluid-Structure Interaction
  Lagrangian and Eulerian meshes can be used in the same analysis and coupled together allowing the solution of Fluid-Structure Interaction problems
- Arbitrary Motion
- The coupling surfaces can be of any shape and can undergo arbitrary motions
- The Lagrange mesh acts as a boundary to the flow of materials in the Euler mesh.
- The Euler mesh loads the structure

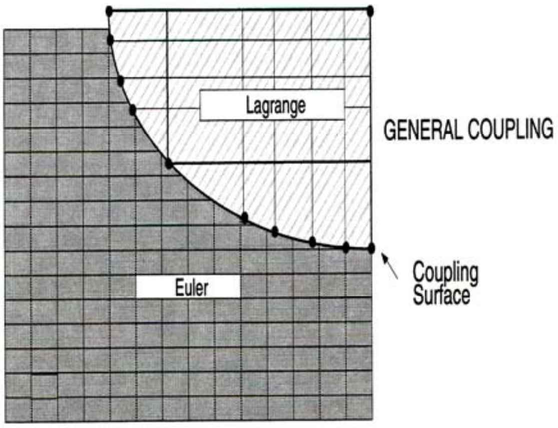

Fig.5 ALE Formulation

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).

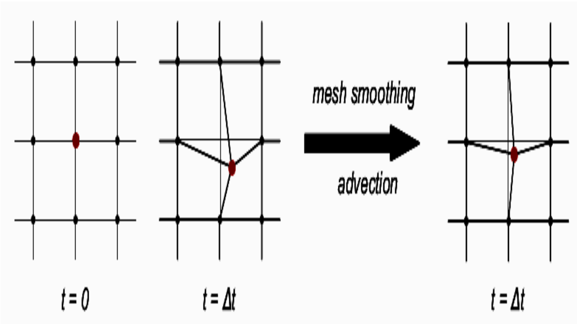

Fig.6 Mesh Deformation In ALE Formulation

The ALE solving procedure is similar to Eulerian procedure. The only difference is the mesh smoothing. In the Eulerian formulation the nodes are moved back to their original positions, while in the ALE formulation the positions of the moved nodes are calculated according to the average distance to the neighbouring nodes (Fig.6). A similar calculation scheme is also used in other comparable codes (i.e. MSC/Dytran).

In MSC-DYTRAN there are two types of ALE elements: Single material and Multi material.

Single material element type can contain only one phase (fluid) at one moment, while the multi material element type is able to contain several materials. 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 analysis of fluid tanks, where fluid movement inside the tank is of interest and the boundary surface is continuously changing due to interaction between fluid and tank surfaces (Fig. 7).

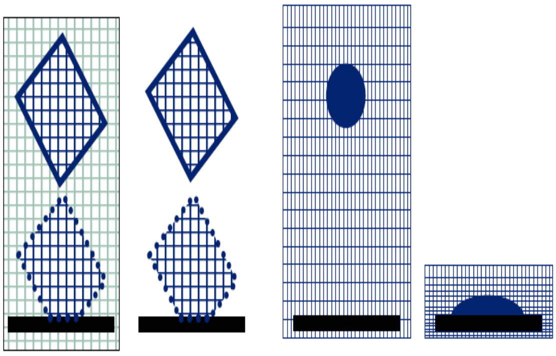

Fig.7 Boundary Surface Chage In Fluid And Tank Interaction

4.Smoothed Particle Hydrodynamics (SPH):

The SPH method is an integration scheme which was developed by Lucy, Gingold and Monaghan (1977). It is based on the Lagrangian formulation with the purpose to avoid the mesh restrictions when large deformations appear within the finite element method. The main difference between the standard methods and the SPH is the absence of the mesh, since the SPH formulation is essentially a mesh less method (Fig.8)

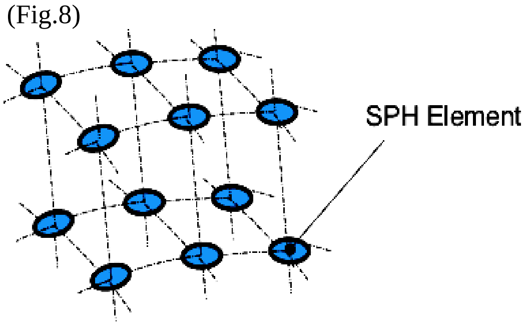

Fig.8 SPH Formulation

Four approaches to fluid flow modelling in MSC-DYTRAN have been presented in the paper. Different formulations (Lagrangian, Eulerian, ALE and SPH) can be used to analyze a fluid motion in tank. Computational simulations have shown that the fluid motion and fluid-structure interaction can be accurately described by applying different alternative formulations in the MSC-DYTRAN. The applied models provide a basis for economical computational models that can be used for analyzing more complex problems (e.g. automotive fuel tanks).

III. DISCUSSION

The design of fuel tanks for both sloshing and impact is receiving increased attention. The recent availability of free-surface prediction capabilities in commercial CFD codes, like FLUENT4, has allowed the incorporation of such phenomena as sloshing into the design cycle. The Volume of Fluid (VOF) method especially, has provided a cost-effective way to predict free-surface behavior. Another way of treating free surfaces is the Augmented Eulerian-Lagrangian (ALE) method, as embodied in MSC-Dytran. This method is especially of interest when fluid-structure interaction is concerned. Currently, ALE is incorporated into MSC-Dytran in an explicit Framework, making it unsuitable for long sloshing events, but ideally suited for short-duration impact events.

One of the fuel tank design objectives is to effectively reduce noise level caused by fluid motion inside the tank by designing baffles and separators to control the sloshing. In addition, alternate materials and manufacturing processes are evaluated for fuel tank design in order to reduce weight and cost, and to provide structural integrity for higher structural performance. Sloshing in the tank may be controlled by incorporating baffles, and the effectiveness highly depends on the shape, the location, and the number of baffles inside a tank. Validation of multiple baffle designs via physical testing is a very tedious and expensive. Also, the visual/digital inspection of the sloshing event inside the tank is not adequate for baffles design validation. Due to the complexities associated with the sloshing phenomenon, the CAE simulation is a desired method to meet the design intent, and shorten the development time.

Several CAE codes were employed to simulate sloshing, such as, MSC-Dytran, Fluent, and LS-DYNA. In this case MSC-Dytran is used to analyze the sloshing phenomena.

IV. CASE STUDY

Sloshing has widespread applications in many industries including automotive, aerospace, ship building and motorcycle manufacturing. The goal of sloshing simulation is to first study the sloshing pattern and then improve the tank design to reduce noise levels, stresses on the structure and optimize the baffle arrangements.

The following case study simulates sloshing in a partially filled rigid tank without baffles at a braking speed of 50 Km/hr. Further in continuation of this case study with baffles in the fuel tank can be analyzed. This case study is designed to familiar with the following:

1 - How to define Single Material Euler
2 - How to define a braking velocity field for the fuel tank
3 - How to use Langrangian - Euler Technique to define the interaction between the fuel and the tank.
4 - Which output variables request for post processing

Rigid Tank Properties:
Use MATRIGwith Steel properties as follow:
Density = 7830 Kg/m3
E = 2.068e11 Kg/m/s2
Poisson ratio = 0.3
Thickness = 0.005 m
Water Properties (Instead of Fuel):
Rho=1000Kg/m3
Bulk Modulus=K=a1=2.2e9 Kg/m/s2
Gravity = 9.8 m/s2 in -Y direction

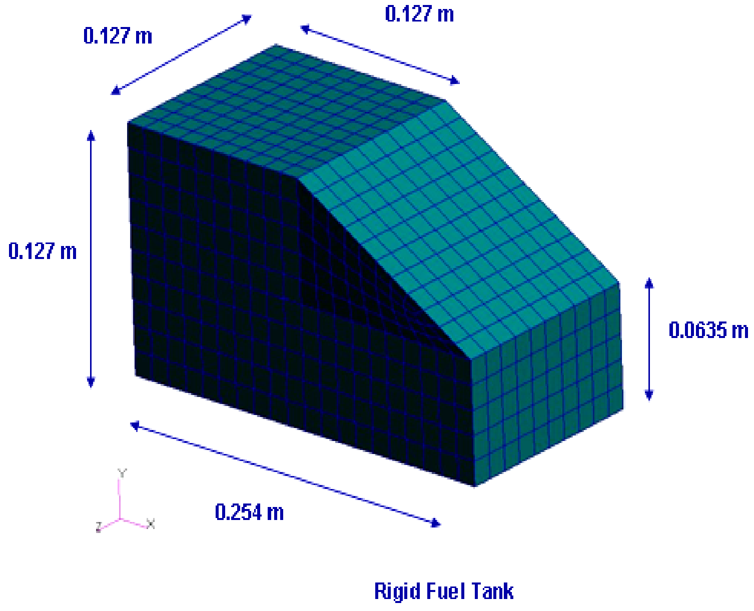

Fig.9 Model Description in SI Units

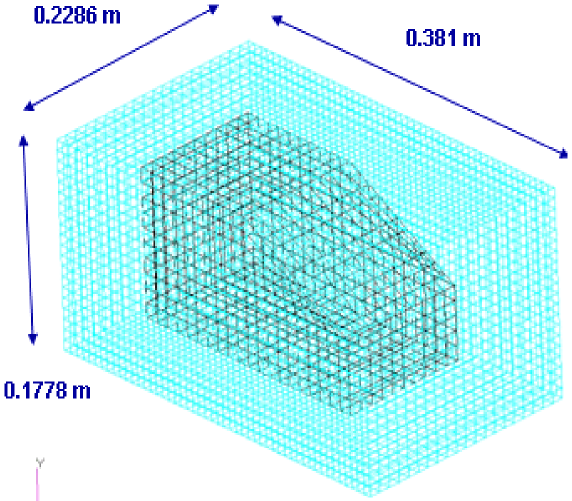

Fig.10 Fuel Tank Model Embedded In Eulerian Box For Fast Coupling

Note :
The Eulerian Mesh has to be aligned with the Basic Coordinate System for Fast Coupling

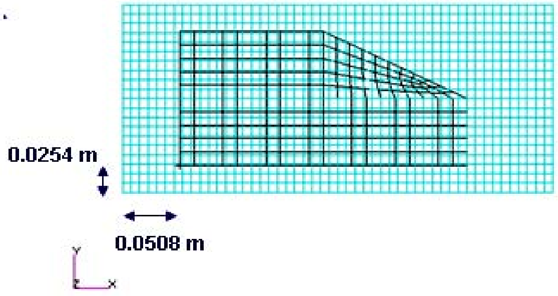

Fig.11 Location From Co-Ordinate System

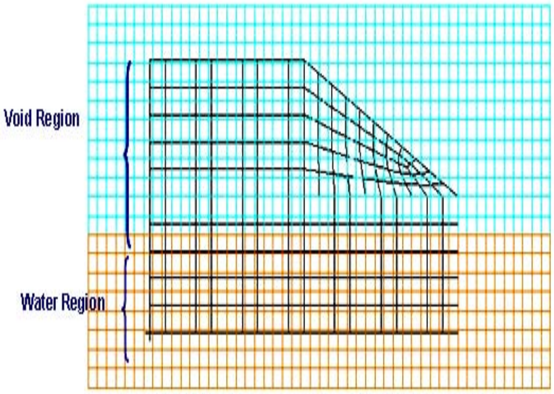

Fig.12 Specification Of Regions

Braking Velocity:
Define the braking velocity at 50 Km/hr (13.88 m/sec) as a time function
Runtime Parameters:
Simulation Time: 0.02 sec
Initial Timestup:1.0e-6
Save Output for 25 steps(0 thru end by 0.0008)

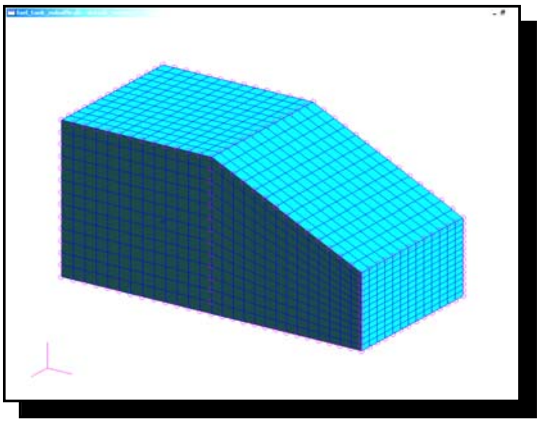

Fig.13 Elements: Euler Zone

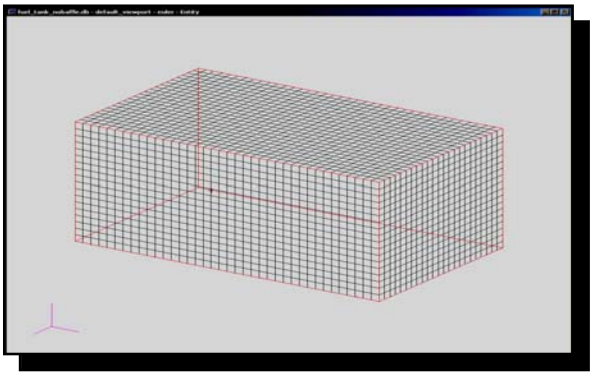

Fig.14 Materials: For Fuel Tank Structure

V. RESULTS

Following Figures are showing the simulation results at different stages

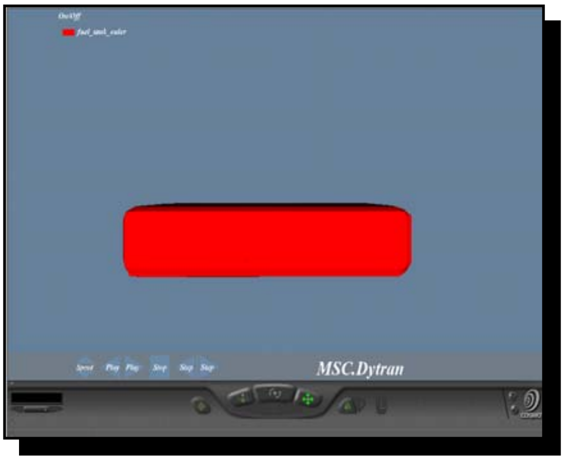

Fig.15 At Steady Condition

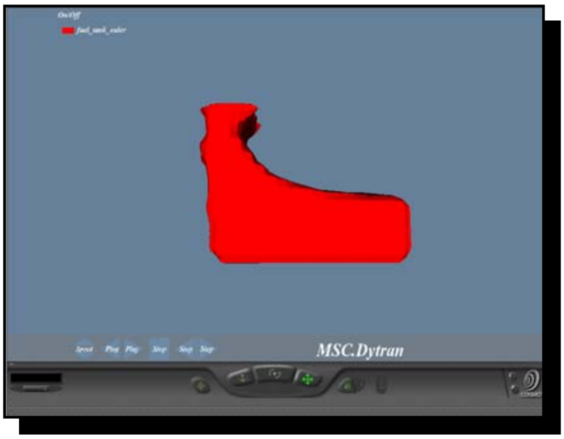

Fig.16 After Applying Brakes

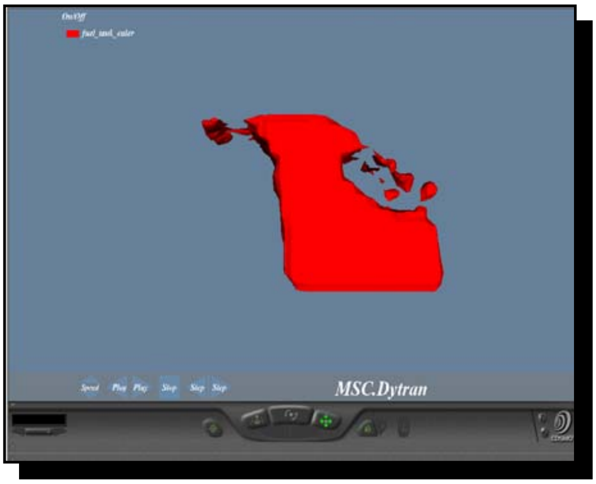

Fig.17 After Complete Stop

VI. CONCLUSION

Since sloshing pattern provides a visual aid for the preliminary study, it would help to pursue the study further for analyzing the phenomena.

Also this study would lend insight into future scope of optimizing the shape of the tank and baffle plate arrangements in the tank.

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