Design of Oil Sump using Coupled Eulerian – Lagragian (CEL) Technique

A. Vishnu Prasanna Moorthy

Engine R&D, Ashok Leyland, India

Abstract: The performance of an IC engine has an ionic bond with the performance of lubricating oil system. Oil sump and Oil Suction Pipe is one such assembly. The oil sump acts as partially filled reservoir of lubricating oil. The oil pump sucks the oil through the oil strainer which is immersed inside the oil sump. Design of oil sump involves designing for capacity, layout, engine tilt angles, and NVH. This paper deals with design of oil sump for engine tilt angles. When the vehicle is cornering / moving on roadways with inclinations, a set of complicated gravitational and inertial forces act on the lubricating oil. Due to these forces, the oil is pushed towards oil sump sides depending on the resultant of the above forces. This resulting oil movement may have serious implications on the engine performance, if the oil strainer is not immersed in oil and the pump sucks air into the lubricating oil system. The resultant forces acting on the lubricating oil system are difficult to calculate using classical design approach since it involves sloshing type fluid structure interactions. Since the problem is highly non linear and considering the importance of this design aspect, the verification has been attempted using Fluid-structure interaction capability in Abaqus Explicit. Coupled Eulerian- Lagragian technique has been used and the oil was modeled using Equation of State (EOS) – Mie Gruneisen form. The oil movement in dynamic tilting condition has been visualized and verified that sump provides oil to engine at all required tilting conditions.

Keywords: Oil sump, Tilting, Fluid structure interaction, Coupled Eulerian-Lagragian, Equation of state

1. Introduction

In an internal combustion engine, the oil sump acts primarily as a container which stores lubricating oil and supplies it to the components via suction system immersed inside it. A general layout of sump and suction – strainer system in a heavy duty diesel engine is shown in Figure 1. The amount of oil (capacity) in the sump is arrived from empirical relations involving the total oil flow rate required for rotating parts in the engine and the number of times the oil needs to be re circulated through the system. In general heavy duty diesel engines require large sump capacity in order to cater to extended oil change interval periods. In order to have such high capacities, sumps have deep well design. The positioning of this deep well (Front well / mid well/ rear well) depends on the vehicle layout. Due to standard vehicle configuration (Layout of anti-roll bars, front cross members, front axles, engine positioning, etc) mostly buses require rear well sump and trucks require front well sumps.

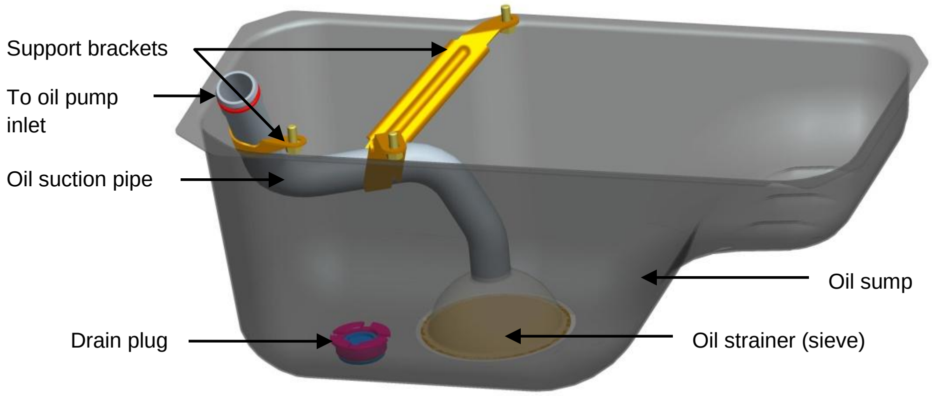

Figure 1. Layout of suction – strainer system in oil sump

As the sump has to be deep drawn, it requires a material with high ductility and the part with sufficient amount of drafts on side walls and large radii on the ends to have good formability. This in turn affects the capacity of the sump and volume distribution at critical areas. So design for manufacturing also critically affects the shape of the sump.

Another important target for this sump design is to meet the NVH criteria which are based on the overall limit targeted for the engine. Depending on the target and the cost of the system, either of the following designs can be used viz. fully decoupled design, sandwiched steel sump, semi – decoupled design and direct mounting design (in the ascending order for low NVH and in descending order of cost)

Another critical part of the design would be to meet the tilting target set for the vehicle (Depending on gradeability and operating conditions). When vehicle is tilting in any direction, the oil is pushed towards that direction. This situation is aggravated when it is combined with vehicle cornering / braking / acceleration. The resultant oil movement will depend on the resultant of the above forces. Under such conditions, system design should ensure that strainer is always immersed in the oil. If this is not ensured, oil pump will suck air into the lubricating circuit, eventually leading to the risk of engine seizure. (Due to reduction in oil film thickness)

Since it is difficult to proceed with classical design approach, it is necessary to opt for finite element analysis. The fluid structure interaction (FSI) available in Abaqus/Explicit is being harnessed to complete the design. This paper defines the analysis methodology to simulate FSI for sump & oil and using to verify the design of rear well oil sump for the new engine platform being developed in Ashok Leyland.

2. System description

The system analyzed was a rear well oil sump for the new design of heavy duty 4 cylinder diesel engine developed in Ashok Leyland. The cross section of the engine is shown in Figure 2 to understand the layout of sump and suction-strainer system.

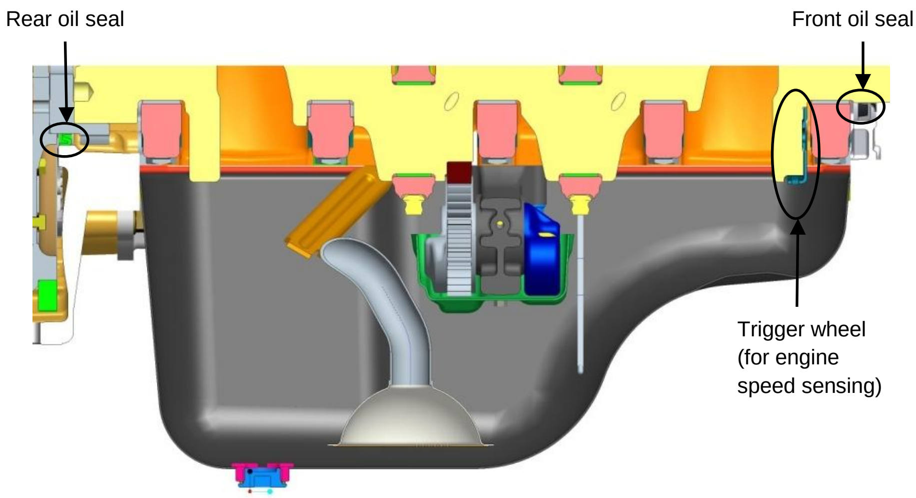

Figure 2. Cross-sectional view of the Engine

The details of the system analyzed are given below:

1. Engine : 4 cylinder common rail engine
2. Engine oil : SAE 15W40
3. Oil sump capacity : 16L
4. Max oil level : 18L
5. Min oil level : 12L
6. Installation angle : 1.5° / 3° - longitudinal, flywheel down.

Other loading conditions for a heavy duty truck as per internal company standards (ALS.010.05, 02.05.1999) are given below:

1. Max Deceleration (braking) : 0.6g
2. Cornering (acceleration) : 0.3g

where "g" is acceleration due to gravity – 9.81 m/s^2.

The tilt angle targets for the system under study are discussed in detail in the following section.

3. Tilt angle target

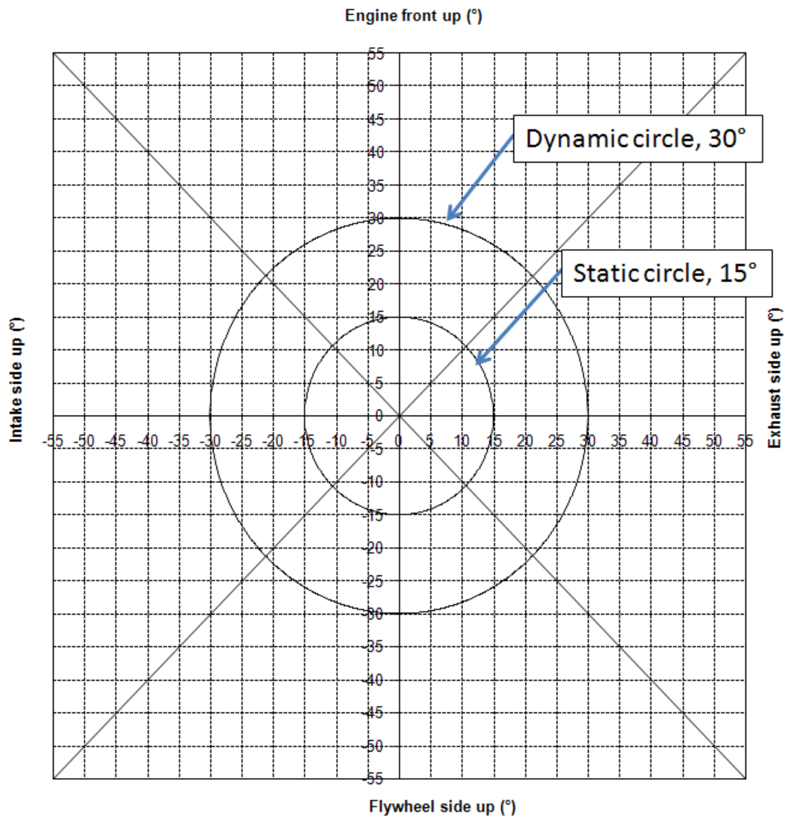

Figure 3: Tilt angle circle

In Figure 3, Stationary tilt angles represent vehicle driving conditions that can be constantly maintained (e.g. going uphill or downhill a steep road) and Dynamic tilt angles represent vehicle driving conditions that only occur for a short time (e.g. fast cornering, going downhill plus heavy braking). When operating inside the static circle, the oil should not reach the front and rear oil seal failing which will lead to oil leakage in the long run. Also the oil should not reach the trigger wheel mounted near the crankshaft front end, as it affects the engine speed sensing. When operating in dynamic circle, it must be ensured that the oil strainer sieve is immersed in oil completely.

4. Model setup- Abaqus/CAE

The pre-processing has been done in Abaqus/CAE. Following sections brief about the complete model setup.

4.1 3D model setup

The following 3D models made in CAD software are exported in .stp format. These files are then imported inside the analysis model as separate parts.

1. Oil sump – sheet metal part.
2. Oil model – Solid model representing a min volume -12L. (Worst case for oil starvation)
3. Cuboid model – To represent Eulerian mesh.
4. Oil suction – strainer system (just for display)
5. Cranktrain (just for display)

Simplified geometry of oil sump is taken to reduce the computational costs. The flange ends are extended by 80mm on the top to serve as boundary for oil. (In actual case, crankcase acts as boundary) As a best practice, the cuboid model for the Eulerian mesh is made large enough compared to the sump in order to ensure that contact is properly enforced and any unwanted loss of material from the Eulerian domain is thereby prevented during the complete course of analysis.

4.2 Material

Steel material properties have been used for sump. Oil has been modeled using equation of state (EoS) – Mie Gruneisen form. Some of the properties are placed below:

Density of steel, ρ = 7.85E-09 tonne/mm^3
Density of the oil, ρ = 8.58E-10 tonne/mm^3
Bulk modulus, K_{0s} = 1.5E+03 N/mm^2
Dynamic viscosity, η calculated from Kinematic viscosity of oil, 15 cSt at 100°C.
Coeff of thermal exp, α = $6 * 10^{-4}\ K^{-1}$
Gruniesen ratio, Γ_0 is calculated from the above properties.

4.3 Section

Solid section has been used for sump and Eulerian section for the cuboid model representing the oil.

4.4 Assembly

All the parts indicated in section 4.1 have been instanced into the assembly. A reference point is created at the bottom area of the sump to create a coupling and to facilitate the tilting boundary conditions.

4.5 Step definition

A dynamic, explicit step has been defined with a time period of 2s. The effect of this time is explained in the results section. Nlgeom is kept checked since it involves lot of non-linearity. Automatic time incrementation has been used without any mass scaling as the materials defined by EoS is not affected by mass scaling.

4.6 Interaction

Frictionless tangential property has been defined for the interaction behavior. As it involves fluid structure interaction, general contact in Abaqus/Explicit has been used.

The whole sump is coupled to the reference point defined in the assembly.

All other parts have been constrained using display body constraint and they are restrained to move along with the reference point defined for sump tilting.

4.7 Load and boundary condition

For such FSI problems, initial condition has to be defined to specify the initial volume occupied by different fluids in the 3D space defined for the Eulerian material.

To ease the effort of analyst to create such complex model, Abaqus has come up with an excellent tool, called **"Volume Fraction tool".** A pre-requisite to use this is that the Eulerian model (cuboid 3D model) has to be hex meshed. To use this both the simple cuboid model and the complex initial fluid state model (in this case the solid oil model as described in section 4.1 model description) has to be selected as shown in Figure 4.

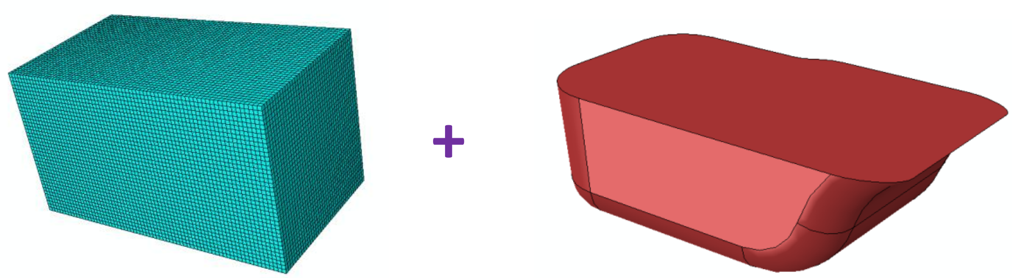

Figure 4. Eulerian model and initial oil state geometry

The volume fraction tool performs Boolean operation of solid model and the mesh. This creates a set of nodes (Figure 5) that defines the initial oil level in the sump.

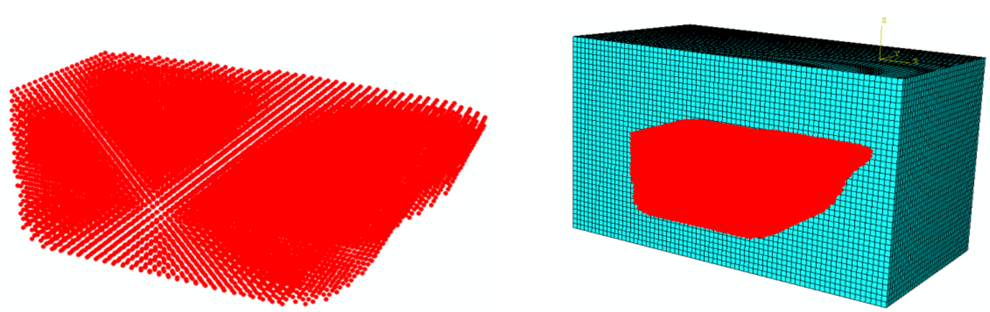

Figure 5. Nodes created from Volume fraction tool

After creation, the solid model used for the above purpose can be suppressed in the assembly in order to exclude it from the analysis. In the predefined field, the initial condition is specified by giving the material assignment for the Eulerian material using the discrete field created with the volume fraction tool.

The Eulerian mesh motion is activated in step 1 for the Eulerian material section. Oil sump is selected as the target object to follow.

In order to have realistic simulation for such problems, gravity load is applied throughout the analysis. The sump is restrained in all degrees of freedom in initial state. In step 1, the boundary condition is modified by specifying the desired angle of rotation (in radians) in desired direction. For simulation to occur without any errors, proper definition of amplitude is absolute necessary for the above two loads (Gravity and rotation)

4.8 Mesh

Sump has been meshed with second order tetrahedral elements, C3D10M. The Eulerian cuboid model has been meshed with EC3D8R elements. The details are given in Table 1 & Figure 6.

Component	No: of nodes	No: of elements
Oil sump	133357	76489
Oil (Eulerian)	115200	107991

Table 1. Mesh details

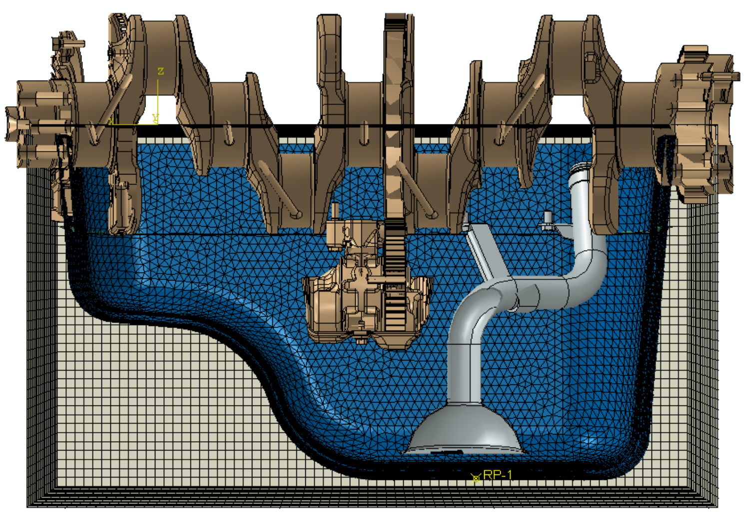

Figure 6. Sectional view of the assembly in meshed condition

4.9 Job

From iterations, it has been found that analysis of this nature requires more than 3,00,000 increments. So the double – precision executable for Abaqus/ Explicit has been used for this analysis. The job is run with domain level parallelization with 8 processors in order to reduce the total computation time. Apart from the usual field output requests, Element Volume Fraction (EVF) should be requested as field output for CEL problems.

5. Results

The model setup described above is from the final iteration. But previous iterations consist of various modifications in the setup. They are described as below:

Since the sump is a sheet metal part with 1.5mm thickness, initially it was analyzed as shell model. After analysis it was found that lot of Eulerian material penetrations were happening through the contact interface. This was primarily due to the reason that outward normal direction of all shell elements in a model is not unique. So the model setup was changed by modifying the CAD model with 10mm thickness and analyzed as solid model. The penetrations across the interface were reduced to a good extent with solid model as they have unique outward normal direction.

Initially iterations were carried out with seed size of 15 for Eulerian model as the computation time was very high. (9 hours 40 minutes with 8 processors) With this setup, the penetrations were more and loss of material from the boundary was high. Then a seed size of 10 was used. This increase in mesh density has increased the analysis time to 23 hours and 20 minutes with the same domain level parallelization. This has greatly reduced the material loss (Figure 8). This can be found out from the history output for Total energy (ETOTAL). This in general has to be constant for accurate analysis. But when there are oscillations in the system due to improper time/mass scaling, Total energy will not be constant and when there is material loss from the domain, it will further change to a negative quantity. (Comparative trend pattern shown in Figure 7)

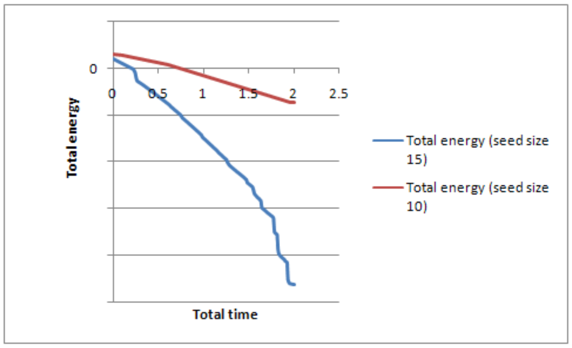

Figure 7. Total energy vs. Total time

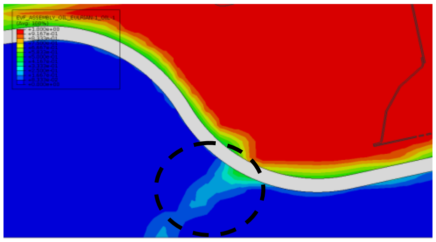

Figure 8. Material loss from domain

In actual case it will take approximately 5 -7 s for 30° tilting. But performing this analysis for such time period will take extremely high amount of increments (>> 20,00,000) and computation time will run into days. So time scaling can be used to reduce the computation time. The consequence of such time scaling will be extremely high accelerations and sloshing effects. The final iteration is performed with 2 seconds. It took 4,91,204 increments to complete the analysis. This is relatively low compared to the estimated one for actual tilting (as indicated above) and also the reason for choosing double precision Abaqus/Explicit executable. Figure 8 shows the acceleration of the one of the nodes in the Eulerian model (oil) at the end of the step.

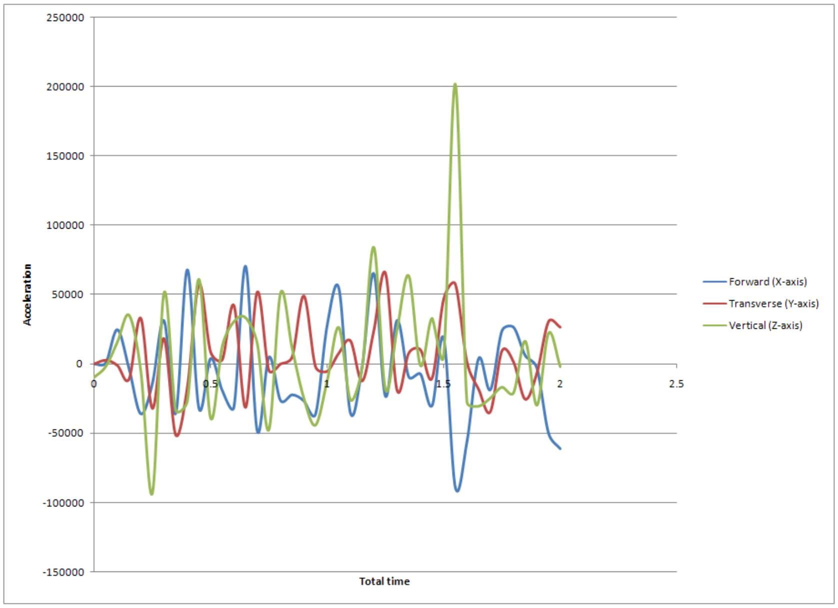

Figure 8. Acceleration of oil

Sloshing effect is inferred by the oscillations in the acceleration in all three directions. The peak acceleration shows the oil bubble lifting up into the air and returning again to the oil pool in the sump. Though gravity boundary condition was given as -9810mm/s^2 and the deceleration of 0.6g, the acceleration of the oil reach as high as ±10g. This is purely due to the time scaling effect.

For a rear well oil sump, the worst case tilting condition is taken as the downhill condition, as the oil will move out of the well portion and reach the rotating parts sooner compared to other tilting conditions. The figures 9 and 10 show the final results of oil level at 15° (static circle) and at 30° (dynamic circle). Results of other boundary conditions from tilt circle are not discussed here.

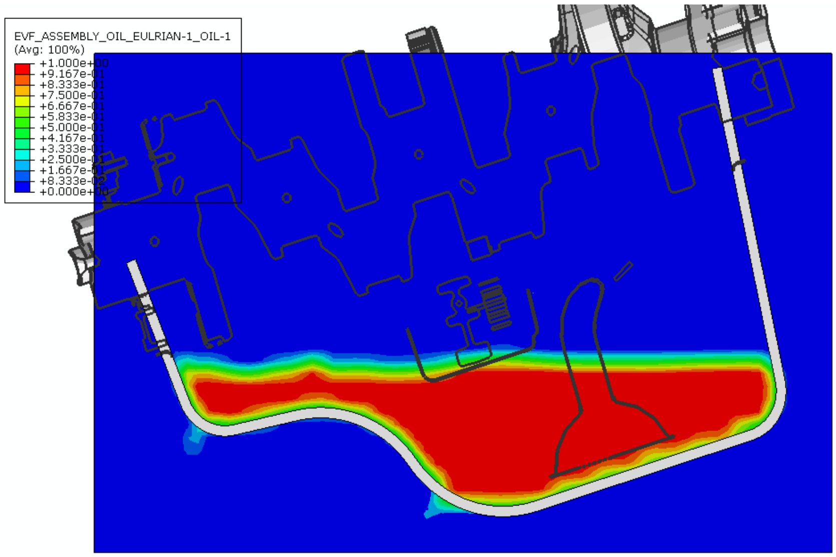

Figure 9. Downhill, 15°

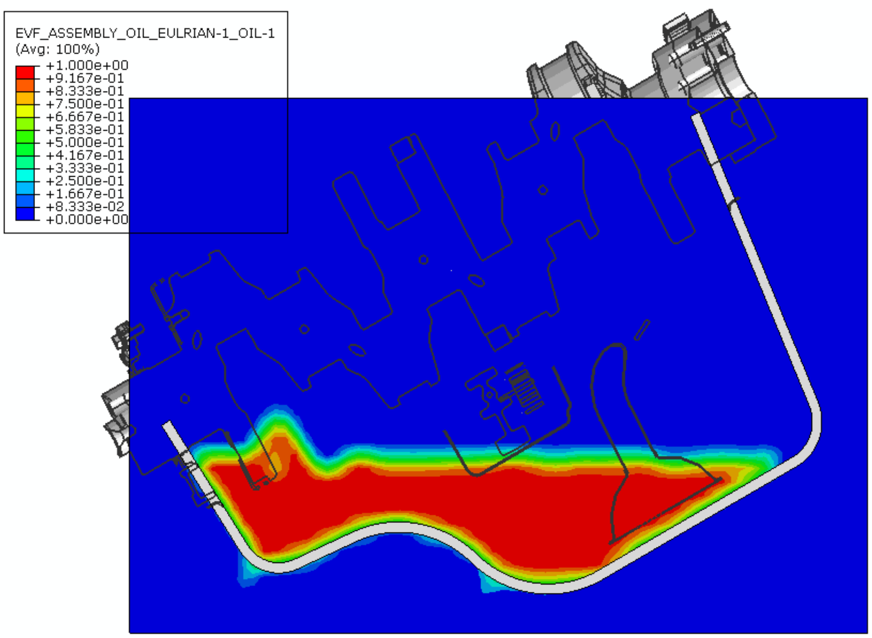

Figure 10. Downhill, 30°

6. Conclusion

The seed size of Eulerian model can still be reduced from 10 to 5 to reduce the material loss and to get constant Total energy. But the present model gives fair results and can be relied upon.

However if the seed size is reduced to 5, special method called “Selective subcycling” must be used. In this analysis model, as automatic time incrementation is used, the minimum increment is based upon the critical element. From the message file of various iterations, it has been observed that only few elements in Eulerian model those near the sump wall boundary /interface are found to be critical elements. So using “Selective subcycling”, solver uses small time increments for those critical elements only and large increments for the other elements. This way the total computation time is reduced drastically. To use this, node sets has to be created accordingly.

With the time scaling, the accelerations experienced are the worst case when compared to the boundary conditions. Even with this condition, in static circle, the oil doesn’t reach oil seals and the trigger wheel and in dynamic circle, the strainer is found to be completely immersed in oil. So the design is found to be safe.

7. References

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