Fluid Structure Interaction for Immersed Bodies

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ABSTRACT

A new method for automatically constructing the coupling surface along shell edges is developed. By using this new "edge" option together with "shell thickness" option in the *CONSTRAINED_LAGRANGE_IN_SOLID card, we can accurately model problems involving shell structures with leading edges cutting into ALE materials. Engineering problems include bird striking at propulsion system fan blades; helicopter impacting water. This new feature is implemented in the latest LS-DYNA 971 release 7600 and ready to use with minor input deck modifications.

Before, in order to correctly model the FSI, blades had to be meshed by using Lagrange solid elements. This approach can ensure an accurate coupling interface but the time step size is greatly reduced due small element sizes. The lengthy running time for the problem makes this approach impractical. The new "edge" and "thickness" feature will construct a proper coupling surface from shell elements and provide reasonable time step sizes for the simulations.

Keywords:
Fluid structure interaction, Edge coupling, ALE

1. INTRODUCTION

In the LS-DYNA ALE FSI package, the Lagrange coupling interface is represented by N-by-N quadrature points generated based on "coupling segments". These "coupling segments" are outer surface segments for solid elements and mid-surface segments for shell elements. This approach works fine for structures meshed by solid elements. But for structures modeled by shell elements, there are certain conditions that have to be met. They are: 1. Fluids on two sides of shell structures have to be of different ALE multi-material group IDs and remain on their respective sides; 2. Shell thickness should be small enough such that the thickness offset will not affect the overall system response; 3. Either shell edges do not come in contact with fluids or that coupling effect can be negligible.

These conditions causes difficulties in modeling some types of engineering problems such as shells immersed in fluids, for example, heart valves; shells impacting fluids with an angle, for example, bird striking blades. Certain engineering fixes can be taken to circumvent those difficulties. For instance, condition 1 can be met by modeling fluids on each side of shells using different ALE material IDs and switching material ID when fluids flow around structures to opposite side. Doing this, however, will double the memory usage for ALE elements and increase the CPU time drastically. Also, we may construct a dummy shell for FSI coupling purpose and attach it to the shell structures. But generally speaking, these fixes are cumbersome and costly.

The newly added "edge" and "shell thickness offset" options offered the solution by a). Generating coupling segments with an offset equals to half the shell thickness to the mid-surface shell elements; b). Generating extra coupling segments along shell edges. Compared to the engineering fixes mentioned above, it neither requires extra memory usage nor slows the calculation. Also, user effort is limited to minor modifications in the input deck.

This paper is organized as follows. We will describe some underlying difficulties for modeling immersed bodies in Section 2. We then introduce the "edge" and "shell thickness" options in the next section with some general guidelines for dealing with FSI with shells. Section 4 is a numerical example comparing results with and without "edge" option. Section 5 provides a summary and some concluding remarks.

2. MODELING IMMERSED BODIES

The fluid structure interaction between a shell structure and the fluid it is immersed in involves three key aspects: 1. Constructing coupling interface on the Lagrange structure side; 2. Constructing coupling interface on the ALE fluid/solid side; 3. Detecting penetrations between two interfaces and applying penalty forces to separate them.

In the LS-DYNA ALE FSI package, the Lagrange coupling surface consists of certain numbers of coupling segments. Those segments are either the outer surface segments for solids or mid-surface segments for shells. Then for each segment, N-by-N sampling points are generated on which the penetrations between structures and fluids are measured.

The fluid coupling surface is determined by tracking the 0.5 volume fraction interface. After each advection step, the fluid interface is reconstructed based on element/nodal volume fractions.

After the coupling interfaces have been located, the distance between two coupling interfaces is then measured at each coupling point. Penalty forces are applied to both sides of coupling surfaces if any penetration is observed. The penalty spring stiffness is determined by either a global frequency analysis, or the local frequency of the Lagrange structure side. Also, the user can specify a spring stiffness by giving a load curve defining the relation between penetration and penalty pressure.

For problems with a shell structure immersed in fluid, the above-mentioned method will have some fundamental difficulties. At first, as the shell is immersed in fluid, it is impossible to track the fluid coupling interface as now everywhere the volume fraction is 1. Secondly, shell edge segments are not included in the set of coupling segments. The fluid flowing through shell edges can not be detected and hence can not be prevented. Finally, the Lagrange surface is offset by half the shell thickness. This will cause a delay in the fluid structure interaction. While it is generally harmless for thin shells, it can cause severe distortion in the simulation result for thick shells.

There are still, however, some ways to modify the finite element model to circumvent these difficulties. The most straightforward solution would be to use solid elements instead of shells for Lagrange structures. This will cause more memory usage, more CPU time for each cycle and much smaller time step sizes and, hence, a much longer running time. The next solution in line would be to separate the fluid into two ALE multi-material groups. It leads to more memory usage and additional algorithm complexity. And still, it does not solve the problems around shell edges. Another way is to construct dummy shells conform to the Lagrange surface and constrain them to Lagrange structures. Although it can successfully resolve the coupling surfaces, this approach only works for user provided load curve coupling stiffness. The other two stiffness options involve a mass-scaling algorithm to prevent excessive penalty force applied to fluid based on local nodal masses.

3. SHELL EDGE AND THICKNESS OFFSET OPTION

The "edge" option is activated by adding "_EDGES" at the end of the *CONSTRAINED_LAGRANGE_IN_SOLID card. The Lagrange side has to be specified by part or parts. "Shell thickness offset" will be automatically turned on once "edge" option is used.

These two options will, 1. Construct coupling segments along shell element edges; 2. Offset the mid-surface coupling segments by half shell thickness towards shell normal direction. This *CLIS card will be used to couple the upper surface and edge surface of shell structures to the fluid. Another *CLIS card needs to be defined to couple the lower shell surface to the fluid. It is with the exact same setup with the exceptions of: 1. Opposite coupling normal direction; 2. "Shell thickness" option specified; 3. Edge option turned off.

Below is an example keyword input deck setup.

```
*CONSTRAINED_LAGRANGE_IN_SOLID_EDGES
$     slave    master     sstyp     mstyp     nquad     ctype     direc     mcoup
          6       200         1         0         3         4         2       -22
$     start       end      pfac      fric    frcmin      norm   normtyp      damp
      0.000     0.000     0.000              0.000         0
$        cq      hmin      hmax     ileak     pleak   lcidpor     nvent  blockage
      0.000     0.000     0.000         0     0.000         0         0         0
$4A IBOXID    IPENCHK   INTFORC  IALESOFT    LAGMUL    PFACMM      THKF
          0         0     0.000
*CONSTRAINED_LAGRANGE_IN_SOLID
$     slave    master     sstyp     mstyp     nquad     ctype     direc     mcoup
          6       200         1         0         3         4         2       -22
$     start       end      pfac      fric    frcmin      norm   normtyp      damp
      0.000     0.000     0.000              0.000         1
$        cq      hmin      hmax     ileak     pleak   lcidpor     nvent  blockage
      0.000     0.000     0.000         0     0.000         0         0         0
$4A IBOXID    IPENCHK   INTFORC  IALESOFT    LAGMUL    PFACMM      THKF
          0         0     0.000                                    1.0
```

Some users have been using this new feature and have compared results to previous setups using solid Lagrange meshes. There are several points that need to be mentioned in comparing results from those two setups.

1. At corners, coupling directions are different between shells and solids if nodal based normal is used. Segment based normal needs to be used for Lagrange solids to get consistent result with Lagrange shells.
2. The nodal mass of a shell node is two times the mass of a solid one. As the mass scaling algorithm in penalty force calculation depends on local nodal mass, this will cause deviated results unless load curve stiffness is used.
3. Time step sizes are different between these two setups. The one with Lagrange solids is much smaller. While general response should be similar, sometimes this difference can cause local discrepancies.

4. NUMERICAL EXAMPLE

To illustrate the enhanced performance brought by the new features, we study a classical bird-striking-blade problem with and without "edge" and "thickness" options.

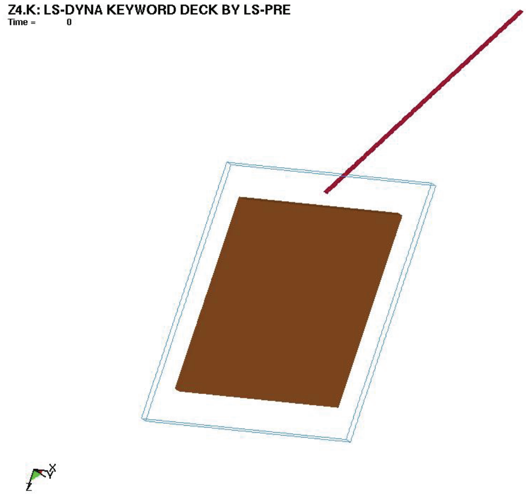

Figure 1. Bird striking blade – Problem setup and initial state.

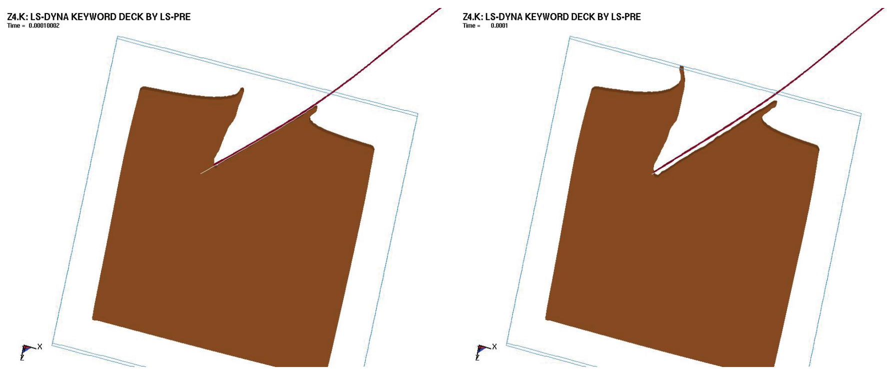

Figure 2. Bird striking blade (a) without "edge" option; (b) with "edge" option.

From the above Figure 2a, we can see that without "edge" option, the blade tip penetrated into the bird without being detected. Furthermore, as the Lagrange coupling interface was set at the mid-surface, the two fluid surfaces generated by blade cutting into bird conform to the blade mid-surface. At the blade tip, the distance between these two surfaces was zero. This contradicted the discontinuity condition at the blade tip.

We then turned on "edge" option and kept everything else unchanged. Note "edge" option automatically turns on "thickness" option. The final configuration is shown in

Figure 2b. With the "edge" and "thickness" options added, the fluid structure interaction was accurately simulated by ALE coupling method.

5. CONCLUSION

Simulations of fluid structure interactions between Lagrange shell structures and fluid requires an accurate construction of both the Lagrange and ALE fluid coupling surfaces. The interface-tracking algorithm in LS-DYNA had some fundamental defects when dealing with Lagrange shell structures.

The newly developed "edge" and "thickness offset" options in LS-DYNA ALE package greatly enhanced the accuracy and efficiency for fluid structure interactions between shell structures and ALE fluids/solids. As LS-DYNA generates extra edge coupling segments and automatically moves the surface segment, modifications to existing models are kept minimal.

REFERENCE

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