Fluid Structure Interaction with *MAT_SOFT_TISSUE and EFG Elements

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ABSTRACT

This paper presents LS-DYNA 970.5434a transient simulations for the fluid-structure interaction (FSI) in a prototype biomedical duct. Standard and element free Galerkin (EFG) elements are compared for the nearly incompressible membrane out of *MAT_SOFT_TISSUE, which is a composite reinforced hyperelastic material. The coupling of a multi-fluid arbitrary Lagrangian Eulerian (ALE) solid domain to an EFG solid domain is possible and its LS-DYNA implementation keeps developing. The paper describes particularities of this coupling. The EFG simulation for nearly incompressible materials necessitates a non-default support of 1.4x1.4x1.4 or even higher for accurate results. The EFG simulation demands higher computation times than the standard formulation with reduced integration and type 6 hourglass control. An example is shown, in which the high ratio of the elastic moduli chosen for the fibers and the bulk of the soft tissue material generates a severe hourglass problem that only the EFG method can cope with. The standard formulation, however, is remarkably robust and it proves difficult generating an extreme situation where only EFG works and the solver run would abort otherwise. So the potential of the EFG method lies in the accurate prediction without introducing non-physical energy in the system for hourglass stabilization, in situations, where selective reduced or full integration show a too stiff behavior and reduced integration has a hourglass problem. Although LS-DYNA 5434a is already much faster than 5434, a more computational efficient implementation of EFG for solid elements is required. Therefore, the features of the LS-DYNA 971 beta version, which address this lack of performance, are assessed as well. The paper features an abstracted input deck.

INTRODUCTION

The development goal for LS-DYNA is to enable the solution of coupled multi-physics problems in one run [1]. LSTC wants to provide a package that allows users to perform all their analysis [2]. So it is worth a try to evaluate novel features of LS-DYNA to assess what is already accomplished. This paper shows results for simulations with multi-material arbitrary Lagrangian Eulerian elements (ALE) for the fluid structure interaction (FSI) in a prototype valve with a soft tissue membrane. There are other sources of motivation to use LS-DYNA for this problem besides curiosity. Among them are: 1) you already have LS-DYNA and are proficient with the code ; 2) you expect the efficiency of parallel crash simulation to carry over; 3) you rely on the advanced material modeling.

The meshless element free Galerkin (EFG) formulation [3] is a novel element formulation that promises smooth and robust results without locking for high distortion problems and materials like nearly incompressible biomedical tissues. In this paper `*MAT_SOFT_TISSUE`, which is a composite reinforced hyperelastic material, is assessed. An important feature of EFG is that it does not introduce non-physical energy to control hourglass modes. Enabling EFG is typically an input deck tweaking and nearly independent of pre-processing. In this sense it is similar to enabling an implicit simulation. In 5434a implicit EFG is not yet implemented, though.

The prototype biomedical valve treated here originates from an example input deck of the FSI_TUTOR by LSTC. It goes beyond this contribution as it tests FSI with EFG besides standard elements and searches for a better representation of the soft tissue membrane domain in the ALE background mesh. The biomedical character of the simulation of the prototype duct boils down to the facts that multi-

fluids (here three) interact with a *MAT_SOFT_TISSUE structure, and the dimensions (in the millimeter scale) are smaller than in typical process engineering. The aim of this paper is to test multi material ALE formulation for solid elements (*SECTION_SOLID_ALE, ELFORM=11, MMALE) in a setting and with materials that are useful for biomedical applications. One fact should be stated right at the start: MMALE is purely explicit and mass scaling does not work. Therefore for a high spatial resolution, small solid elements, and a high degree of incompressibility, be prepared for a small timestep and a lot of cycles.

Sample Problem

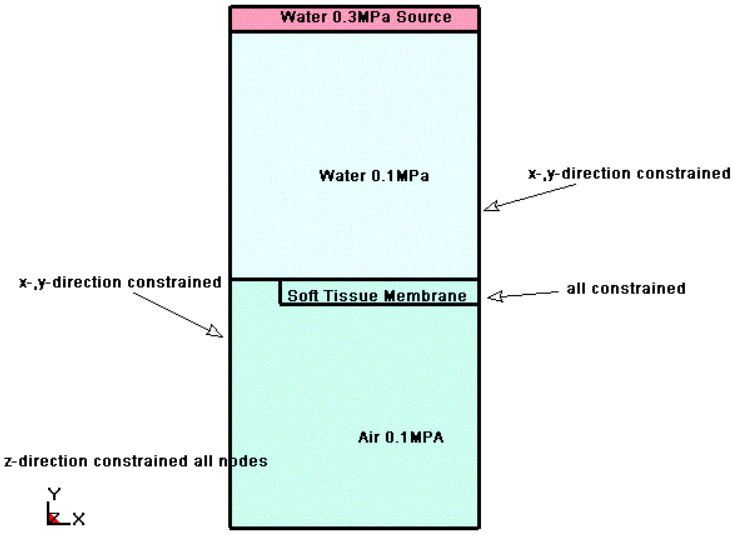

Fig 1: Geometry of the sample problem.

The sample problem consists of a prototype duct where a soft tissue membrane with an orifice separates a domain of water of 0.1MPa pressure from an air domain at atmospheric pressure (Figure 1). The water domain is forced by a step change to 0.3MPa at the upper boundary stemming from an ambient pressure source. This axisymmetric problem cannot be modeled axisymmetrically because there are no axisymmetric multi-material ALE elements. The fluids move in a mesh of one layer of multi-material ALE solids, where the z direction is constrained at all nodes. On the section card for the domain of the source AET=4, which means ambient pressure source. The forcing pressure is induced by the E0 parameter on *EOS_GRUENEISEN. On the inside or axis and outside the x- and y-direction are constrained. The support of the nearly incompressible soft tissue membrane is fully constrained on the outer side. The membrane is modeled with *MAT_SOFT_TISSUE. This is a Mooney-Rivlin rubber that is reinforced by stiffer fibers. For the Mooney-Rivlin parameters C1 and C2 prototype values of 5MPa are assumed; and the modulus of the fiber is 500MPa. The fibers are directed in the through-thickness direction of the membrane in order to generate a hourglass problem. A bulk modulus of 5GPa is assumed. An abstracted input deck is in the appendix.

FSI in LS-DYNA is the *CONSTRAINED_LAGRANGE_IN_SOLID card. This paper focuses on penalty coupling, which is typical for airbag simulation. Coupling by constraints seems to be a somewhat legacy feature. A reasonable fine mesh and

tweaking of the parameters provide for a simulation without apparent leakage [4]. It is a good practice to cover the solid rubber domain, which is slave to the ALE domain, with a layer of shells out of *MAT_NULL. As the main focus of LS-DYNA is the coupling to a Lagrangian shell structure like airbags, cards like *DATABASE_FSI, *INITIAL_VOLUME_FRACTION_GEOMETRY and FSI in general work better this way at the moment. Here FSI is formulated with reference to this shell surface. So the modeling allows for the aesthetically pleasing result that the domain occupied by the rubber solids is empty (filled with *MAT_VACUUM) in the ALE background mesh and no outer fluid enters it. This modeling technique might be absolutely necessary in some applications. The coupling.k part in the appendix gives further information.

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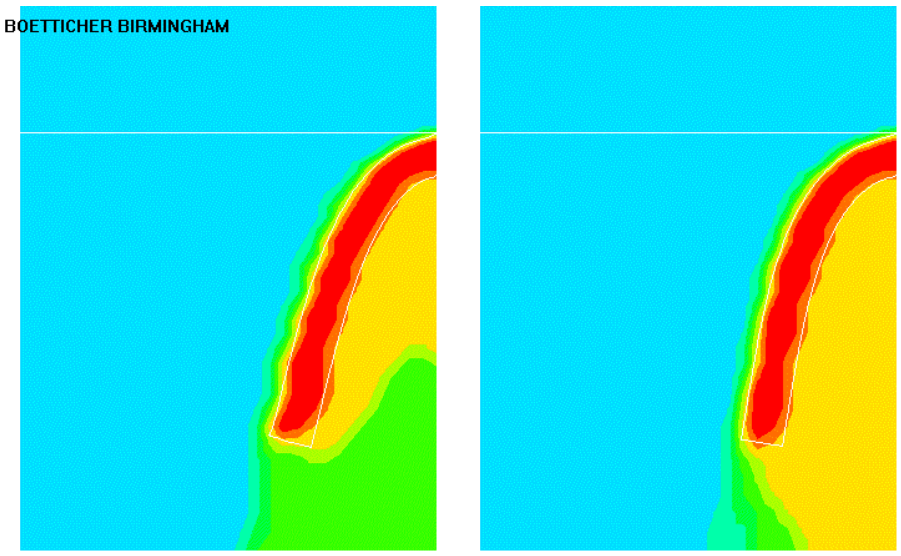

Fig 2: A volume fraction distribution where in the case shown at the left the hourglass coefficient has not been explicitely scaled down. Then counterforces are generated by default even for MMALE solids. Even for a double precison run the lower fluid rises non-physically at the outer wall. The simulation on the left, which uses *HOURGLASS,1,1,.00001 with HGEN=1 on the *PART card for the MMALE solids, shows a more realistic picture. The model posesses a filling of the soft tissue domain with *MAT_VACUUM that provides that this domain remains spare in the ALE background mesh and no outer fluid enters this domain.

LS-DYNA treats EFG pretty much like just another element formulation and, therefore, EFG in LS-DYNA is easy. The user just has to tweak the input deck by inserting a *CONTROL_EFG card and change a *SECTION_SOLID to *SECTION_SOLID_EFG with ELFORM=41. The meshless character of the method is not apparent to the user in plots. Previous investigations [4-6] led to the advice to prescribe a bigger non-default support of at least 1.4x1.4x1.4 on the second row in *SECTION_SOLID_EFG for nearly incompressible materials, which have a high Poisson's ratio and a high bulk modulus. Note that EFG decks run faster in 5434a than before. So, always use the newest version! This paper compares the EFG formulation to the standard formulation for solids (ELFORM=1, reduced integration) with hourglass control type 6, which is preferred by implicit simulations.

Results

Figure 2, which shows a time point of the transient development of the displacement of the membrane, displays the influence of the default hourglass control that may be easily overlooked like in [4]. If the user does not bother about hourglass control, as it seems not applicable to MMALE solids that do not deform, the generation of counterforces according to the default hourglass control type 1 is active. For a correct solution forces have to be scaled down explicitly!
Figure 3 displays a comparison of the standard formulation `ELFORM=1` with hourglass control type 6 and default parameters, and EFG solids for the soft tissue membrane. Figure 4 displays the internal energy and the hourglass energy, only nonzero for the standard formulation, in the membrane. This example clearly shows the power of the EFG formulation for generating smooth results. In spite of employing non-physical energy to control hourglass modes in the standard formulation the hourglass modes are not prevented and the internal energies become unequal. For full integration (`ELFORM=3`) the results show a non-physical dilatational deformation of the membrane with strong negative growth of the internal energy [6]. The standard formulation is, however, pretty robust and it proves difficult generating an extreme situation where only EFG works and the solver stops for the standard formulation by choosing an even softer tissue.
An influence of the timestep on the FSI results was observed in former work [4]. Change of the automatically calculated timestep by a higher degree of incompressibility, higher bulk modulus or higher Poisson's ratio, or by the `TSSFAC` parameter on `*CONTROL_TIMESTEP` altered the results considerably. Therefore, the variation of the simulation results with a higher Poisson's ratio could not be discriminated from timestep effects. There still exists a damping influence of `TSSFAC`. This damping effect is greater than the difference between using the van Leer scheme (`METH=2` on `*CONTROL_ALE`) and the simple donor cell scheme (`METH=1`). The van Leer scheme is recommended as it shows less dissipation and dispersion and is used here. It could be ruled out that the difference between single or double precision solver is the source of the damping effect. So this damping seems to be a function of the count of advection cycles. Smartly controlling this count remains a task for future work. However, one effect regarding the initial one hundred timesteps has been tracked down now. Smaller elastic parameters lead to an intrusion of the lower fluid through the interface. Scaling down these initial timesteps to artificially small values by calling a respective curve with the `LCTM` parameter on `*CONTROL_TIMESTEP` prevents this intrusion (Figure 5).

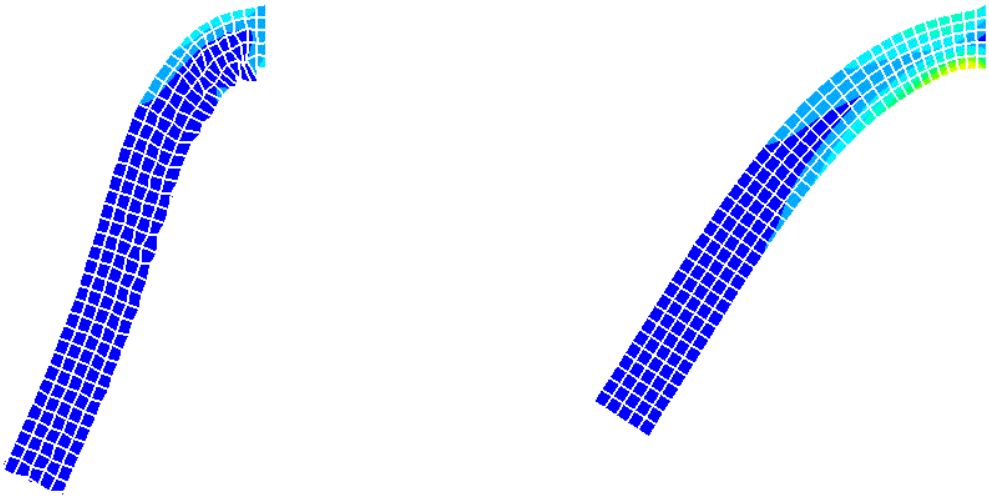

Fig 3: In this plot of the vMises stress the soft tissue membrane on the left shows a hourglassing pattern in spite of using a hourglass control type 6 with default parameters that generates non-physical energy to control hourglass modes. On the right the mebrane is modelled with EFG elements for the same case. No hourglass pattern is apparent and no non-physical energy for controlling hourglass modes is generated.

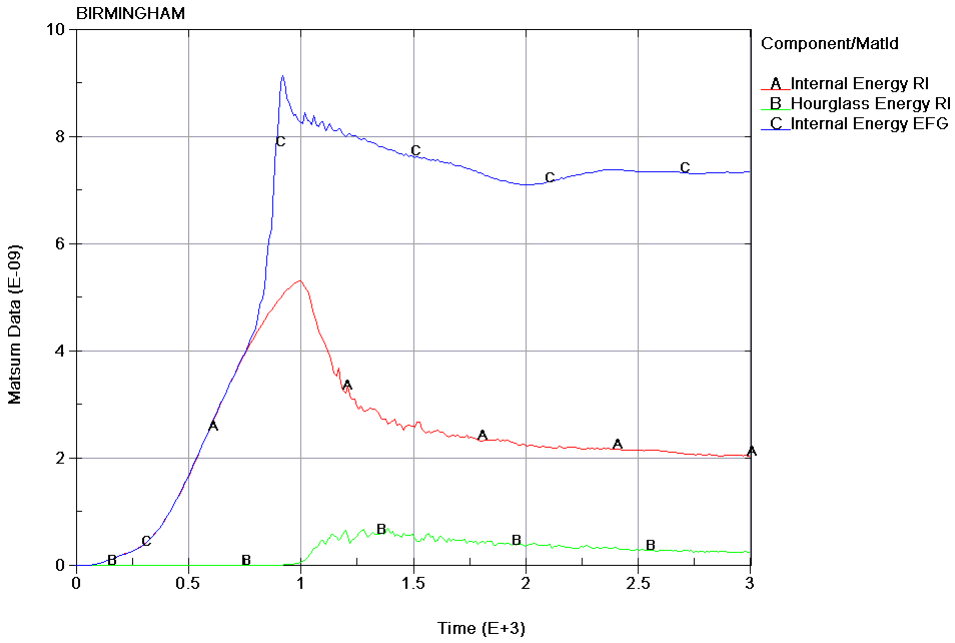

Fig 4: Internal and hourglass energy in the membrane.

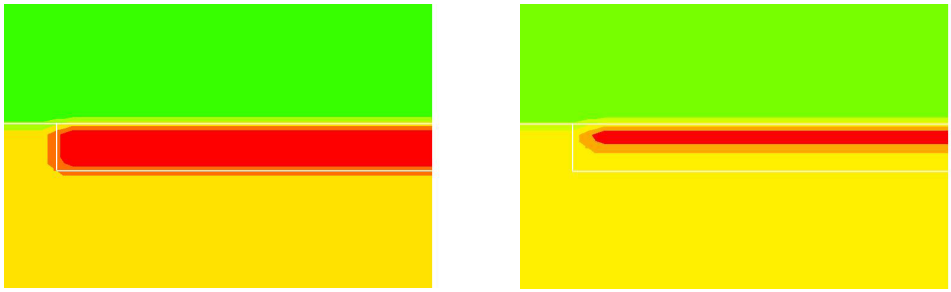

Fig 5: Volume fraction distribution after 100 cycles. On the left with artificial shortening of the timestep. With default timestep, as shown on the right, the lower fluid intrudes.

In spite that only 400 of the 4060 solid elements in the (double) model are switched to EFG, the CPU time increases by 24%. In LS-DYNA 971 three new features, EFGPACK, mixed transformation method, and two-point Gauss integration, are implemented to speed up the EFG solid computation. EFGPACK, specified on `*CONTROL_EFG`, was added to automatically compute maximum workspace in the initialization phase and to improve efficiency in the matrix operation, linear solving and memory assignment. On the `*SECTION_SOLID_EFG` now various method for imposing essential boundary conditions and transformation can be prescribed as shown in the appendix. With the 971.4308 version the model for bending of a `*MAT_SOFT_TISSUE` EFG beam has a smaller computation time [6]. However, the internal energy stored by the bending differs for different approximations. Additionally, the FSI in the full MMALE deck does not work at the moment and the assessment has to be postponed until the release of LS-DYNA 971.

Summary and Conclusions

FSI with EFG and MMALE is possible with LS-DYNA. For a proper initialization of the fluid structure interface the first one hundred timesteps should be made artificially small. The hourglass coefficient in the MMALE solids must be scaled down explicitly. For a composite hyperelastic material like *MAT_SOFT_TISSUE and for a high ratio of the moduli of fiber and bulk material standard elements with reduced integration and hourglass control type 6 may show hourglass patterns. A substitution with EFG elements with non-default 1.4x1.4x1.4 support can prevent these hourglass patterns. On the other hand is the standard formulation remarkably robust and it proves difficult generating an extreme situation where only EFG works. Version 5434a shows promising advances in the efficiency of the implementation of EFG solids. The 971 beta version introduces an even faster implementation; however the full FSI model does not work at the moment. The damping effect due to shortening of the stable time step needs further investigation in the future.

References

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2. Cleve Ashcraft, Roger Griemes and Bradley Maker, “Experience with LS-DYNA implicit MPP”, 8th Intern. LS-DYNA User Conference, 2004, Dearborn
3. C.T. Wu, "Element Free Galerkin (EFG) Method in LS-DYNA", LSTC seminar notes, 2004

4.
5. Rudolf Bötticher, “Comparison of EFG and Standard Elements for the Rubber Membrane of a Biomedical Valve”, 22. CADFEM Users` Meeting, 2004, Dresden
6. Rudolf Bötticher, “Comparison of EFG and Standard Elements for Thermo-mechanical Metalforming Simulations”, 3. LS-DYNA Forum, 2004, Bamberg, www.dynamore.de
7. Rudolf Bötticher, Supplementary Material Published at www.rudolf-boetticher.de

Abstracted Input Deck

```
*KEYWORD
$main deck
*TITLE
Boetticher Birmingham
$ I modelled the generation of node coordinates, element connections and
$ SPC constraints using ANSYS APDL. Then I edited the input deck with a
text
$ editor. This is for me a logical milestone of a LS-DYNA simulation.
*NODE
$ 10mm radius duct with 20mmm length and 1mm length of the ambient pressure
$ source is treated here
$ the soft tissue membrane has a 8mm radial extension and is 1mm thick
$ constraints are given with *BOUNDATY_SPC rather than on *NODE
     1 0.000000000E+00 2.000000000E+00 0.000000000E+00       0       0
*ELEMENT_SOLID
       1      1      1       3      34      33      64      65      96
95
*ELEMENT_SHELL
    4061       5    3847    3845    3914    3915
*SET_NODE_LIST
       1     0.000     0.000     0.000     0.000
       1         2        63        64       125       126       156
157
*BOUNDARY_SPC_SET
$ no movement in x- and y-direction on inner and outer side
       1         0         1         0         1         0         0
0
*SET_NODE_LIST
       2     0.000     0.000     0.000     0.000
       3         4         5         6         7         8         9
10
*BOUNDARY_SPC_SET
$ just one slice of solids, no movement in z-direction
       2         0         0         0         1         0         0
0
*SET_NODE_LIST
       3     0.000     0.000     0.000     0.000
      32        33        34        35        36        37        38
39
*BOUNDARY_SPC_SET
$ fixed support of the soft tissue membrane
       3         0         1         1         1         0         0
0
*INCLUDE
addendum3D.k
*INCLUDE
coupling.k
*END
*KEYWORD
$addendum3d.k file
*CONTROL_STRUCTURED
*CONTROL_TERMINATION
$ unit of time is mcrs=E-6 s
$ units of deck are g-cm-mcrs-K
$ this means unit of pressure is 100 GPa approx. 1 Mbar
$ this means unit of work/energy is 0.1 MJoule
```

```
$ Another input deck was prepared in SI units like in CFX that avoids small
$ numbers in the computations. There was virtually no difference in the
$ results and run times. With the new compilers the error-prone scaling of
$ material properties does not pay off in better results. I, therefore,
$ recommend to build future decks in SI units. It is easier to find
material
$ values in SI units.
$ ENDTIM
3000
*CONTROL_TIMESTEP
$ for a proper initialization of the FSI-interface, the timestep has to be
$ small in the beginning
,,,,,222
*DEFINE_CURVE
222
0,1.E-2
1,1.E-2
10,1
10000,1
$ DATABASE CONTROLS
*CONTROL_ENERGY
         2         2         2         2
*DATABASE_EXTENT_BINARY
         0         0         3         1         0         0         0
0
         0         0         4         0         0         0
*DATABASE_BINARY_D3PLOT
        50                   0
*DATABASE_BINARY_D3THDT
        50
*DATABASE_GLSTAT
        10
*DATABASE_ELOUT
        10
*DATABASE_MATSUM
        10
*CONTROL_ALE
$ van Leer scheme is recommended, however simple donor cell advection
$ delivers fair results
$ playing around with NADV and PRIT did non solve the problem of spurious
$ stiffening of the rubber membrane for short time steps
$    DCT      NADV      METH      AFAC      BFAC      CFAC      DFAC
EFAC
       2         1         2   -1.0000
$    START       END     AAFAC      PRIT    VLIMIT       EBC
,,,,0
$=========================================================================
===
$ PART, SECTION, MAT and EOS DEFINITIONS
$=========================================================================
===
$ MMALE (ELFORM=11) FORCED BY AMBIENT PRESSURE INFLOW (AET=4)
$ -----------------------------------------------------------------------
---
*PART
ambient pressure source with 3 MPa
$    PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
TMID
       1         1         1         1         1         0         0
0
*SECTION_SOLID_ALE
$    SECID    ELFORM       AET
         1        11         4
$     AFAC      BFAC      CFAC      DFAC     START       END     AAFAC

*MAT_NULL
$ Ref.: Horst Stoecker (Ed.), Taschenbuch der Physik, 1994, Harri
Deutsch:Ffm.
$ p. 152 density: g/cm**3=1.E-3*kg/m**3
$ p. 588 viscosity: Pa s is approx. 1.E-5 Mbar*mcrs
$    MID       RHO        PC        MU     TEROD     CEROD        YM
PR
```

```
       1     1.003  .0000000  1.002e-8  .0000000  .0000000  .0000000
.0000000
*EOS_GRUNEISEN
$ the energy/pressure source given bei E0 forces the system with (E0*GAMMA)
$ 3.E-6*100 GPa = 0.3 MPa approx. 3 bar
$ C has the unity of velocity (cm/mcrs= 1.E4 m/s) and is of the order
$ of velocity of sound
$ S1 and GAMMA are dimensionless   Ref.: FSI_TUTOR
$ another reference for S1=1.92 is p. 63 of
$ Mark L. Wilkins, Computer Simulation of Dynamic Phenomena, 1999,
Springer: Berlin
$    EOSID       C        S1        S2        S3     GAMMA         A
E0
       1     0.165  1.920000  .0000000  .0000000  0.100000  .0000000
3.0000e-5
$       V0
  .0000000
$=========================================================================
===
*PART
upper fluid - water at 293K and normal pressure
         2         2         2         2         1         0         0
*SECTION_SOLID_ALE
         2        11

*MAT_NULL
$      MID       RHO        PC        MU     TEROD     CEROD        YM
PR
         2     1.003  .0000000  1.002e-8  .0000000  .0000000  .0000000
.00000
*EOS_GRUNEISEN
$    EOSID         C        S1        S2        S3     GAMMA         A
E0
         2     0.165  1.920000  .0000000  .0000000  0.100000  .0000000
0.0
$       V0
  .0000000
*PART
lower fluid - air domain at 293K and normal pressure
$ that means normal pressure
         3         3         3         3         1         0         0
*SECTION_SOLID_ALE
         3        11

*MAT_NULL
$ Ref.: Horst Stoecker (Ed.), Taschenbuch der Physik, 1994, Harri
Deutsch:Ffm.
$ p. 587 density: g/cm**3=1.E-3*kg/m**3
$ p. 588 viscosity: Pa s is approx. 1.E-5 Mbar*mcrs
$ p. 590 heat capacities: unit of work is 0.1 MJoule here
         3  1.293e-3  .0000000 1.840e-10  .0000000  .0000000  .0000000
.00000
*EOS_IDEAL_GAS
3,718E-8,1005E-8,0,0,293,1.0
*MAT_SOFT_TISSUE
$ the reinforcment (collagen) does not support compressive loads
$ prototype parameters (unit 100 GPA approx. Mbar)
$ C1,C2 Mooney Rivlin Parameters 5 MPa, C2 should be positive
$ see the reference to the work of Weiss&Quapp&Puso in LS-DYNA manual
$ (with C3=C4=C5=0 the behavior is very similar to MAT27)
$ C5 fiber modulus 500 MPa, initially stretched XLAM=1.0
$ XK bulk modulus 5 GPA; 0.5-C1/CK is an estimate for Poisson`s ratio
$MID,RHO,C1,C2,C3,C4,C5
4,1.0,0.00005,0.00005,0,0,0.005
$XK,XLAM
0.05,1.0,0

$fiber orientation in material y direction
0,1
*PART
Lagrangian soft tissue membrane
$ standard element formulation
```

```
         4        11         4         0         6         0         0
$ EFG formulation
$        4         5         4         0         0         0         0
*SECTION_SOLID
$ standard is reduced integration (RI)
11,1
*HOURGLASS
$ implicit prefers this type
6,6
*HOURGLASS
$ control parameter for MMALE must be scaled down explicitly!
1,.00001
*CONTROL_EFG

$2      in 971 for using EFGPACK
*SECTION_SOLID_EFG
$ for consistent simulation non-default 1.4x1.4x1.4 support at least is
$ recommended in 5434a see: www.rudolf-boetticher.de
5,41
1.4,1.4,1.4
$1.4,1.4,1.4,,,2,2      in 971 for envoking mixed transformation
$ with two point Gauss integration
*END
*KEYWORD
$ coupling.k
*SECTION_SHELL
$ null shells as border line; should be bypassed while processing
        18         2    1.0000       2.0       0.0       0.0         0
  0.01      0.01      0.01      0.01      0.00
*MAT_NULL
$ ghost density of air used
18,1.293E-3
*PART
Shell-Border
5,18,18
*MAT_VACUUM
$ filling for the domain occupied by the Lagrangian soft tissue
$ in the ALE background mesh ghost density of air assumed
17,1.293E-3
*SECTION_SOLID_ALE
17,11

*PART
$ the following part does only appear in SelPar in LS-PrePost,
$ if the FLUID box is ticked
Filling ALE Background
11,17,17
*SET_PART_LIST
2
1,2,3,11
*SET_PART_LIST
3
4,5
$ if you have a double model like in some pictures of this paper
$ such part lists are useful to identify the fluids left and right
*SET_PART_LIST
11
1
*SET_PART_LIST
12
2
*SET_PART_LIST
13
3
*SET_PART_LIST
14
11
*ALE_MULTI-MATERIAL_GROUP
$      SID   SETTYPE
        11         0
        12         0
        13         0
```

```
        14         0
$
*CONSTRAINED_LAGRANGE_IN_SOLID
$ coupling: slave is surface of null shells
$ PFAC has been reduced to 0.1 from the default 0.5 of CTYPE=5
$ DIREC=3 showed less optical leakage
$ the mesh is fine and NQUAD may be left on default
$  SLAVE    MASTER     SSTYP     MSTYP     NQUAD     CTYPE     DIREC
MCOUP
       5         2         1         0         0         5         3
0
$    START       END      PFAC      FRIC
,,0.1
$,,-111

*DEFINE_CURVE
$ the user may specify a penalty curve; obviously the advice for airbags
$(1 bar for 1 mm) is not good for small dimensions and high pressures
111
0,0
0.01,3.E-5
*INITIAL_VOLUME_FRACTION_GEOMETRY
$ puts the vacuum filling in the rubber domain
$ a single command has to be used; multiple commands do not work
13,0,3
1,1,4
5,1,1
*END
```