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Veryst Engineering | Engineering Through The Fundamentals

Lasergate Leaf Dynamics
Part 2: Effect of Initial Condition and Partial Stress

Andrew Spann, Ph.D.
Senior Engineer
aspann@veryst.com

James Ransley, Ph.D.
Senior Engineer
jransley@veryst.com

Nagi Elabbasi, Ph.D.
Principal Engineer
nelabbasi@veryst.com

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contact@veryst.com
www.veryst.com

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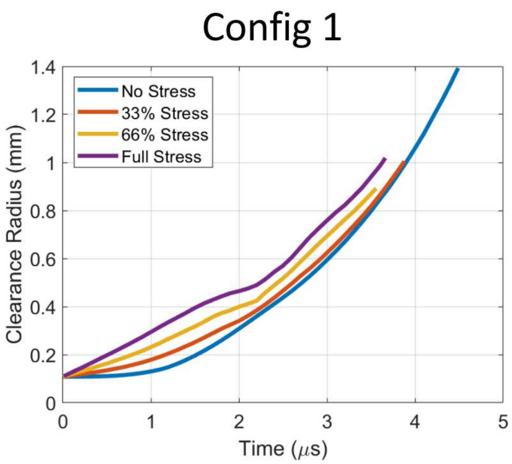
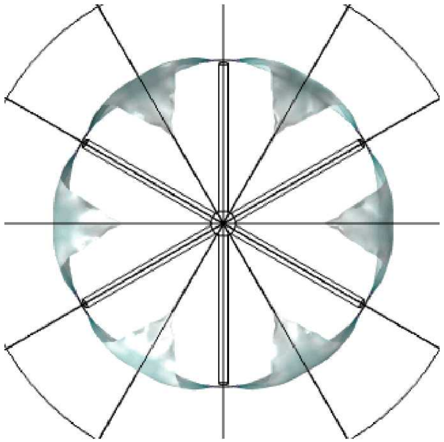
Executive Summary

- An improved meshing scheme allows simulations to proceed further than before, though convergence difficulty is still encountered upon full opening
- Changing the initial shape of the window does not greatly affect the rate of opening
- Changing the initial window stress greatly affects the initial snap-back upon opening, but the long-term trendline as full opening nears is less strongly affected
- At 60 psi pressure, the opening time is approximately 4-4.5 µs for the configurations tested in this study





100% Stress, t = 3.5 µs

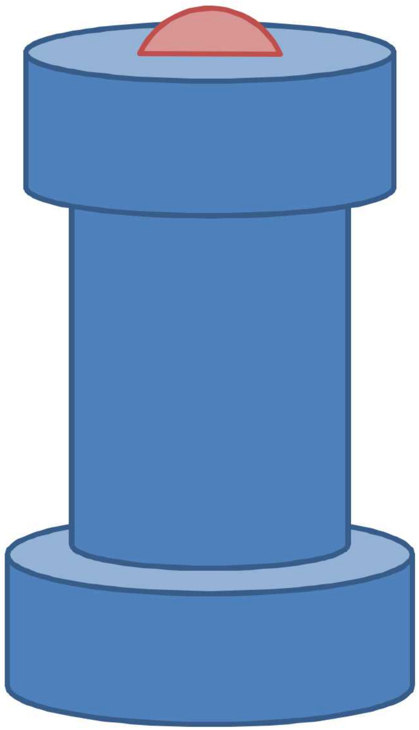
Outline

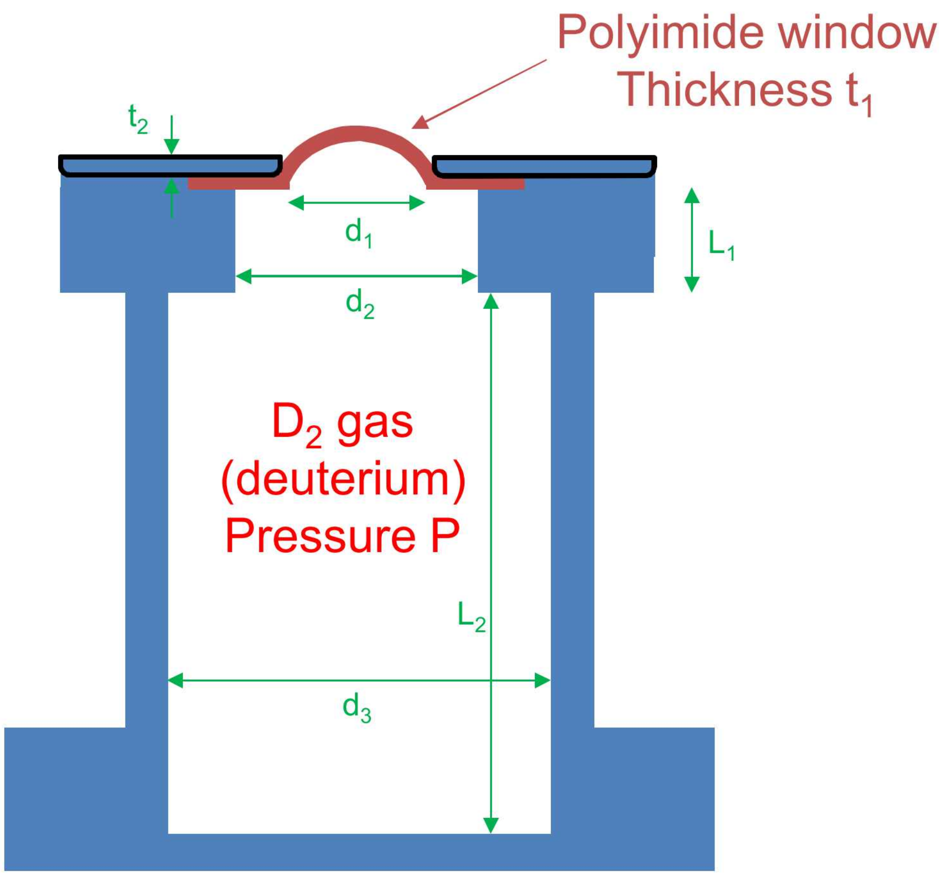
- Simulation Setup
- Window Opening Starting from Different Shapes (link)
- Window Opening: 60 psi Shape, Different Stress Levels (link)
- Conclusion (link)
- Appendix: Mesh Resolution Tests (link)

Simulation Setup

Gas Cell Geometry

- Geometry diagram as received from Sandia





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Gas Cell Geometry Parameters

- In most simulations we neglect the height t_2 of the top plate above the window
- All gas cell walls other than polyimide window assumed to be rigid
- In this slide deck, we investigate Config 1 as well as a 60 psi version of Config 2

Constant Dimensions	Variable Parameters
$L_1 = 2$ mm $L_2 = 12$ mm $d_2 = 3$ mm $d_3 = 4.6$ mm $t_2 = 600$ μm	Config 1: $d_1 = 3$ mm $t_1 = 1.77$ μm P = 60 psia Config 2: $d_1 = 2.2$ mm $t_1 = 1.56$ μm P = 90 psia Config 3: $d_1 = 2.2$ mm $t_1 = 1.56$ μm P = 120 psia

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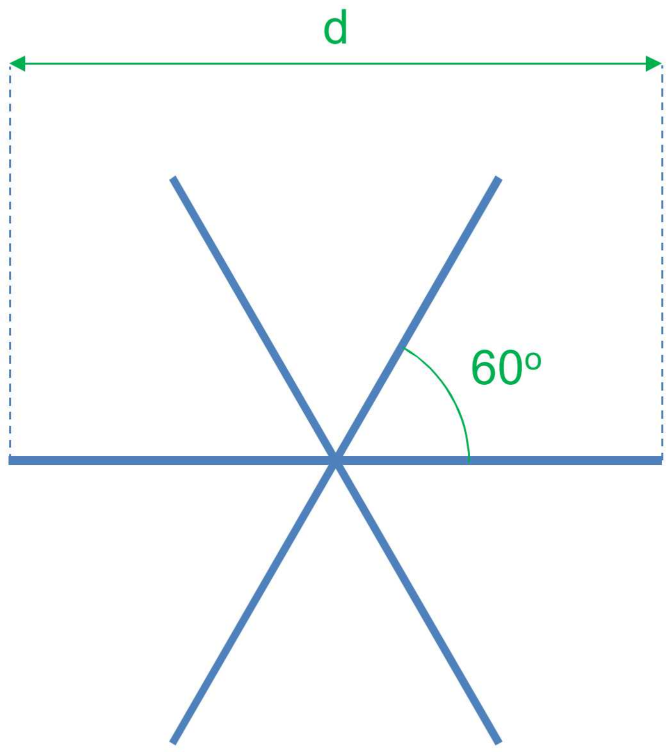
Asterisk Geometry

- Geometry diagram as received from Sandia



Variable Parameters

2mm Asterisk:
d = 1.85 mm
110 μm wide

3mm Asterisk:
d = 2.96 mm
177 μm wide

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Polyimide Window Properties

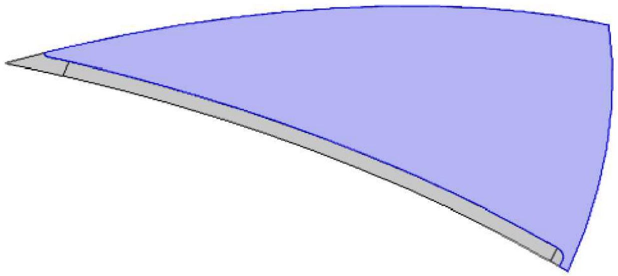
- A range of properties are reported for polyimides; we use the following representative values

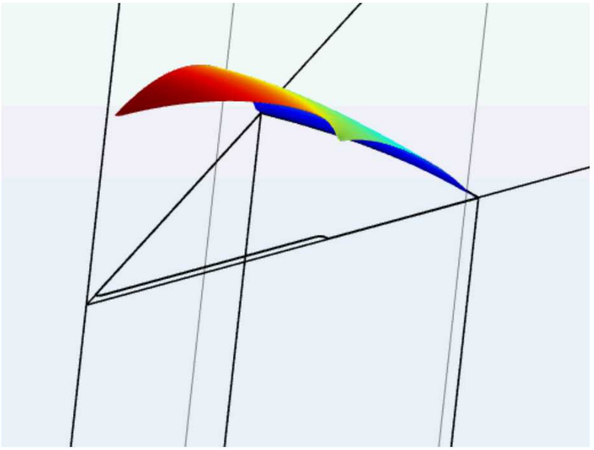
Parameter	Value
Young's Modulus E	3 GPa
Poisson Ratio ν	0.35
Density ρ	1420 kg/m^3

- In our simulations, we use a nearly-incompressible hyperelastic neo-Hookean model with the following parameters which are equivalent in the limit of small deformation
  - $\mu = \frac{E}{2(1+\nu)}$
  - $\kappa = \frac{E}{3(1-2\nu)}$
- We are aware of the limitation that using a hyperelastic material model for a compressible material (ν=0.35) is not ideal, but we do not expect results to be significantly affected

3D Symmetry

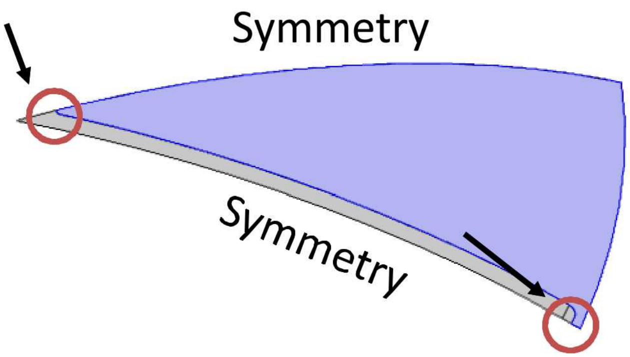
- Cylindrical gas cell is assumed to be symmetrically divided into 12 half-sectors, 30° each
- We have previously established that the opening rate did not change greatly when using 6 sectors of 60° each and an asymmetric asterisk design

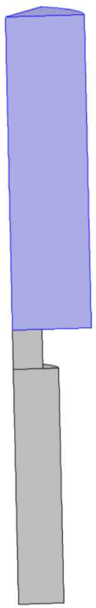




Simulation Notes

- Asterisk corners rounded for numerical stability, 20 μm radius
- Simulation uses laminar flow
  - Flow will quickly become turbulent at the opening, so the spreading of the jet is not fully accurate with a laminar flow
  - We looked into incorporating a RANS turbulence model and also High Mach Number flow in COMSOL but encountered convergence issues
- External air domain has 8 mm diameter, extends 16 mm past cell
- Pressure boundary at far end, walls/symmetry on sides
- For numerical stability, vacuum pressure is 0.1 atm and other pressures are gauge pressures above this





COMSOL Fluid-Structure Interaction

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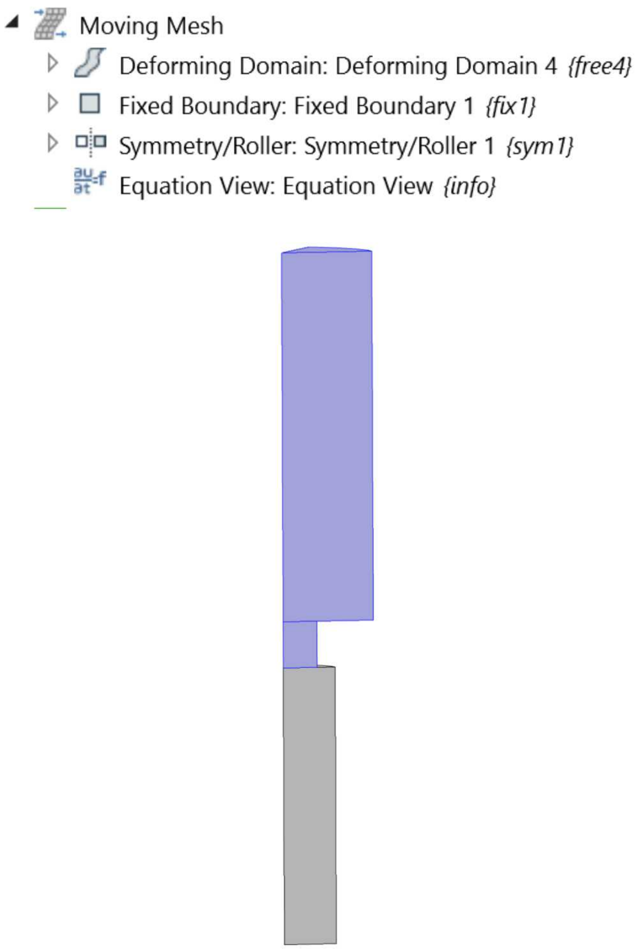
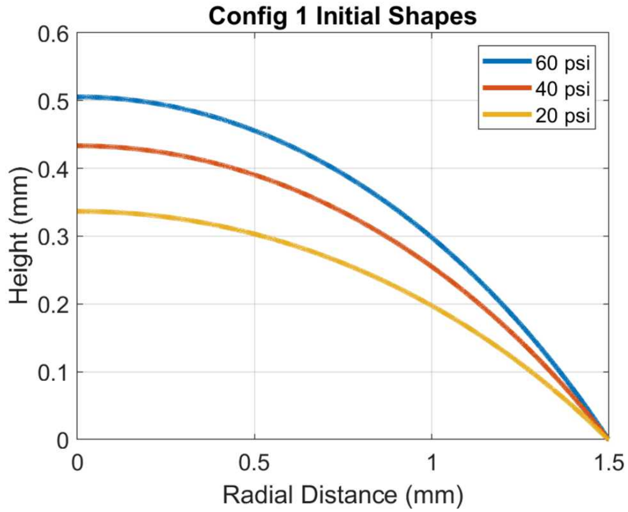
- Fluid-structure interaction implemented in COMSOL using a moving mesh
- To obtain initial condition, solid mechanics problem solved for using a pressure load on bottom surface of window
- Mesh for entire fluid domain typically has ~100,000 elements, and is more refined near the window than further away
- In these simulations, we have assumed that the membrane is not under pre-stress (other than the initial pressurization of the chamber), but this is straightforward to change

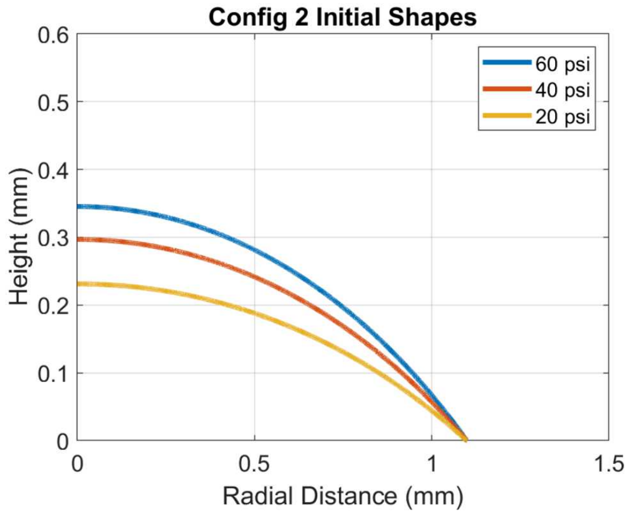


Window Opening: Effect of Starting Shape

Initial Shape Profiles

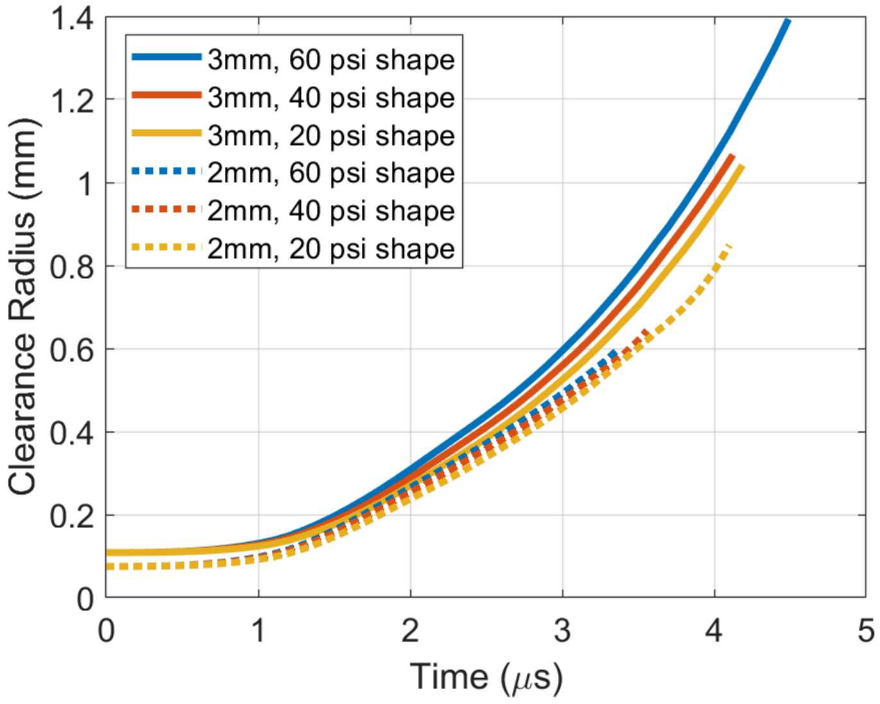
- Membrane initial shape that asterisk is cut from
- In unstressed simulations, the window membrane begins with this level of deformation
- In later partially pressurized simulations, the window's no-stress reference shape starts at a lower pressure and additional pressure is added to the bottom surface to inflate the membrane to the 60 psi shape





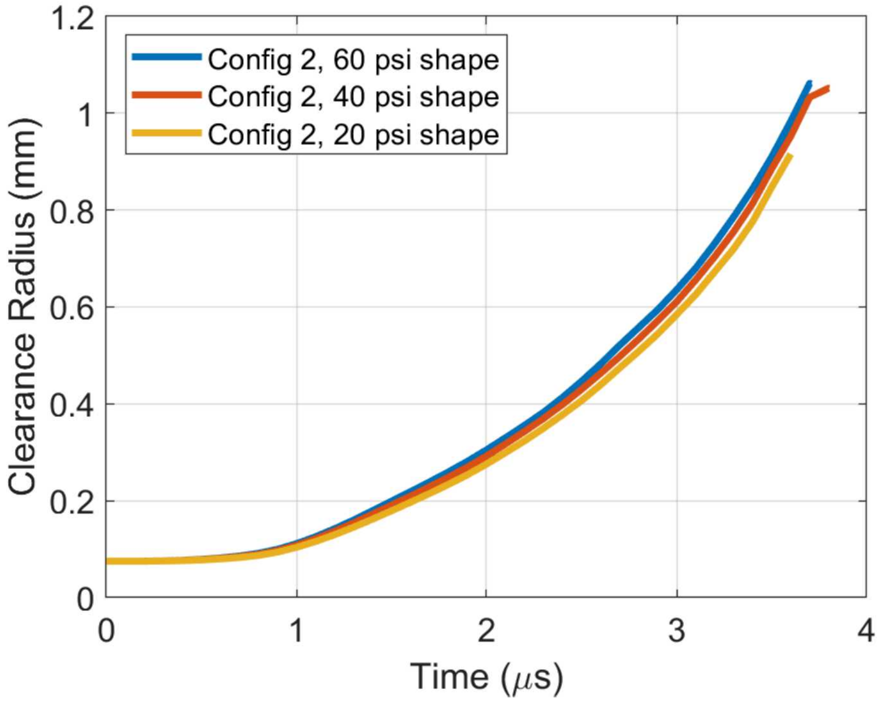
Effect of Shape on Opening Rate – Config 1

- We plot the clearance radius around the center for the 3 mm and 2 mm asterisk cuts with the baseline geometry with a 60 psi pressure
- Changing the starting shape has only a modest effect on the opening of the window
- At short times, the rate of opening is similar for the 2 mm and 3 mm asterisks, but over long times the 2 mm cut opens slower



Effect of Shape on Opening Rate – Config 2

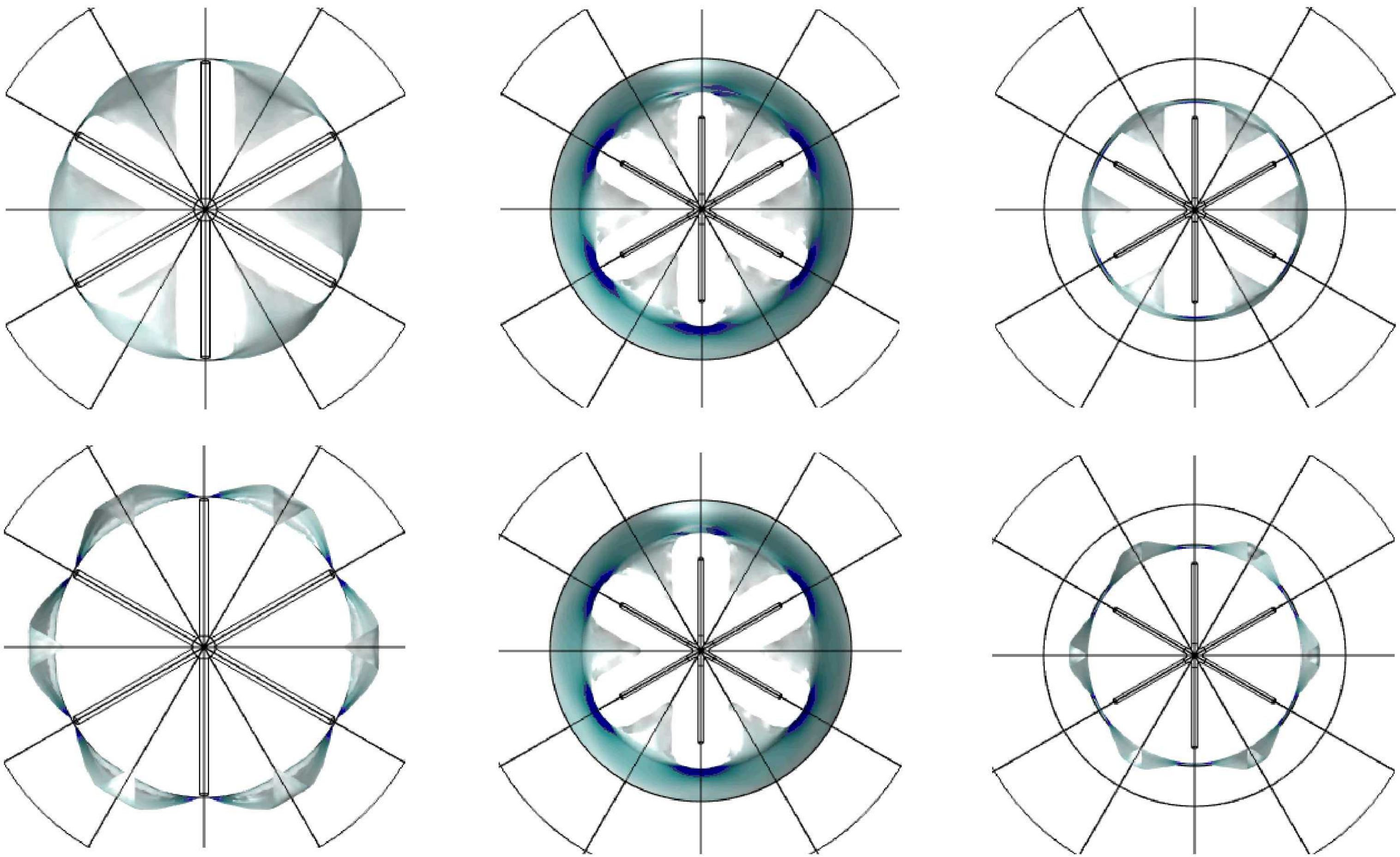
- Config 2's window consists of a membrane stretched over a 2.2 mm opening; a 60 psi pressure is used
- As with the previous case, the difference in shape has only a small change in results
- The flatter initial shapes experience a higher stress and strain, so it is intuitive that the opening will be slower



Window Opening, 60 psi No-Stress

Config 1, 3mm, t = 3 µs | Config 1, 2mm, t = 3 µs | Config 2, 2mm, t = 3 µs

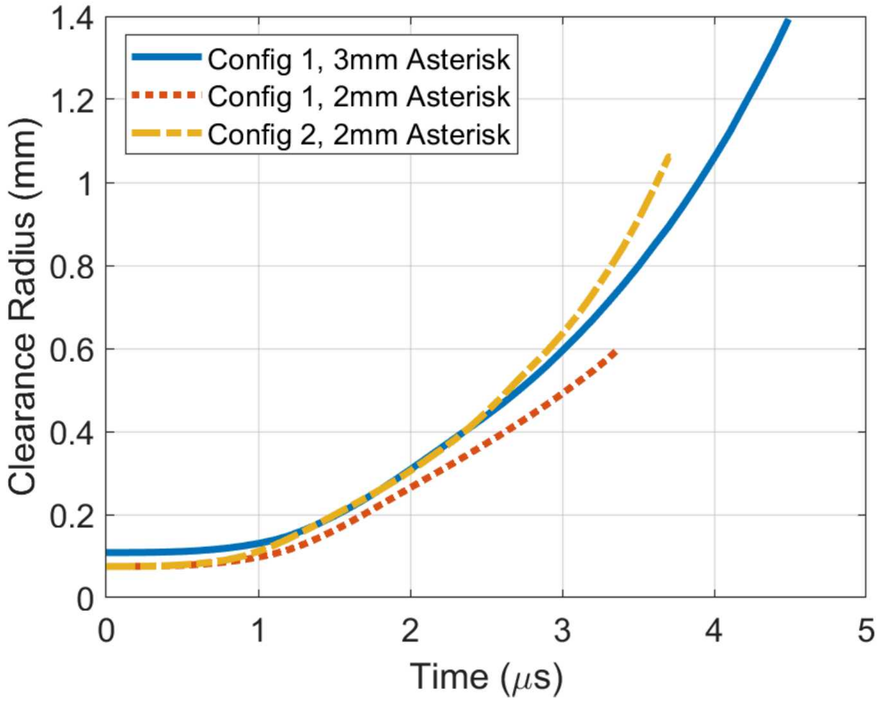
Last Stable Time



Config 1, 3mm, t = 4.19 µs | Config 1, 2mm, t = 3.35 µs | Config 2, 2mm, t = 3.71 µs

No Stress Opening Comparison

- All of the no-stress 60 psi shape cases from the previous slides are plotted on the right
- For Config 1 (membrane stretches across a 3 mm opening), the smaller asterisk initially opens at the same rate but then opens slower after 2 µs
- In Config 2, the membrane is slightly thinner (1.56 µm vs 1.77 µm), which ultimately leads to a faster opening



Window Opening: Effect of Starting Stress

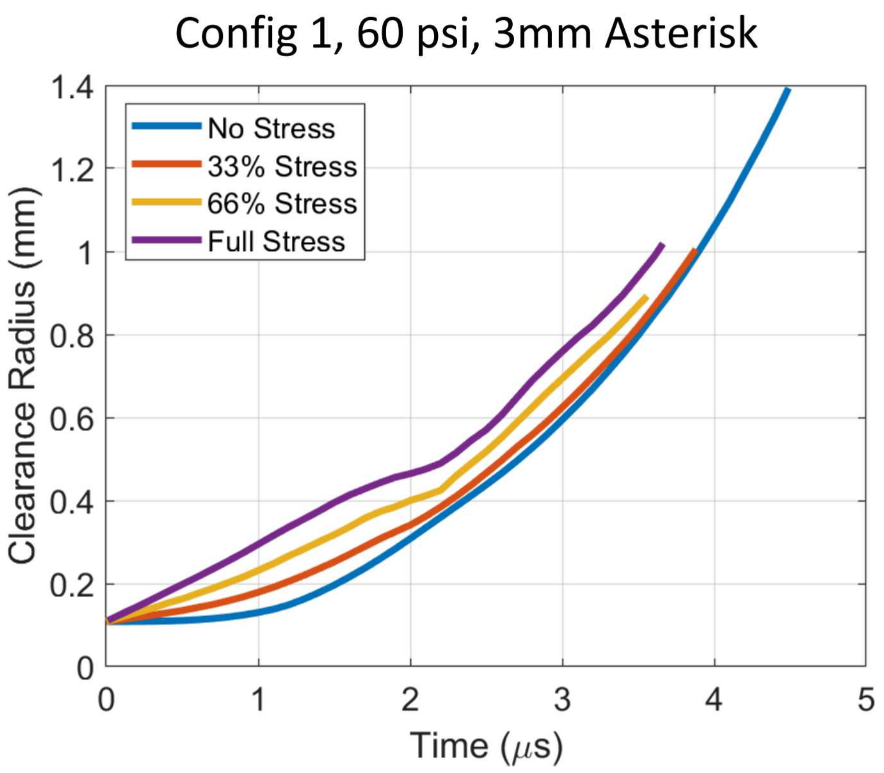
Initial Condition Stress Check

- We create partially stressed states by starting from a reference shape that represents the membrane equilibrium at a lower pressure then adding the remaining pressure in a stationary analysis to arrive at the initial condition for the time-dependent study
  - i.e. 33% stress state is the 40 psi reference shape with 20 psi pressure
  - The 100% stress case is the scenario we expect from physics
- We confirm in the simulation that these partially pressurized window membranes have the expected fraction of first principal stress as the fully pressurized window

Condition	Mean First Principal Stress in Window at t=0	% Stress
Flat window + 60 psi pressure	0.295 GPa	100%
20 psi shape + 40 psi pressure	0.194 GPa	66%
40 psi shape + 20 psi pressure	0.0987 GPa	33%
60 psi shape, no pressure	0 GPa	0%

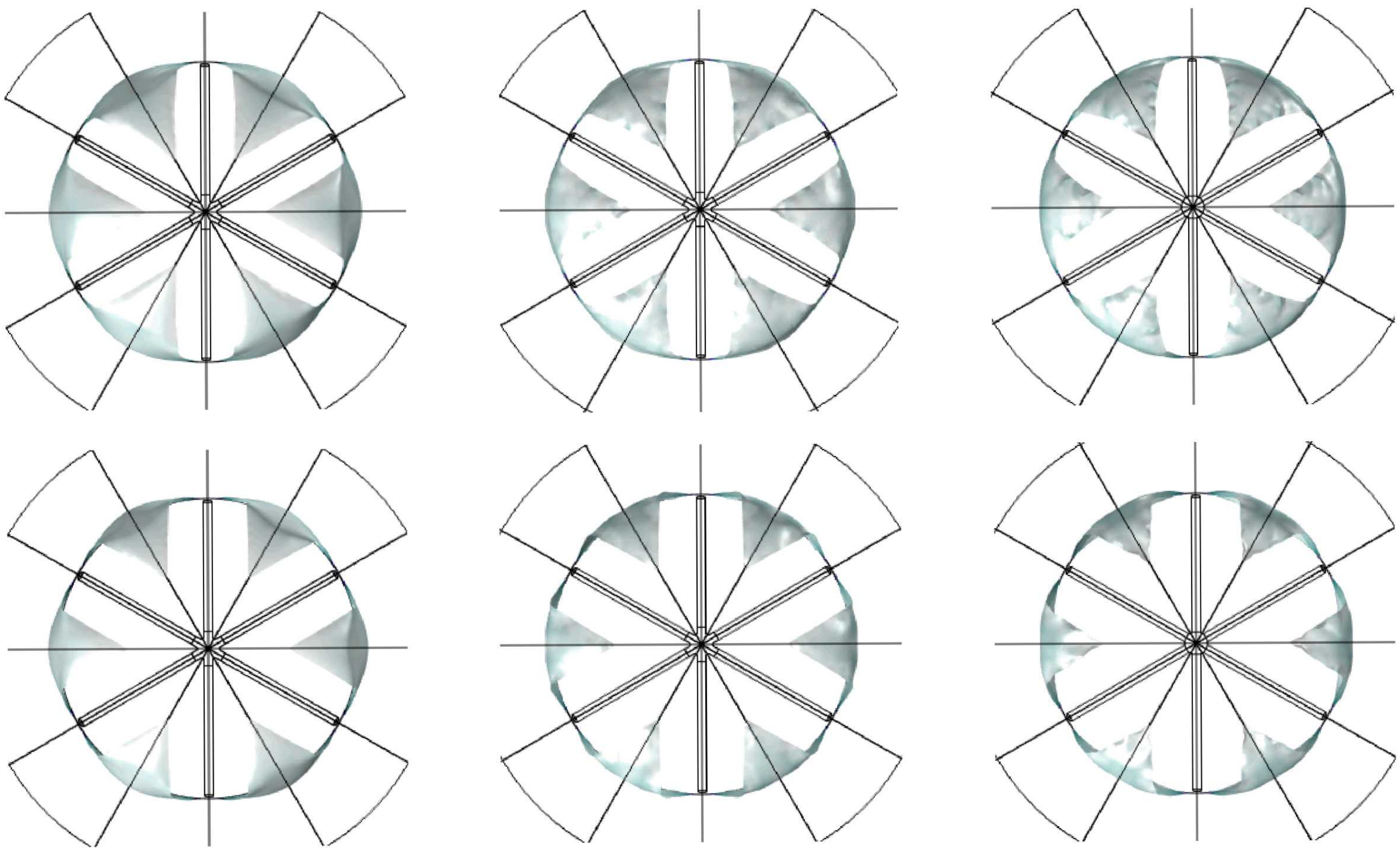
Effect of Stress on Opening Rate

- Here we show simulations which have the same shape and asterisk cut but differing amounts of stress in the membrane
- The presence of membrane stress causes the window to pull back faster
- The opening rate is initially linear but later trends closer to the no-stress curve



Window Opening, 60 psi, Config 1, 3mm

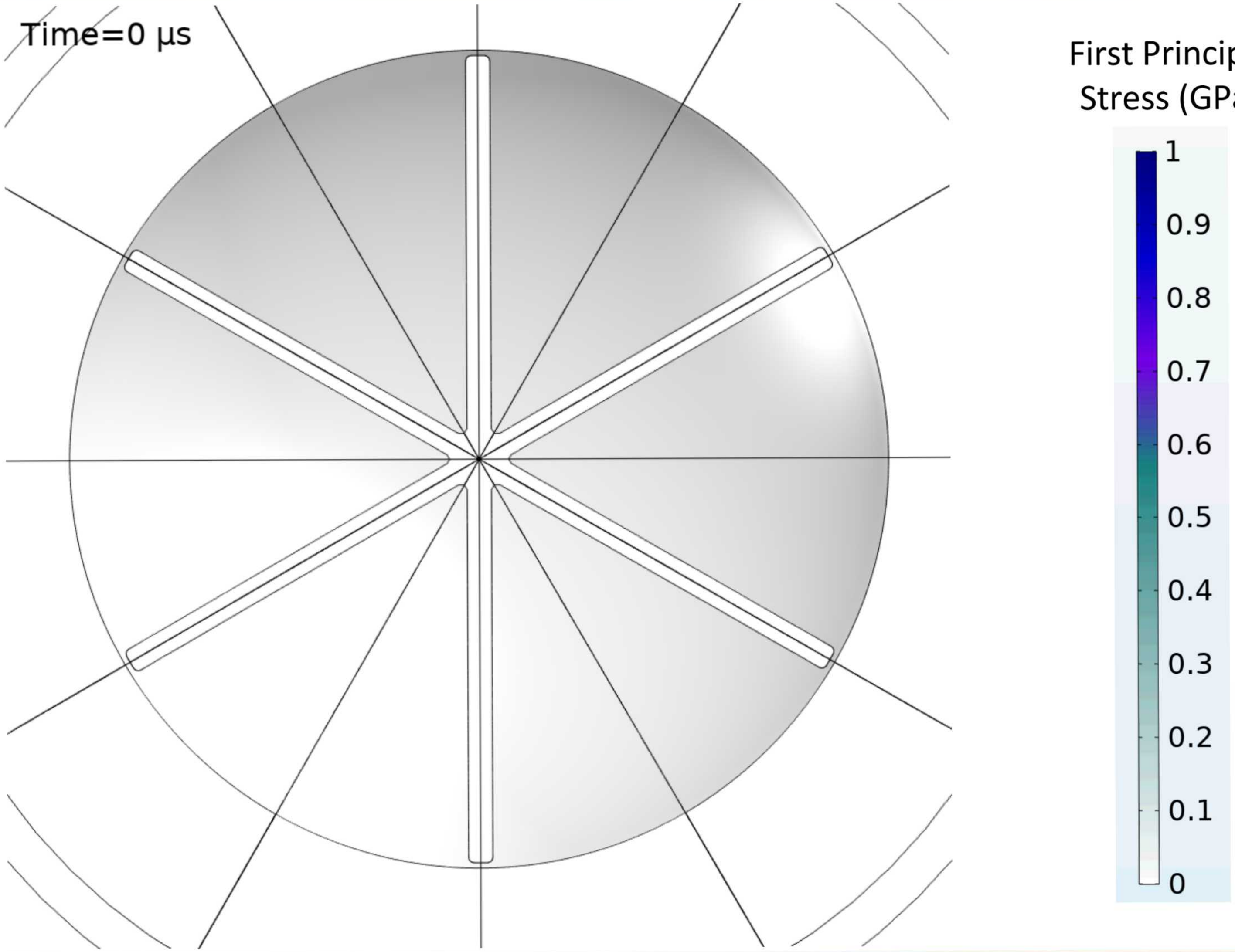
No Stress, t = 3 μs | 66% Stress, t = 3 μs | 100% Stress, t = 3 μs



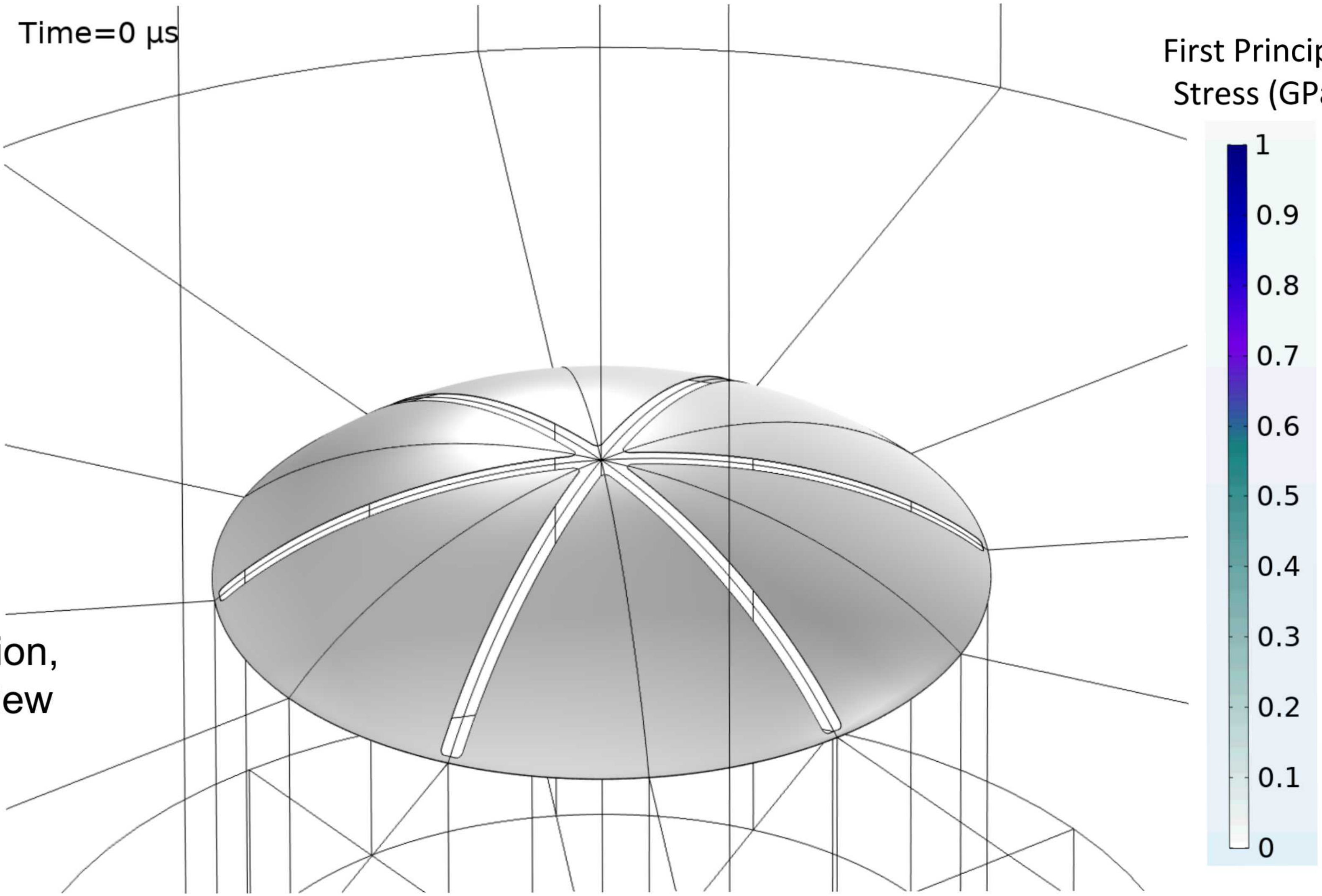
No Stress, t = 3.5 μs | 66% Stress, t = 3.5 μs | 100% Stress, t = 3.5 μs

Window Opening – Config 1, No Stress

Animation, Overhead View

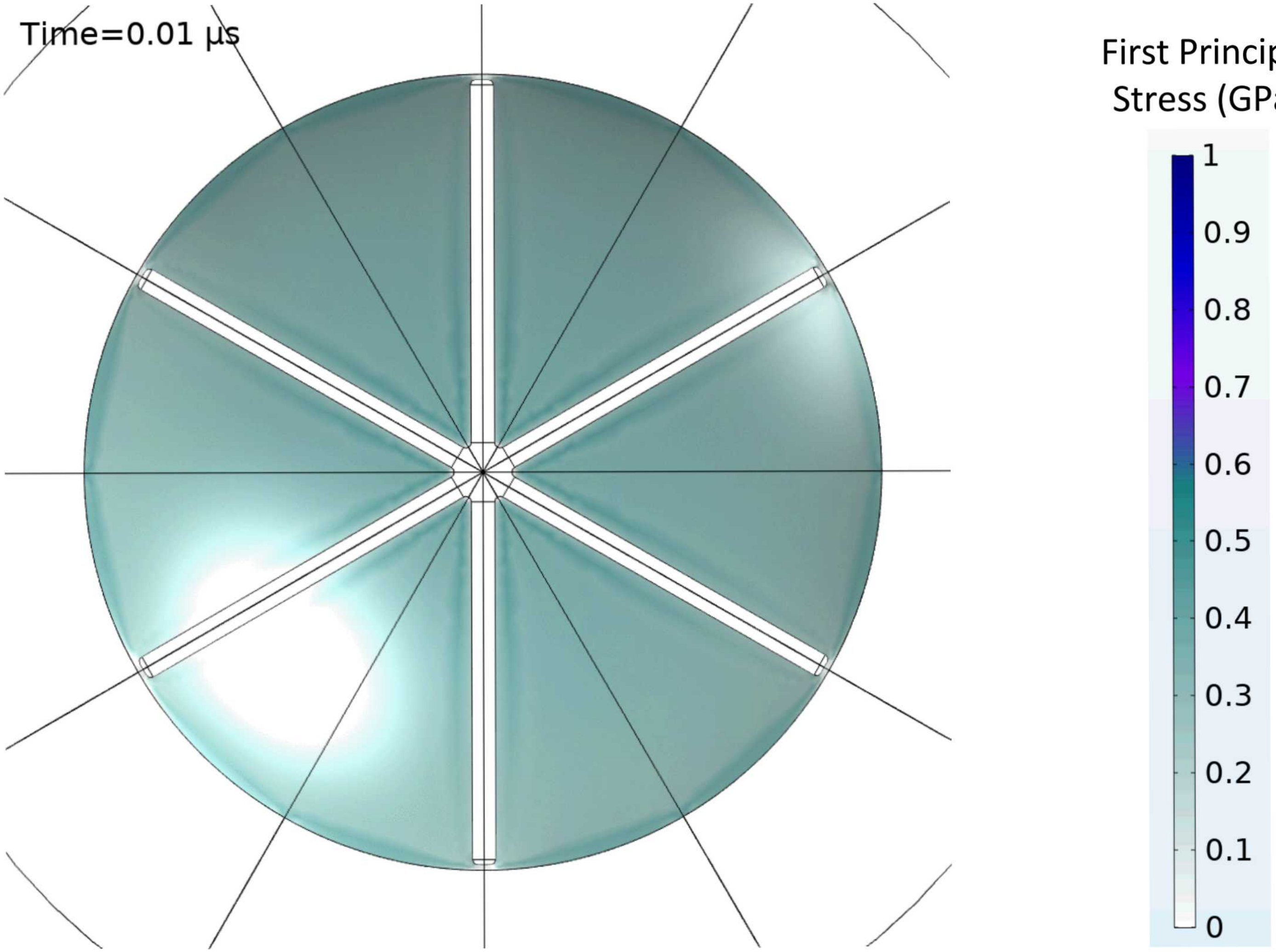


Window Opening – Config 1, No Stress



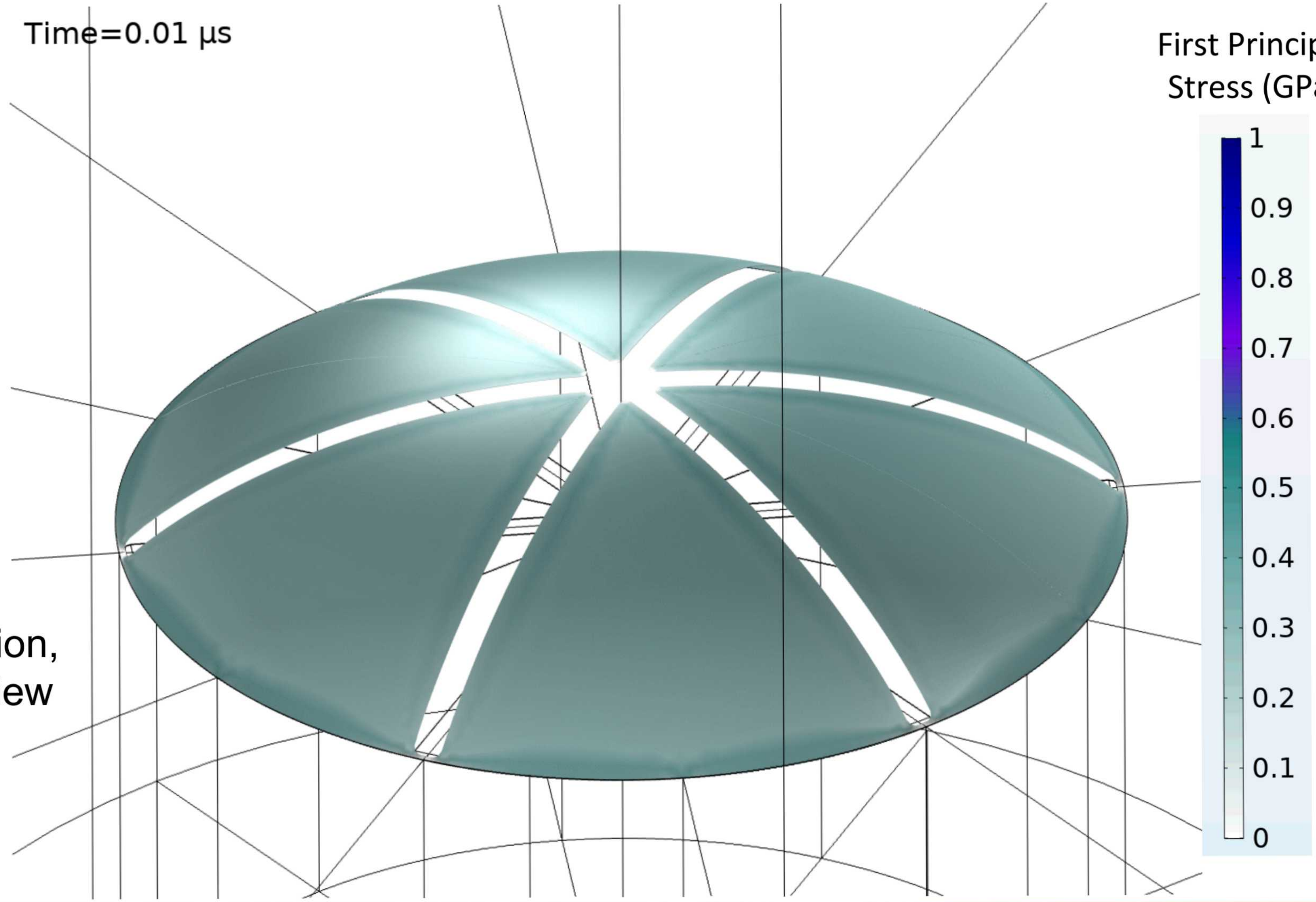
Animation, Side View

Window Opening – Config 1, 100% Stress



Animation, Overhead View

Window Opening – Config 1, 100% Stress

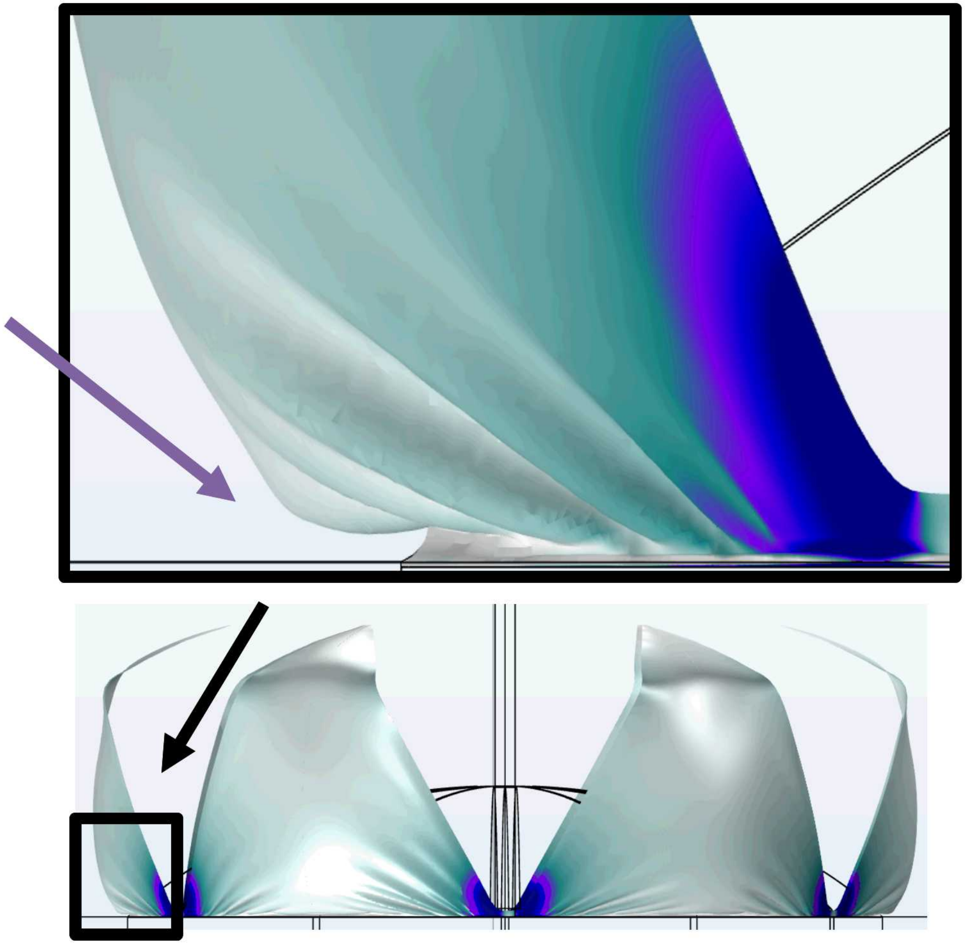


Animation, Side View

Conjectured Window Behavior After Opening

- The simulation encounters convergence difficulty as the window opens; we want to know if the window is at risk of closing
- Note that the base of the window folds back as the window opens
- This suggests that the window will not easily close given that the passing air creates a tension in the membrane
- Our results are not sensitive to mesh choice (see Appendix)

Config 1, 3mm, No Stress, 60 psi
t = 4 μs (High Resolution Mesh)



Conclusion

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- An improved meshing scheme allows simulations to proceed further than before, though convergence difficulty is still encountered upon full opening
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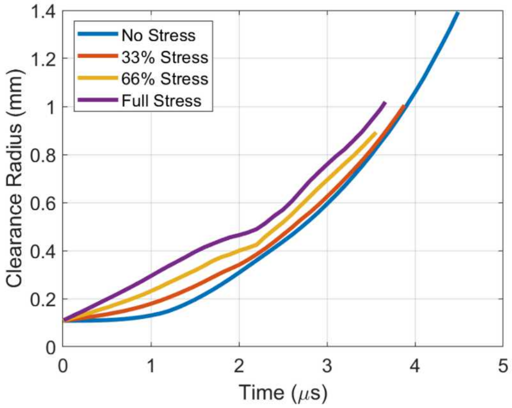
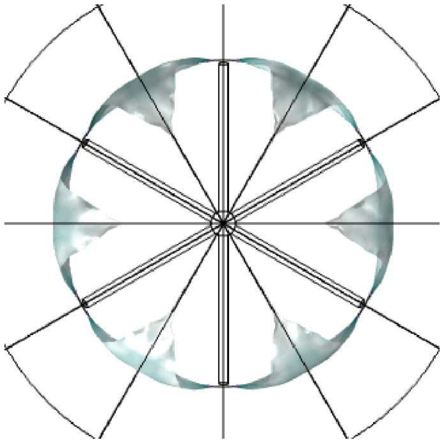
Config 1





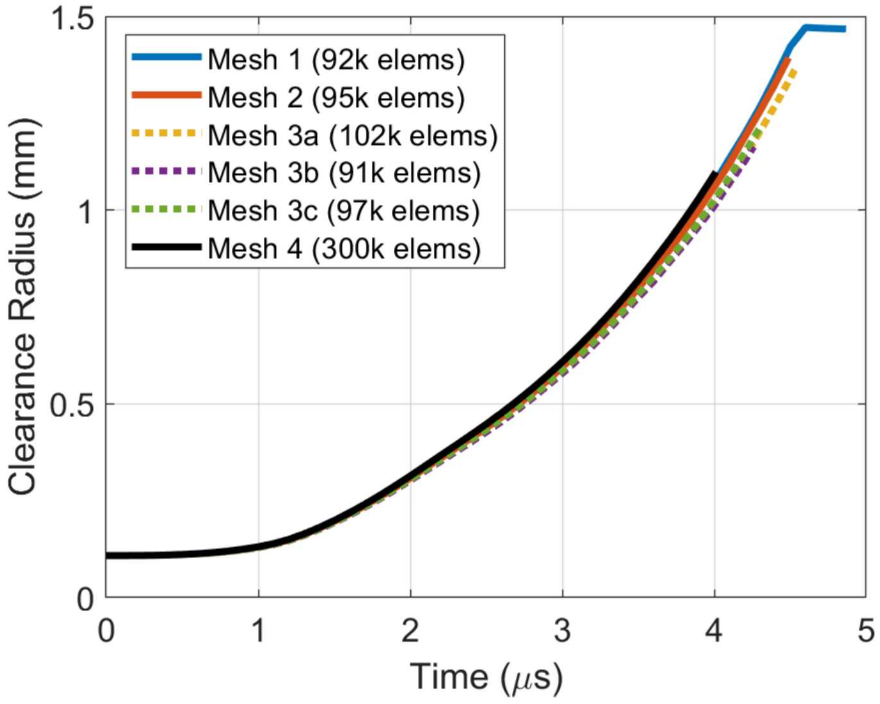
100% Stress, t = 3.5 µs

Appendix: Mesh Resolution Tests

Mesh Resolution Test

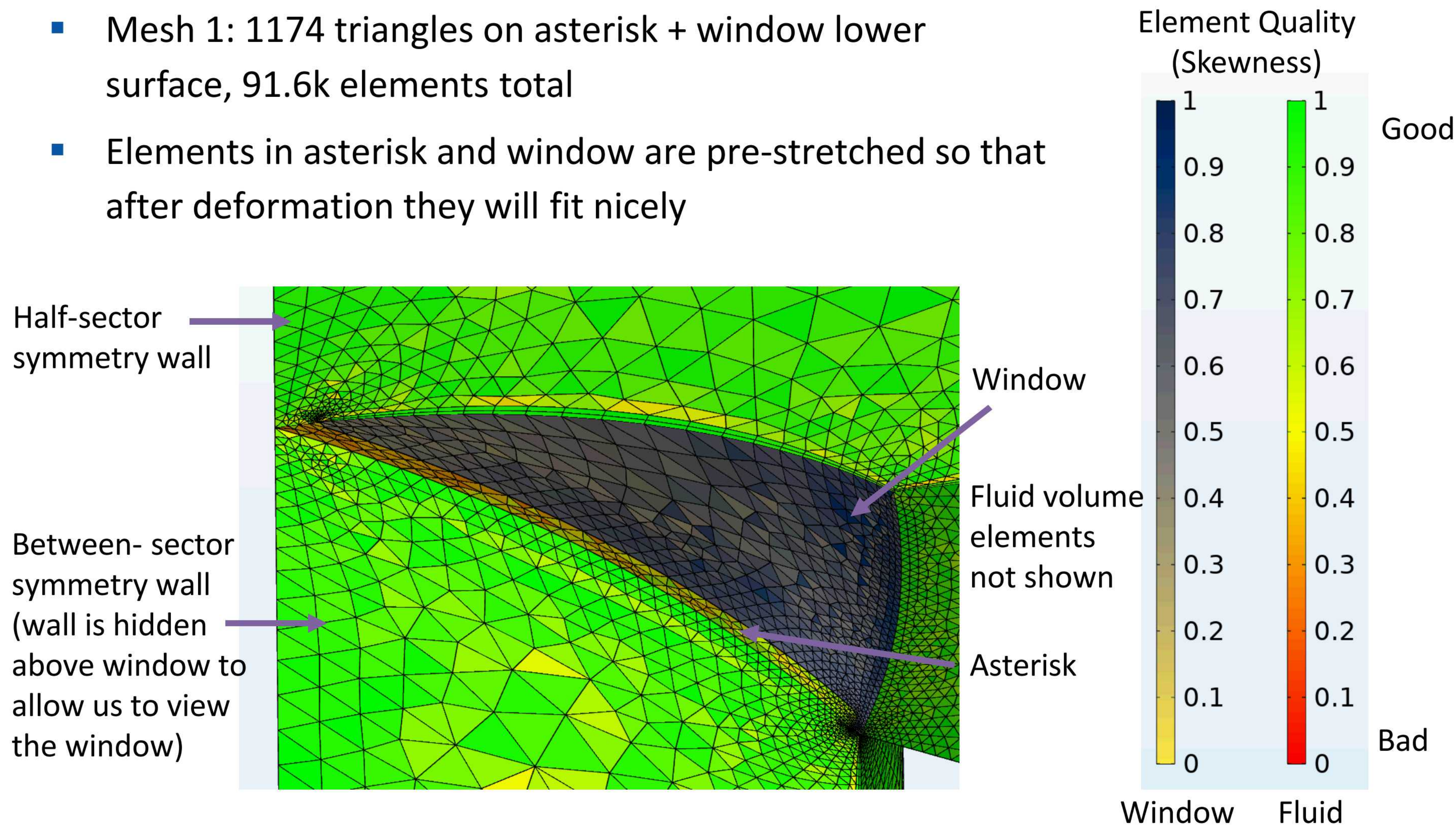
- We test several mesh variations (see next slides) and find consistent results for predicted opening rate of the baseline case with 3 mm asterisk
- Mesh 3 variants (dashed lines) predict a slightly longer opening time because the mesh is coarse in vertical direction
  - Mesh 3 variants used a pre-biased aspect ratio in the vertical direction
  - Goal was to have elements deform into a better shape, but this did not improve convergence

No-stress 60 psi Config 1, 3mm Asterisk



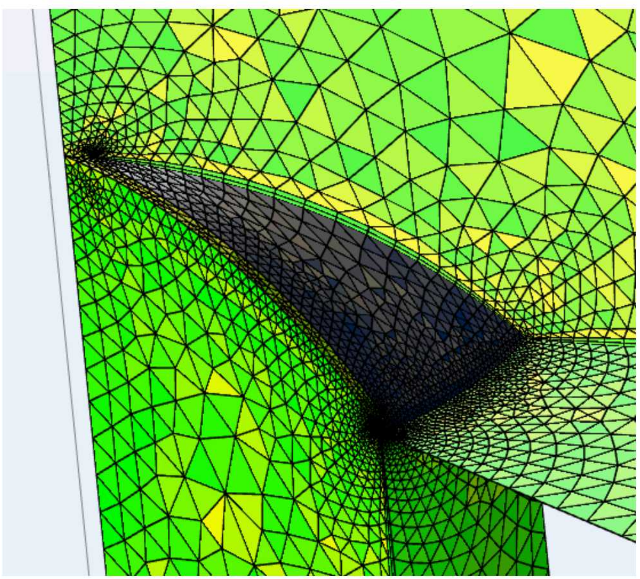
Meshes Used

- Mesh 1: 1174 triangles on asterisk + window lower surface, 91.6k elements total
- Elements in asterisk and window are pre-stretched so that after deformation they will fit nicely

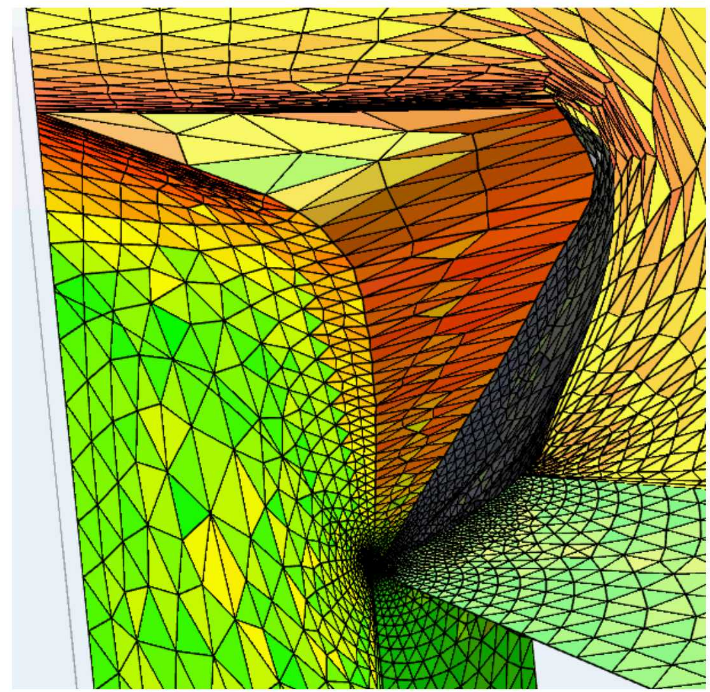


Challenge in Effective Meshing

- As window opens, the elements become stretched and highly deformed
- Largest problem regions are near the tip of asterisk, the cut asterisk, and the boundary layer immediately above the window



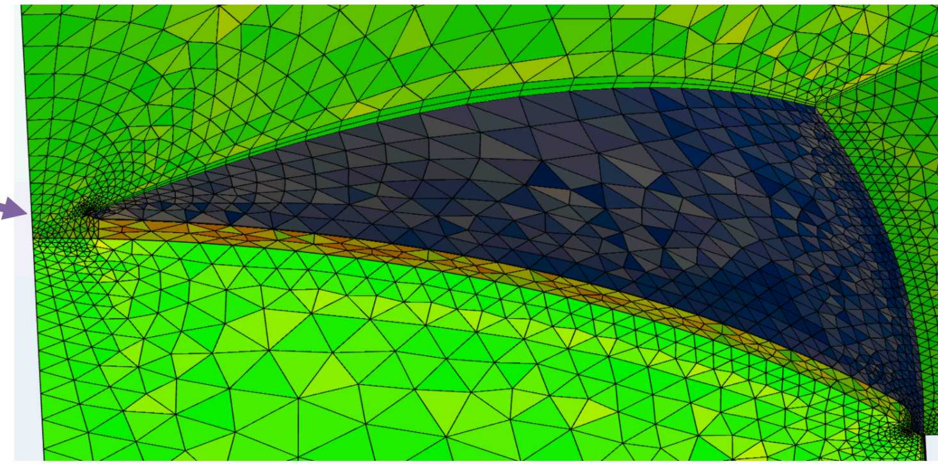
Mesh 1, t = 0 μs

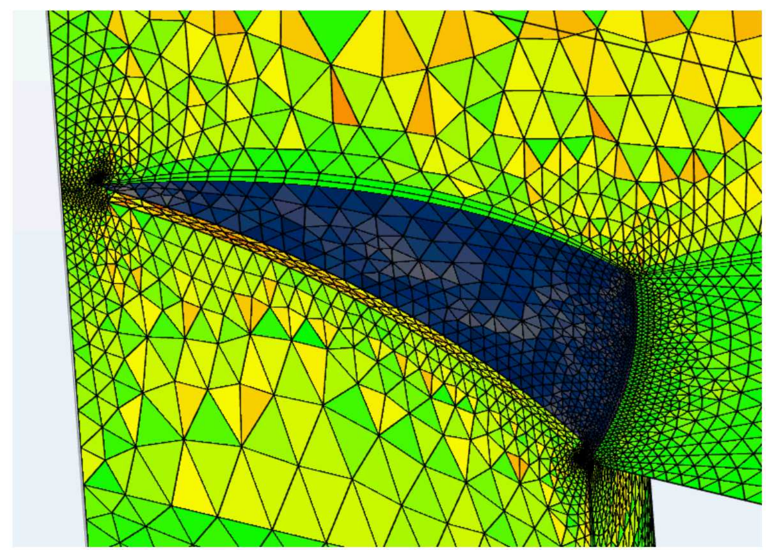


Mesh 1, t = 4.867 μs

Meshes Used

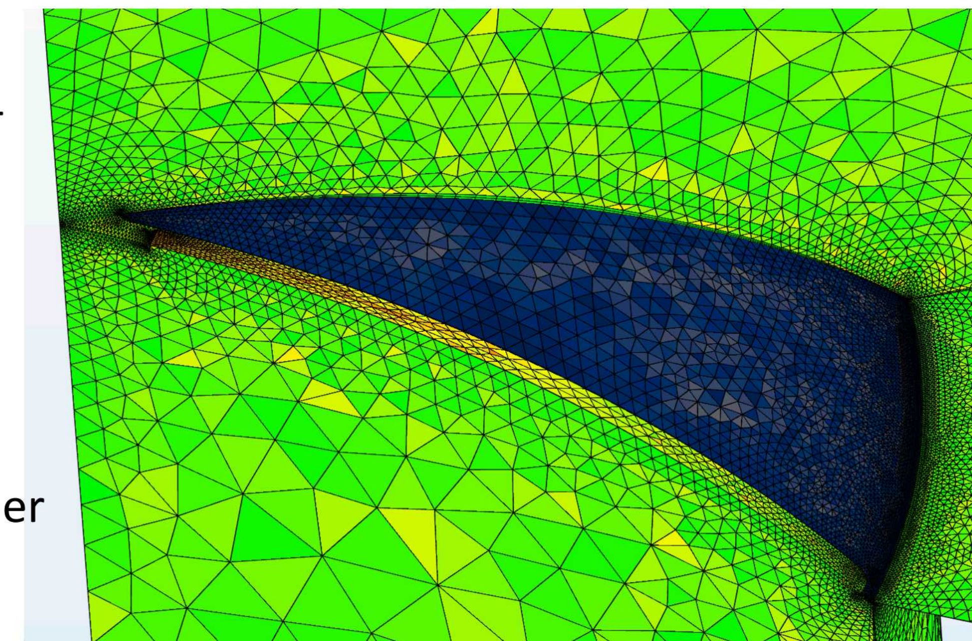
- Mesh 2: 1187 triangles on asterisk + window, 94.9k elements total
  - Refined area near asterisk tip
  - This became the default meshing scheme for further simulations; in retrospect Mesh 1 had better convergence
- Mesh 3a: 1330 triangles on asterisk + window, 102.3k elements total
  - Attempts to pre-bias elements in the vertical direction
  - But end state deformation is not improved by this scheme





Meshes Used

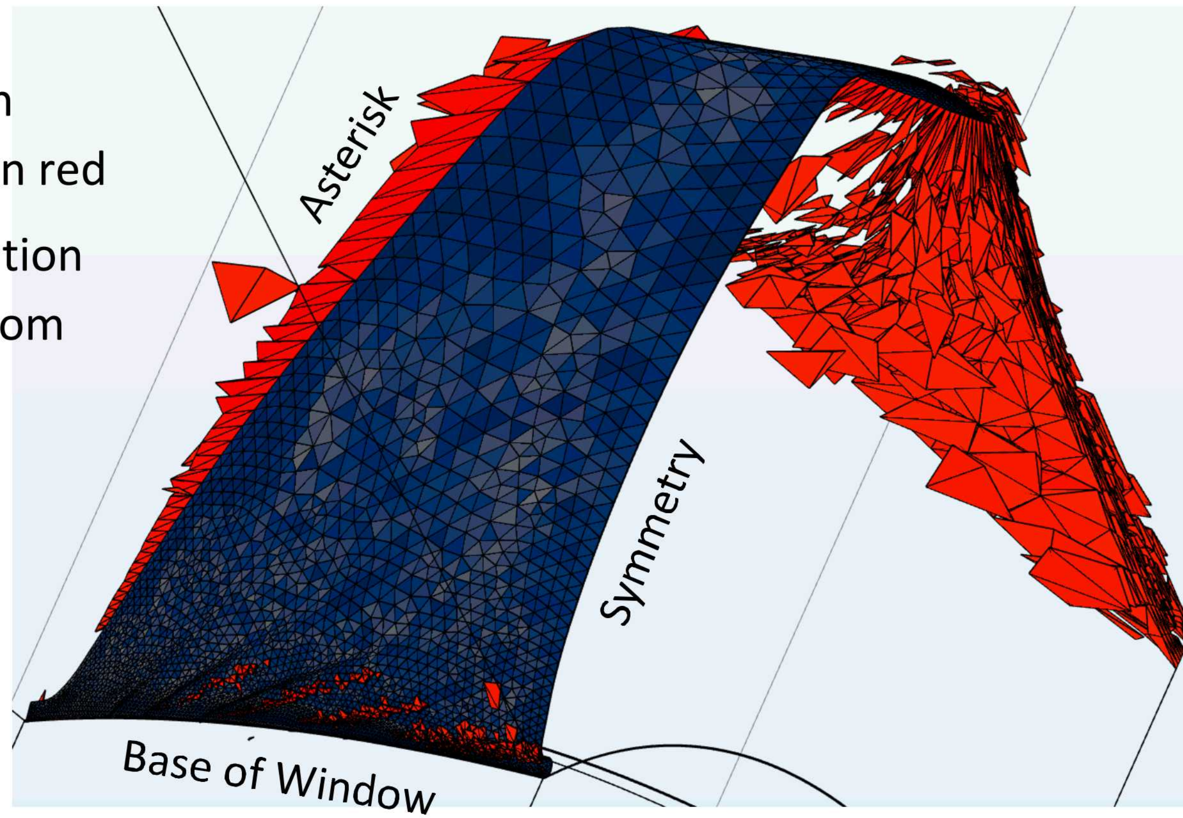
- Variants on Mesh 3:
  - Mesh 3b: 1330 triangles on asterisk + window, 90.8k elements total
  - Mesh 3c: 1400 triangles on asterisk + window, 97.2k elements total
  - Same results, no improvement
- Mesh 4: 7450 triangles on asterisk + window, 300.5k elements total
  - High resolution mesh check
  - Same results as Meshes 1, 2
  - Longer run time, encounters convergence issues slightly earlier (t = 4 μs)



High Resolution Mesh: Failure Condition

- High resolution mesh shown at the time of nonconvergence
- The worst 1% of all mesh elements in the simulation elements are highlighted in red
- It is difficult for the simulation to handle the distortion from the ripple patterns in the window

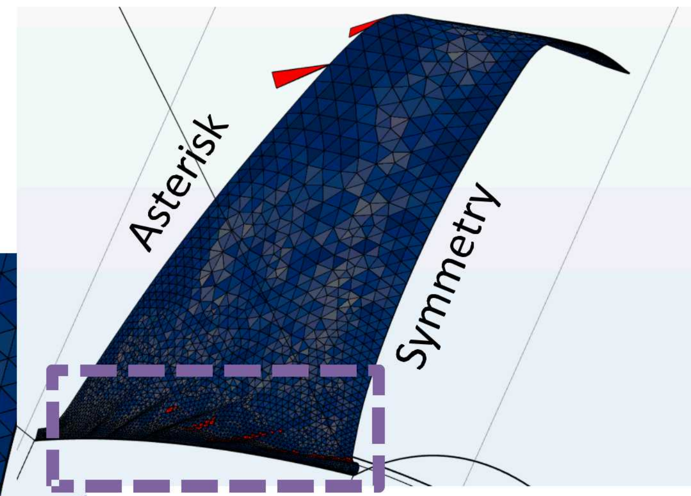
No-stress 60 psi Config 1, 3mm Asterisk
Mesh 4, t = 4.011 μs

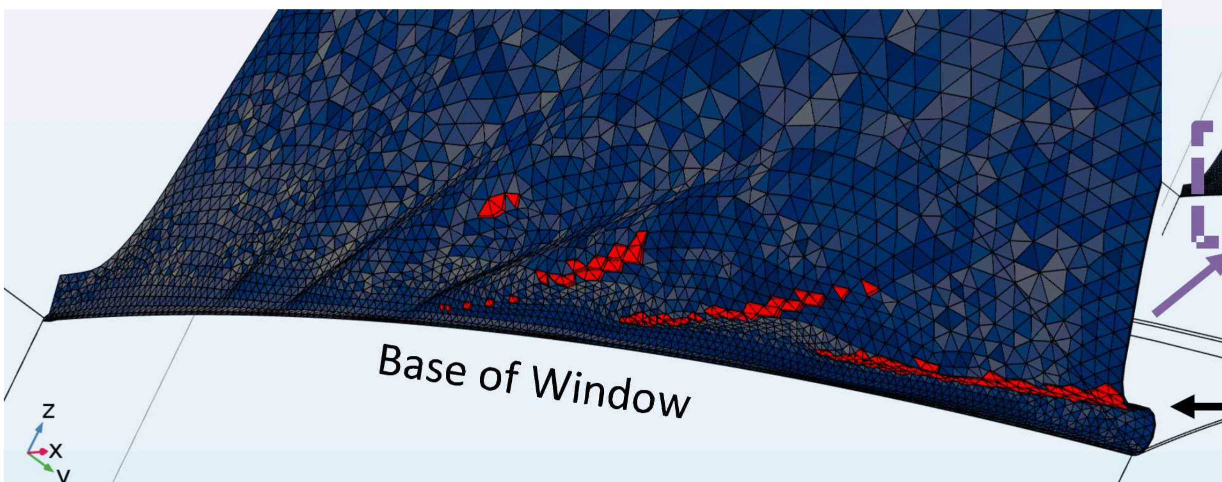


High Resolution Mesh: Worst Elements

- The worst 0.1% of all mesh elements in the simulation elements are highlighted in red
- These elements lie in the fluid just above the window
- It is difficult for the simulation to handle the distortion from the wrinkling patterns in the window

No-stress 60 psi Config 1, 3mm Asterisk
Mesh 4, t = 4.011 μs





Bottom of window folds back