A mechanical model for dynamical tractions on the retina in the presence of posterior vitreous detachment

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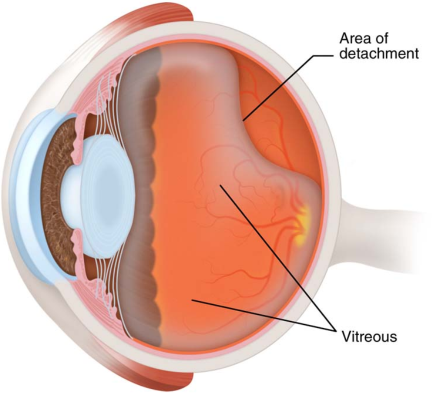
Joint work with:

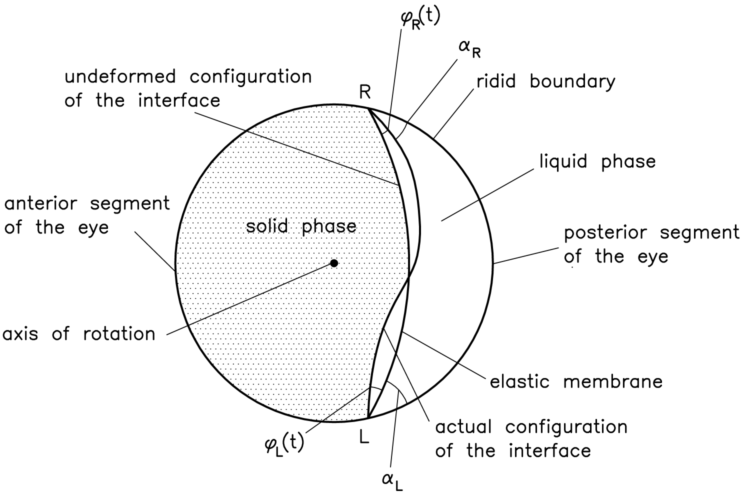
Rodolfo Repetto, Alessandro Testa and Elisa Colangeli

[*Biomech Model Mechanobiol*, 2010]

Posterior vitreous detachment



Posterior vitreous detachment



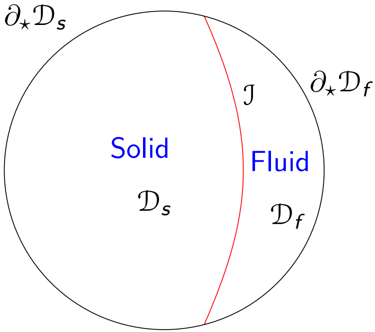
Posterior vitreous detachment

Tractions on the retina can be induced by

- eye-rotation generated oscillations
- quasi-static shrinkage of the vitreous

How to best evaluate the presence or absence of vitreous traction and how to quantitate the degree of vitreous traction is presently not known [Sebag-1989]

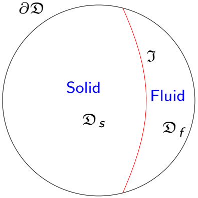
The mechanical model



Balance principle (solid & fluid)

For any test velocity field $\mathbf{w}$

$$\int_{\mathfrak{D}} \mathbf{b} \cdot \mathbf{w} \, dV + \int_{\partial\mathfrak{D}} \mathbf{t} \cdot \mathbf{w} \, dA - \int_{\mathfrak{D}} \mathbf{T} \cdot \operatorname{grad} \mathbf{w} \, dV = 0$$



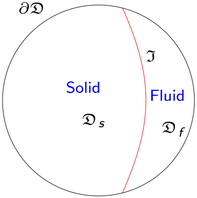
$\mathbf{b}$	bulk force per unit volume on $\mathfrak{D}$
$\mathbf{t}$	traction per unit area on $\partial\mathfrak{D}$
$\mathbf{T}$	Cauchy stress tensor

Balance principle (solid & fluid)

For any test velocity field $\mathbf{w}$

$$\int_{\mathfrak{D}} \mathbf{b} \cdot \mathbf{w} \, dV + \int_{\partial \mathfrak{D}} \mathbf{t} \cdot \mathbf{w} \, dA - \int_{\mathfrak{D}} \mathbf{T} \cdot \operatorname{grad} \mathbf{w} \, dV - \int_{\mathfrak{I}} \boldsymbol{\tau} \cdot [\![\mathbf{w}]\!] \, dA = 0$$

$\mathbf{b}$	bulk force per unit volume in $\mathfrak{D}$
$\mathbf{t}$	traction per unit area on $\partial\mathfrak{D}$
$\mathbf{T}$	Cauchy stress tensor
$\boldsymbol{\tau}$	interface stress

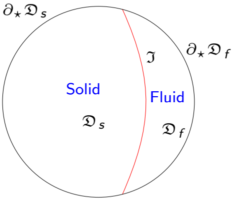


Balance principle (fluid)

For any test velocity field $\mathbf{w}$

$$\int_{\mathfrak{D}_f} \mathbf{b}_f \cdot \mathbf{w}_f \, dV + \int_{\partial_\star \mathfrak{D}_f} \mathbf{t}_f^\star \cdot \mathbf{w}_f \, dA + \int_{\mathfrak{I}} \mathbf{t}_f \cdot \mathbf{w}_f \, dA - \int_{\mathfrak{D}_f} \mathbf{T}_f \cdot \operatorname{grad} \mathbf{w}_f \, dV = 0$$

$\mathbf{b}_f$	bulk force per unit volume in $\mathfrak{D}_f$
$\mathbf{t}_f^\star$	traction per unit area on $\partial_\star \mathfrak{D}_f$
$\mathbf{t}_f$	traction per unit area on $\mathfrak{I}$
$\mathbf{T}_f$	Cauchy stress tensor

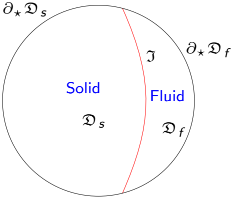


Balance principle (solid)

For any test velocity field $\mathbf{w}$

$$\int_{\mathfrak{D}_s} \mathbf{b}_s \cdot \mathbf{w}_s \, dV + \int_{\partial_\star \mathfrak{D}_s} \mathbf{t}_s^\star \cdot \mathbf{w}_s \, dA + \int_{\mathfrak{I}} \mathbf{t}_s \cdot \mathbf{w}_s \, dA - \int_{\mathfrak{D}_s} \mathbf{T}_s \cdot \operatorname{grad} \mathbf{w}_s \, dV = 0$$

$\mathbf{b}_s$	bulk force per unit volume in $\mathfrak{D}_s$
$\mathbf{t}_s^\star$	traction per unit area on $\partial_\star \mathfrak{D}_s$
$\mathbf{t}_s$	traction per unit area on $\mathfrak{I}$
$\mathbf{T}_s$	Cauchy stress tensor



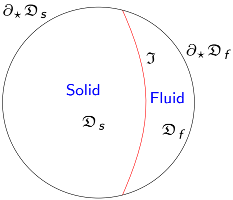
Balance principle (solid & boundary membrane)

For any test velocity field **w**

$$\int_{\mathfrak{D}_s} \mathbf{b}_s \cdot \mathbf{w}_s \, dV + \int_{\partial_\star \mathfrak{D}_s} \mathbf{t}_s^\star \cdot \mathbf{w}_s \, dA + \int_{\mathfrak{I}} \mathbf{t}_s \cdot \mathbf{w}_s \, dA$$

$$- \int_{\mathfrak{D}_s} \mathbf{T}_s \cdot \operatorname{grad} \mathbf{w}_s \, dV - \int_{\mathfrak{I}} \mathbf{N}_m \cdot \operatorname{grad}_m \mathbf{w}_s \, dA + \int_{\partial \mathfrak{I}} \mathbf{f}_m^\star \cdot \mathbf{w}_s \, d\ell = 0$$

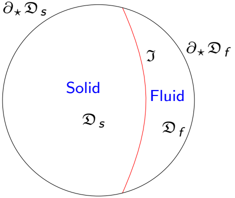
$\mathbf{b}_s$	bulk force per unit volume in $\mathfrak{D}_s$
$\mathbf{t}_s^\star$	traction per unit area on $\partial_\star \mathfrak{D}_s$
$\mathbf{t}_s$	traction per unit area on $\mathfrak{I}$
$\mathbf{T}_s$	Cauchy stress tensor
$\mathbf{N}_m$	Membrane stress tensor
$\mathbf{f}_m^\star$	traction on $\partial \mathfrak{I}$



Balance equations (solid & boundary membrane)

$$\begin{aligned}
&\mathrm{div}\,\mathbf{T}_s + \mathbf{b}_s = 0 && \text{in} \quad \mathfrak{D}_s\\
&\mathbf{t}_s^\star = \mathbf{T}_s\,\mathbf{n} && \text{on} \quad \partial_\star\mathfrak{D}_s\\
&\mathrm{div}_m\,\mathbf{N}_m + \mathbf{t}_s = \mathbf{T}_s\,\mathbf{n} && \text{on} \quad \mathfrak{I}\\
&\mathbf{f}_m^\star = \mathbf{N}_m\,\mathbf{n}_m && \text{on} \quad \partial\mathfrak{I}
\end{aligned}$$

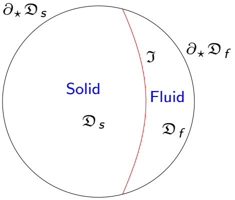
$\mathbf{f}_m^\star$	traction on $\partial\mathfrak{I}$
$\mathbf{N}_m$	membrane stress tensor
$\mathbf{n}_m$	unit vector normal to $\partial\mathfrak{I}$



Balance equations (fluid)

$$
\begin{aligned}
\operatorname{div}\mathbf{T}_f + \mathbf{b}_f &= 0 && \text{in} \quad \mathfrak{D}_f \\
\mathbf{t}_f^\star &= \mathbf{T}_f\,\mathbf{n} && \text{on} \quad \partial_\star\mathfrak{D}_f \\
\mathbf{t}_f &= \mathbf{T}_f\,\mathbf{n} && \text{on} \quad \mathfrak{I}
\end{aligned}
$$

$\mathbf{b}_f$	bulk force per unit volume in $\mathfrak{D}_f$
$\mathbf{t}_f^\star$	traction per unit area on $\partial_\star\mathfrak{D}_f$
$\mathbf{t}_f$	traction per unit area on $\mathfrak{I}$
$\mathbf{T}_f$	Cauchy stress tensor



Material characterization

Incompressibility

$$\det \mathsf{F} = 1$$

$$\operatorname{div} \mathbf{v_f} = 0$$

Viscoelastic solid

$$\mathbf{T}_s = -p_s \mathbf{I} + \hat{\mathbf{T}}_s(\mathsf{F}) + 2\mu_s \operatorname{sym} \operatorname{grad} \mathbf{v_s}$$

Newtonian fluid

$$\mathbf{T}_f = -p_f \mathbf{I} + 2\mu_f \operatorname{sym} \operatorname{grad} \mathbf{v_f}$$

Neo-Hookean response

$$\hat{\mathbf{T}}_s(\mathsf{F}) = 2c_0 \operatorname{dev}(\mathsf{F}\mathsf{F}^{\mathsf{T}})$$

Inertial forces

$$\mathbf{b}_s = -\rho_s \dot{\mathbf{v}}_s$$

$$\mathbf{b}_f = -\rho_f \left(\dot{\mathbf{v}}_f + (\operatorname{grad} \mathbf{v}_f) \mathbf{v}_f \right)$$

Balance equation (fluid)

$$\operatorname{div} \mathbf{T}_f + \mathbf{b}_f = 0$$

$$\mathbf{b}_f = -\rho_f \left(\dot{\mathbf{v}}_f + (\operatorname{grad} \mathbf{v}_f)\mathbf{v}_f\right)$$

$$\mathbf{T}_f = -p_f \mathbf{I} + 2\mu_f \ \operatorname{sym} \operatorname{grad} \mathbf{v_f}$$

Navier-Stokes equation on $\mathfrak{D}_f$

$$-\rho_f \left(\dot{\mathbf{v}}_f + (\operatorname{grad} \mathbf{v}_f)\mathbf{v}_f\right) - \operatorname{grad} p_f + \mu_f \Delta \mathbf{v}_f = 0$$

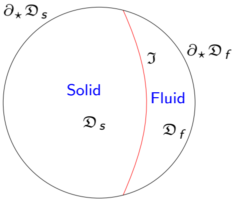
Boundary conditions (solid & fluid)

$$\boldsymbol{\tau} = \mathbf{t}_f = -\mathbf{t}_s \qquad \text{on} \quad \mathfrak{I}$$

$$\mathbf{v}_s = \mathbf{v}_f \qquad \text{on} \quad \mathfrak{I}$$

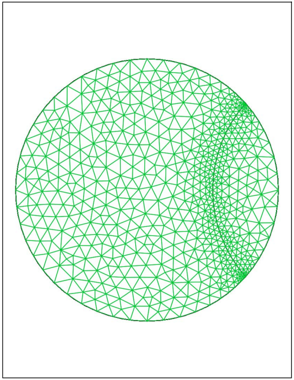
$$\mathbf{u}_s = \bar{\mathbf{u}} \qquad \text{on} \quad \partial_\star \mathfrak{D}_s$$

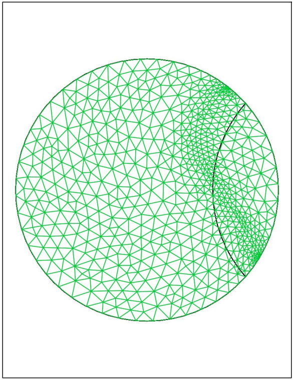
$$\mathbf{v}_f = \dot{\bar{\mathbf{u}}} \qquad \text{on} \quad \partial_\star \mathfrak{D}_f$$



Moving grid

$$\gamma : \mathcal{D} \to \mathfrak{D}$$





$$\gamma_s = \phi_s$$
$$\Delta \gamma_f = 0$$

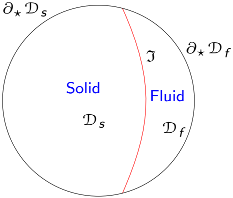
Balance principle for the solid in the *reference shape*

For any test velocity field w

$$\int_{\mathcal{D}_s} \mathrm{b}_s \cdot \mathrm{w}_s \, dV + \int_{\partial_\star \mathcal{D}_s} \mathrm{t}_s^\star \cdot \mathrm{w}_s \, dA + \int_{\mathcal{I}} \mathrm{t}_s \cdot \mathrm{w}_s \, dA$$

$$- \int_{\mathcal{D}_s} \mathrm{S}_s \cdot \operatorname{grad} \mathrm{w}_s \, dV - \int_{\mathcal{I}} \mathrm{N}_m \cdot \operatorname{grad}_m \mathrm{w}_s \, dA + \int_{\partial \mathcal{I}} \mathrm{f}_m^\star \cdot \mathrm{w}_s \, d\ell = 0$$

b_s	bulk force per unit volume in $\mathcal{D}_s$
$\mathrm{t}_s^\star$	traction per unit area on $\partial_\star \mathcal{D}_s$
t_s	traction per unit area on $\mathcal{I}$
S_s	Piola stress tensor
N_m	Membrane stress tensor
$\mathrm{f}_m^\star$	traction on $\partial \mathcal{I}$



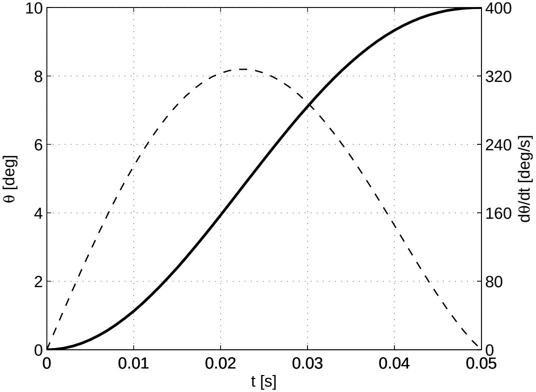
Balance equation for the fluid in the *reference shape*

$$\operatorname{div} \mathsf{S}_f + \mathsf{b}_f = 0$$

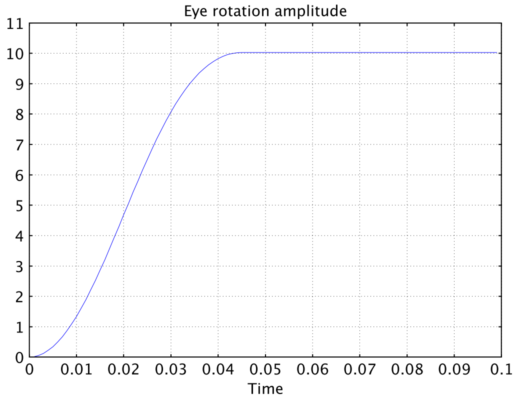
$$\mathsf{b}_f = -\rho_f \left(\dot{\mathsf{v}}_f + \operatorname{grad} \mathsf{v}_f \Gamma^{-1}(\mathsf{v}_f - \dot{\mathsf{u}}_\gamma)\right) \det \Gamma$$

$$\mathsf{S}_f = \left(-p_f \mathsf{I} + 2\mu \operatorname{sym}(\operatorname{grad} \mathsf{v}_f \Gamma^{-1})\right) \Gamma^{-\mathsf{T}} \det \Gamma$$

Saccadic movement



Saccadic movement



Constitutive parameters

Nickerson et al. (2008)	G'	10 Pa
	G''	3.9 Pa
Swindle et al. (2008)	G'	3.46 ± 0.30 Pa
	G''	0.71 ± 0.12 Pa

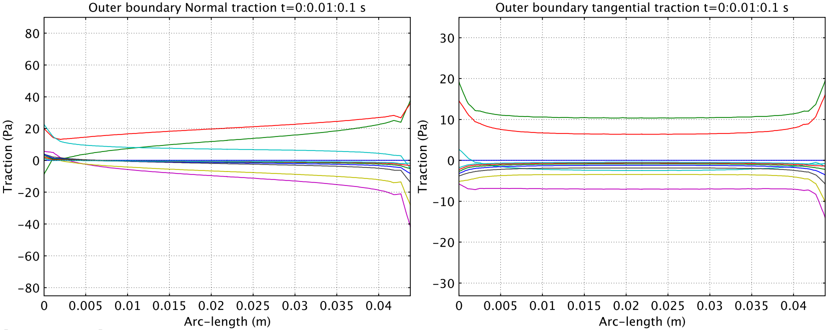
(porcine samples)

Constitutive parameters

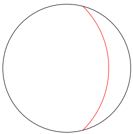
Radius	$R = 0.012\,\mathrm{m}$
Fluid viscosity	$\mu_f = 10^{-3}\,\mathrm{Pa} \times \mathrm{s}$
Mass density	$\rho_s = \rho_f = 1000\,\mathrm{kg/m^3}$

Boundary traction
for different values of the solid elastic modulus

Boundary traction (vs. solid elastic modulus)



[c3_case_003]

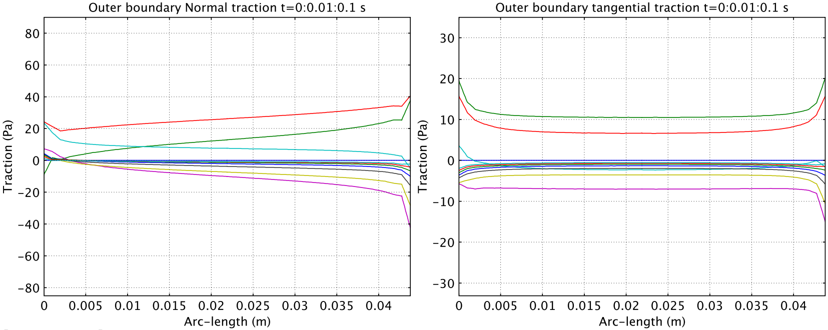


$c_0 = 2$ Pa

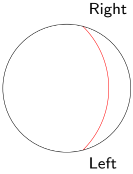
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Boundary traction (vs. solid elastic modulus)

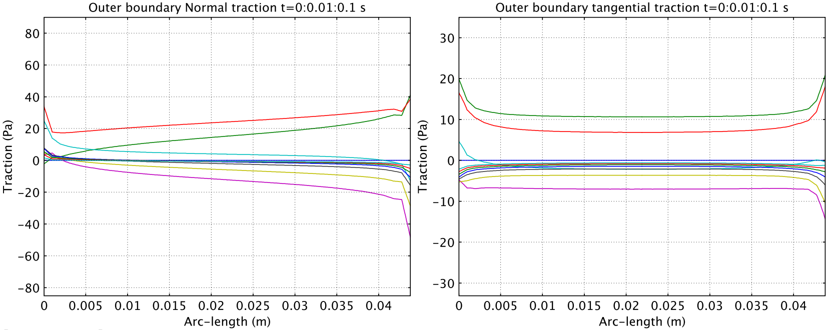


[c3_case_006]



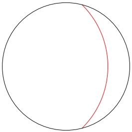
$$c_0 = \color{red}{3} \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)



[c3_case_007]

Right



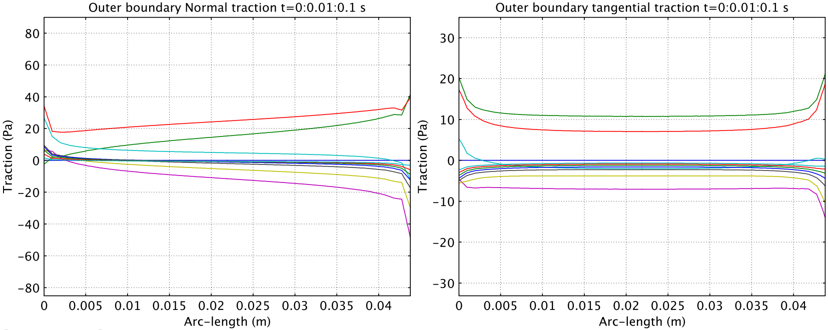
Left

$c_0 = \color{red}{4}$ Pa

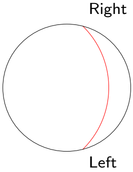
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Boundary traction (vs. solid elastic modulus)

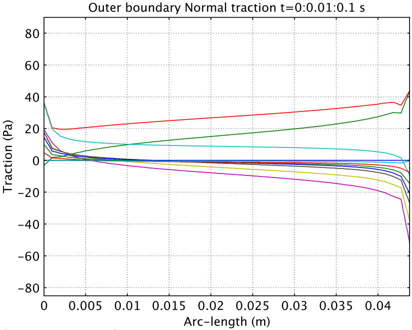


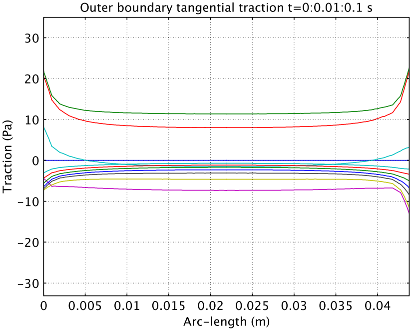
[c3_case_008]



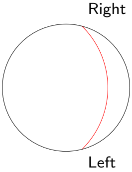
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)





[c3_case_008_b]

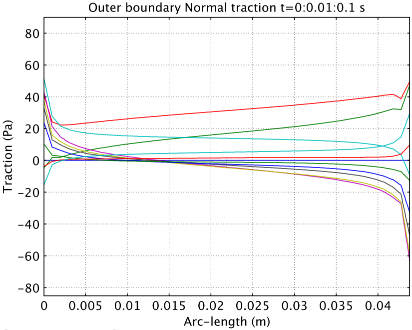


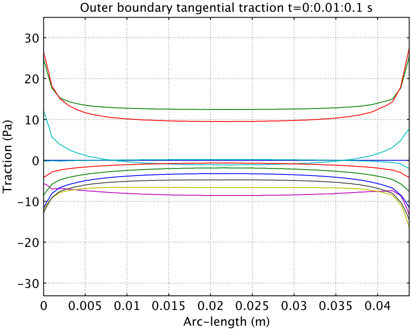
$$c_0 = \color{red}{10} \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

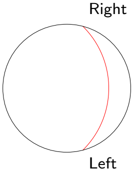
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)

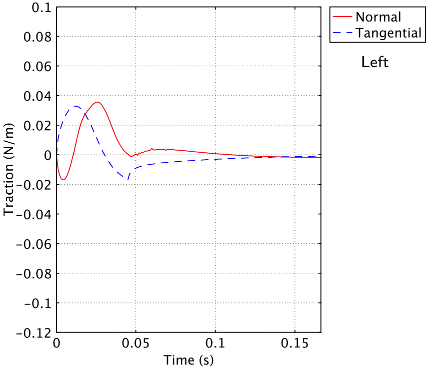


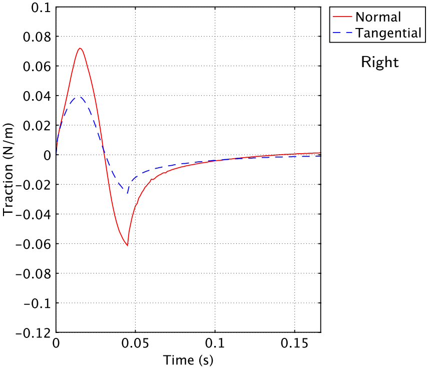


[c3_case_008_t]

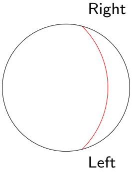


$$c_0 = \textcolor{red}{20} \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$



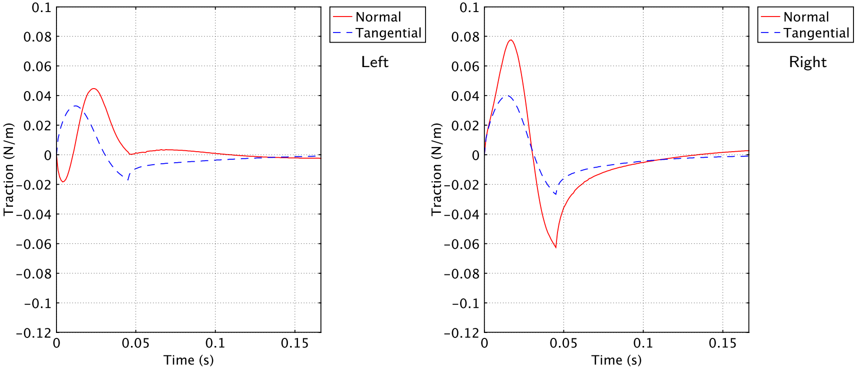


[c3_case_003]

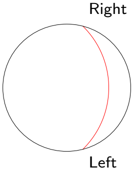


$$c_0 = 2 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)



[c3_case_006]

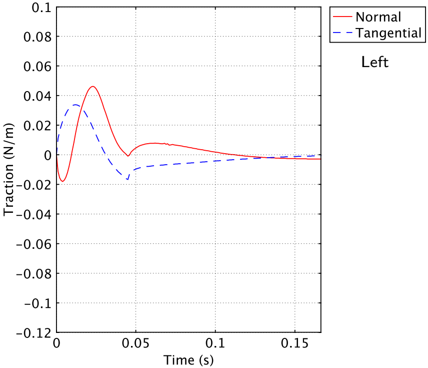


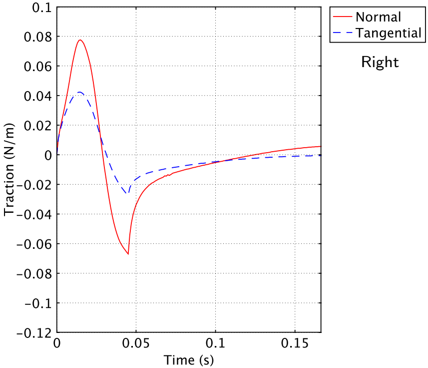
$$c_0 = \color{red}{3} \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

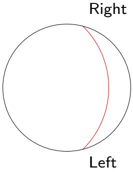
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)



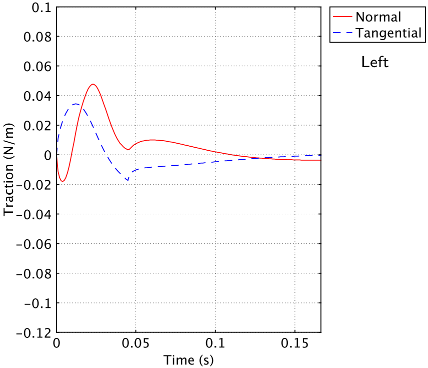


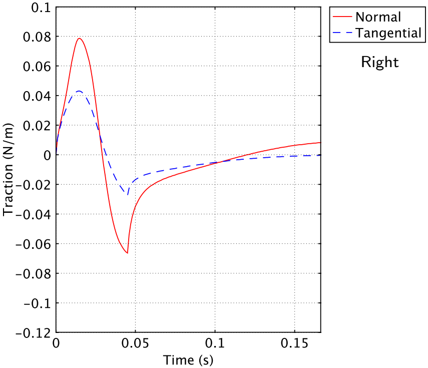
[c3_case_007]



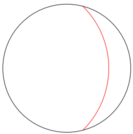
$$c_0 = 4 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)





[c3_case_008]

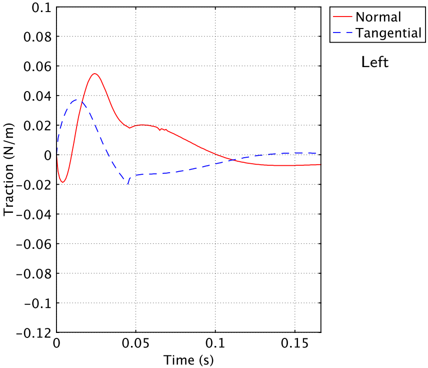


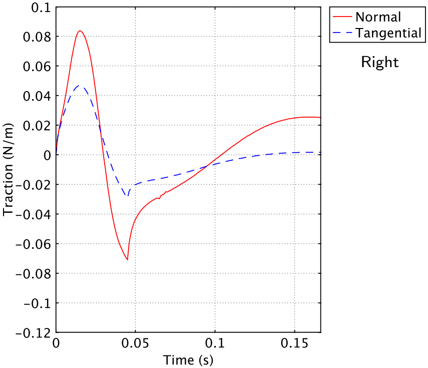
$$c_0 = \color{red}{5} \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

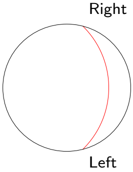
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)





[c3_case_008_b]

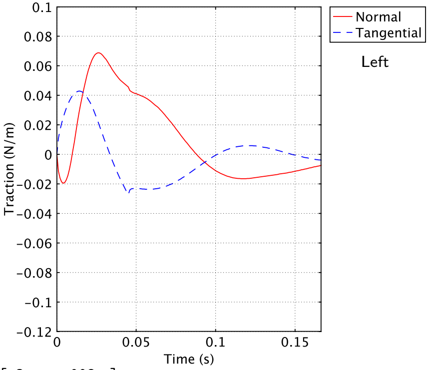


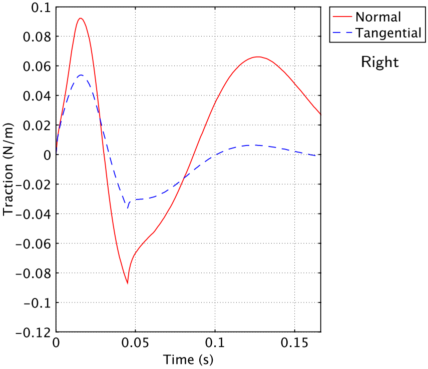
$$c_0 = \color{red}{10} \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

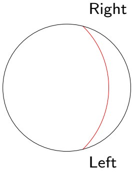
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. solid elastic modulus)





[c3_case_008_t]

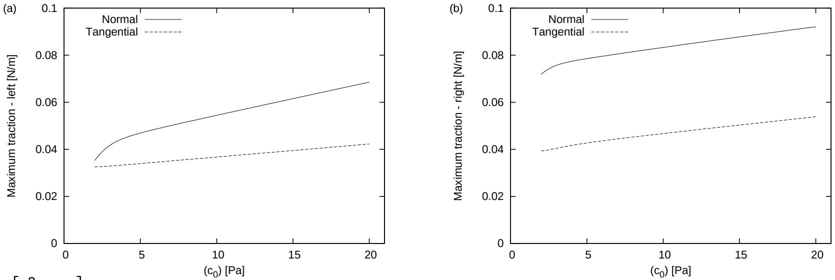


$c_0 = {\color{red}20}$ Pa

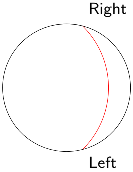
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Boundary traction (vs. solid elastic modulus)



[c3_case]

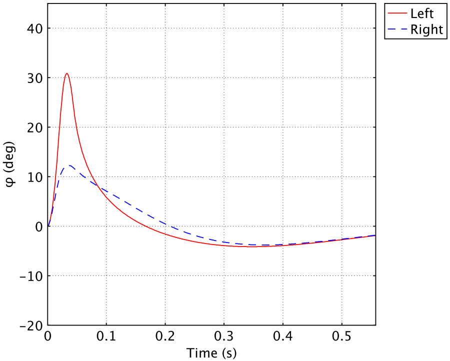


$$
\begin{aligned}
c_0 &= {\color{red}2 \div 20} && \text{Pa} \\
m_0 &= 20 && \text{Pa} \\
\mu_s &= 0.5 && \text{Pa s}
\end{aligned}
$$

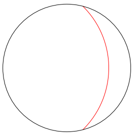
Membrane oscillations

for different values of the solid elastic modulus

Membrane oscillations (vs. solid elastic modulus)



[c3_case_003]

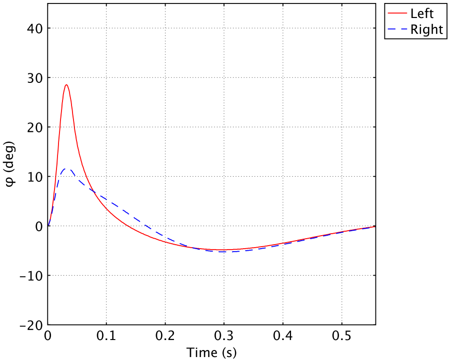


$c_0 = 2$ Pa

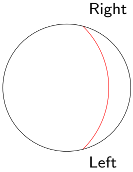
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Membrane oscillations (vs. solid elastic modulus)



[c3_case_006]

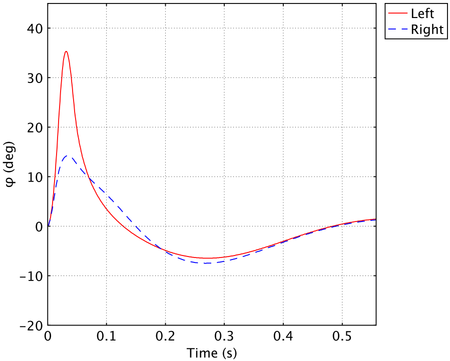


$c_0 = 3$ Pa

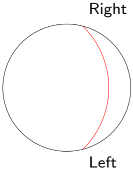
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Membrane oscillations (vs. solid elastic modulus)



[c3_case_007]

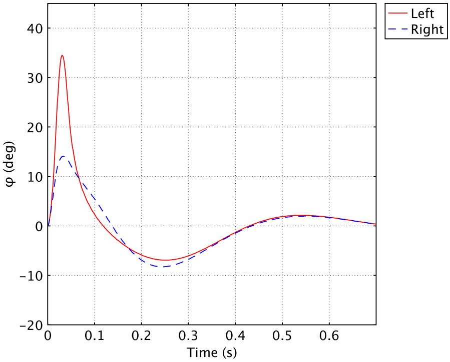


$$c_0 = 4 \quad \text{Pa}$$

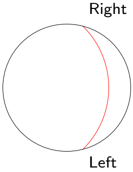
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Membrane oscillations (vs. solid elastic modulus)



[c3_case_008]

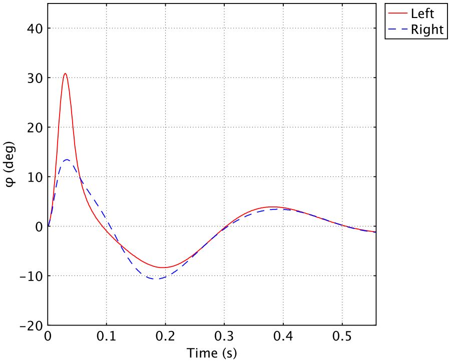


$c_0 = 5$ Pa

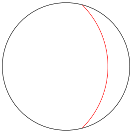
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Membrane oscillations (vs. solid elastic modulus)



[c3_case_008_b]

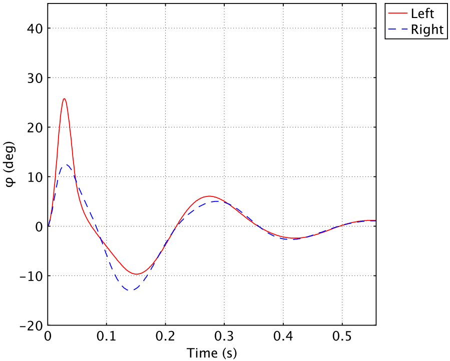


$c_0 = 10$ Pa

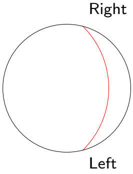
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Membrane oscillations (vs. solid elastic modulus)



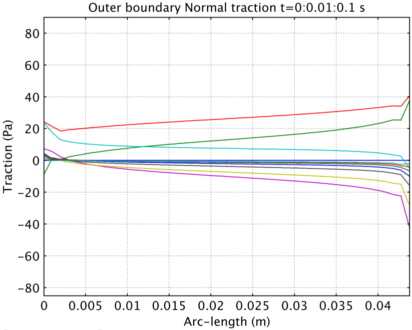
[c3_case_008_t]

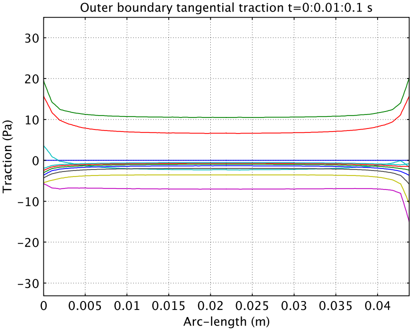


$$c_0 = 20 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

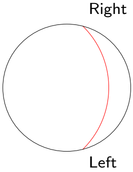
Boundary traction
for different values of the solid viscosity

Boundary traction (vs. solid viscosity)



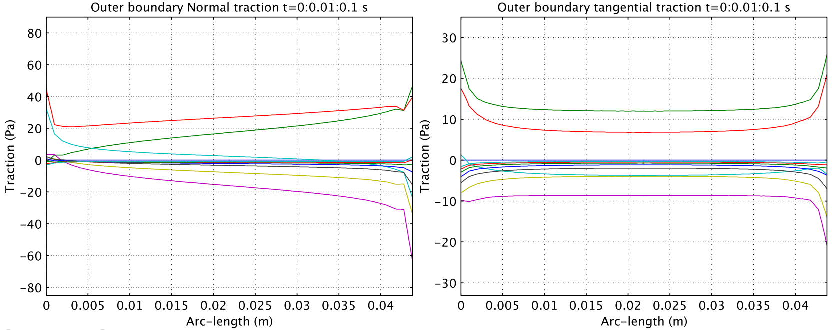


[c3_case_006]

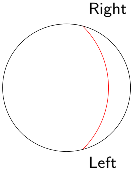


$$c_0 = 3 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.50 \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)



[c3_case_010]

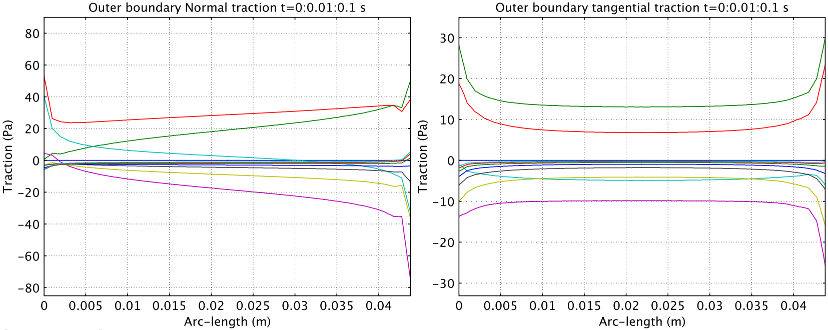


$$c_0 = 3 \quad \text{Pa}$$

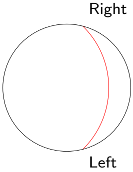
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = {\color{red}0.75} \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)



[c3_case_011]

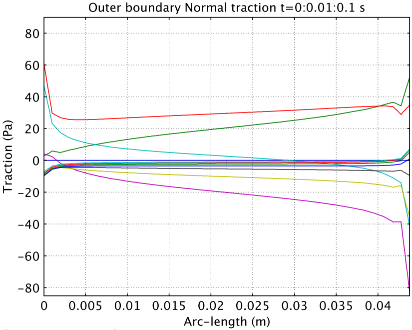


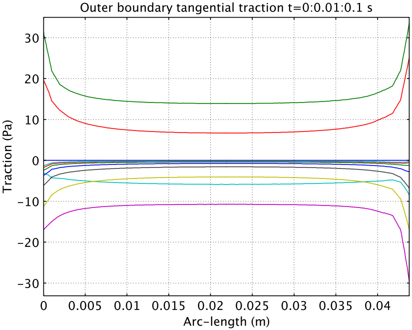
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

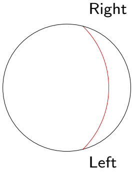
$$\mu_s = \color{red}{1.00} \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)





[c3_case_011_b]

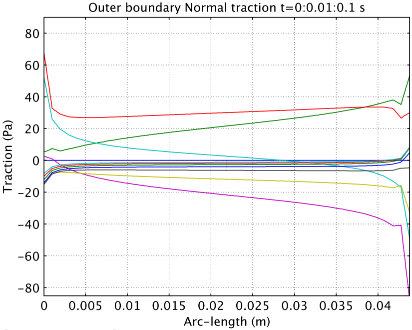


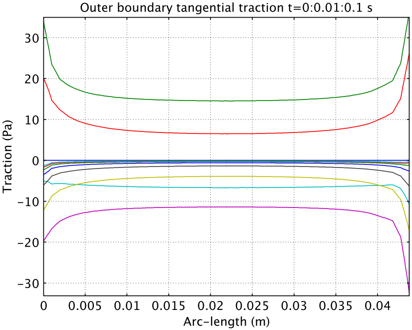
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

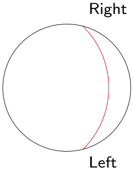
$$\mu_s = 1.25 \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)





[c3_case_011_t]

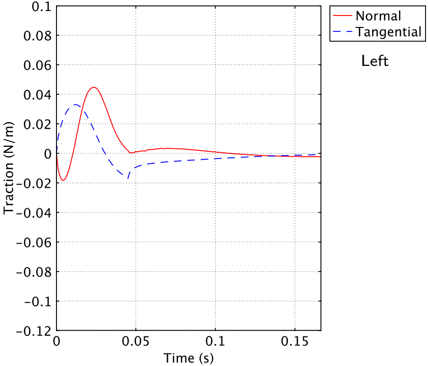


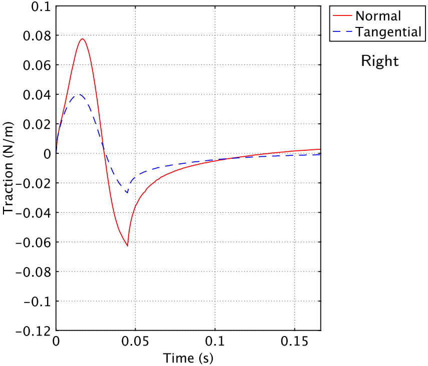
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 1.50 \quad \text{Pa s}$$

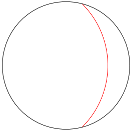
Boundary traction (vs. solid viscosity)





[c3_case_006]

Right



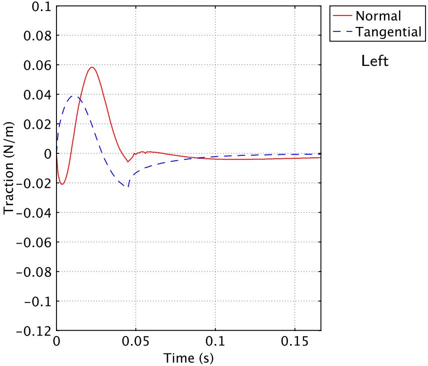
Left

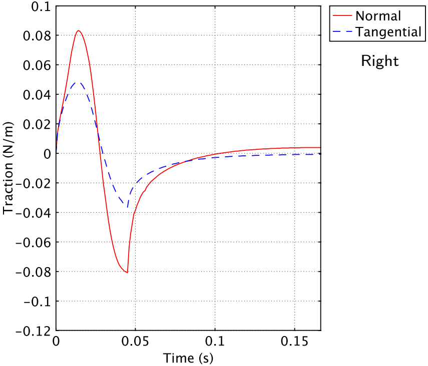
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

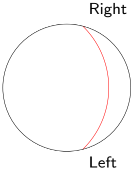
$$\mu_s = 0.50 \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)





[c3_case_010]

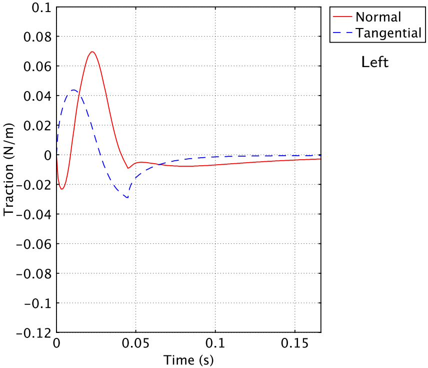


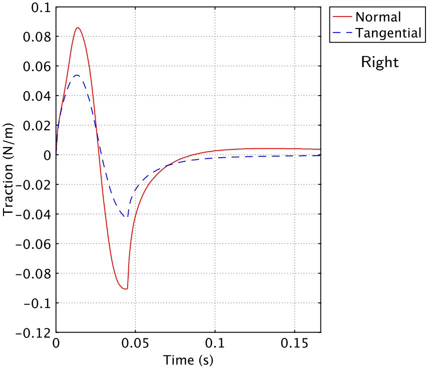
$c_0 = 3$ Pa

$m_0 = 20$ Pa

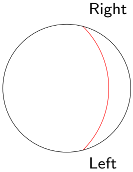
$\mu_s = 0.75$ Pa s

Boundary traction (vs. solid viscosity)



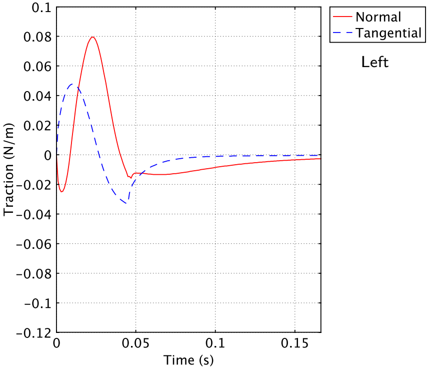


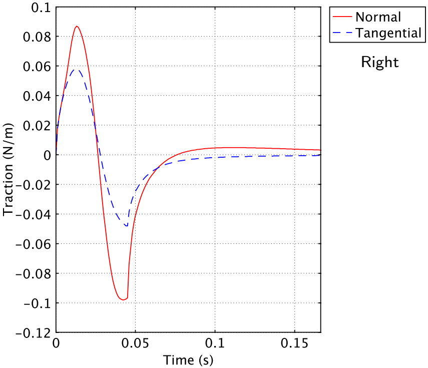
[c3_case_011]



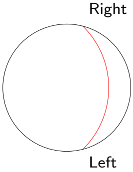
$$c_0 = 3 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 1.00 \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)





[a2_case_011_b]

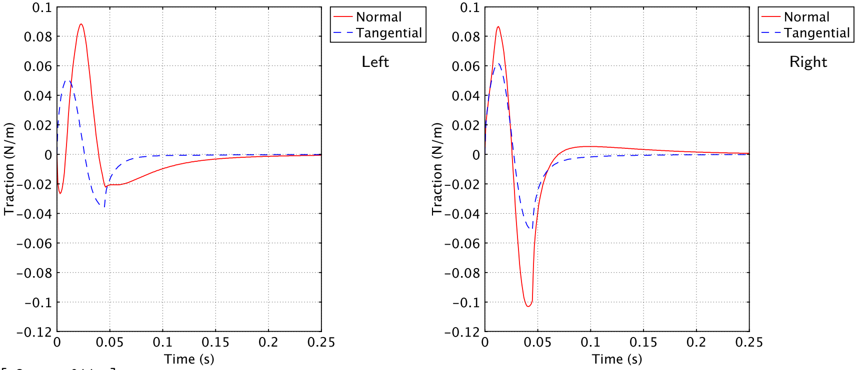


$$c_0 = 3 \quad \text{Pa}$$

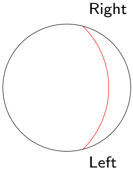
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 1.25 \quad \text{Pa s}$$

Boundary traction (vs. solid viscosity)



[a2_case_011_t]



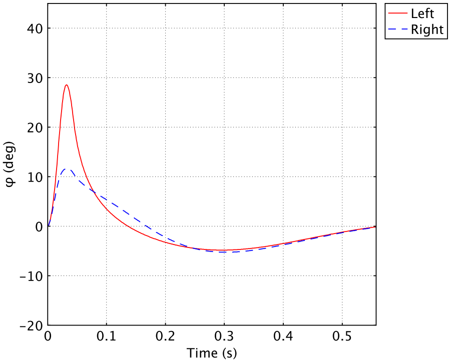
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

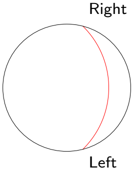
$$\mu_s = 1.50 \quad \text{Pa s}$$

Membrane oscillations
for different values of the solid viscosity

Membrane oscillations (vs. solid viscosity)



[c3_case_006]

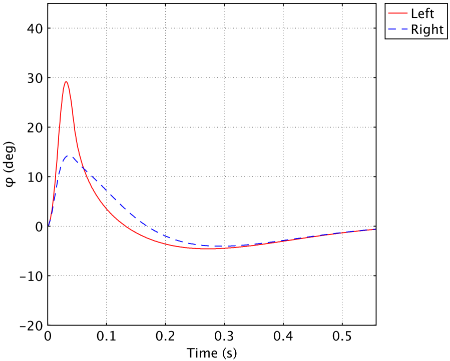


$$c_0 = 3 \quad \text{Pa}$$

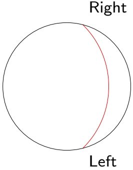
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.50 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)



[c3_case_010]

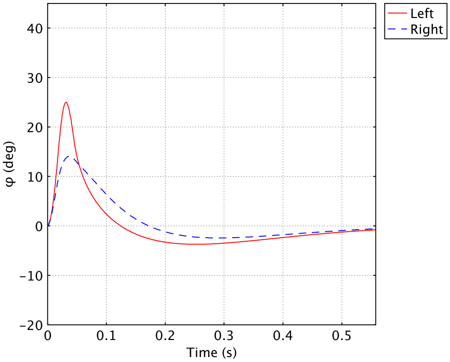


$$c_0 = 3 \quad \text{Pa}$$

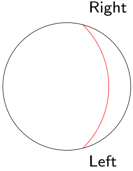
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.75 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)



[c3_case_011]

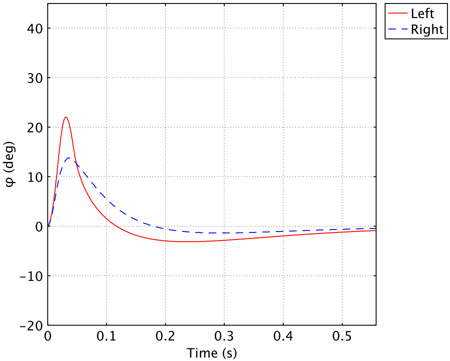


$c_0 = 3$ Pa

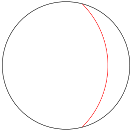
$m_0 = 20$ Pa

$\mu_s = 1.00$ Pa s

Membrane oscillations (vs. solid viscosity)

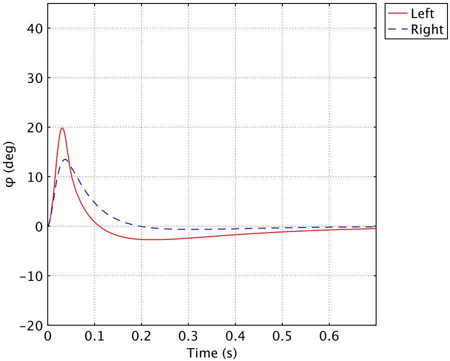


[c3_case_011_b]

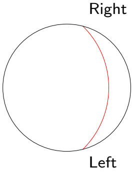


$$c_0 = 3 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 1.25 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)



[c3_case_011_t]



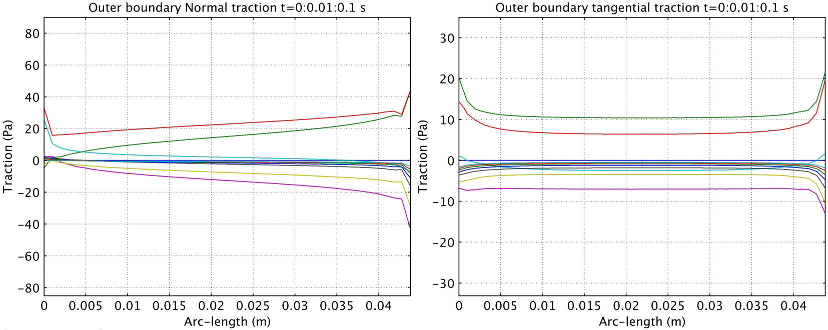
$$c_0 = 3 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

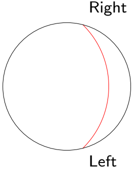
$$\mu_s = 1.50 \quad \text{Pa s}$$

Boundary traction
for different values of the membrane elastic modulus

Boundary traction (vs. membrane elastic modulus)



[c3_case_001]

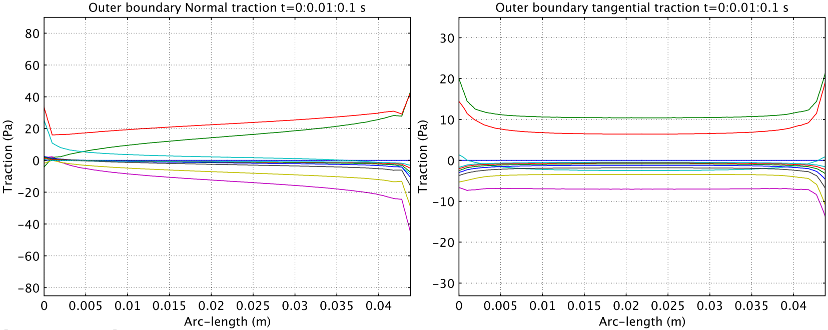


$$c_0 = 2 \quad \text{Pa}$$

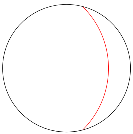
$$m_0 = {\color{red}2} \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)

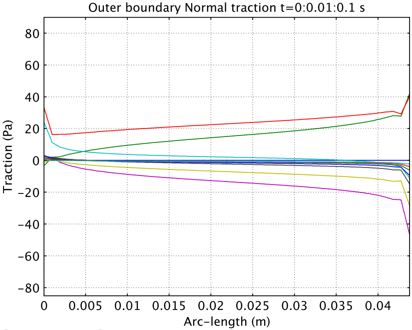


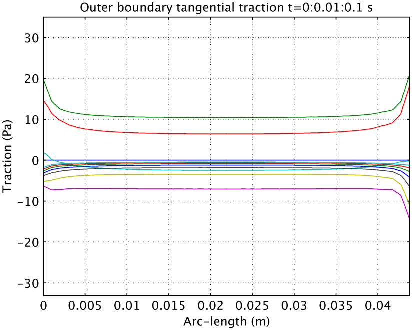
[c3_case_001_b]



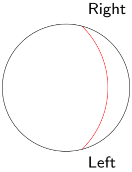
$$c_0 = 2 \quad \text{Pa}$$
$$m_0 = 5 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)





[c3_case_002]

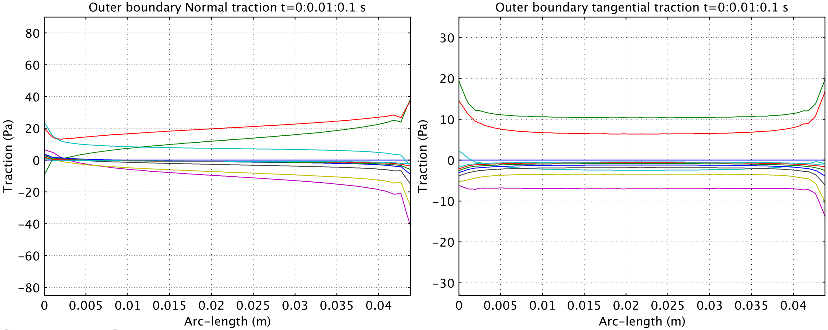


$c_0 = 2$ Pa

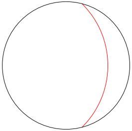
$m_0 = 10$ Pa

$\mu_s = 0.5$ Pa s

Boundary traction (vs. membrane elastic modulus)



[c3_case_002_b]

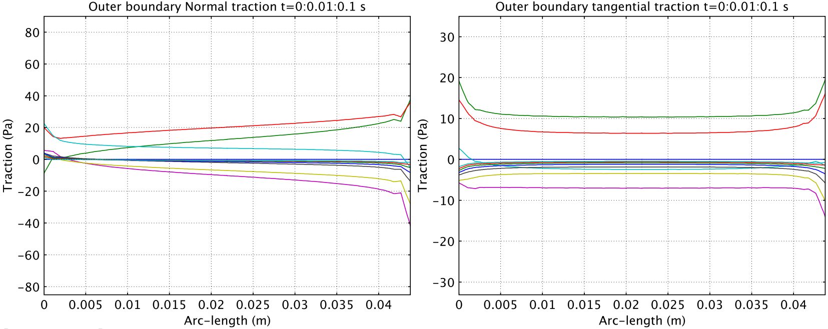


$$c_0 = 2 \quad \text{Pa}$$

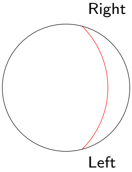
$$m_0 = 15 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)



[c3_case_003]

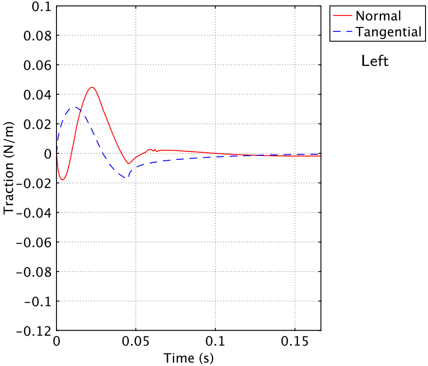


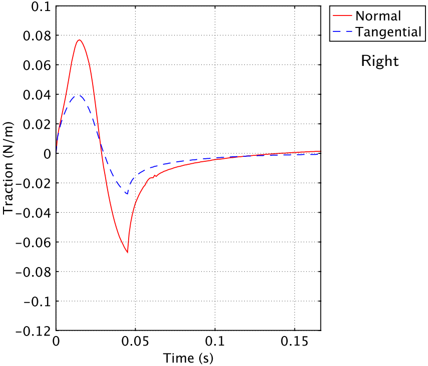
$$c_0 = 2 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

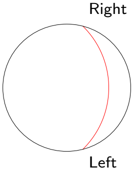
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)





[c3_case_001]

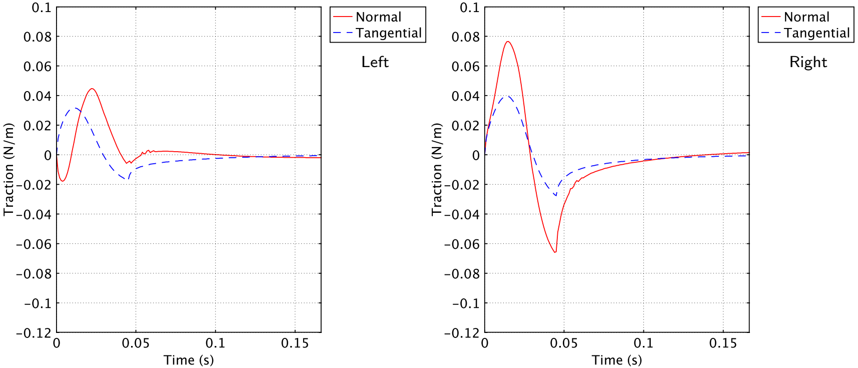


$$c_0 = 2 \quad \text{Pa}$$

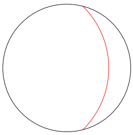
$$m_0 = 2 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)



[c3_case_001_b]

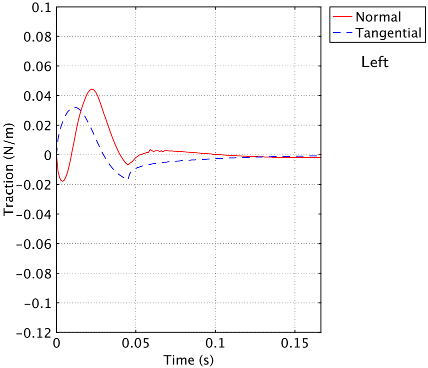


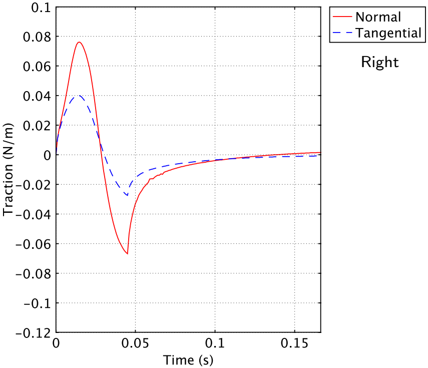
$$c_0 = 2 \quad \text{Pa}$$

$$m_0 = \color{red}{5} \quad \text{Pa}$$

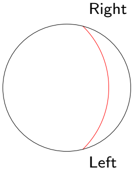
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)





[c3_case_002]

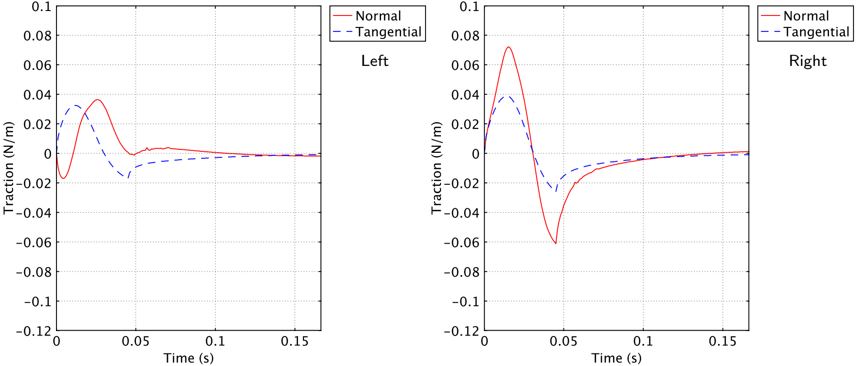


$$c_0 = 2 \quad \text{Pa}$$

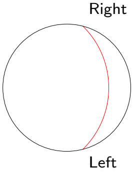
$$m_0 = 10 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)



[c3_case_002_b]

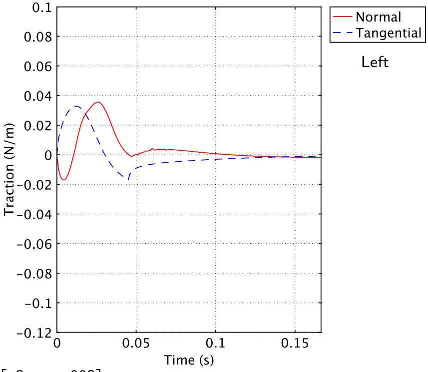


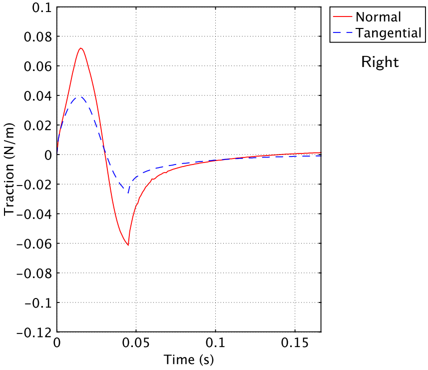
$$c_0 = 2 \quad \text{Pa}$$

$$m_0 = 15 \quad \text{Pa}$$

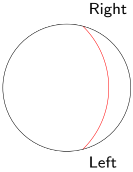
$$\mu_s = 0.5 \quad \text{Pa s}$$

Boundary traction (vs. membrane elastic modulus)





[c3_case_003]

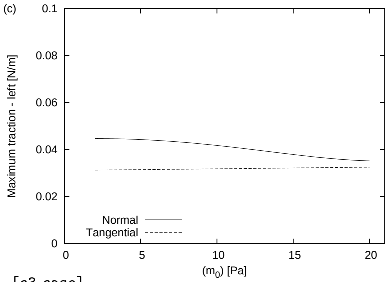


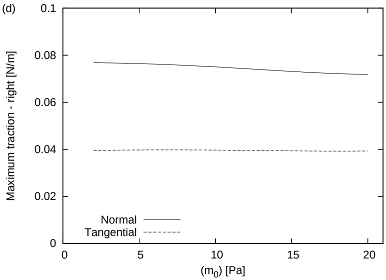
$c_0 = 2$ Pa

$m_0 = 20$ Pa

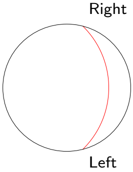
$\mu_s = 0.5$ Pa s

Boundary traction (vs. membrane elastic modulus)





[c3_case]



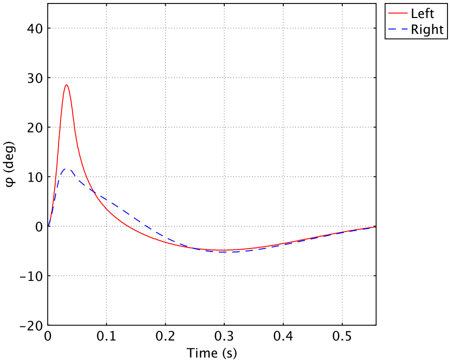
$$c_0 = 2 \quad \text{Pa}$$

$$m_0 = 2 \div 20 \quad \text{Pa}$$

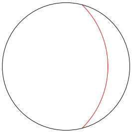
$$\mu_s = 0.5 \quad \text{Pa s}$$

Membrane oscillations
for different values of the solid viscosity

Membrane oscillations (vs. solid viscosity)



[c3_case_006]

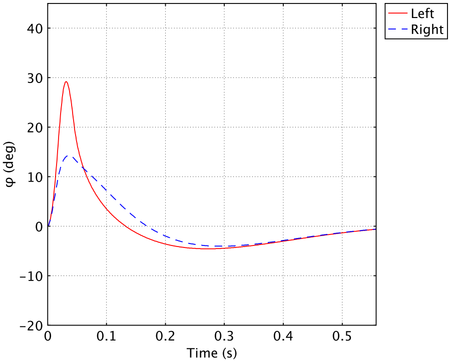


$$c_0 = 3 \quad \text{Pa}$$

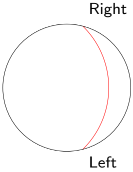
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.50 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)



[c3_case_010]

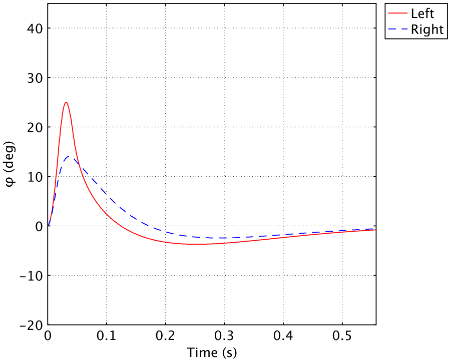


$c_0 = 3$ Pa

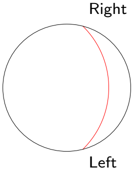
$m_0 = 20$ Pa

$\mu_s = 0.75$ Pa s

Membrane oscillations (vs. solid viscosity)



[c3_case_011]

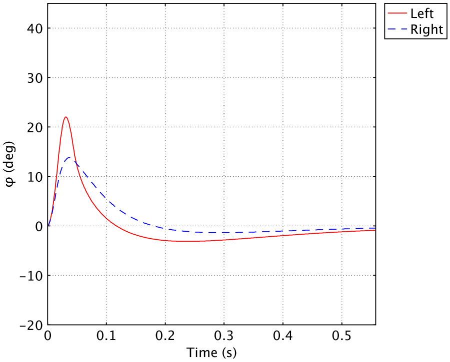


$$c_0 = 3 \quad \text{Pa}$$

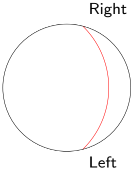
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 1.00 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)

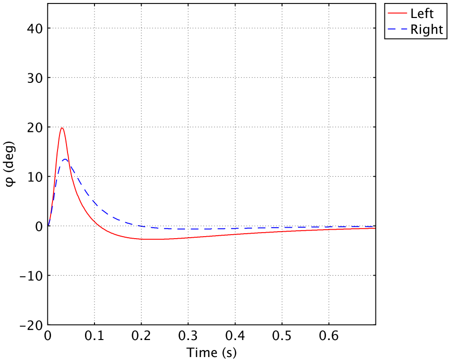


[c3_case_011_b]

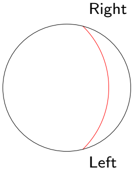


$$c_0 = 3 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 1.25 \quad \text{Pa s}$$

Membrane oscillations (vs. solid viscosity)



[c3_case_011_t]



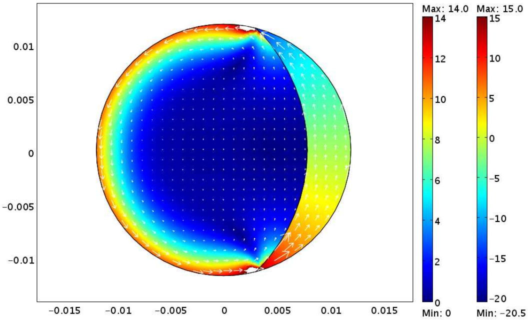
$c_0 = 3$ Pa

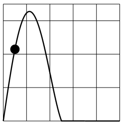
$m_0 = 20$ Pa

$\mu_s = 1.50$ Pa s

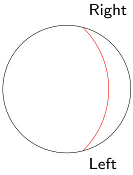
Stress and velocity field in the solid

Deviatoric stress and velocity field in the solid



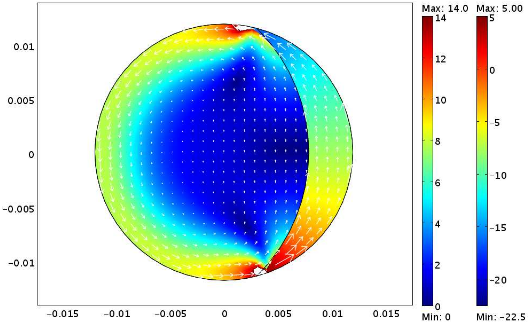


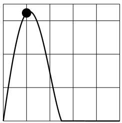
[c3_case_008]



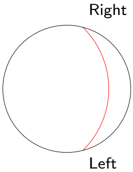
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Deviatoric stress and velocity field in the solid



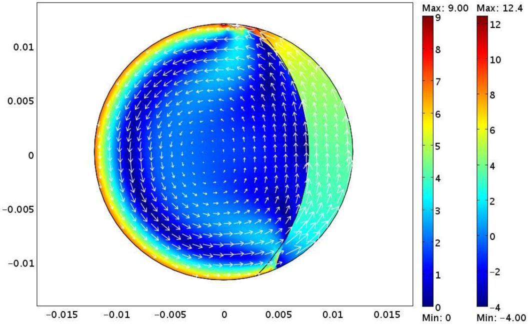


[c3_case_008]

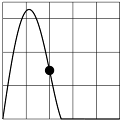


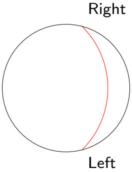
$c_0 =$	5	Pa
$m_0 =$	20	Pa
$\mu_s =$	0.5	Pa s

Deviatoric stress and velocity field in the solid



[c3_case_008]



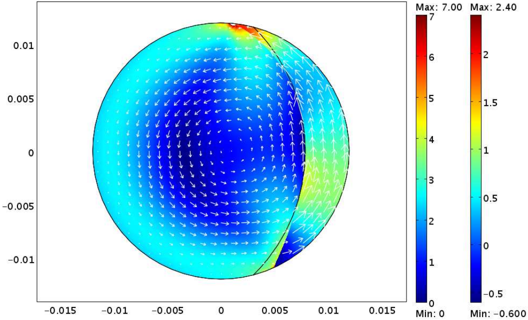


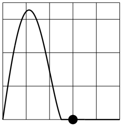
$c_0 = 5$ Pa

$m_0 = 20$ Pa

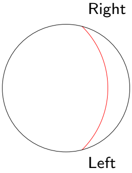
$\mu_s = 0.5$ Pa s

Deviatoric stress and velocity field in the solid





[c3_case_008]

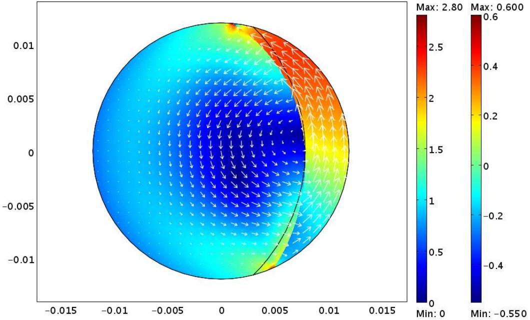


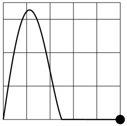
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

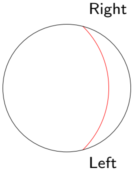
$$\mu_s = 0.5 \quad \text{Pa s}$$

Deviatoric stress and velocity field in the solid



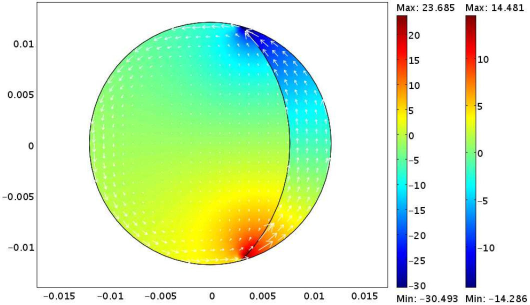


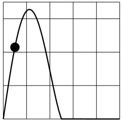
[c3_case_008]



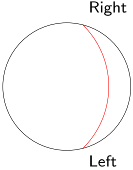
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Pressure and velocity field in the solid



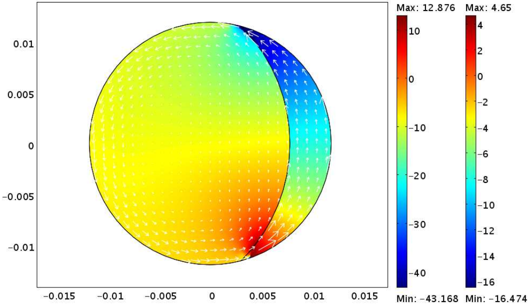


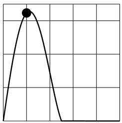
[c3_case_008]



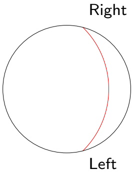
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Pressure and velocity field in the solid

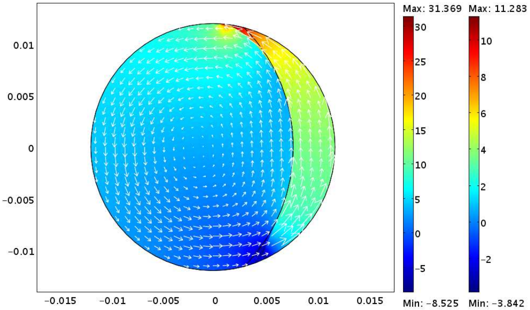


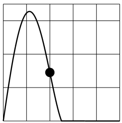


[c3_case_008]

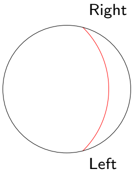


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$



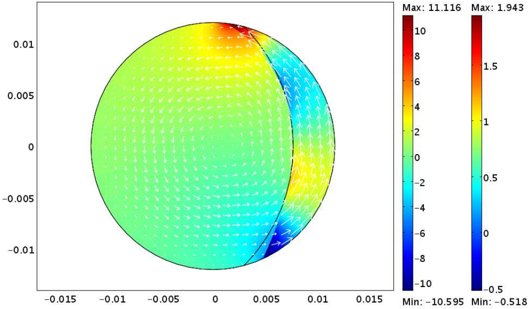


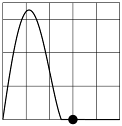
[c3_case_008]



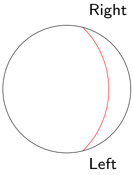
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Pressure and velocity field in the solid



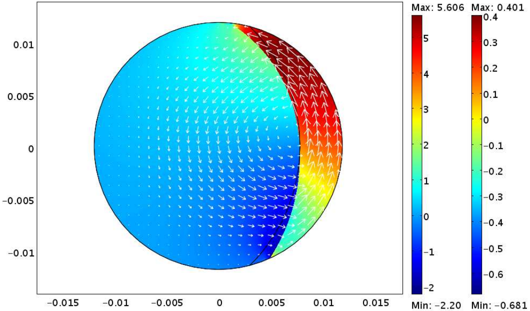


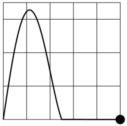
[c3_case_008]



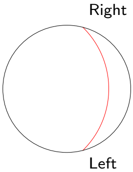
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Pressure and velocity field in the solid





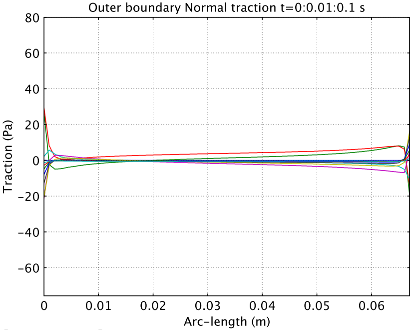
[c3_case_008]

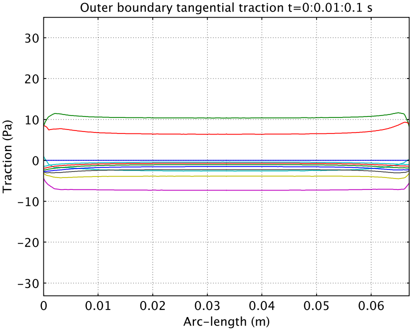


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

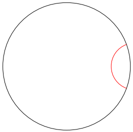
Comparing different PVD conformations

Different PVD conformations



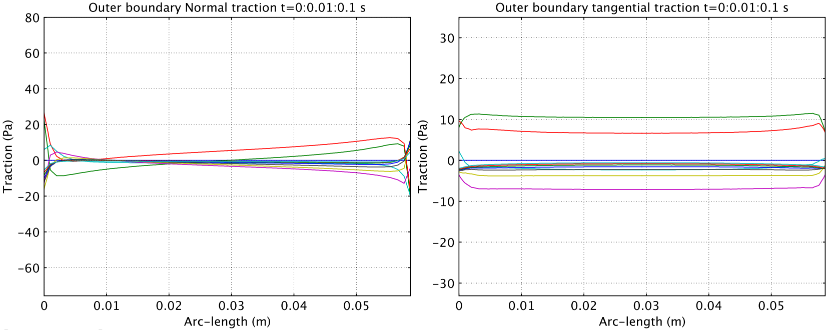


[a1_case_008]

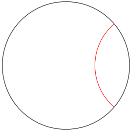


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[a2_case_008]

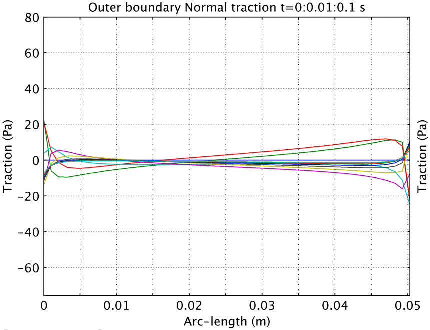


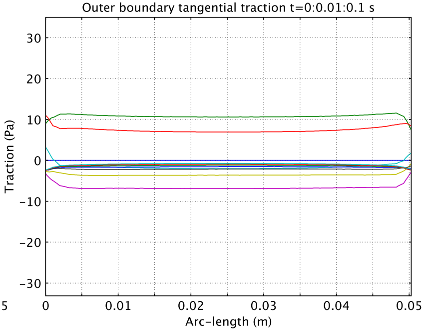
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

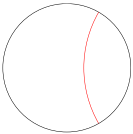
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



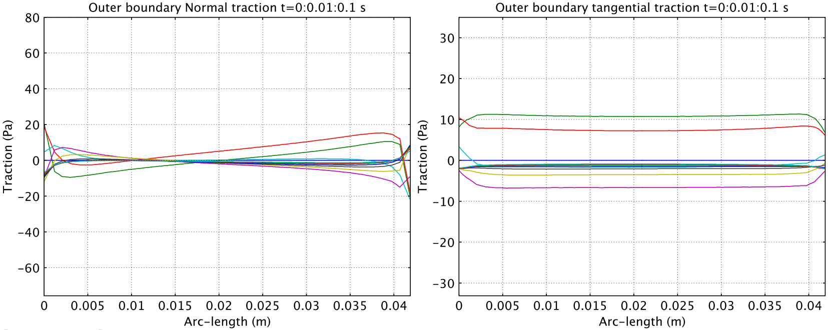


[a3_case_008]

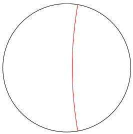


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[a4_case_008]

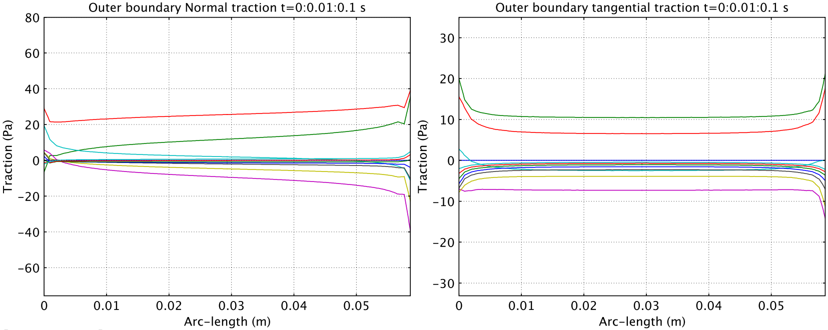


$c_0 = 5$ Pa

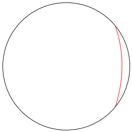
$m_0 = 20$ Pa

$\mu_s = 0.5$ Pa s

Different PVD conformations

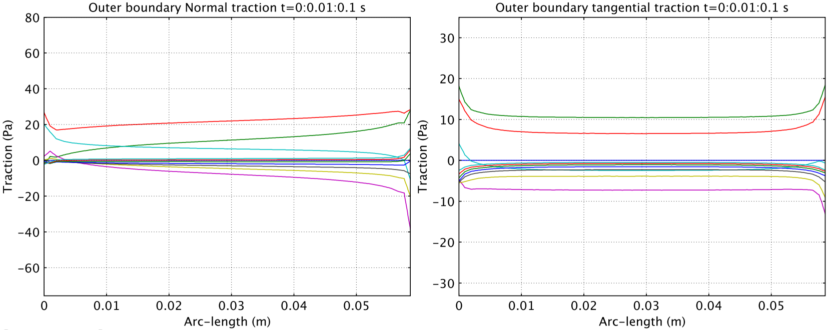


[b5_case_008]

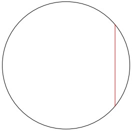


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[b6_case_008]

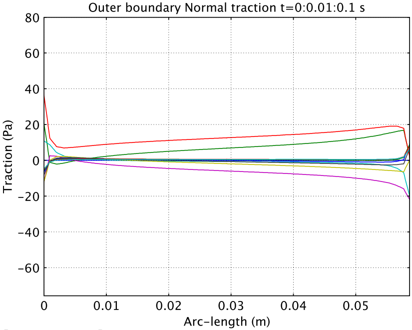


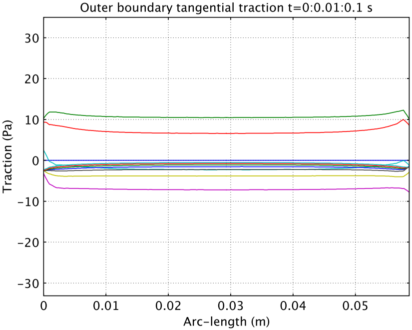
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

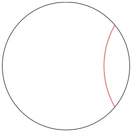
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



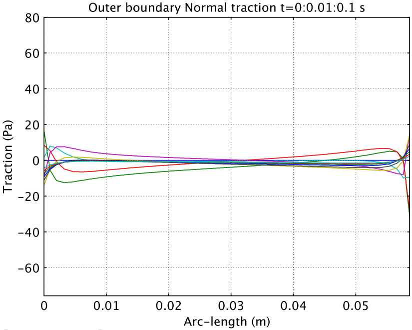


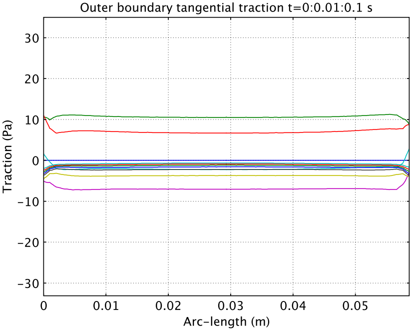
[b7_case_008]



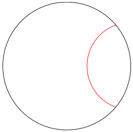
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[b8_case_008]

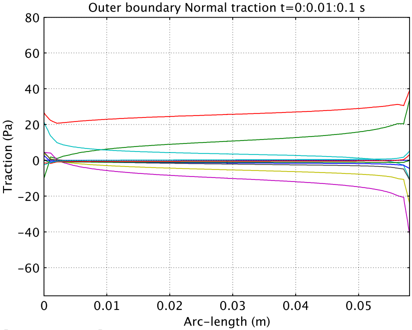


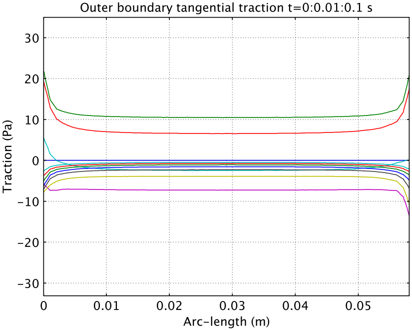
$c_0 = 5$ Pa

$m_0 = 20$ Pa

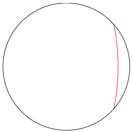
$\mu_s = 0.5$ Pa s

Different PVD conformations



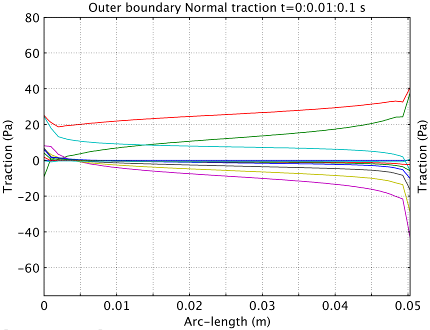


[c1_case_008]

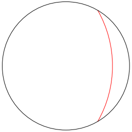


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[c2_case_008]

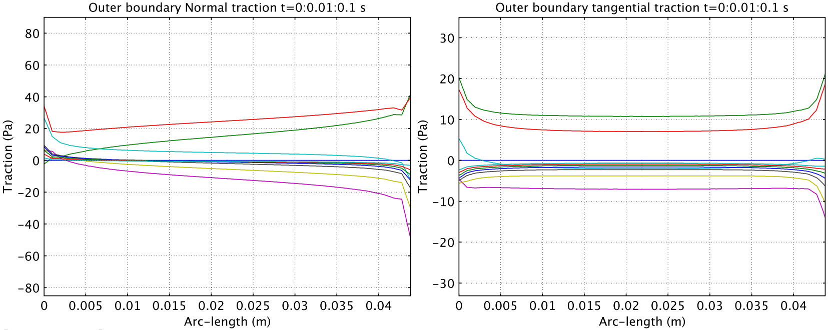


$$c_0 = 5 \quad \text{Pa}$$

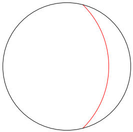
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

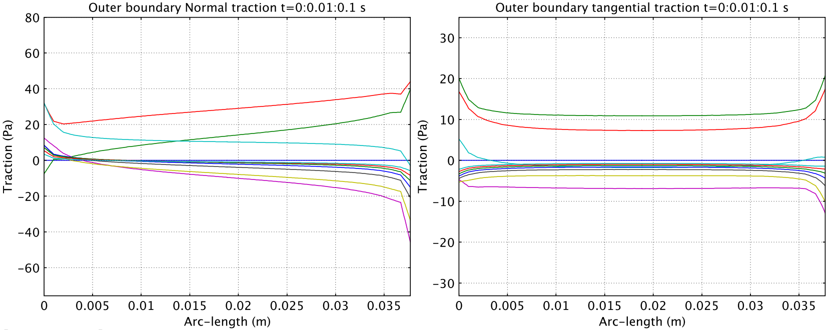


[c3_case_008]

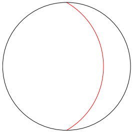


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

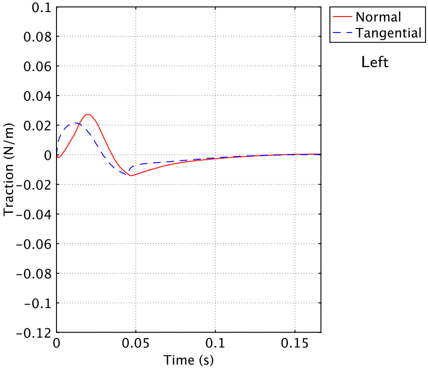


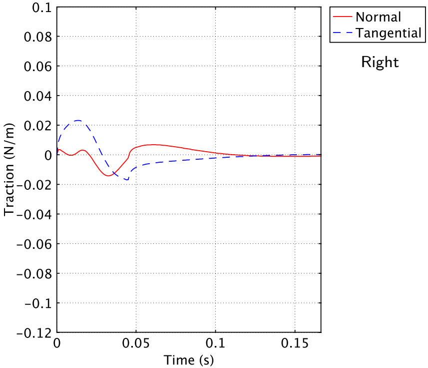
[c4_case_008]



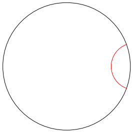
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



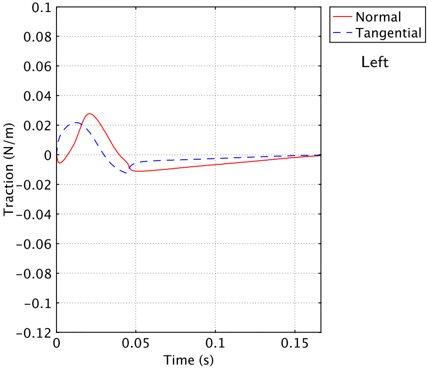


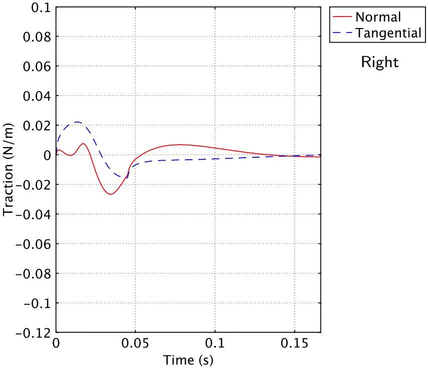
[a1_case_008]



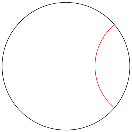
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[a2_case_008]

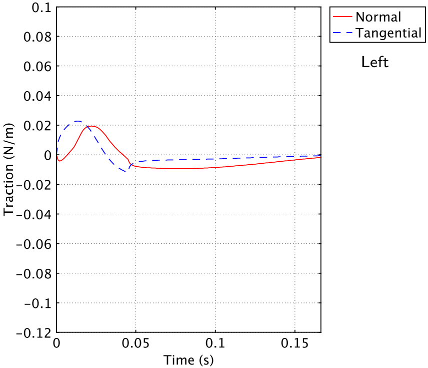


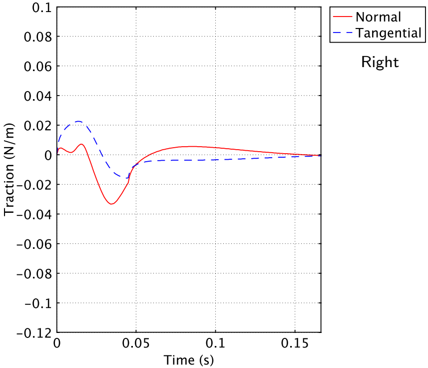
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

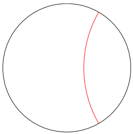
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



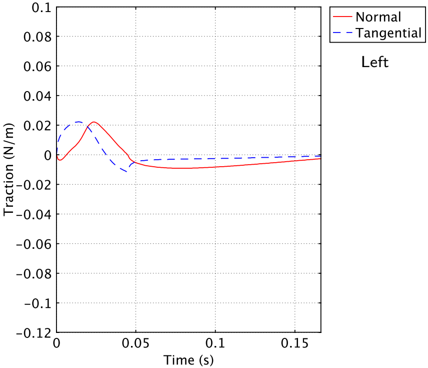


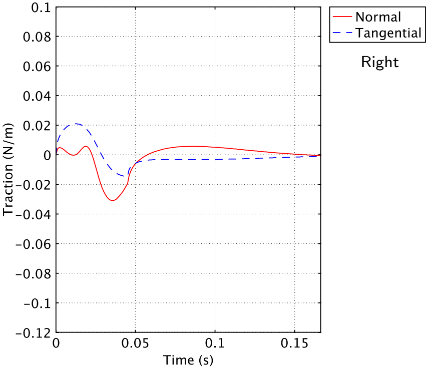
[a3_case_008]



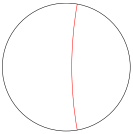
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



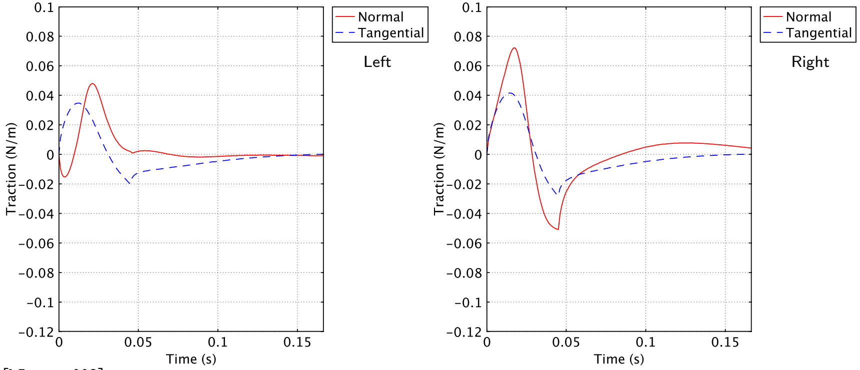


[a4_case_008]

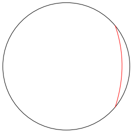


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[b5_case_008]

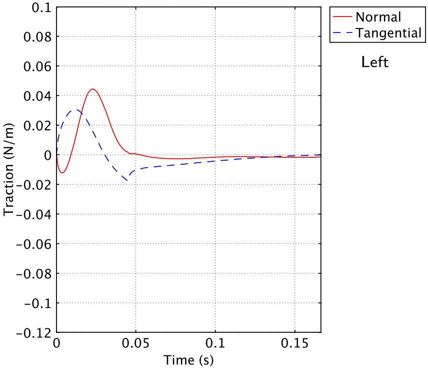


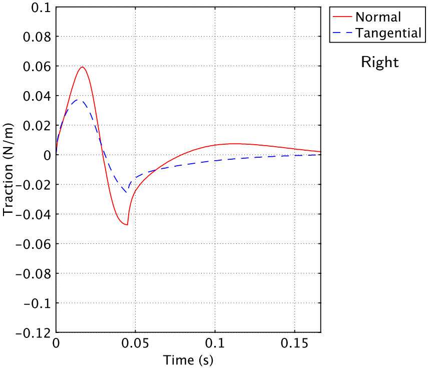
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

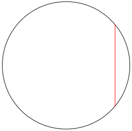
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



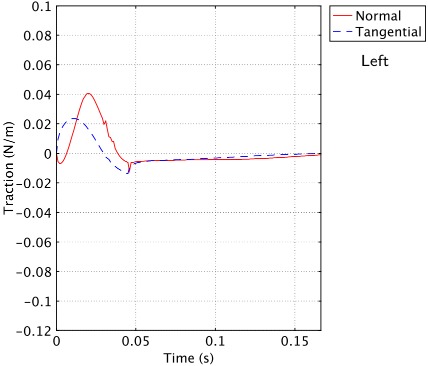


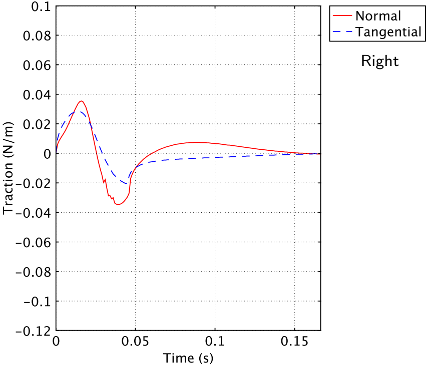
[b6_case_008]



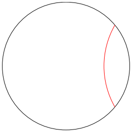
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[b7_case_008]

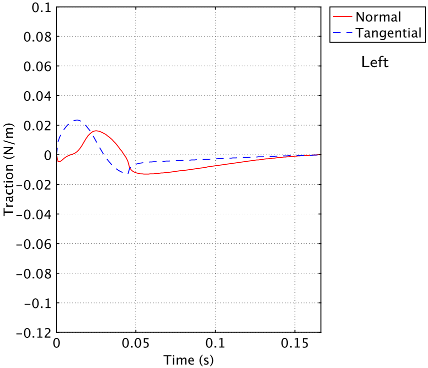


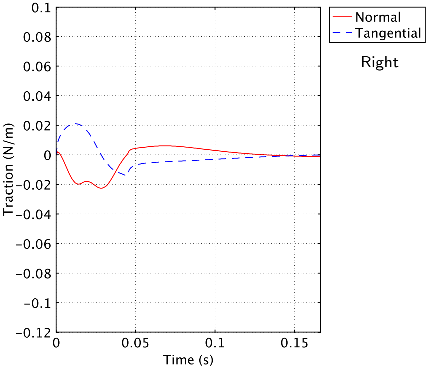
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

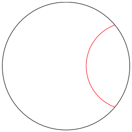
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



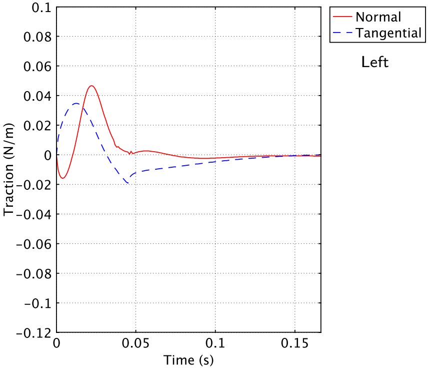


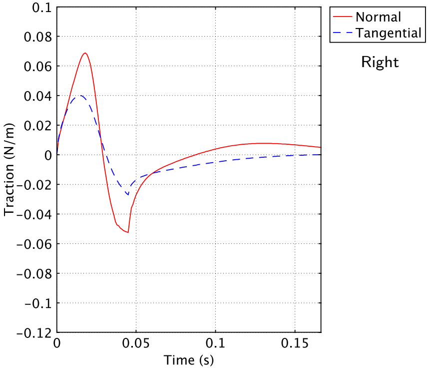
[b8_case_008]



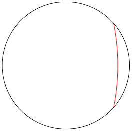
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



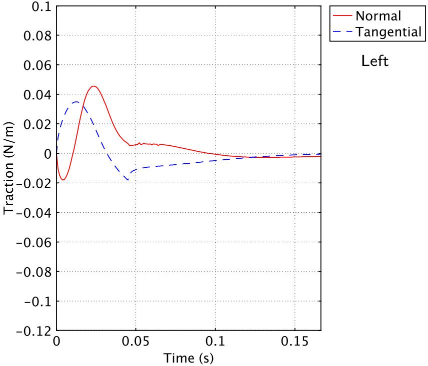


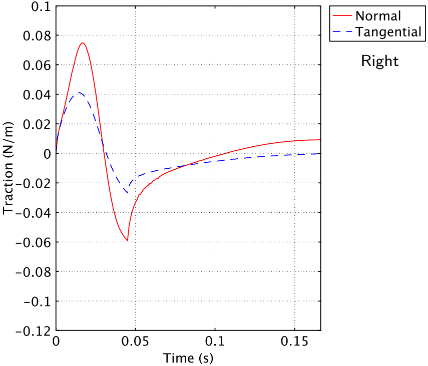
[c1_case_008]



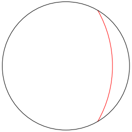
$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[c2_case_008]

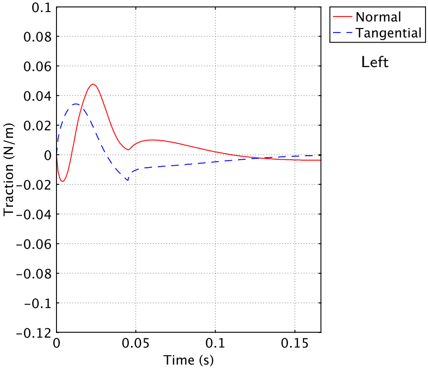


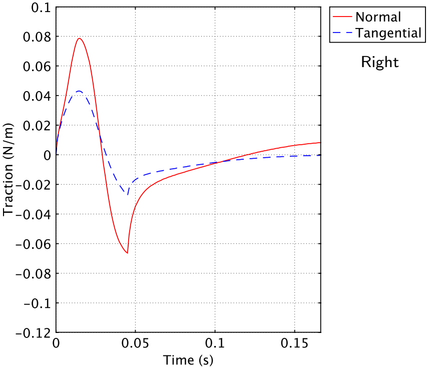
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

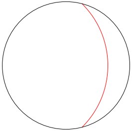
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[c3_case_008]

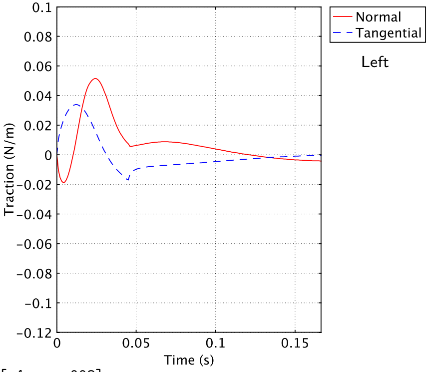


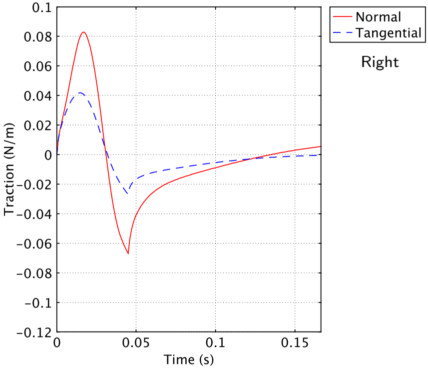
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

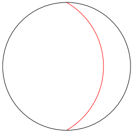
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





[c4_case_008]

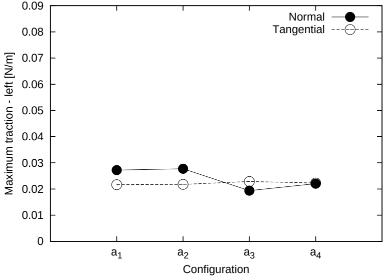


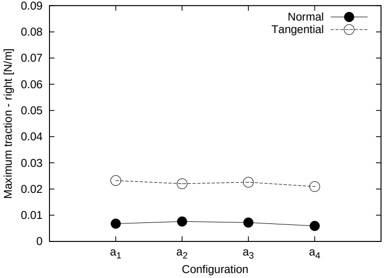
$$c_0 = 5 \quad \text{Pa}$$

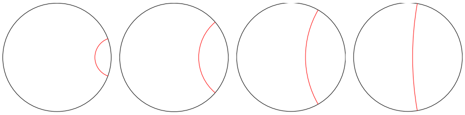
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

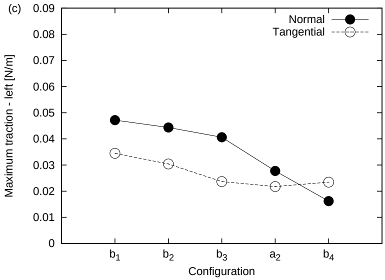


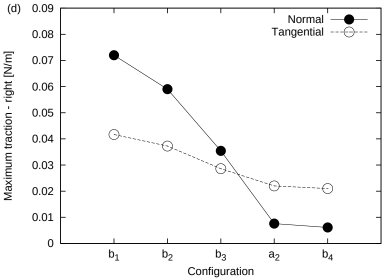


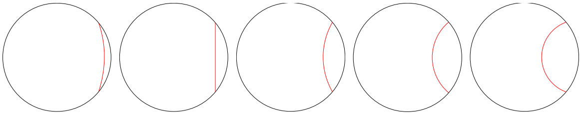


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations





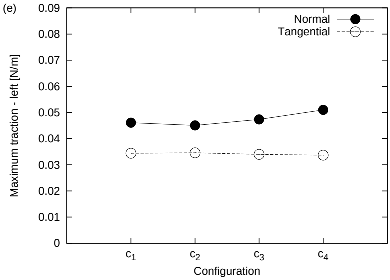


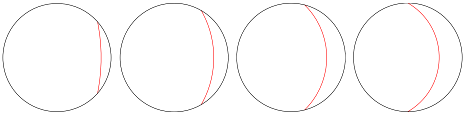
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

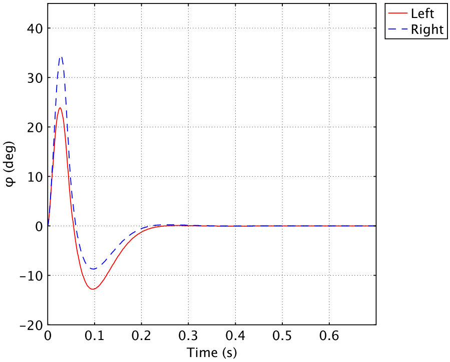
Different PVD conformations



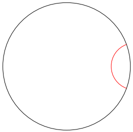


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[a1_case_008]

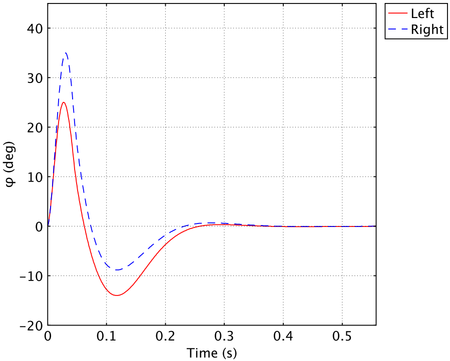


$$c_0 = 5 \quad \text{Pa}$$

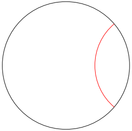
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

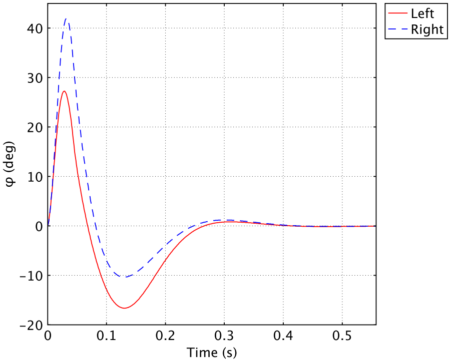


[a2_case_008]

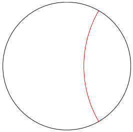


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[a3_case_008]

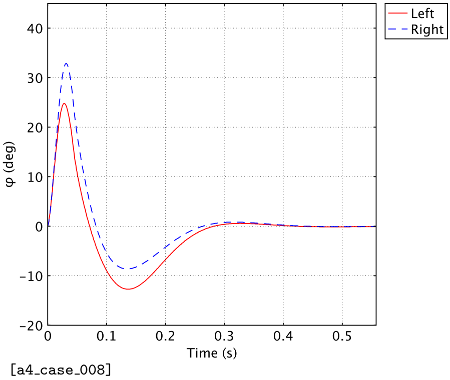


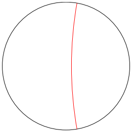
$$c_0 = 5 \quad \text{Pa}$$

$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

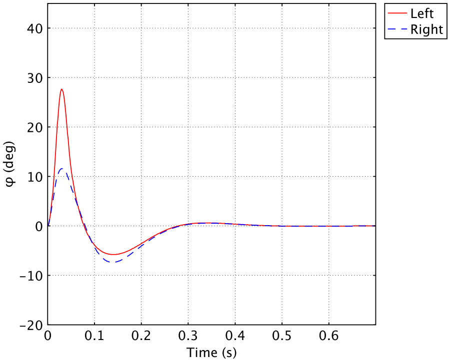
Different PVD conformations



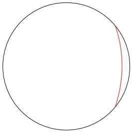


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

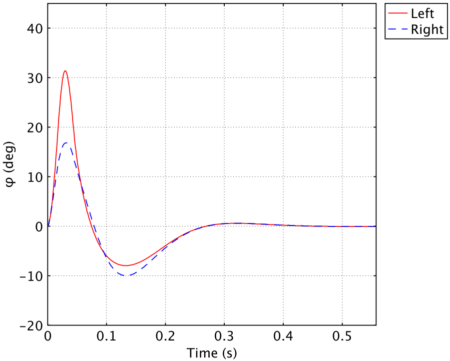


[b5_case_008]

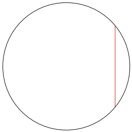


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

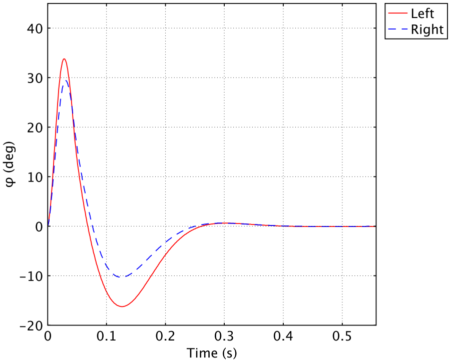


[b6_case_008]

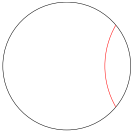


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[b7_case_008]

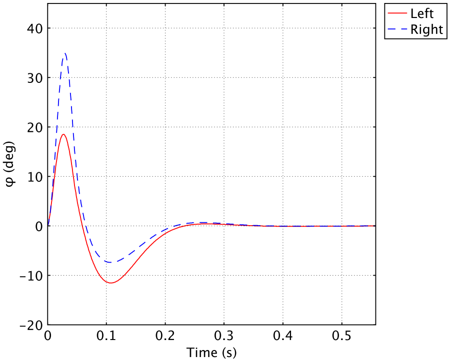


$$c_0 = 5 \quad \mathrm{Pa}$$

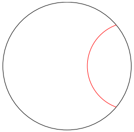
$$m_0 = 20 \quad \mathrm{Pa}$$

$$\mu_s = 0.5 \quad \mathrm{Pa\ s}$$

Different PVD conformations

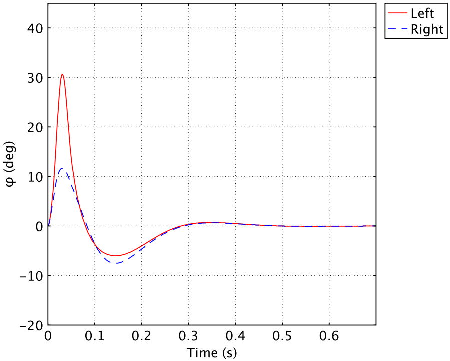


[b8_case_008]

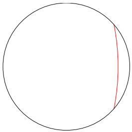


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

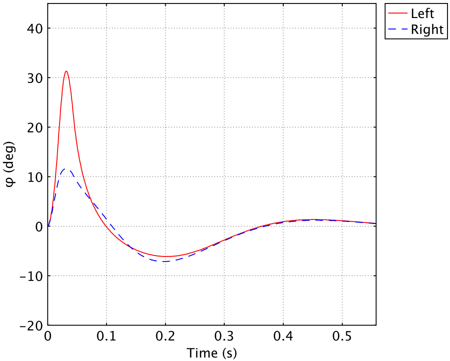


[c1_case_008]

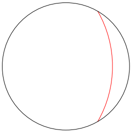


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[c2_case_008]

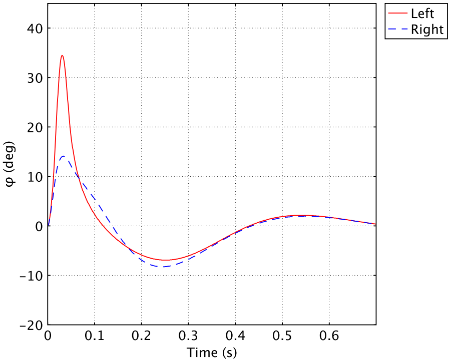


$$c_0 = 5 \quad \text{Pa}$$

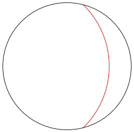
$$m_0 = 20 \quad \text{Pa}$$

$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations

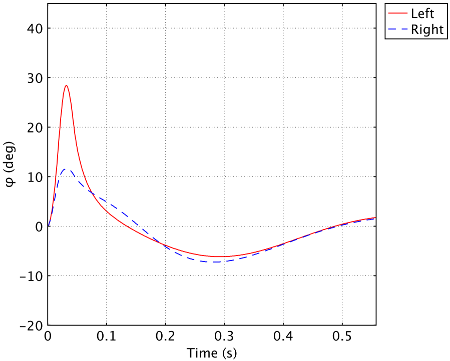


[c3_case_008]

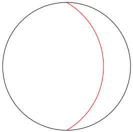


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

Different PVD conformations



[c4_case_008]

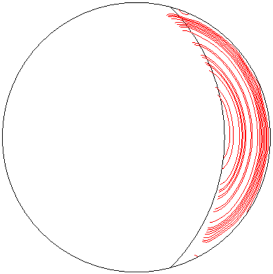


$$c_0 = 5 \quad \text{Pa}$$
$$m_0 = 20 \quad \text{Pa}$$
$$\mu_s = 0.5 \quad \text{Pa s}$$

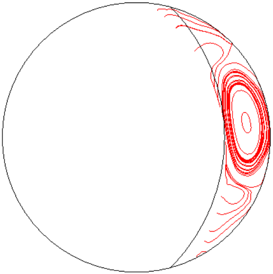
Velocity and pressure in the fluid part of the vitreous

Fluid velocity field

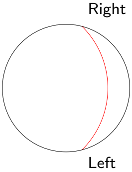
Streamlines of the fluid flow at time=0.09 s



Streamlines of the fluid flow at time=3.7 s



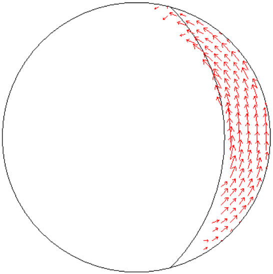
[c3_case_008]



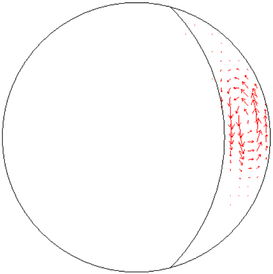
$$
\begin{aligned}
c_0 &= 5 && \text{Pa} \\
m_0 &= 20 && \text{Pa} \\
\mu_s &= 0.5 && \text{Pa s}
\end{aligned}
$$

Fluid velocity field

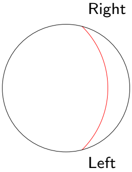
Fluid velocity field at time=0.09 s



Fluid velocity field at time=3.7 s



[c3_case_008]

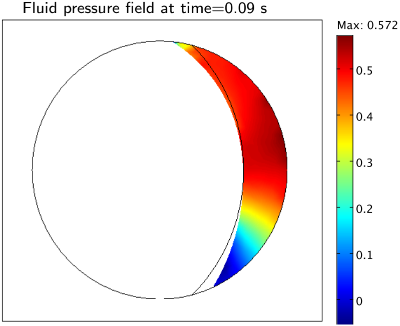


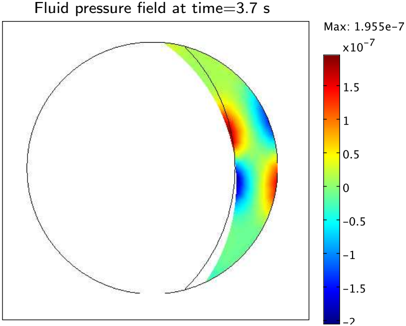
$$c_0 = 5 \quad \mathrm{Pa}$$

$$m_0 = 20 \quad \mathrm{Pa}$$

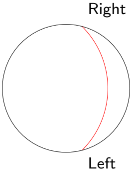
$$\mu_s = 0.5 \quad \mathrm{Pa\ s}$$

Fluid stress field





[c3_case_008]



$$
\begin{aligned}
c_0 &= 5 \quad \text{Pa} \\
m_0 &= 20 \quad \text{Pa} \\
\mu_s &= 0.5 \quad \text{Pa s}
\end{aligned}
$$