Presented at the COMSOL Conference 2008 Hannover

Dynamic Simulation of Electromagnets

European COMSOL Conference

5 November 2008

Division Chassis & Safety
Electronic Brake Systems Simulation

Contents

1. Electronic brake systems by Continental Automotive Systems
   - ABS
   - ESC
2. COMSOL for electromagnetic actuators
   - Magnetic force
   - Armature movement by mesh deformation
   - Fast calculation of system dynamics
3. Conclusion

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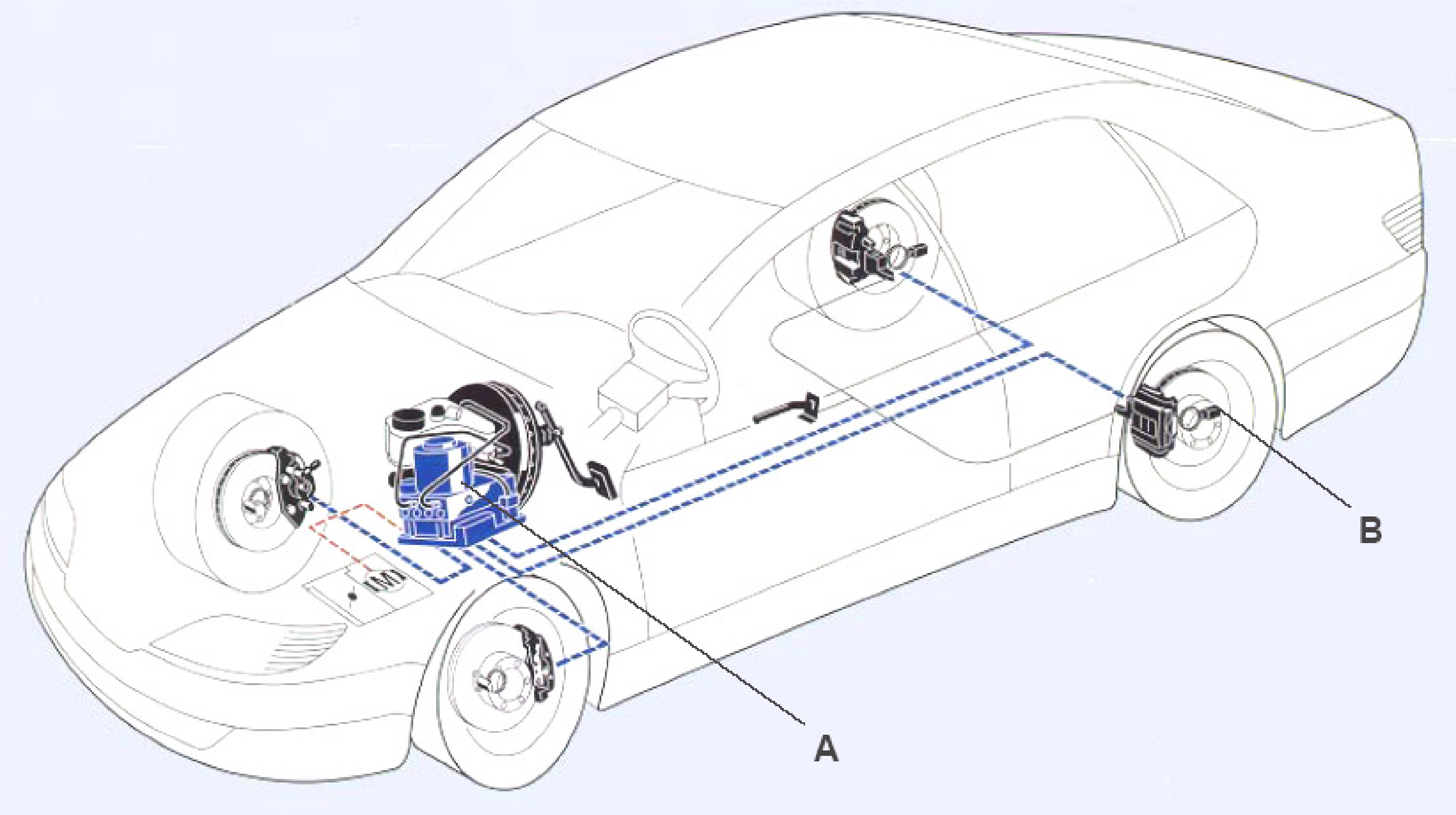
Anti-lock brake system (ABS)

- control slip between wheel and road
- "stick friction > slip friction"
- maximize force between wheel and road
- maintain lateral guiding force

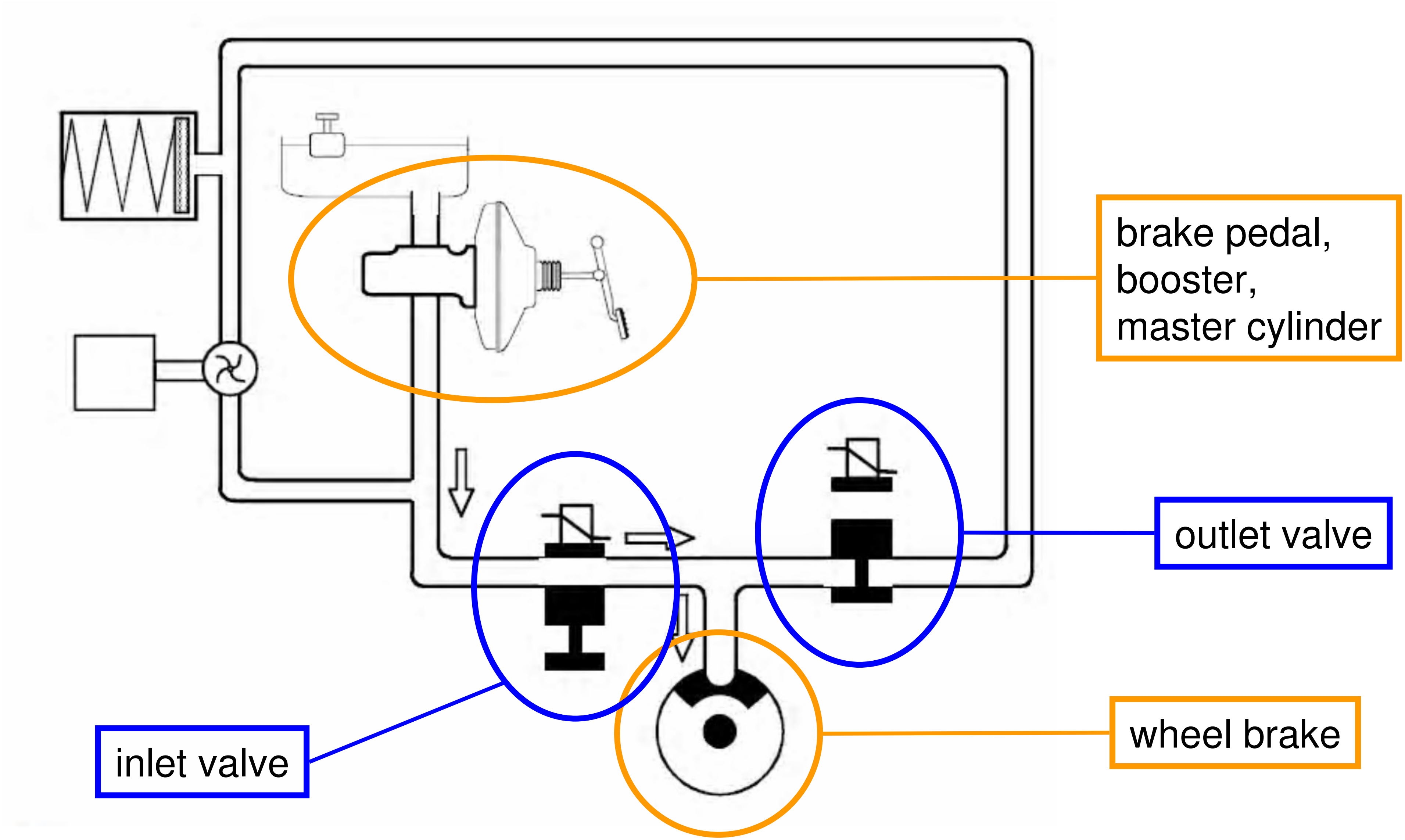
targets:

- vehicle remains stable
- vehicle can be steered
- shorter stopping distance in most situations

ABS components

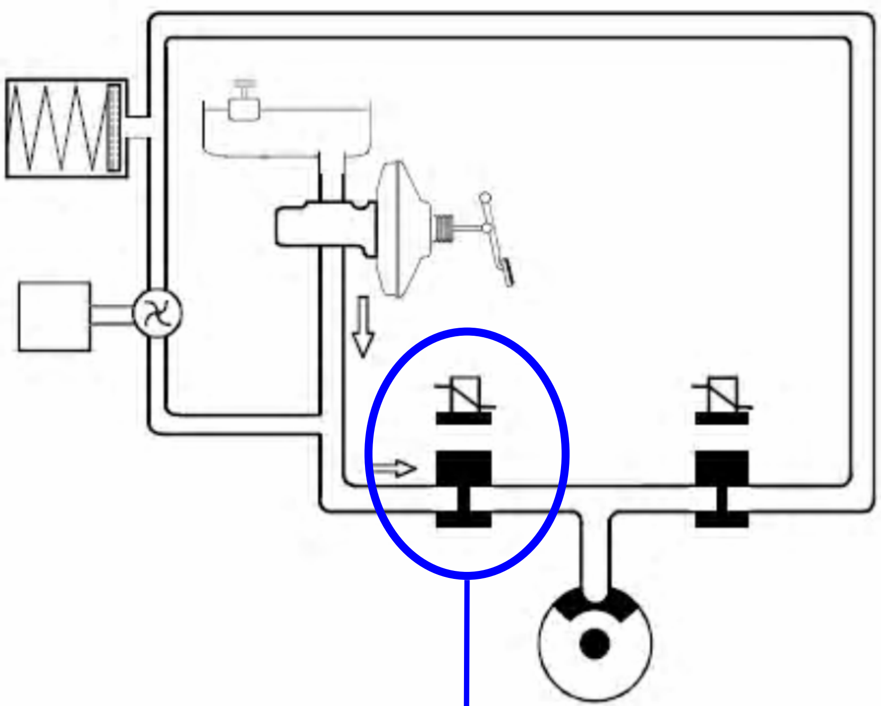


ABS hydraulic layout



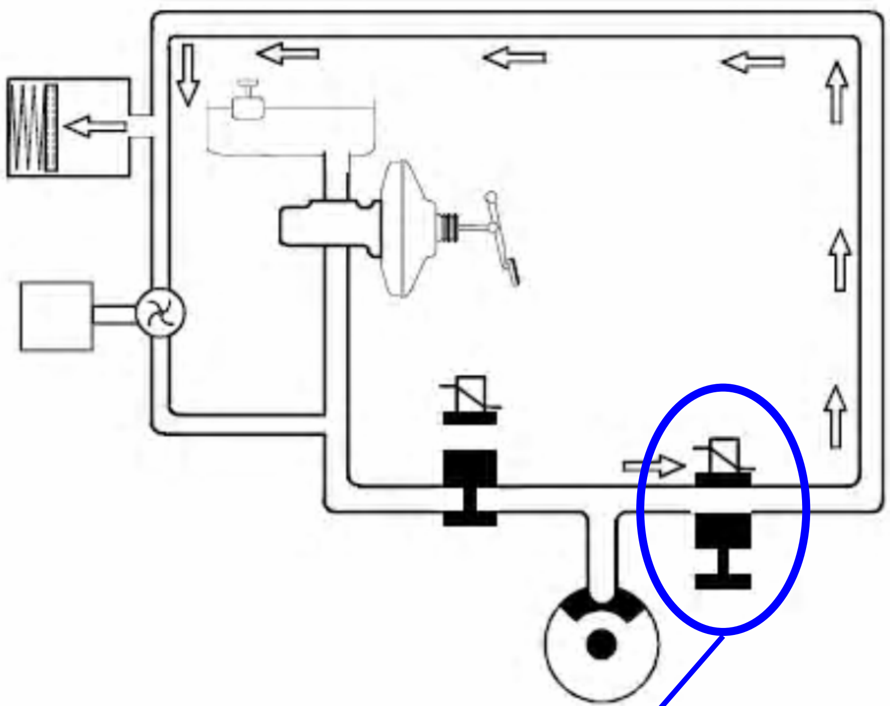
ABS active control

constant pressure phase



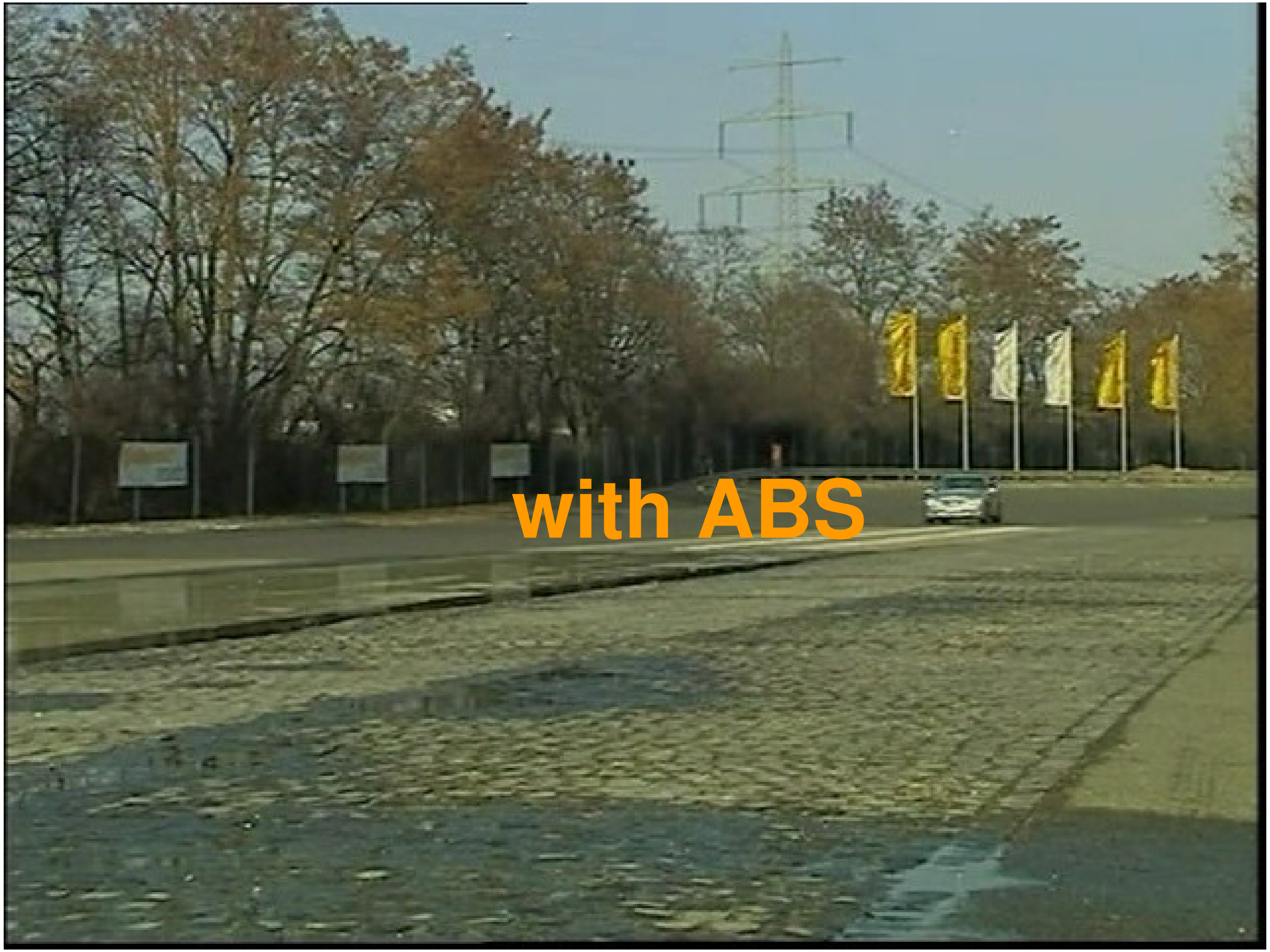
inlet valve closed

pressure decrease phase



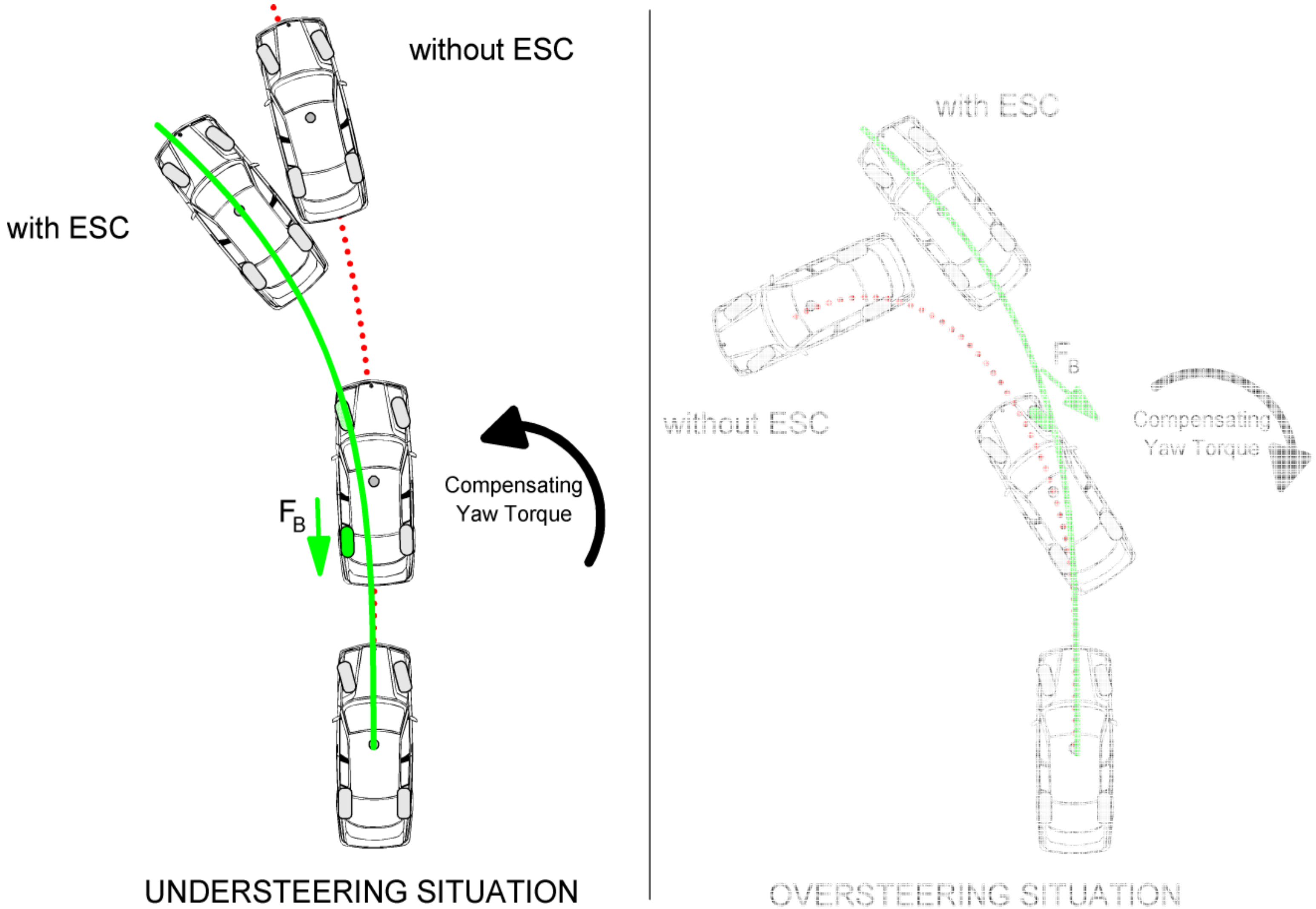
outlet valve open

Antilock Brake System ABS – µ-Split Braking

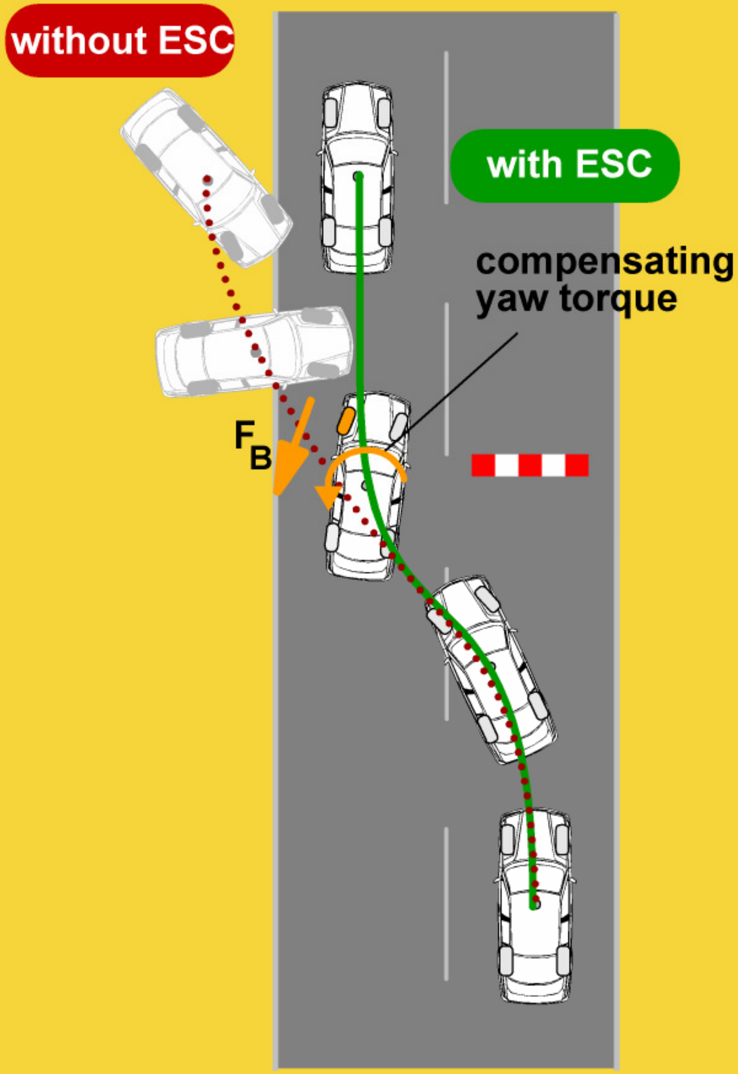


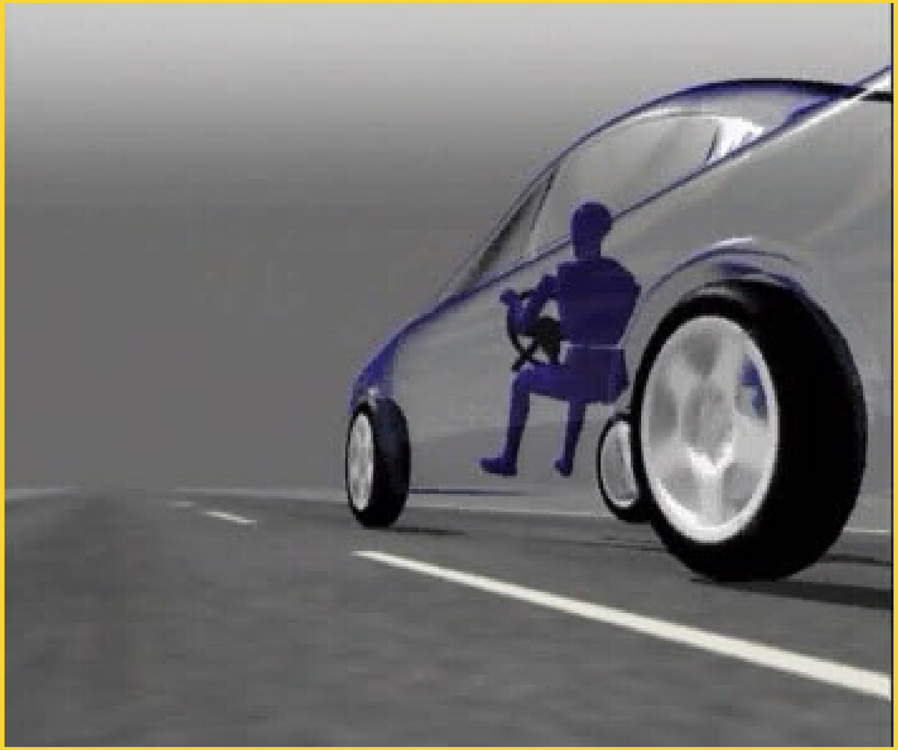
Antilock Brake System ABS – μ-Split Braking

Electronic Stability Control ESC – Active Yaw Control



Electronic Stability Control ESC





	ABS:	Anti-lock Brake System
+	EBD:	Electronic Brake force Distribution
+	TCS:	Traction Control System
+	AYC:	Active Yaw Control
=	ESC:	Electronic Stability Control

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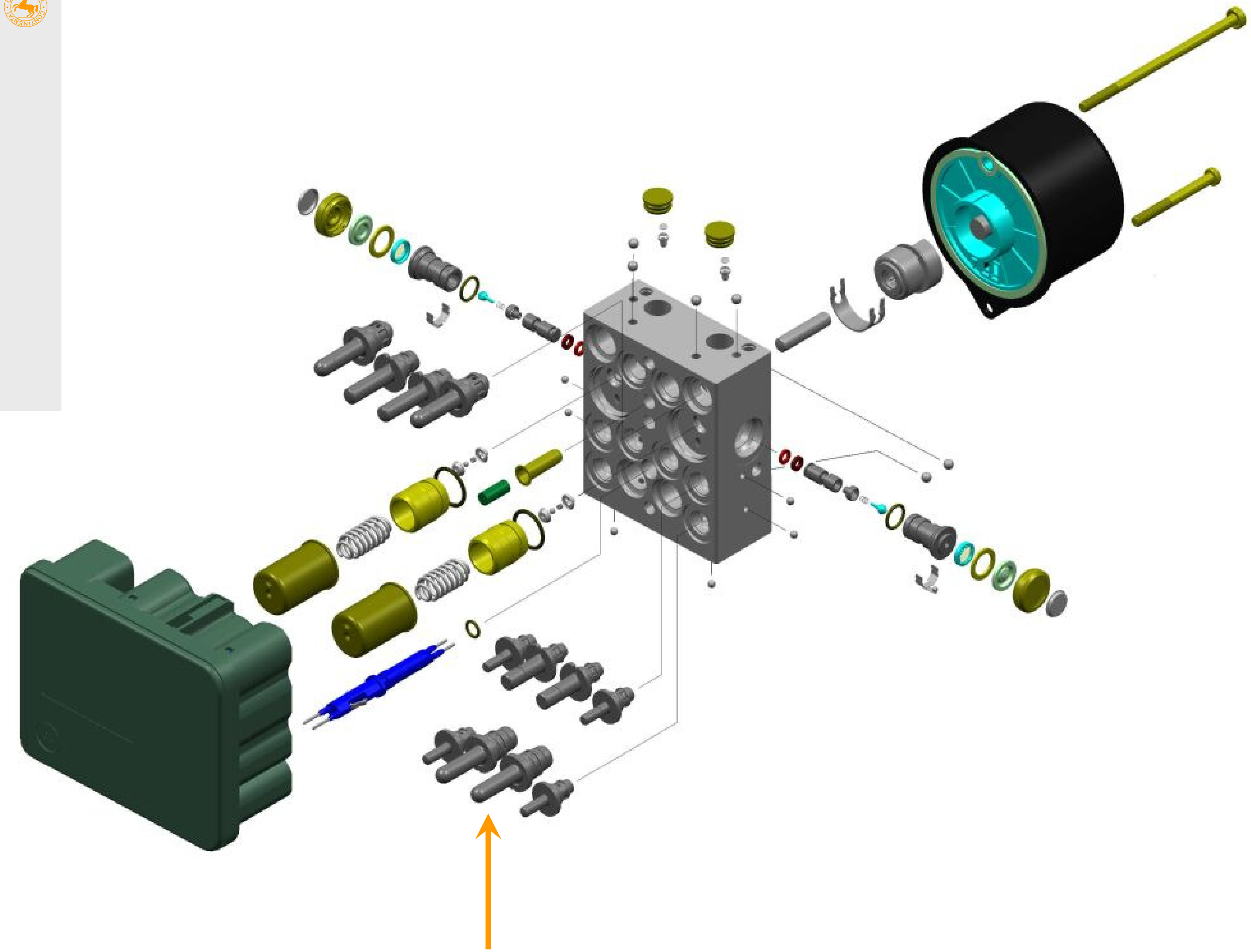
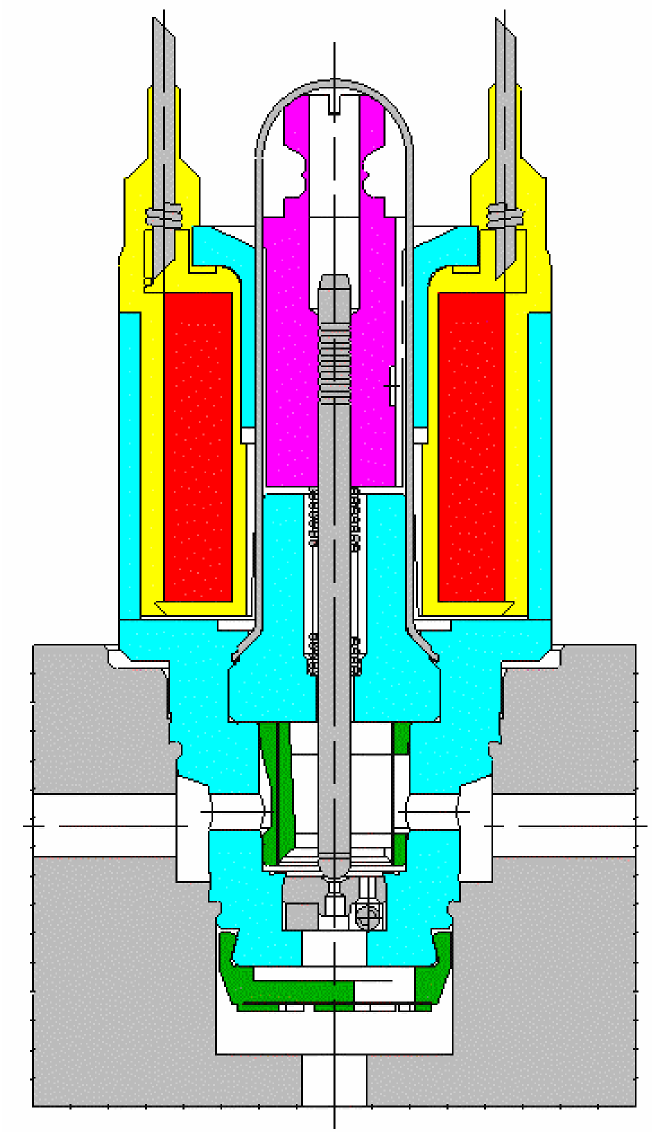
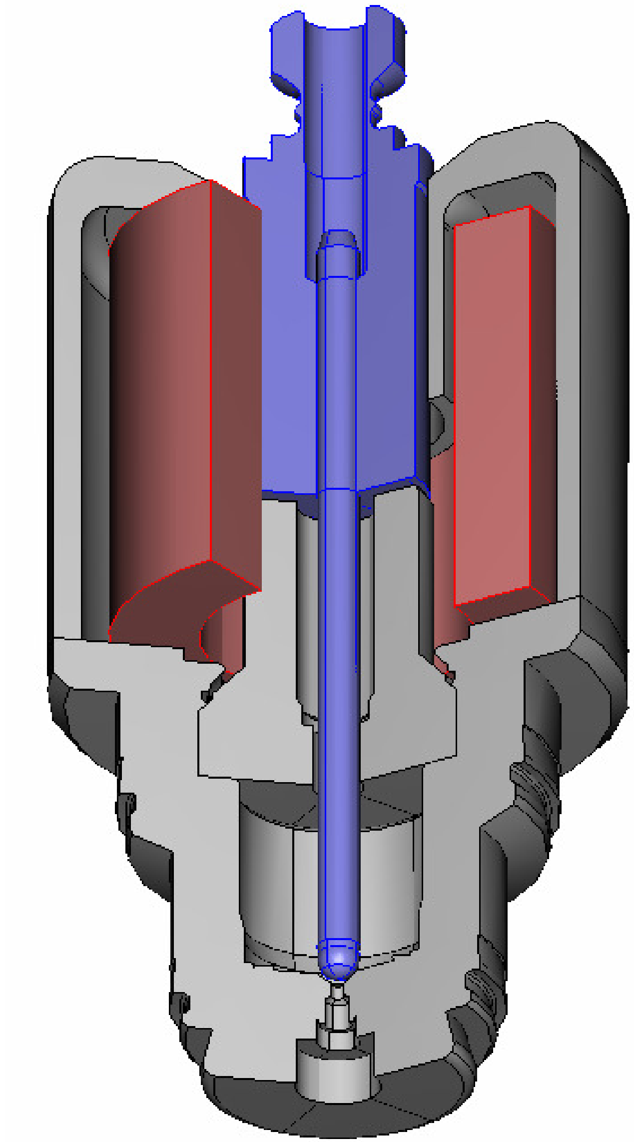
Electronic Stability Control ESC – Exploded View

MK60 ESC



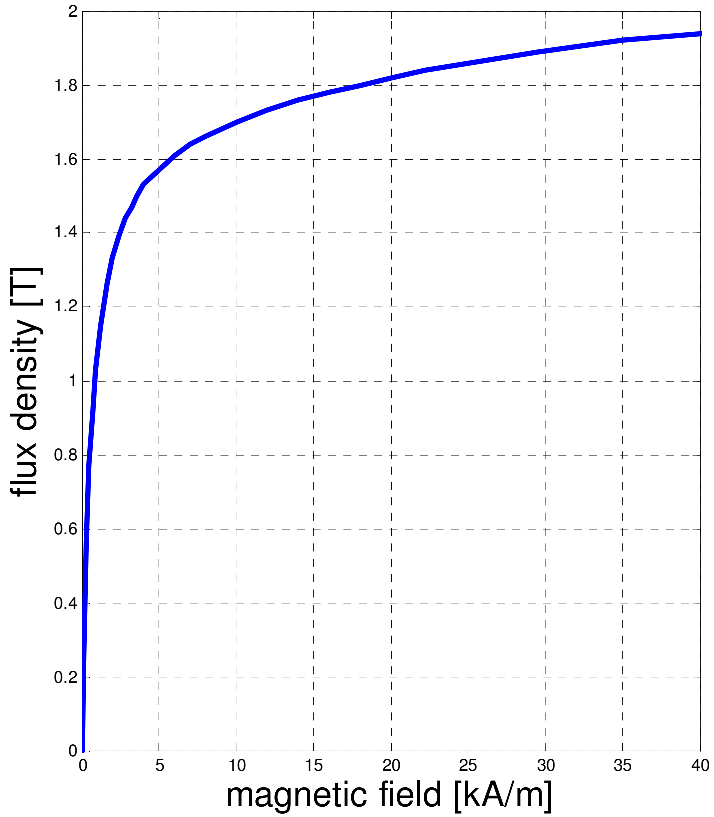
Electromagnetic inlet valve





Magnetization of steel

$$\text{magnetic field} \quad \vec{H} = \frac{1}{\mu_0\ \mu_r}\vec{B} \quad \text{magnetic flux density}$$



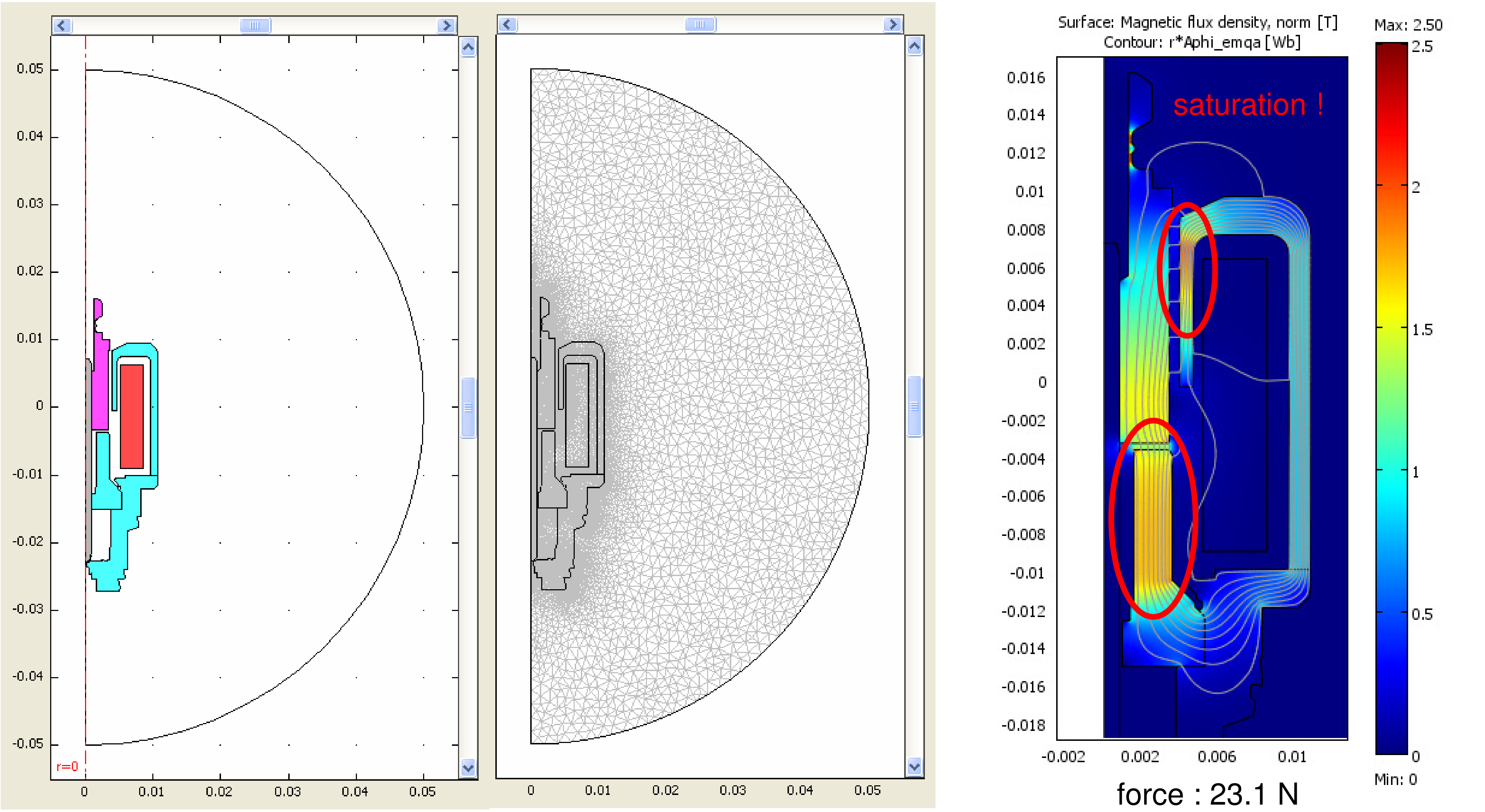
COMSOL > Physics > Subdomain Settings

Quantity	Value/Expression	Unit	Description
v	0 / 0	m/s	Velocity
V_{loop}	0	V	Loop potential
J^e_φ	0	A/m^2	External current density
σ	0	S/m	Electric conductivity
H ↔ **B**	$\mathbf{B} = \mu_0\mu_r\mathbf{H}$		Constitutive relation
μ_r	mu_r(normB_qa)	1	Relative permeability

COMSOL > Physics > Equation System > Subdomain Settings

```
normB_qa = sqrt( eps + abs(Br_qa)^2 + abs(Bz_qa)^2 )
```

Materials, mesh, solution



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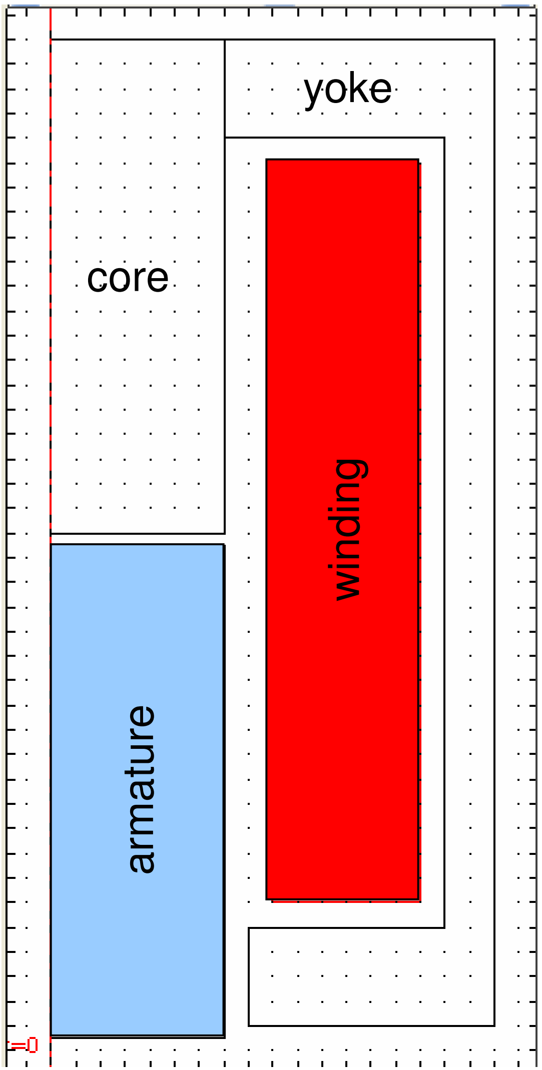
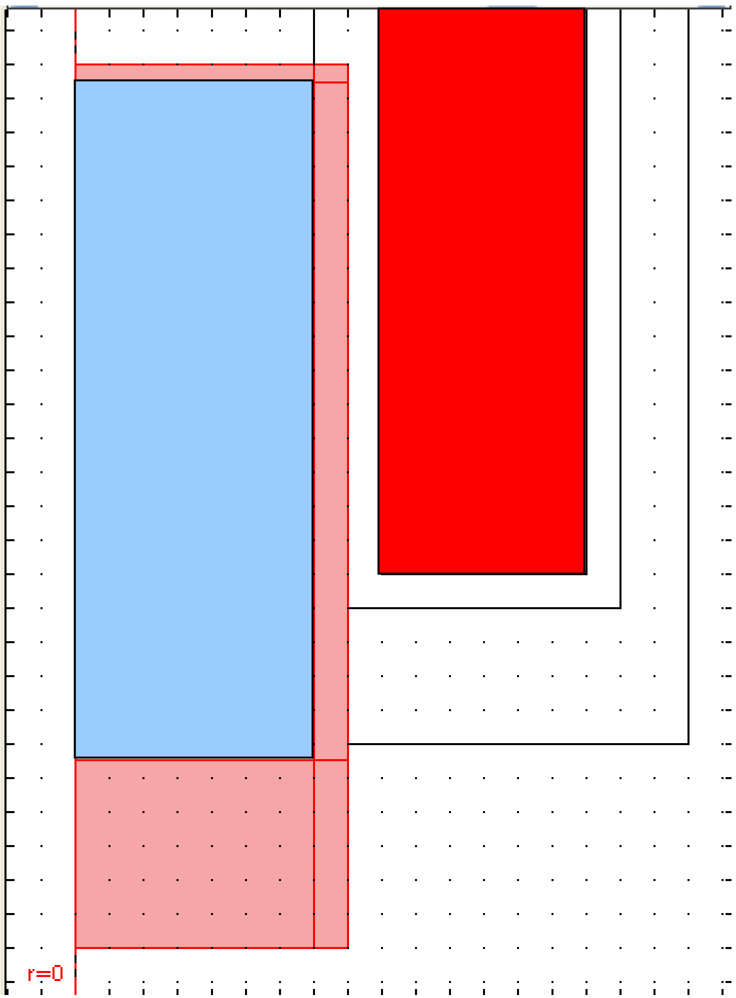
Geometry and deformation domain

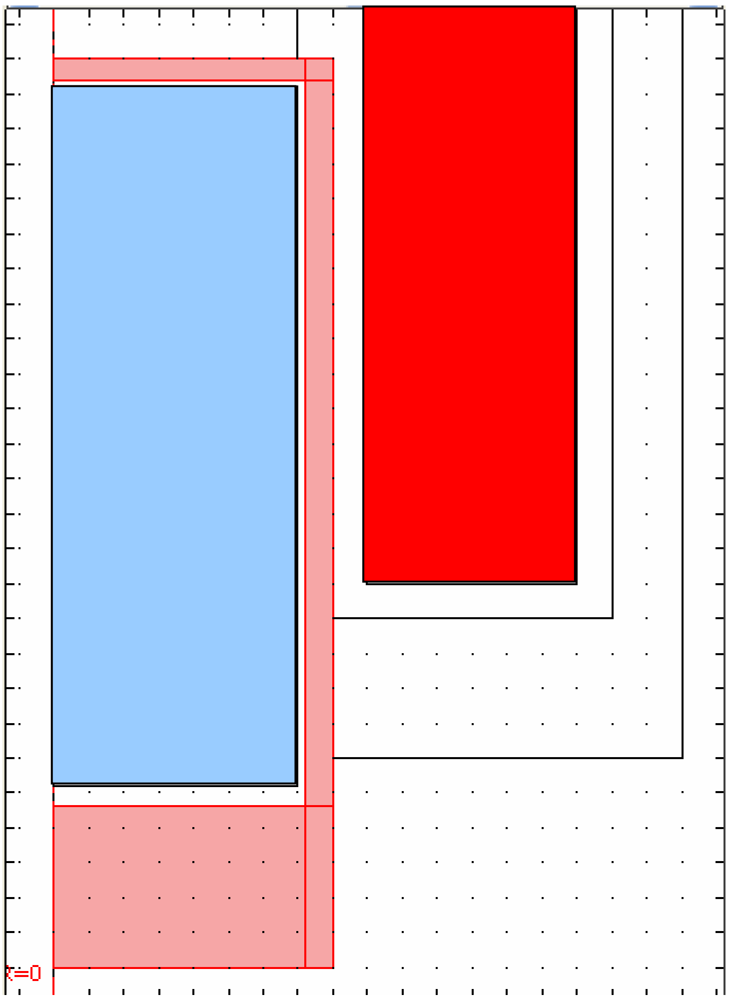
simplified geometry



armature with deformation domain



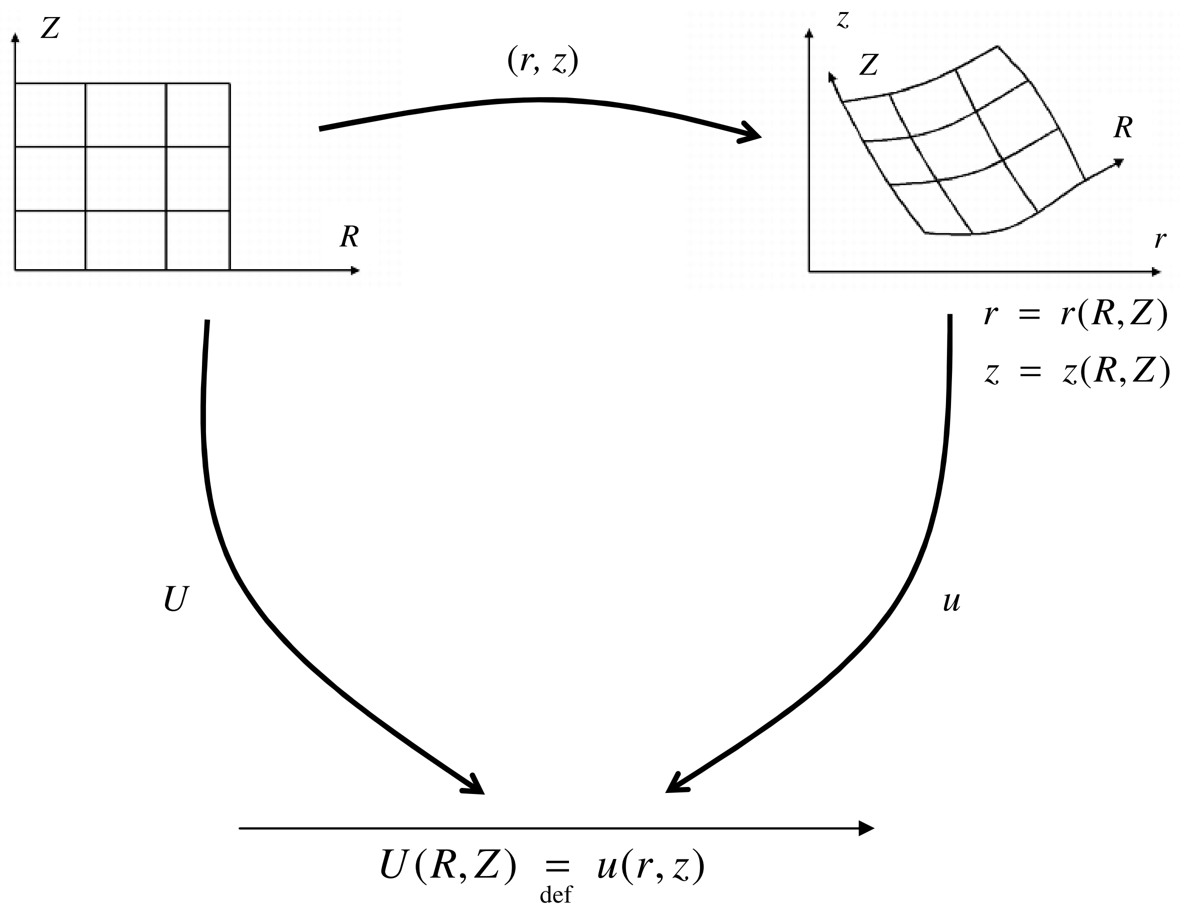
armature with rigid hull



Idea of ALE (“arbitrary Lagrangian-Eulerian”) mesh deformation

reference coordinates

space coordinates



physical equation for $u(r, z)$

→ partial diff´l equation (PDE) for $U(R,Z)$:

chain rule

$$\frac{\partial U}{\partial R} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial R} + \frac{\partial u}{\partial z}\frac{\partial z}{\partial R}$$

$$\frac{\partial U}{\partial Z} = \frac{\partial u}{\partial r}\frac{\partial r}{\partial Z} + \frac{\partial u}{\partial z}\frac{\partial z}{\partial Z}$$

solve system of equations

$$\frac{\partial u}{\partial r} = \frac{1}{\Delta}\left(\frac{\partial U}{\partial R}\frac{\partial z}{\partial Z} - \frac{\partial U}{\partial Z}\frac{\partial z}{\partial R}\right)$$

$$\frac{\partial u}{\partial z} = \frac{1}{\Delta}\left(-\frac{\partial U}{\partial R}\frac{\partial r}{\partial Z} + \frac{\partial U}{\partial Z}\frac{\partial r}{\partial R}\right)$$

$$\text{with} \quad \Delta = \frac{\partial r}{\partial R}\frac{\partial z}{\partial Z} - \frac{\partial r}{\partial Z}\frac{\partial z}{\partial R}$$

insert into PDE for u

Determine the functions $r(R, Z)$ and $z(R, Z)$

1. prescribed

   a) physical deformation (e.g. structural mechanics)

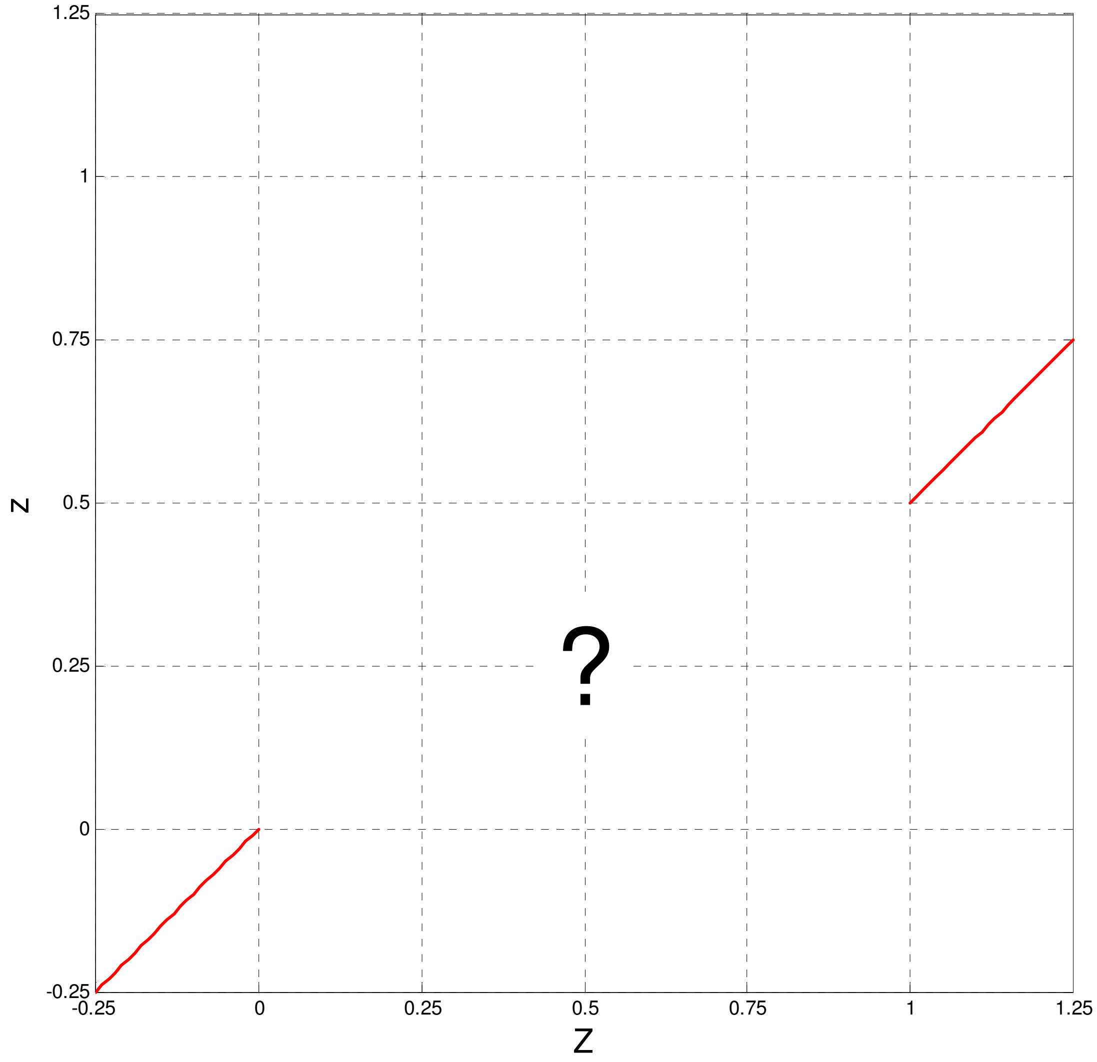
   b) explicit formula — **recommended here** (purely axial motion of rigid parts)

2. from boundary conditions

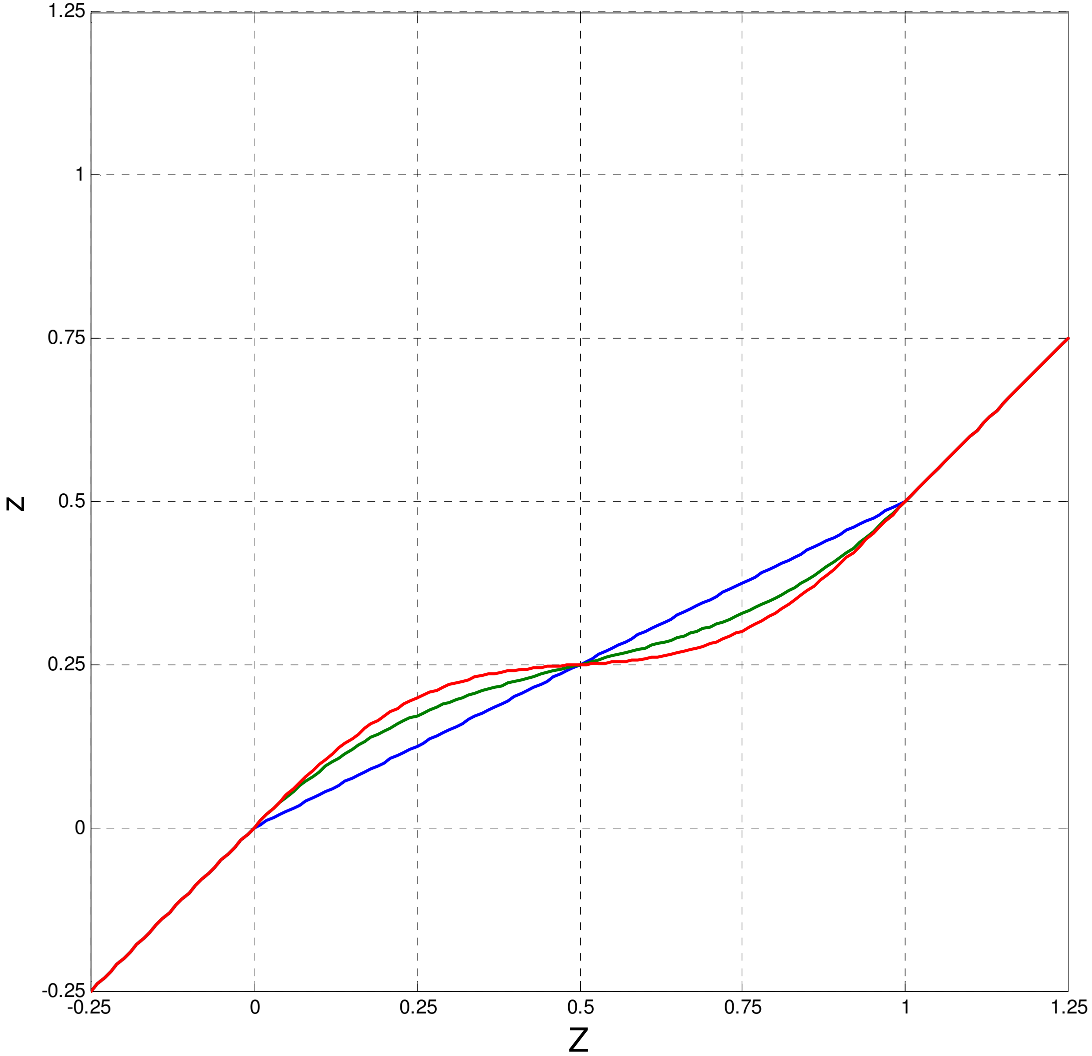
   a) Laplace smoothing: $\frac{\partial^2 r}{\partial R^2} + \frac{\partial^2 z}{\partial Z^2} = 0$

   b) Winslow smoothing: $\frac{\partial^2 R}{\partial r^2} + \frac{\partial^2 Z}{\partial z^2} = 0$

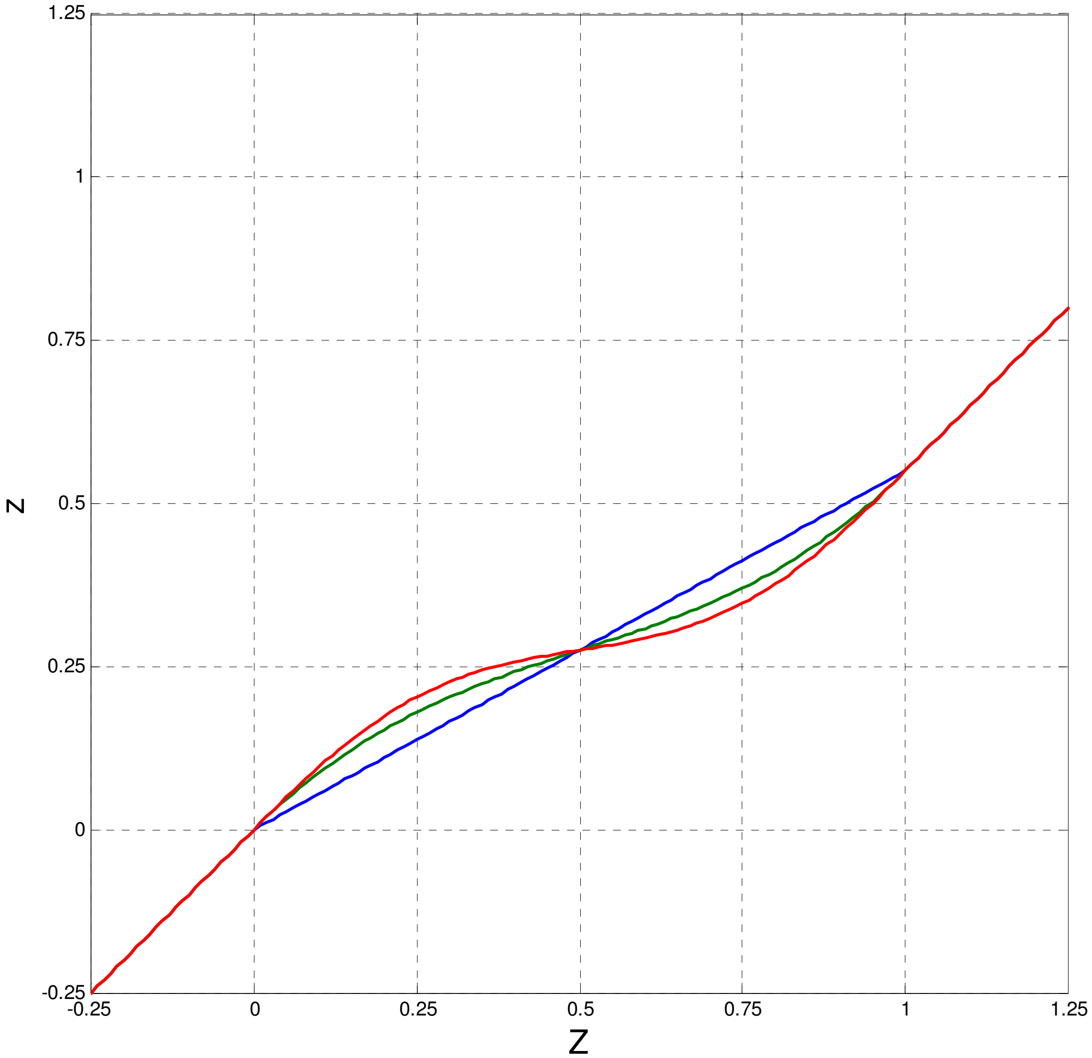
Explicit deformation $z(Z)$



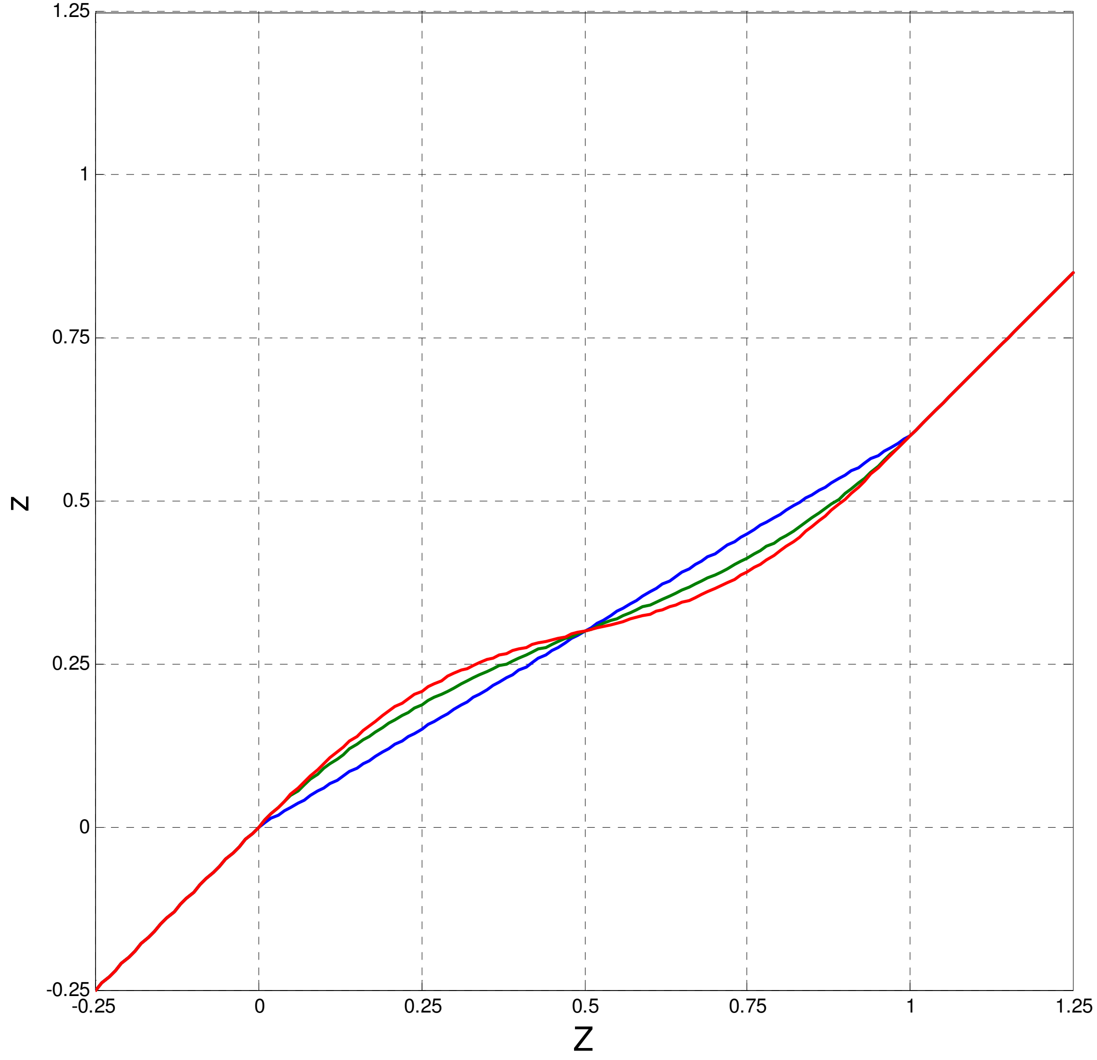
Continuous / differentiable deformations $z(Z)$



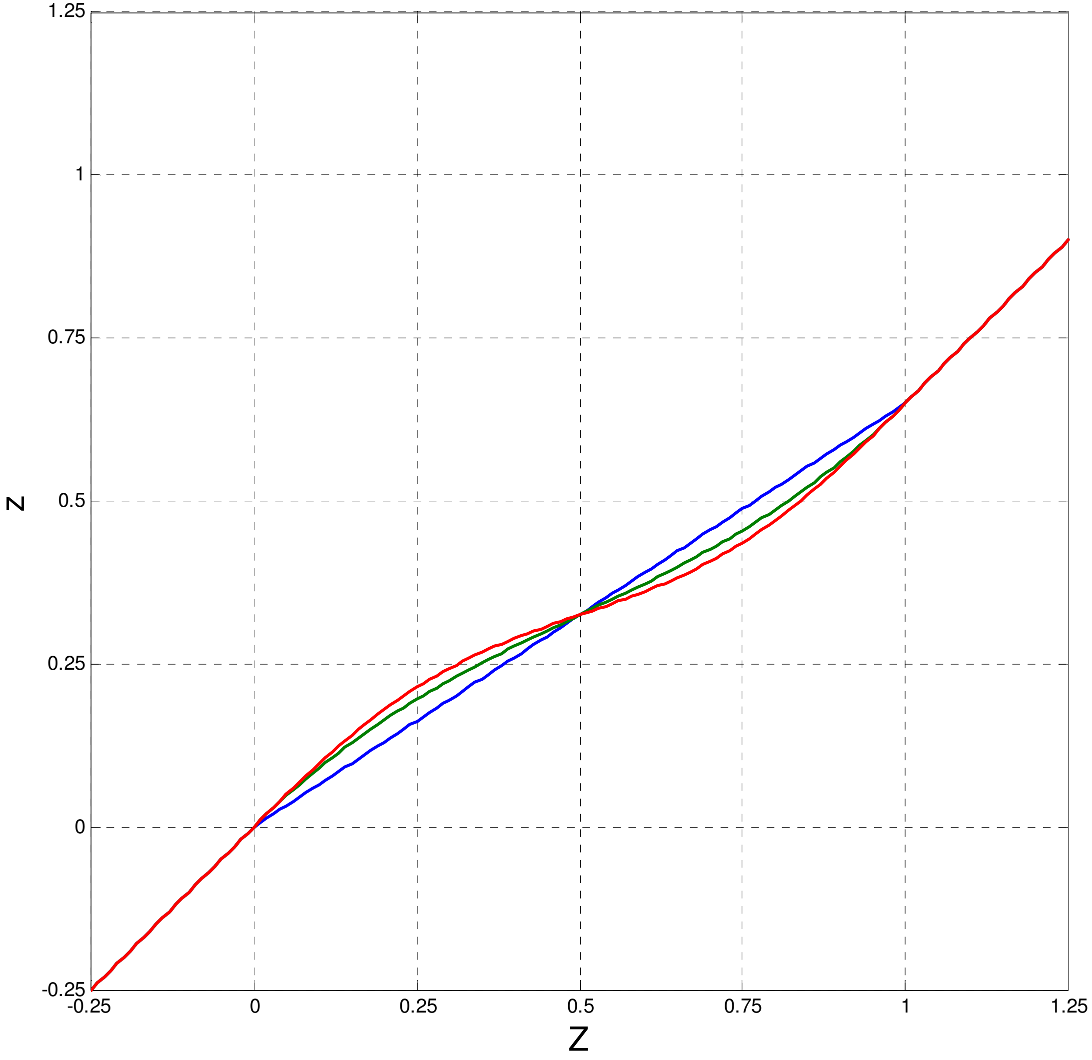
Continuous / differentiable deformations $z(Z)$



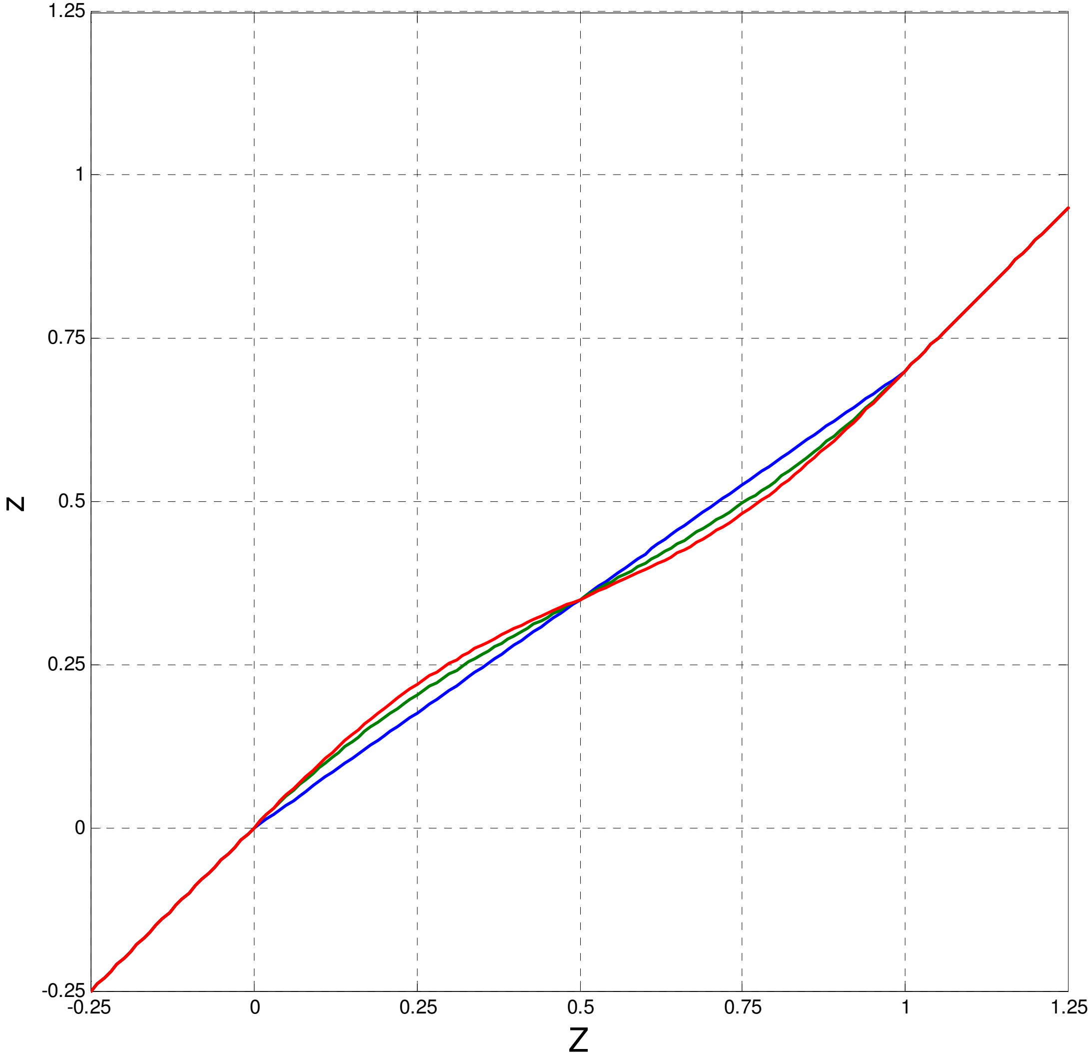
Continuous / differentiable deformations $z(Z)$



Continuous / differentiable deformations $z(Z)$



Continuous / differentiable deformations $z(Z)$



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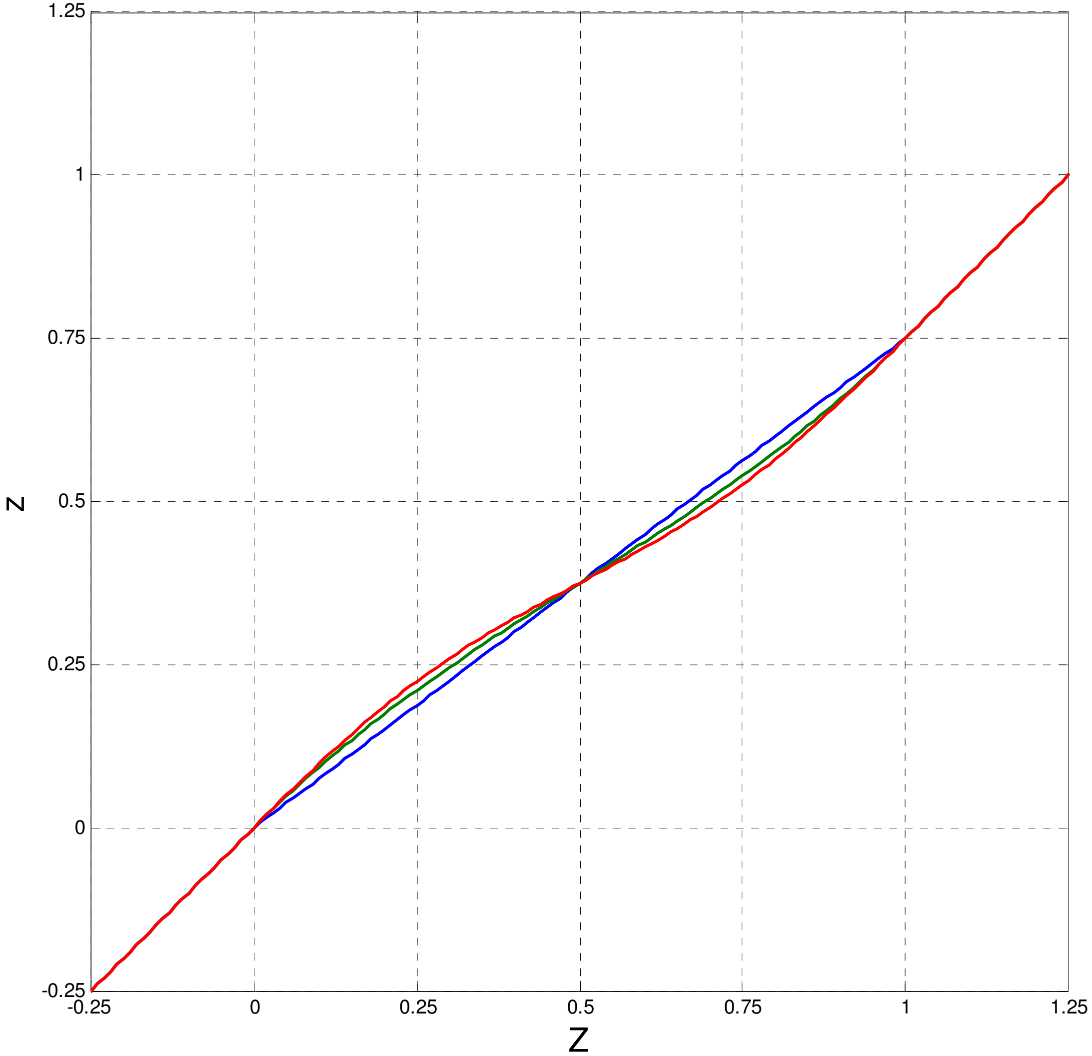
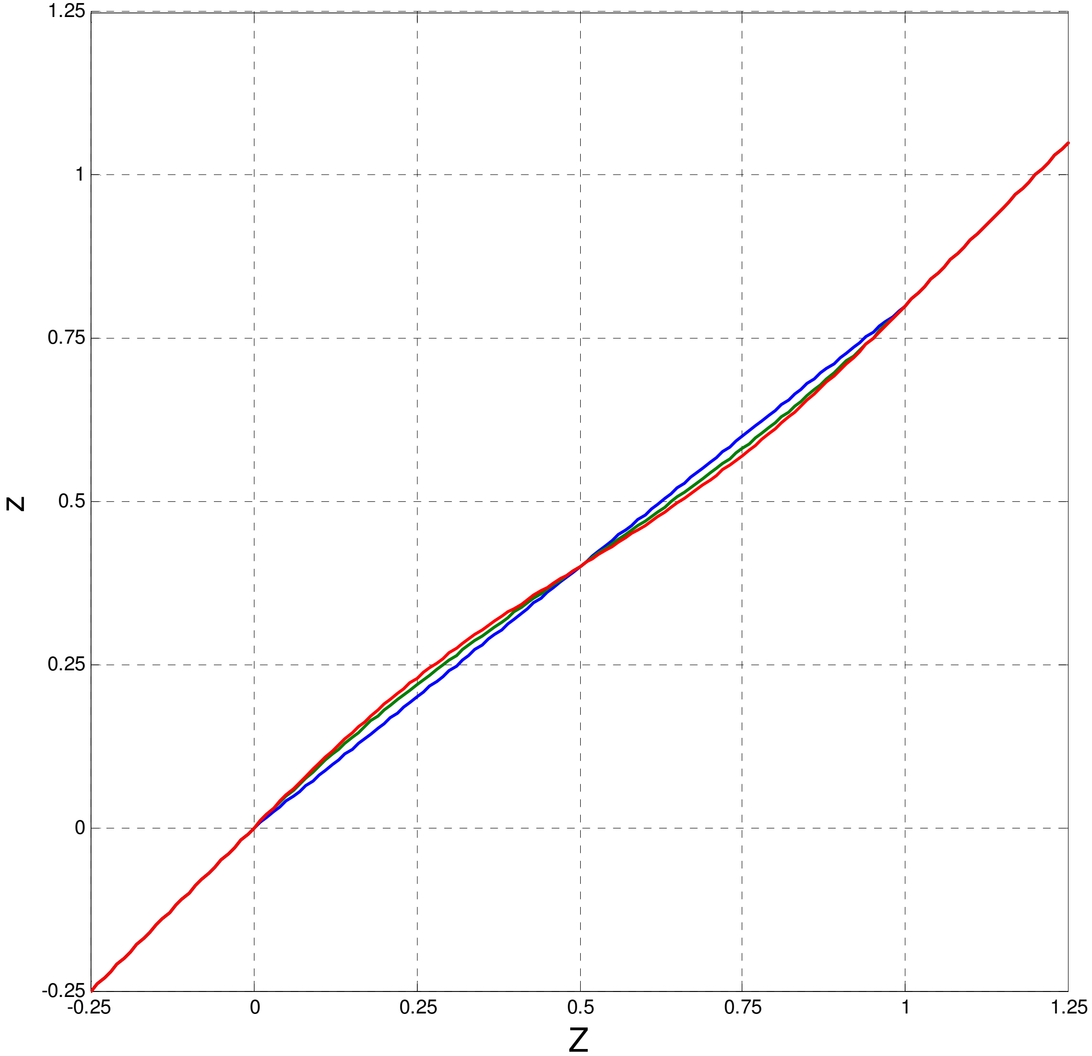
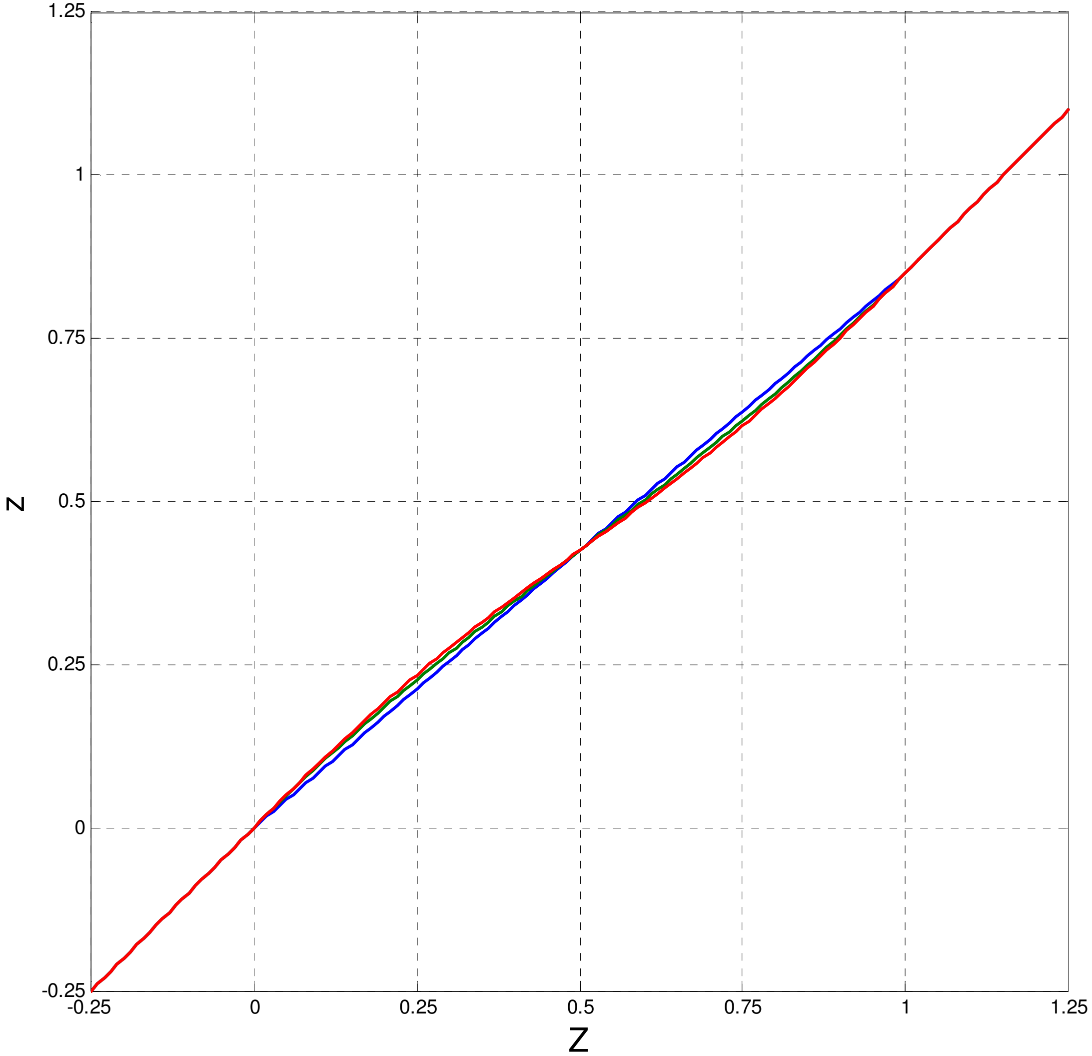


Continuous / differentiable deformations $z(Z)$



Continuous / differentiable deformations $z(Z)$



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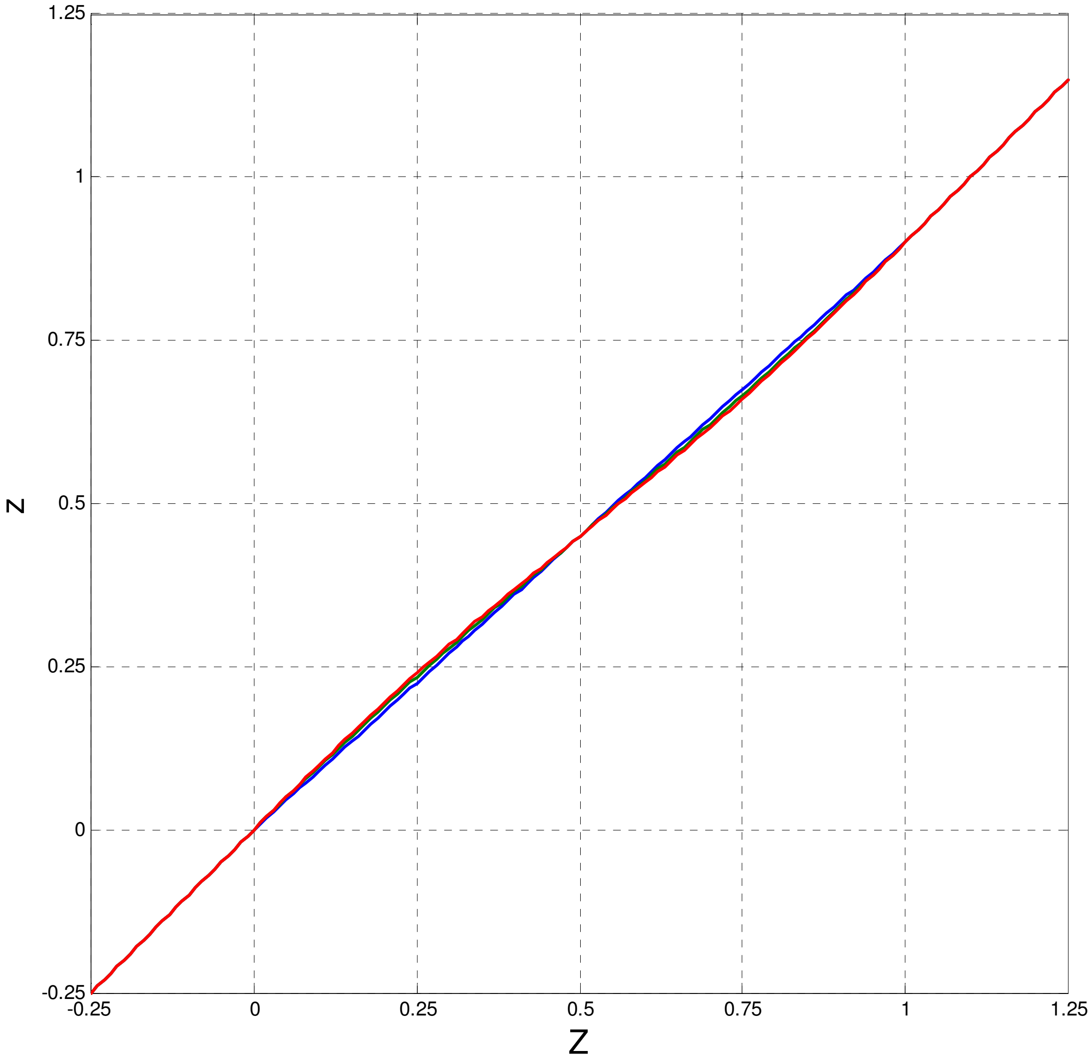
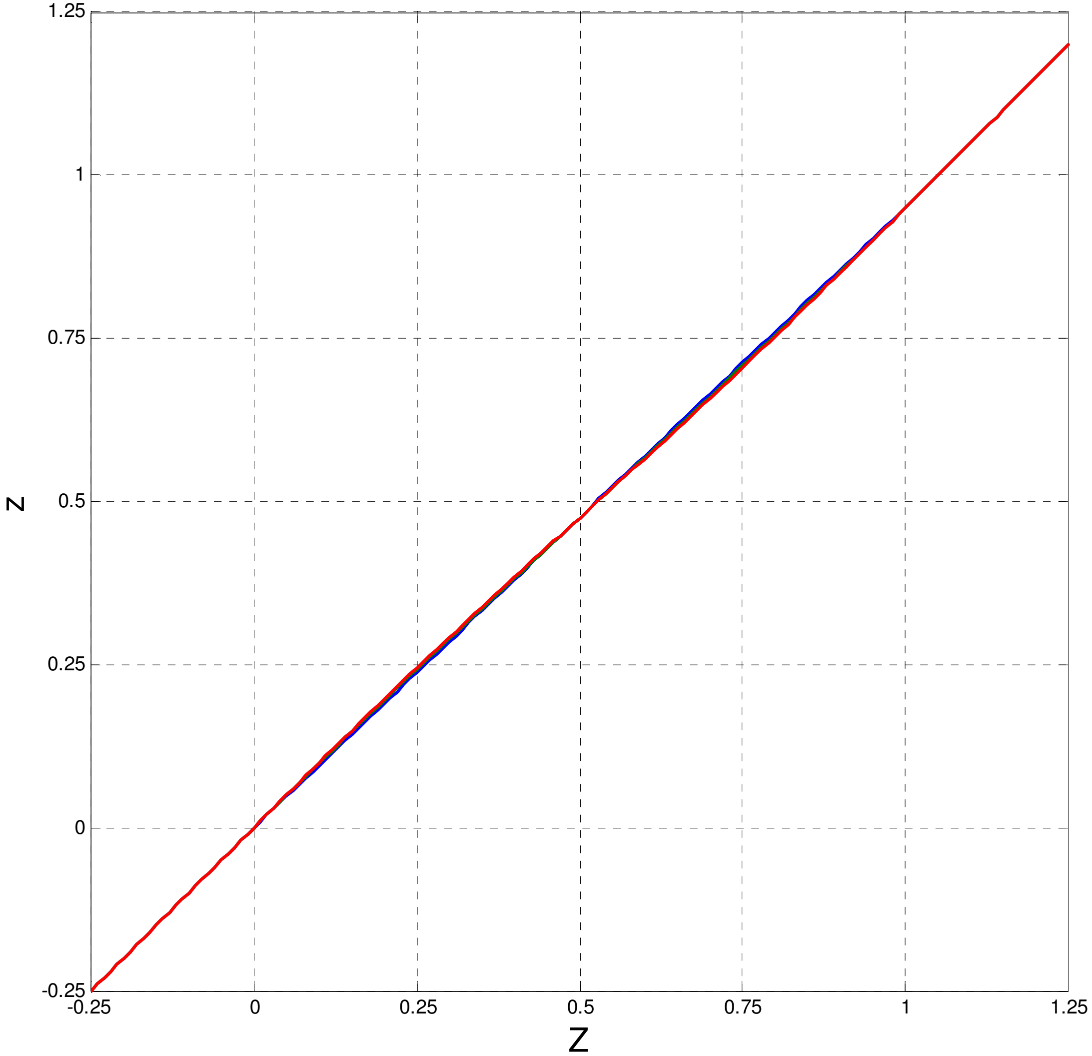
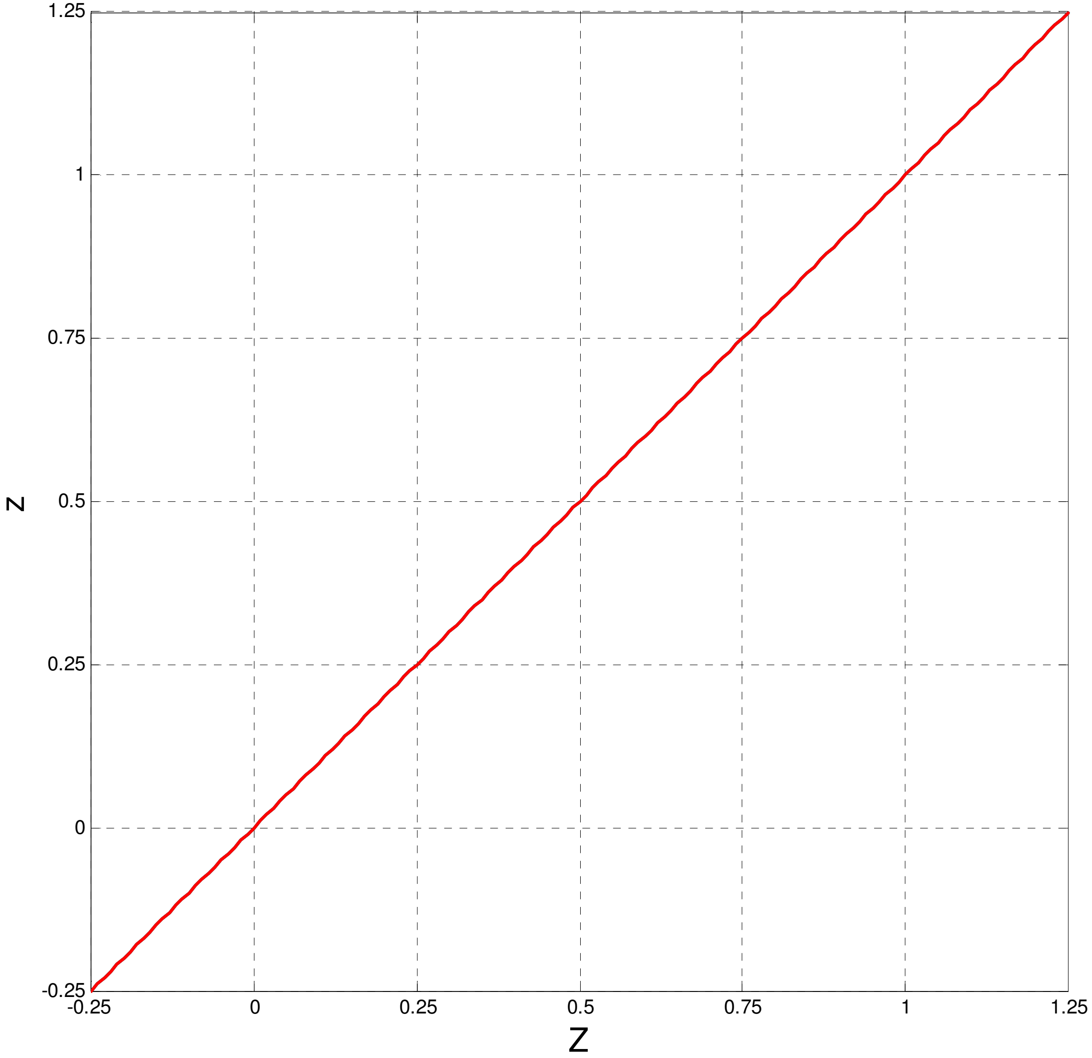


Division Chassis & Safety
Electronic Brake Systems Simulation

Continuous / differentiable deformations $z(Z)$

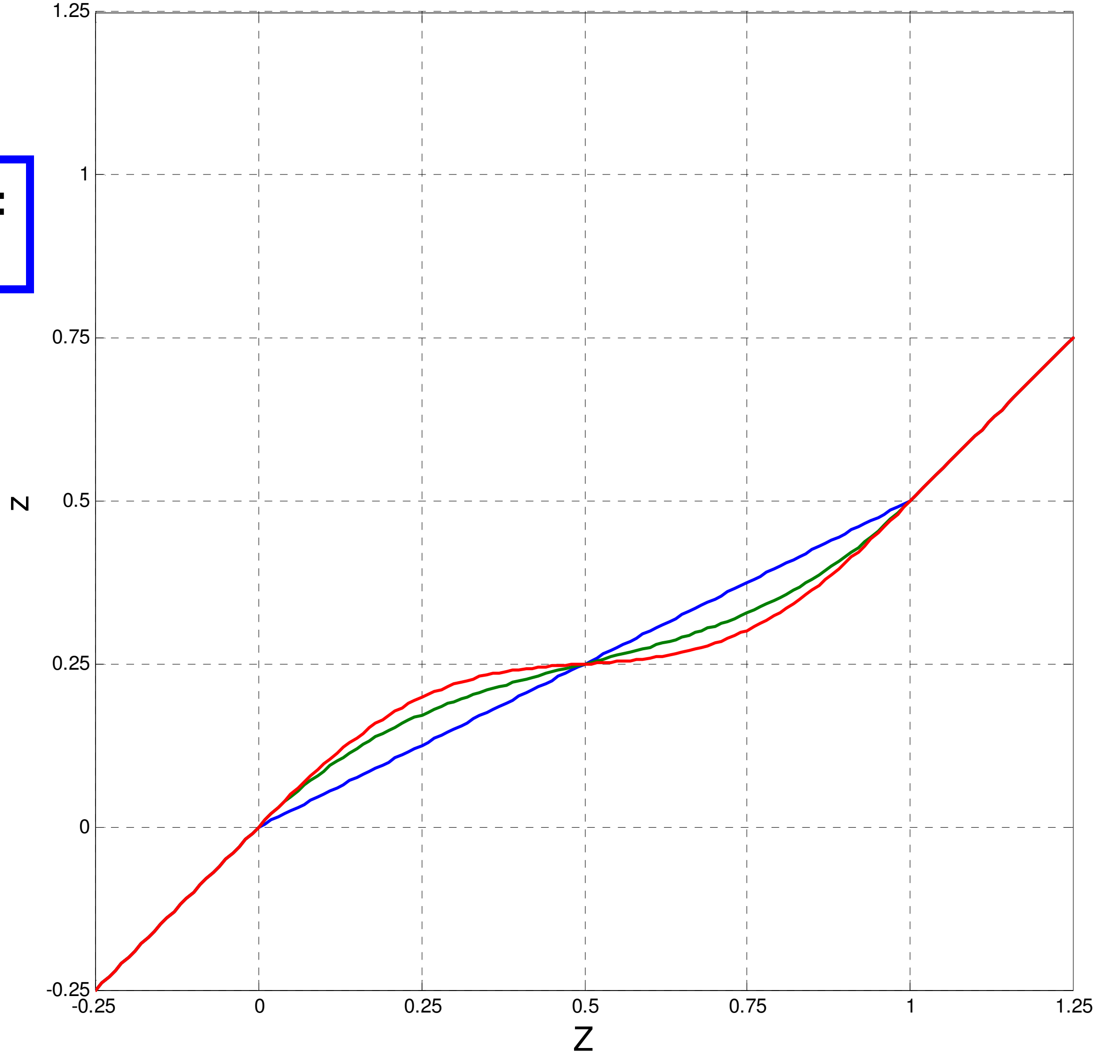


Continuous / differentiable deformations $z(Z)$



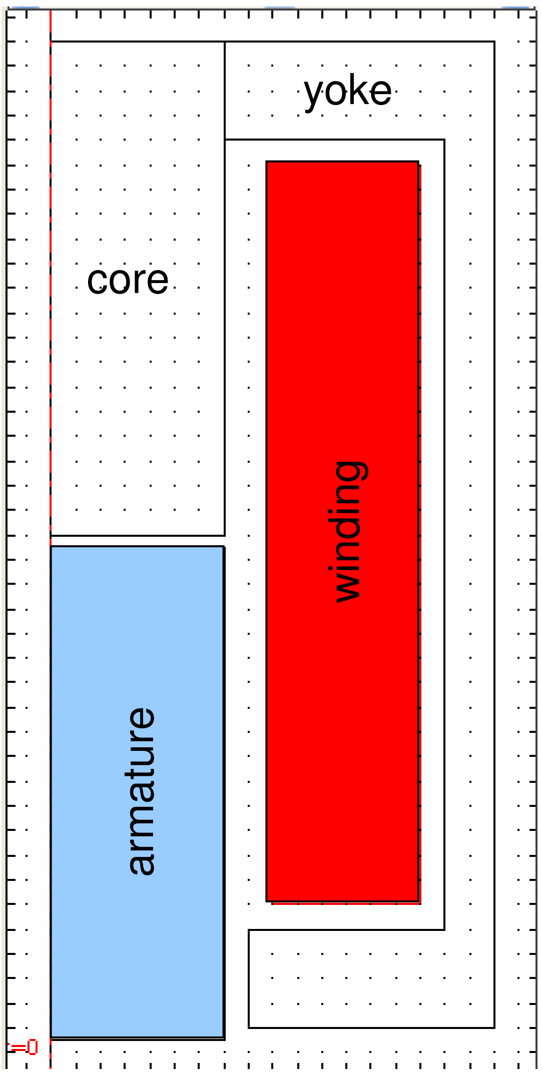
Continuous / differentiable deformations $z(Z)$

recommended here:
linear deformation

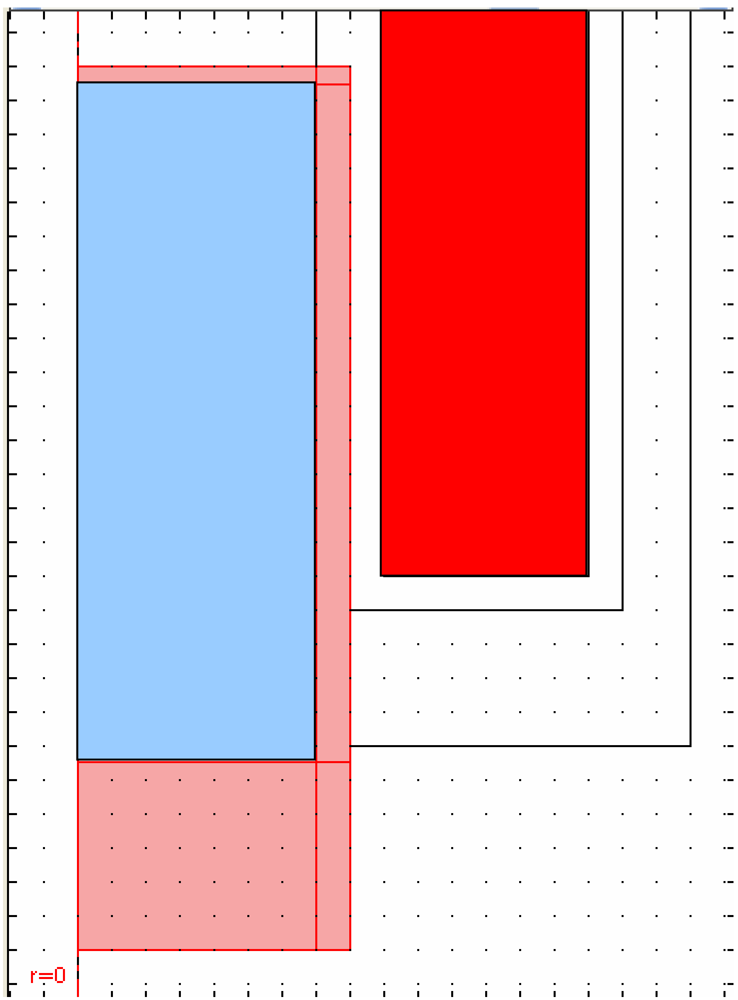


Geometry and deformation domain

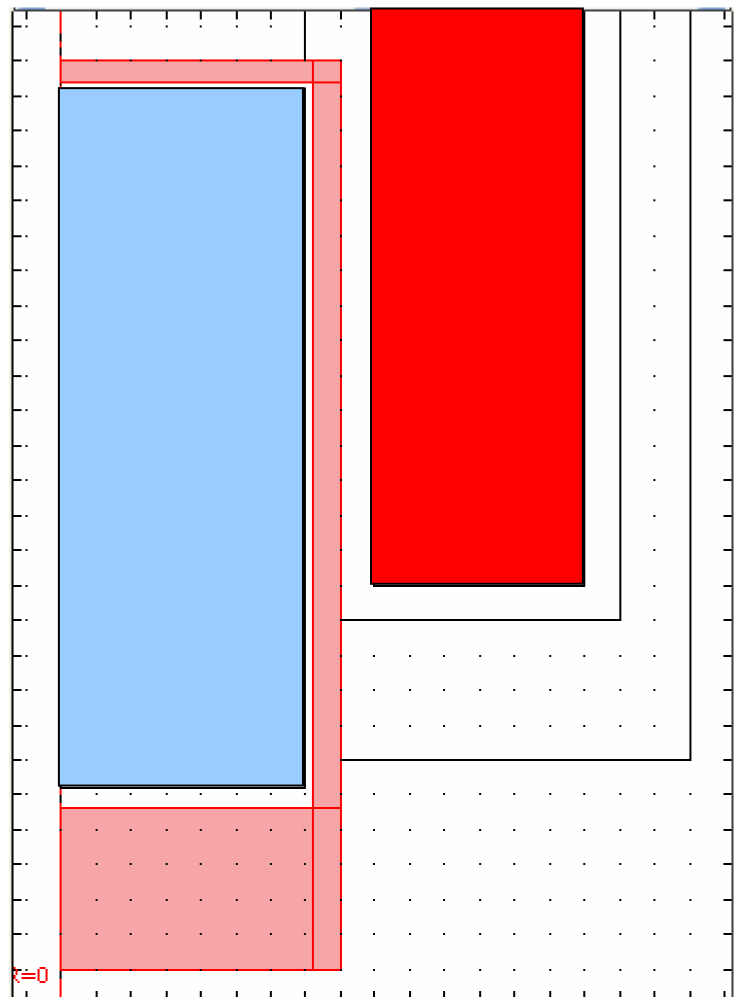
simplified geometry



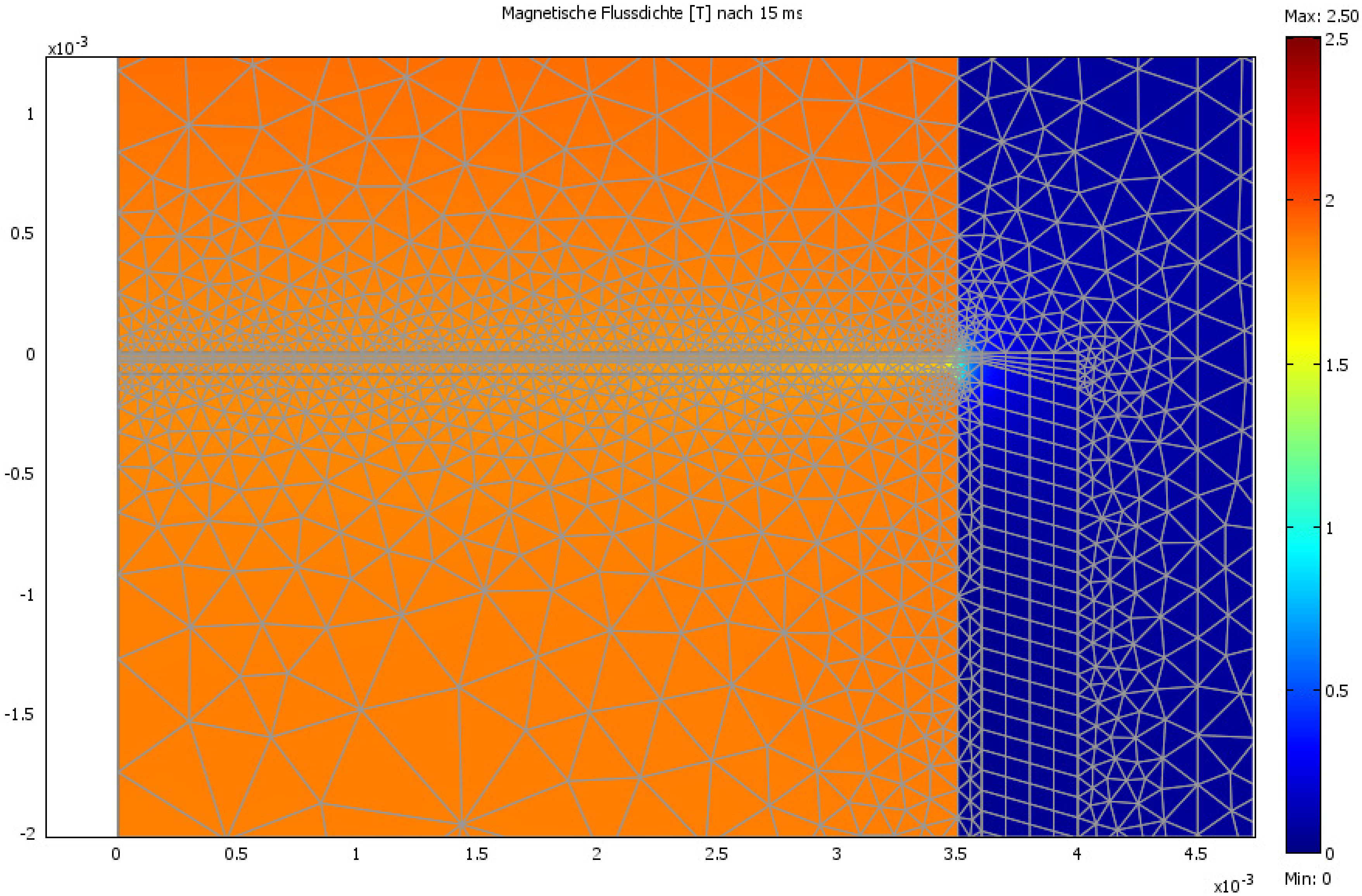
armature with deformation domain



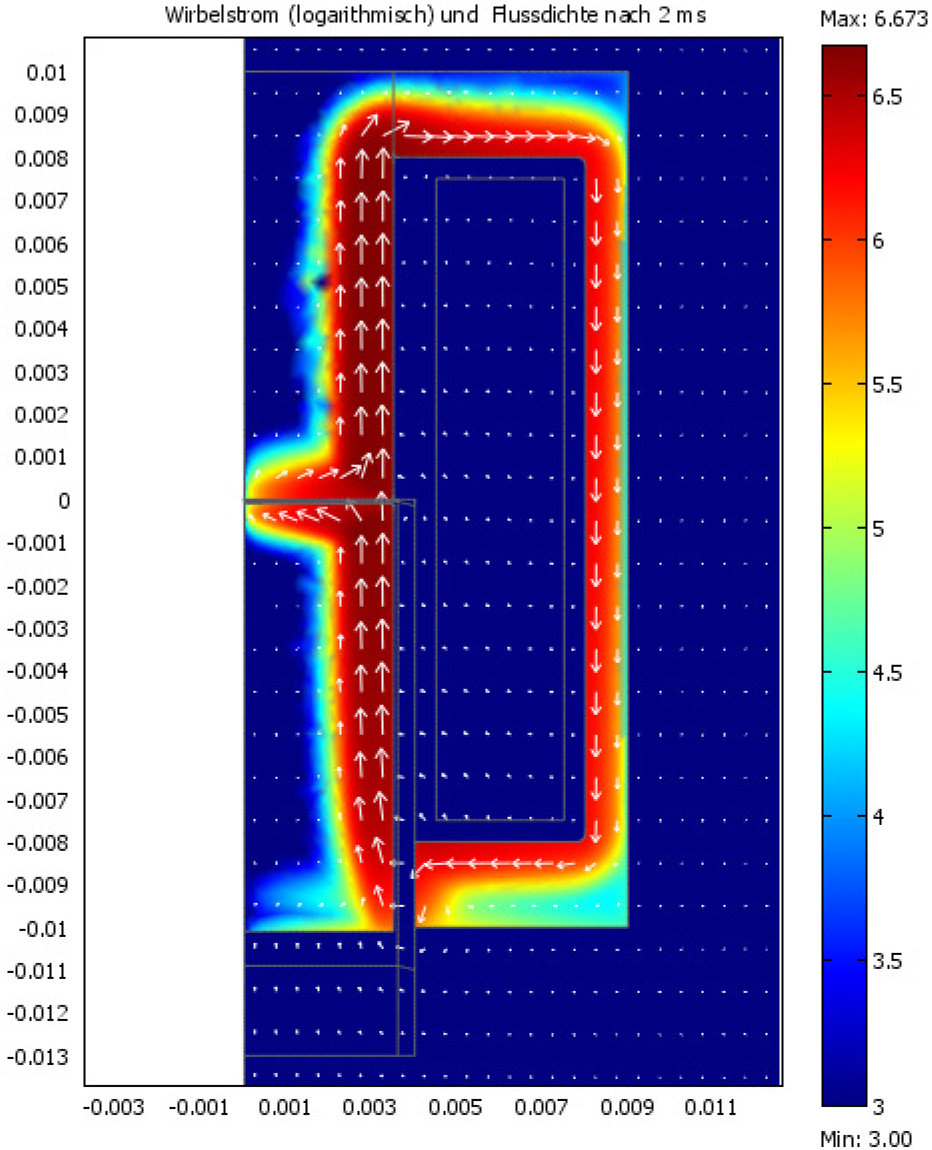
armature with rigid hull



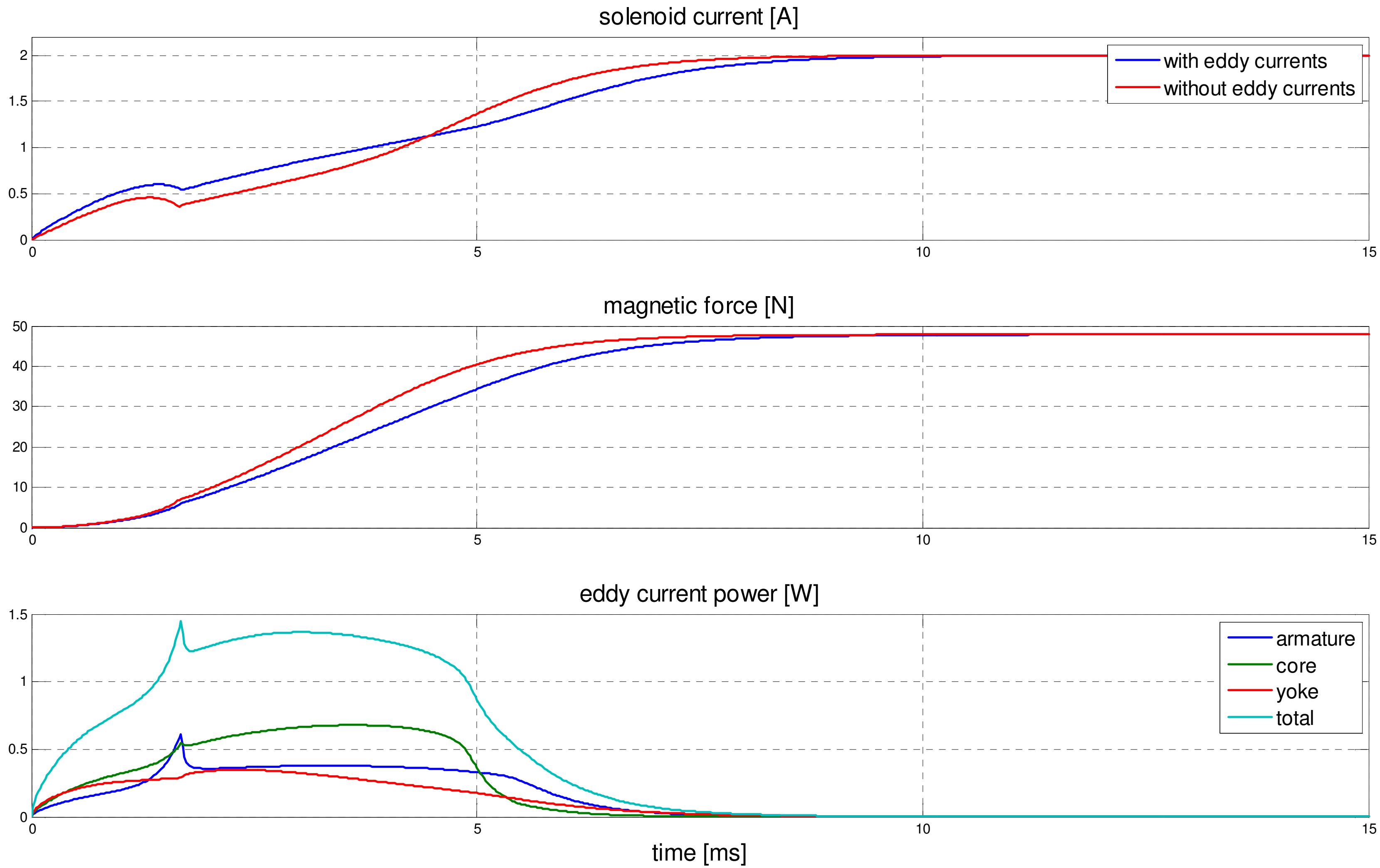
Voltage step response – mesh deformation and magnetic field



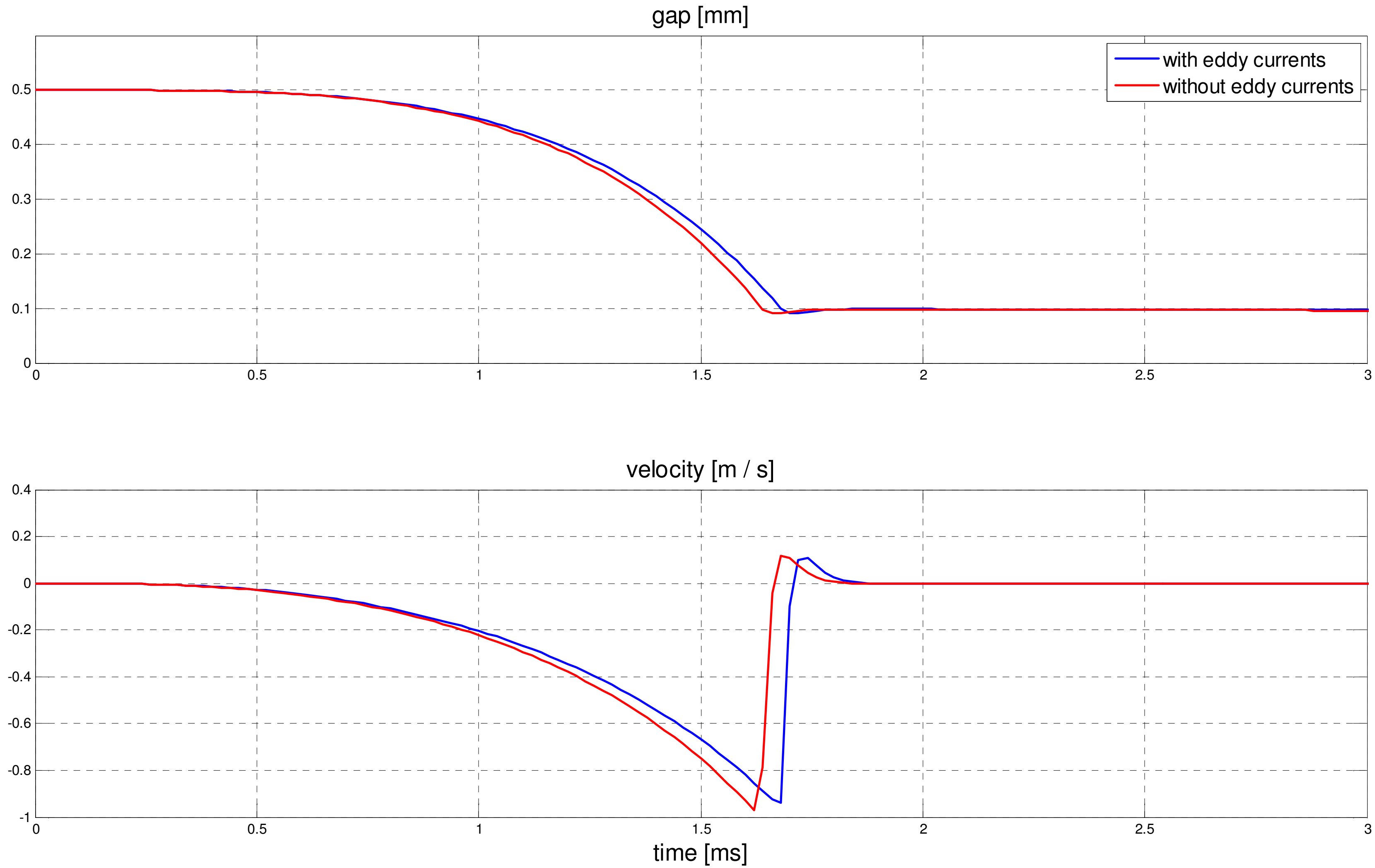
Voltage step response – eddy currents



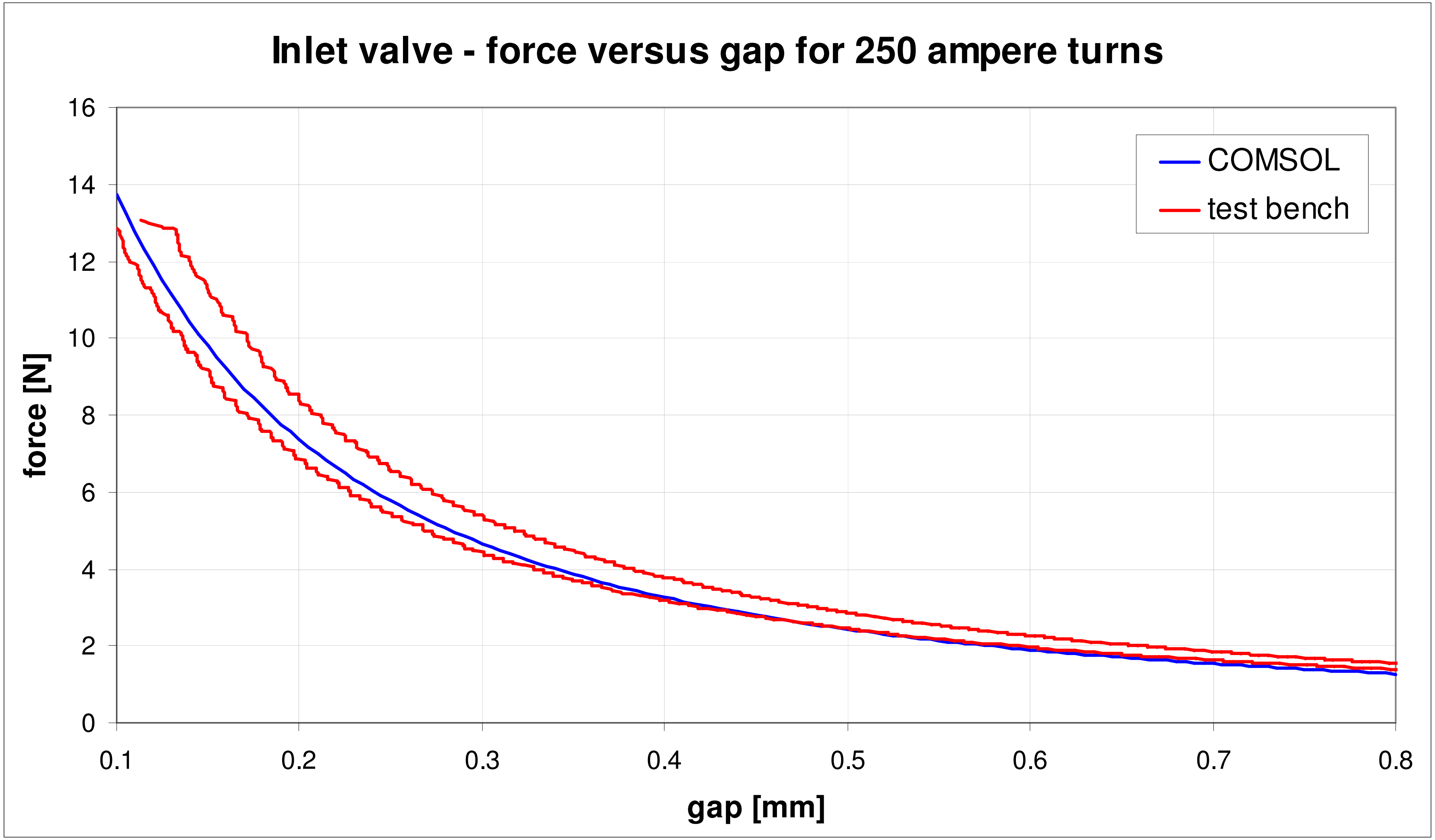
Voltage step response – armature motion



Voltage step response – armature motion



Comparison to experiment



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Static dependence of field on solenoid current (up to eddy currents)

$$\text{rot}\,\vec{H} = \vec{J} = \sigma(\vec{E} + \vec{v}\times\vec{B}) + \vec{J}_{\text{ext}}$$

$$= \sigma(\vec{E} + v\,\vec{e}_z\times\vec{B}) + \frac{n\,I_{\text{ext}}\,\vec{e}_\varphi}{S_{\text{coil}}}$$

$$-\sigma\,\vec{E} + \text{rot}\,\vec{H} - \sigma\,v\,\vec{e}_z\times\vec{B} = \frac{n\,I_{\text{ext}}\,\vec{e}_\varphi}{S_{\text{coil}}}$$

$$\mu_0\,\mu_r\,\vec{H} = \vec{B} = \text{rot}\,\vec{A}$$

$$\vec{E} = -\frac{\partial\vec{A}}{\partial t}$$

0 (neglect eddy currents from field change)

$$\sigma\frac{\partial\vec{A}}{\partial t} + \text{rot}\left(\frac{1}{\mu_0\,\mu_r}\text{rot}\,\vec{A}\right) - \sigma\,v\,\vec{e}_z\times\text{rot}\,\vec{A} = \frac{n\,I_{\text{ext}}\,\vec{e}_\varphi}{S_{\text{coil}}}$$

$$\vec{A} = \vec{A}(I_{\text{ext}},\,v,\,x)$$

Dynamics of solenoid current: integral parameter magnetic flux

$$I_{\text{ext}} = \frac{1}{R}(U_{\text{ext}} + U_{\text{ind}})$$

$$= \frac{1}{R}\left(U_{\text{ext}} + \frac{n}{S_{\text{coil}}} \iint_{S_{\text{coil}}} 2\,\pi\, r\, \vec{E}\, dr\, dz \right)$$

$$= \frac{1}{R}\left(U_{\text{ext}} - \frac{d}{dt} \underbrace{\left(\frac{n}{S_{\text{coil}}} \iint_{S_{\text{coil}}} 2\,\pi\, r\, \vec{A}\, dr\, dz \right)}_{\Psi} \right)$$

$$I_{\text{ext}} = \frac{1}{R}\left(U_{\text{ext}} - \frac{d\,\Psi}{dt} \right), \qquad \Psi = \Psi(\vec{A}) = \Psi\left(\vec{A}(I_{\text{ext}}, v, x) \right)$$

System dynamics

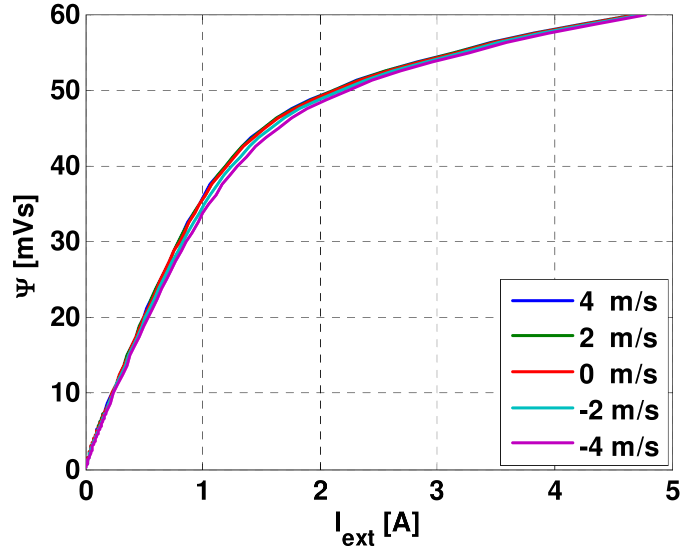
$$I_{\text{ext}} = \frac{1}{R}\left(U_{\text{ext}} - \frac{d\Psi}{dt}\right),$$

$$\Psi = \Psi(I_{\text{ext}}, v, x)$$

↓

$$I_{\text{ext}} = I_{\text{ext}}(\Psi, v, x)$$

- COMSOL solves $\Psi(I_{\text{ext}}) = \Psi_{\text{prescr}}$ for I_{ext}
- look-up table / interpolation

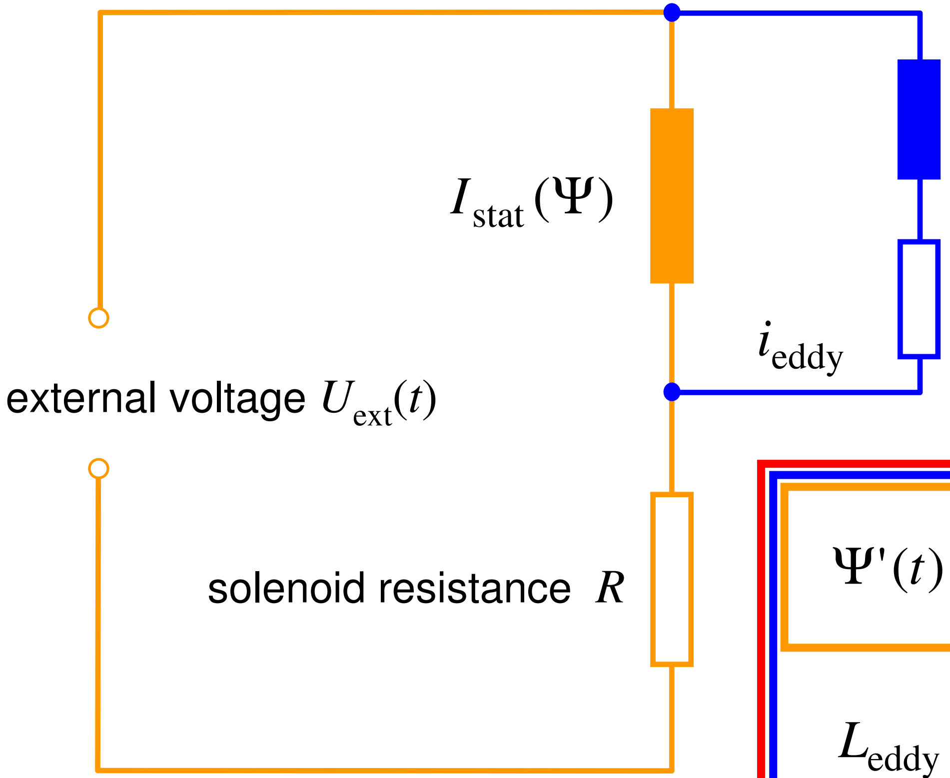


$$\frac{d\Psi}{dt} = U_{\text{ext}} - R \cdot I_{\text{ext}}(\Psi, v, x)$$

+ armature equation of motion

+ simple effective eddy current model

Effective eddy current model



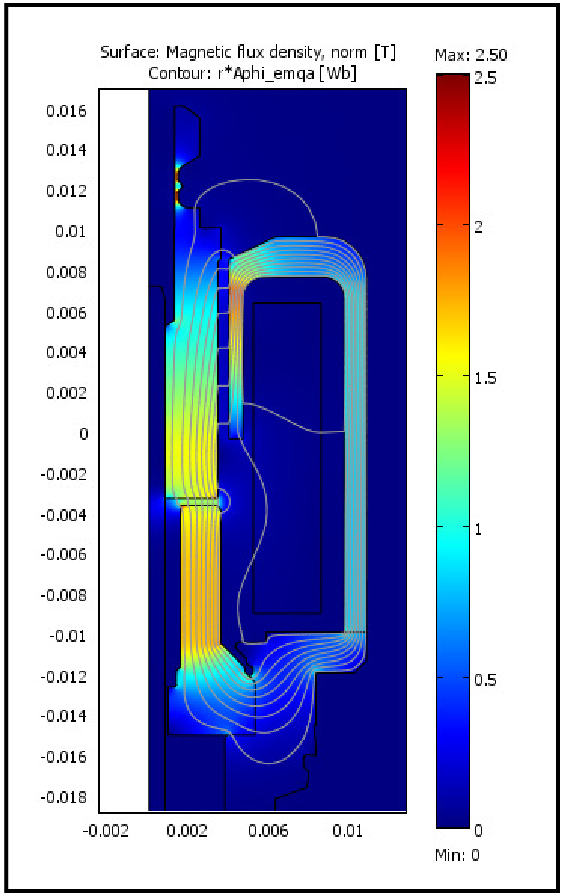
$$\Psi'(t) = U_{ext}(t) - R\Big(I_{stat}\big(\Psi(t) + \underline{\psi(t)}\big) + \underline{i_{eddy}(t)}\Big)$$

$$L_{eddy}\, i_{eddy}'(t) = \Psi'(t) - R_{eddy}\, i_{eddy}(t) \qquad \left(\frac{L_{eddy}}{R_{eddy}} \approx 1\,\mathrm{ms}\right)$$

$$\tau_1\, \psi'(t) = \tau_2\, \Psi'(t) - \psi(t) \qquad (\tau_1 \approx 0.02\,\mathrm{ms})$$

determine L_{eddy}, R_{eddy}, τ_1, τ_2 from least squares fit to Comsol result

Generation of small systems of ordinary differential equations



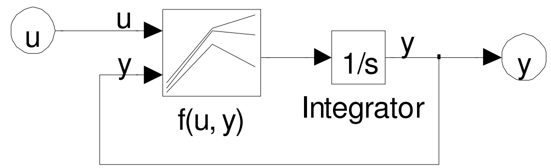
field problem
(e.g. COMSOL)

look-up table

parameter fit

reduced linear model

$$\dot{y} = f(u, y)$$



dynamic system
(e.g. Simulink)

- fast solution
- parameter variation
- integration into comprehensive model

Conclusion – simulation in industrial development

1. efficiency
   - fewer prototypes
   - better experiments
2. product performance
   - more variants
   - automatic optimization
   - functional insight
     - “observe” new quantities
     - isolate parameter influence
3. robust products
   - create limit configurations
   - study tolerances statistically

