15th World Congress on Computational Mechanics (WCCM-XV) &
the 8th Asian Pacific Congress on Computational Mechanics (APCOM-VIII)

Pitch Bearing Parameter Estimation for Virtual Wind Turbine Testing Applications

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Introduction

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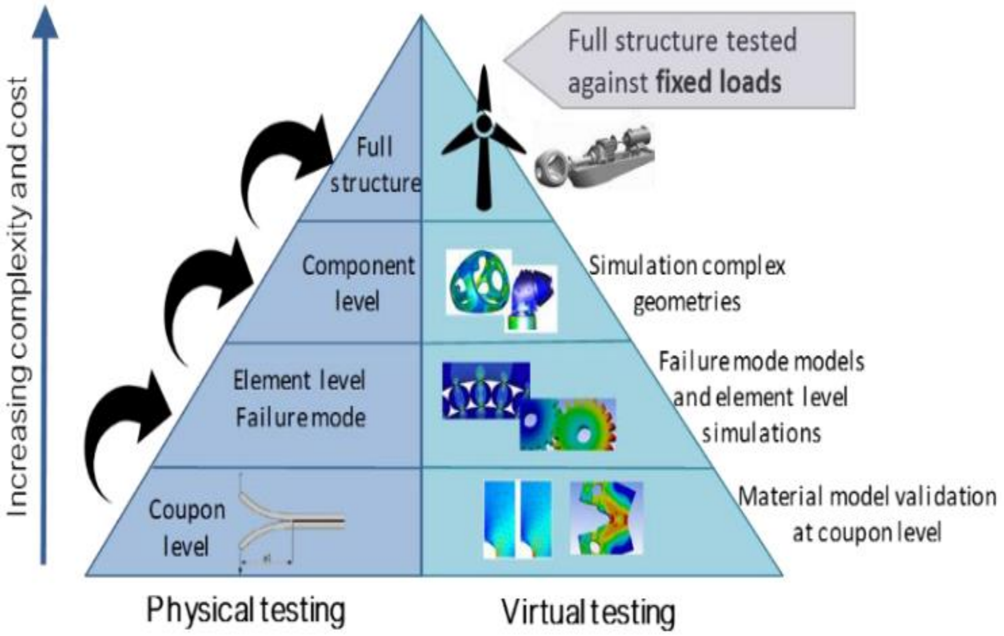
Virtual Testing & Virtual Sensing

In recent years, interest for **Virtual Testing** has increased.

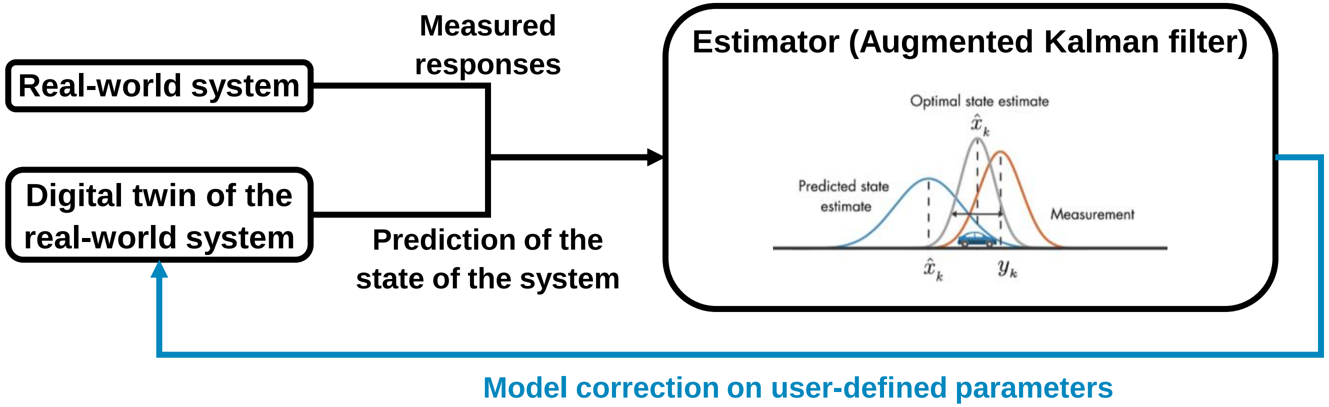
This implies a need for developing ever **increasingly accurate Digital Twins**.

Virtual Sensing can be used to update digital twins using real-world measured data and gaining more accurate results.



Testing pyramid combining physical and virtual testing.

Virtual Sensing for parameter estimation



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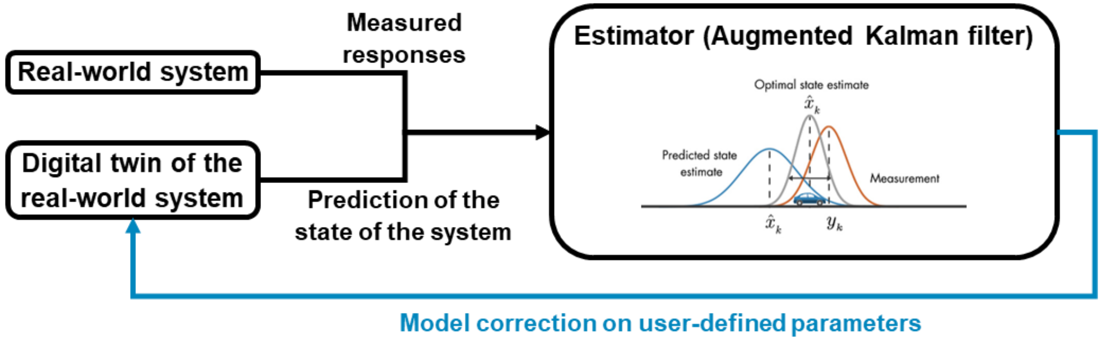
The Augmented Extend Kalman Filter for structural mechanics applications



$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{q} \\ \boldsymbol{v} \\ \boldsymbol{p} \end{bmatrix} = \begin{bmatrix} \text{displacement} \\ \text{velocity} \\ \text{parameters} \end{bmatrix}$$

states / augmented states

Representing system dynamics with Ordinary Differential Equations:

$$\boldsymbol{f}_d(\boldsymbol{x}_{k+1}, \dot{\boldsymbol{x}}_{k+1}) = \boldsymbol{w}_k$$
$$\boldsymbol{y}_{k+1} = \boldsymbol{h}_d(\boldsymbol{x}_{k+1}) + \boldsymbol{v}_{k+1}$$

Plant noise $\boldsymbol{w}_k \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{Q}_k)$

Measurement noise $\boldsymbol{v}_{k+1} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{R}_{k+1})$

Prediction step

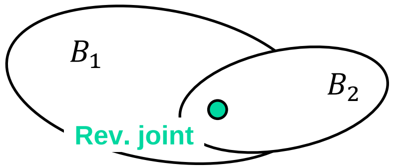
$$\boldsymbol{f}_d(\hat{\boldsymbol{x}}_{k+1}^-, \dot{\hat{\boldsymbol{x}}}_{k+1}^-) = \boldsymbol{0}$$
$$\boldsymbol{P}_{k+1}^- = \boldsymbol{F}_{k+1}\boldsymbol{P}_k^+\boldsymbol{F}_{k+1} + \boldsymbol{Q}_k$$

Kalman Update

$$\boldsymbol{K}_{k+1} = \boldsymbol{P}_{k+1}^-\boldsymbol{H}_{k+1}^T\left(\boldsymbol{H}_{k+1}\boldsymbol{P}_{k+1}^-\boldsymbol{H}_{k+1}^T + \boldsymbol{R}_{k+1}\right)^{-1}$$
$$\hat{\boldsymbol{x}}_{k+1}^+ = \hat{\boldsymbol{x}}_{k+1}^- + \boldsymbol{K}_{k+1}\left(\boldsymbol{y}_{k+1} - \boldsymbol{h}_d(\hat{\boldsymbol{x}}_{k+1}^-)\right)$$
$$\boldsymbol{P}_{k+1}^+ = (\boldsymbol{I} - \boldsymbol{K}_{k+1}\boldsymbol{H}_{k+1})\boldsymbol{P}_{k+1}^-$$

$$\boldsymbol{P} = \mathbf{E}[(\boldsymbol{x} - \hat{\boldsymbol{x}})(\boldsymbol{x} - \hat{\boldsymbol{x}})^T]$$
$$\boldsymbol{F}_{k+1} = \frac{\mathrm{d}\hat{\boldsymbol{x}}_{k+1}^-}{\mathrm{d}\hat{\boldsymbol{x}}_k^+}$$
$$\boldsymbol{H}_{k+1} = \frac{\mathrm{d}\boldsymbol{h}_d(\hat{\boldsymbol{x}}_{k+1}^-)}{\mathrm{d}\hat{\boldsymbol{x}}_{k+1}^-}$$

D. Simon, “Optimal state estimation: Kalman, H_∞, and nonlinear approaches” (2006)



(Flexible) MultiBody systems: dynamics is now represented with Differential Algebraic Equations due to presence of algebraic kinematic equality constraints, which must be enforced during the estimation.

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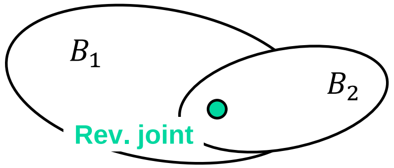
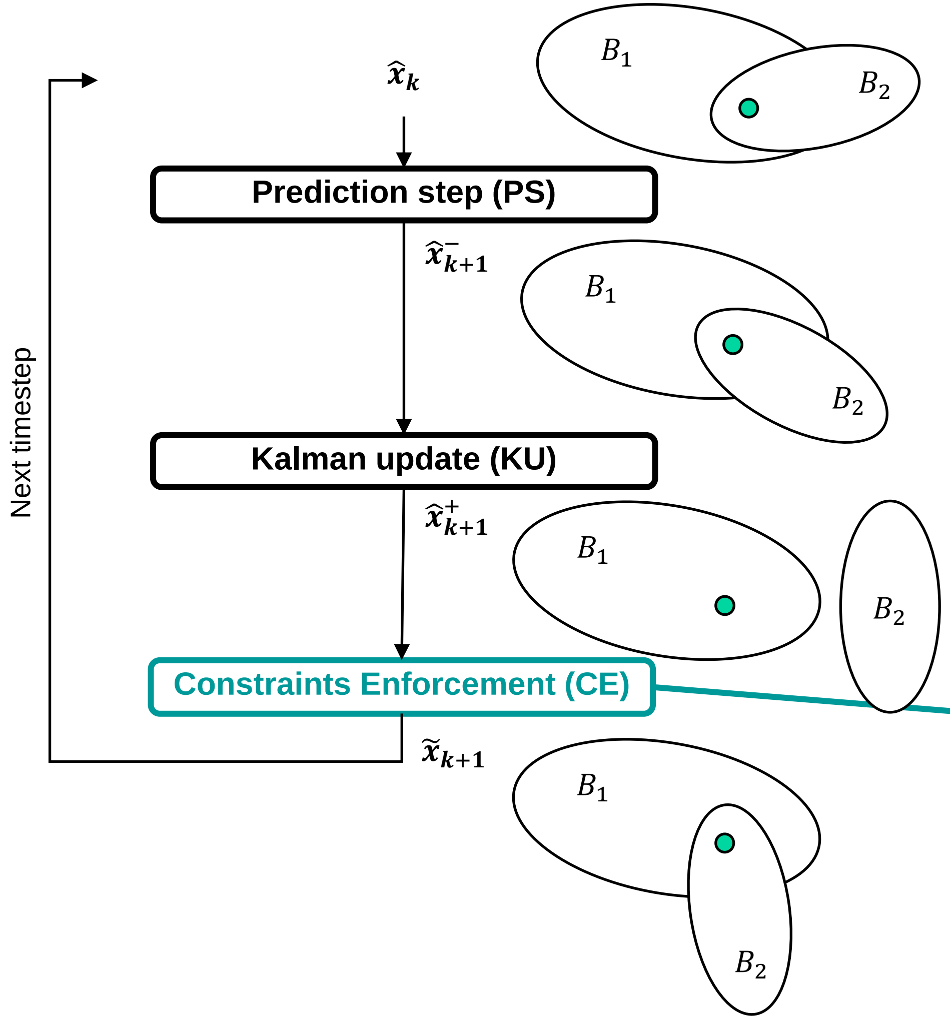
The Augmented Extended Kalman Filter for MultiBody systems (AEKF-MB)



The AEKF-MB structure

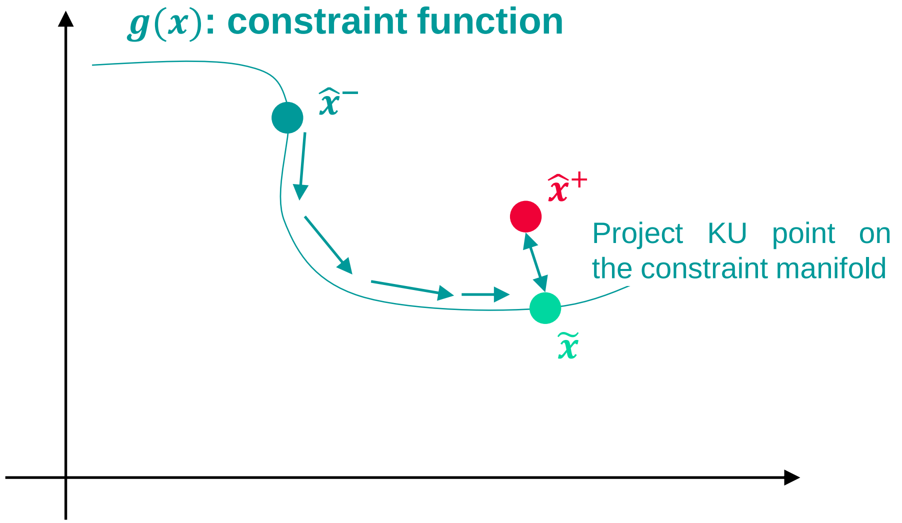


No constraints are violated

No constraints are violated
GGL formulation

Constraints are (potentially) violated

No constraints are violated



Constraints enforced via null-projected gradient descent

$$\tilde{x} \to \min_{\tilde{x}} (\tilde{x} - \hat{x}^+)^T (\tilde{x} - \hat{x}^+)$$
$$\text{s.t.} \quad g(\tilde{x}) = 0 \text{ (constraint function)}$$

IN: $\hat{x}^-, \hat{x}^+, g(x)$

$i = 0$

$\tilde{x}_{i=0} = \hat{x}^-$

until $\tilde{x}_i$ sufficiently close to $\hat{x}^+$:

$$N_i = \mathrm{null}\left(\left(\frac{\partial g_i}{\partial x}\right)_{x=\tilde{x}_i}\right) \to \left(\frac{\partial g_i}{\partial x}\right)_{x=\tilde{x}_i} N_i = 0$$

$$\tilde{x}_{i+1} = \tilde{x}_i - 2N_i\left(N_i^T\,(\tilde{x}_i - \hat{x}^+)\right)$$

$i = i + 1$

OUT: $\tilde{x} = \tilde{x}_i$

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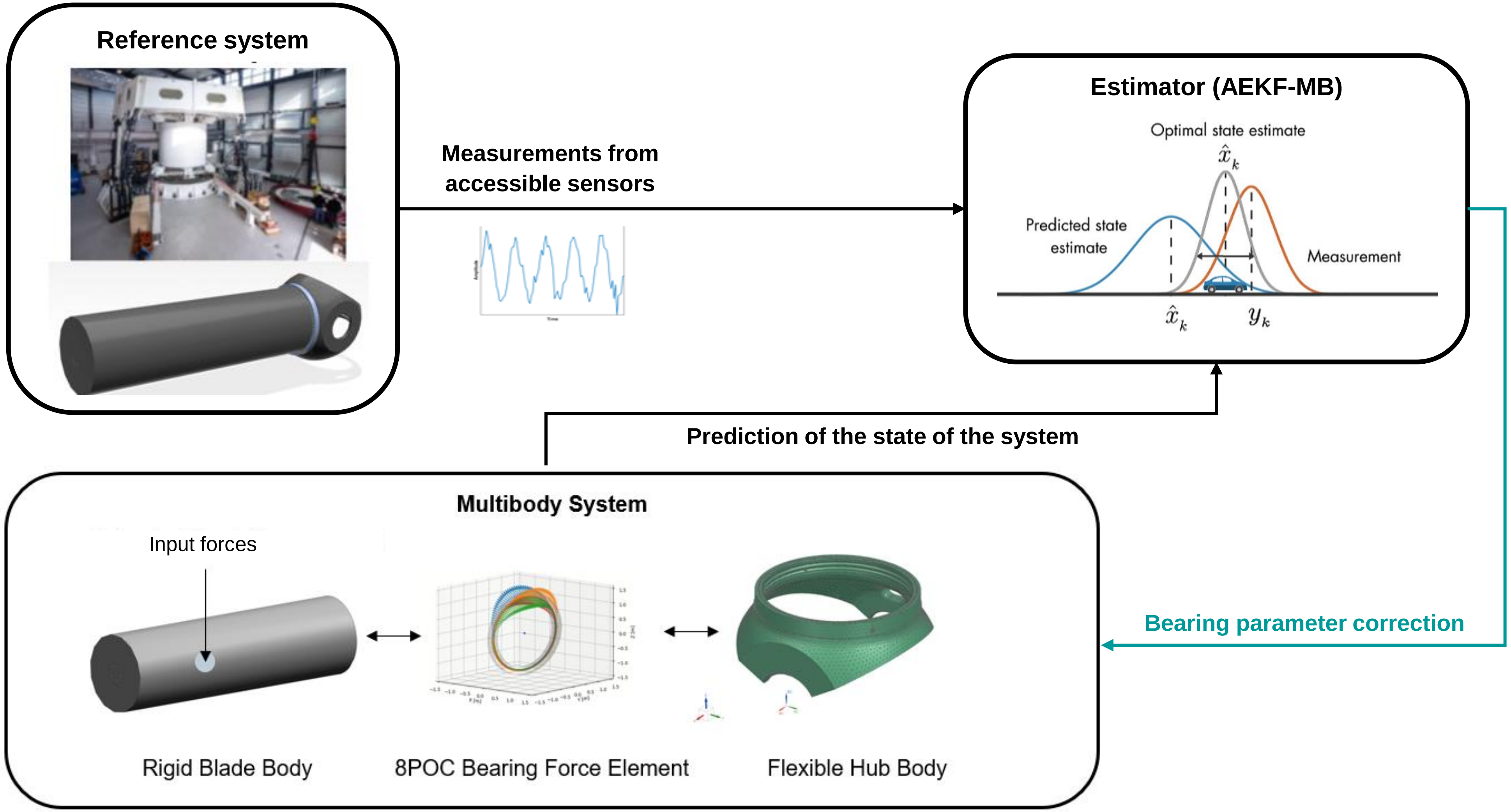
Virtual Sensing for bearing parameters estimation



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Overview

1. **Introduction**
   - Virtual Testing and Virtual Sensing
   - The Augmented Extended Kalman Filter for MultiBody
2. **Virtual Sensing for Bearing 4POC parameter estimation**
3. **Numerical Validation**
4. **Conclusions**

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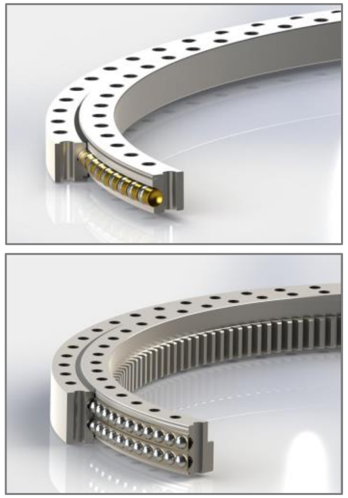
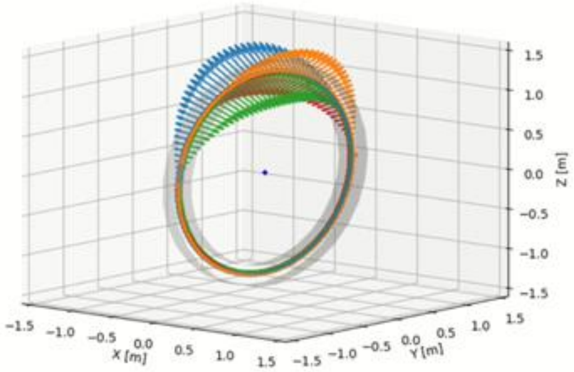
4POC / 8POC bearing analytical model



Single row (top) and double row (bottom) 4POC bearings, from manufacturer Laulagun.



Representation of the contact forces acting on the rolling elements computed by the analytical model.

Analytical model for 4POC / 8POC [1].
Assumptions and limitations:

- Hertzian contact model for rolling elements
- Five degrees-of-freedom external loading
- Low rotational speed
- Neglects frictional effects
- Neglects gyroscopic effects

Relative displacement of inner ring to outer ring

↓

Ball equilibrium problem

↓

Bearing equilibrium problem

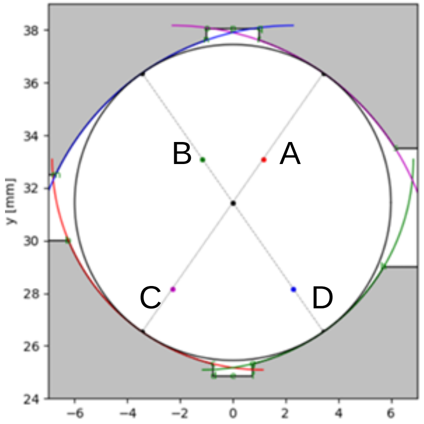
↓

Reaction loads (3 forces, 2 torques)

Each ring has two raceways (left, right).

Raceways center of curvature:

- Inner left: Point A
- Inner right: Point B
- Outer right: Point C (assumed fixed)
- Outer left: Point D (assumed fixed)



Ball equilibrium problem (x #rolling elements)

- Equilibrium of the 4 contact forces acting on the rolling element
- Solution: Ball center location after equilibrium achieved

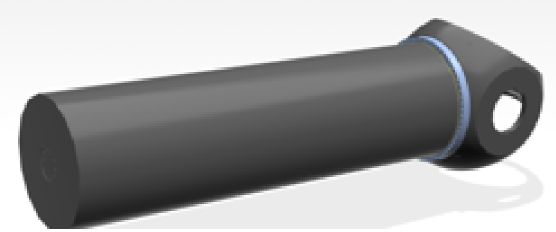
Bearing equilibrium problem (x 1)

- Equilibrium of all contact forces on computed at outer ring center
- Solution: Reaction forces/moments on outer ring center

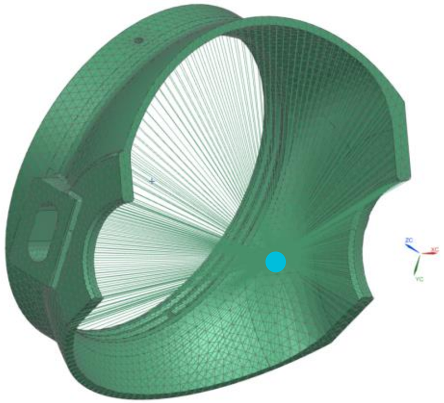
[1] Halpin, J. D., and Tran, A. N. (May 18, 2016). "An Analytical Model of Four-Point Contact Rolling Element Ball Bearings." ASME. *J. Tribol*. July 2016; 138(3): 031404.

The flexible MultiBody system

Reference system



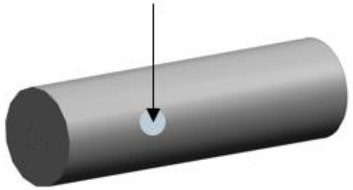
Blade body connected to wind turbine hub, subject to bending.

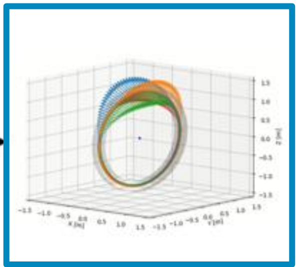


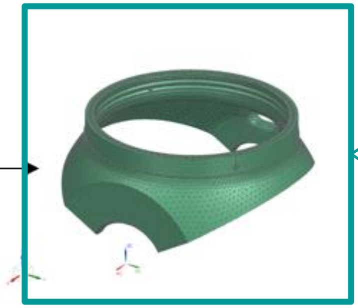
Degrees of freedom of the flexible hub constrained with an RBE2 approach.

Multibody System

Input forces



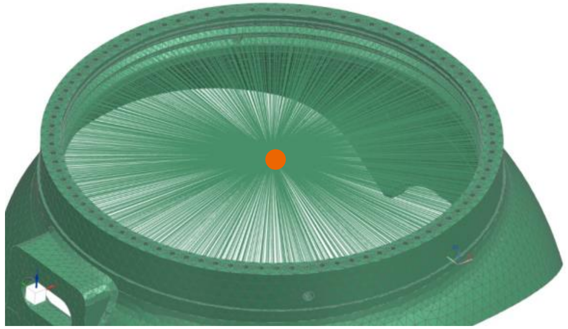




Rigid Blade Body

8POC Bearing Force Element

Flexible Hub Body



Distribution of the total 8POC bearing loads to the flexible hub on the outer raceway surface using an RBE2 approach.

Geometrical limits on maximum and minimum value of rolling elements diameter and raceway radius (from bearing model formulation).

$$d_1 \leq d_{\text{rolling element}} \leq d_2$$
$$r_1 \leq r_{\text{raceway radius}} \leq r_2$$

These constraints must also be enforced during the estimation

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Virtual Sensing for Bearing 4POC parameter estimation

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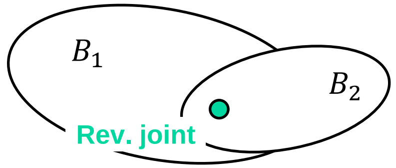
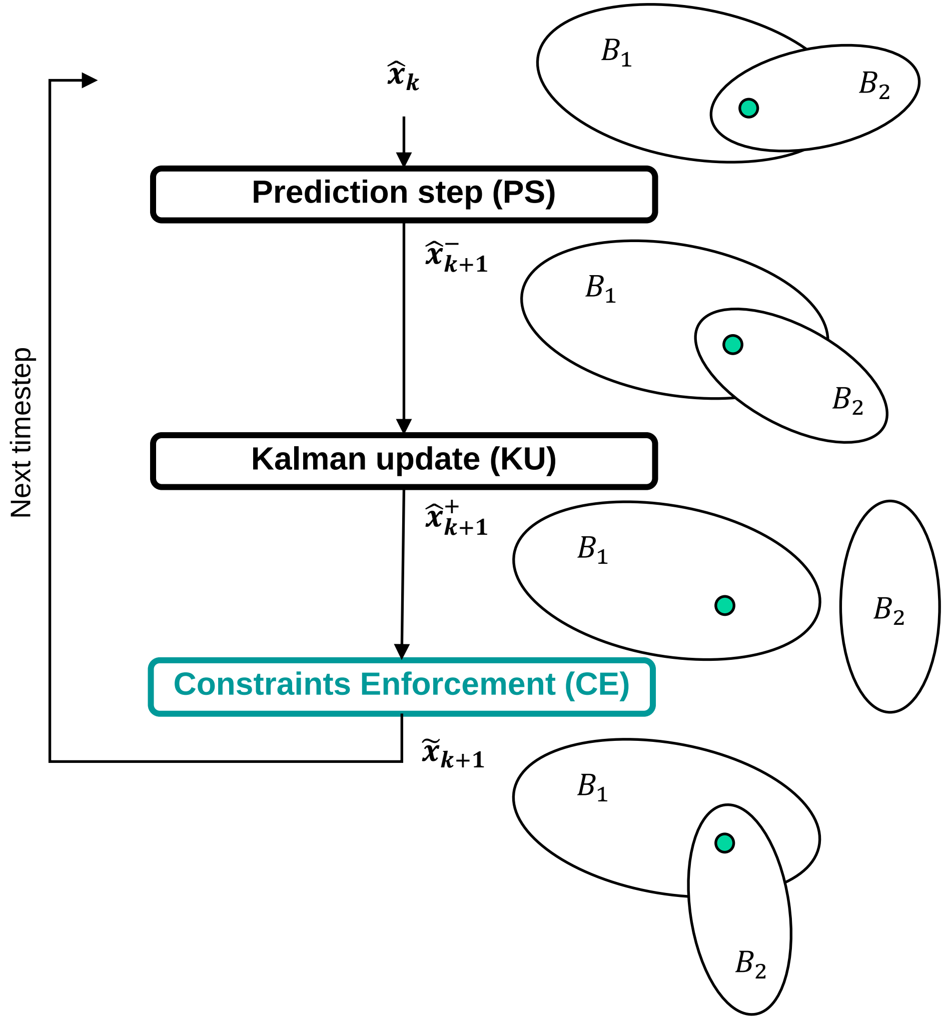
The Augmented Extended Kalman Filter for MultiBody systems (AEKF-MB)



The AEKF-MB structure



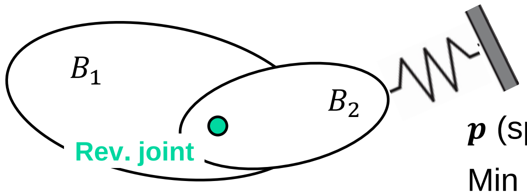
No constraints are violated

No constraints are violated
GGL formulation

Constraints are (potentially) violated

No constraints are violated

Extension of the Constraints Enforcement step for inequality constraints



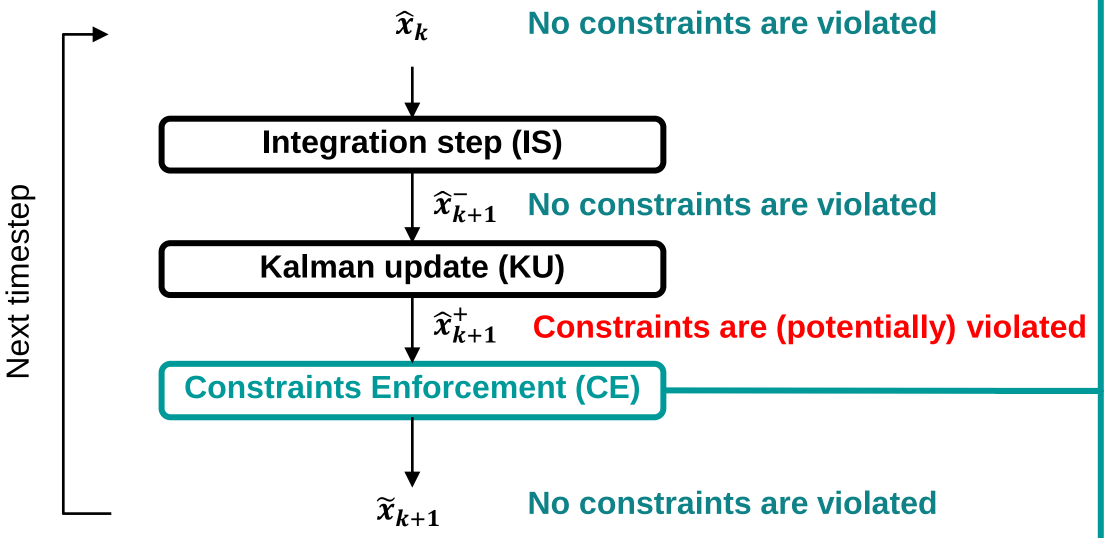
$\boldsymbol{p}$ (spring stiffness)

Min value is 0 → $\boldsymbol{g_p}(\boldsymbol{x}) \geq \boldsymbol{0}$

MultiBody constraints → $\boldsymbol{g_{MB}}(\boldsymbol{x}) = \boldsymbol{0}$

Enforce both types of constraints during CE

The AEKF-MB structure



CE step with parameter constraints

$\tilde{\boldsymbol{x}} \rightarrow \min_{\tilde{\boldsymbol{x}}} (\tilde{\boldsymbol{x}} - \hat{\boldsymbol{x}}^{+})^{\boldsymbol{T}} (\tilde{\boldsymbol{x}} - \hat{\boldsymbol{x}}^{+})$

s.t. $\boldsymbol{g_{MB}}(\tilde{\boldsymbol{x}}) = \boldsymbol{0}$ and $\boldsymbol{g_p}(\tilde{\boldsymbol{x}}) \geq \boldsymbol{0}$

IN: $\tilde{\boldsymbol{x}}^{-}, \hat{\boldsymbol{x}}^{+}, \boldsymbol{g_{MB}}(\boldsymbol{x}), \boldsymbol{g_p}(\boldsymbol{x})$

$i = 0$

$\tilde{\boldsymbol{x}}_{\boldsymbol{i=0}} = \hat{\boldsymbol{x}}^{-}$

until $\tilde{\boldsymbol{x}}_{\boldsymbol{i}}$ sufficiently close to $\boldsymbol{x}^{+}$ and $\boldsymbol{g_p}(\tilde{\boldsymbol{x}}_{\boldsymbol{i}}) \geq \boldsymbol{0}$:

$\boldsymbol{g_i} = \boldsymbol{g_{MB}}(\tilde{\boldsymbol{x}}_{\boldsymbol{i}})$

Active set check:

for $j = 1$ to number of ineq. constraints

if $\boldsymbol{g_{p,j}}(\tilde{\boldsymbol{x}}_{\boldsymbol{i}}) < \boldsymbol{0}$

$$\boldsymbol{g_i} = \begin{bmatrix} \boldsymbol{g_i} \\ \boldsymbol{g_{p,j}}(\tilde{\boldsymbol{x}}_{\boldsymbol{i}}) \end{bmatrix}$$

$$\boldsymbol{N}_i = \textbf{null}\left(\left(\frac{\partial \boldsymbol{g}_i}{\partial \boldsymbol{x}} \right)_{x = \tilde{x}_i} \right)$$

$$\tilde{\boldsymbol{x}}_{\boldsymbol{i+1}} = \tilde{\boldsymbol{x}}_{\boldsymbol{i}} - \boldsymbol{2N_i}\left(\boldsymbol{N_i^T}(\tilde{\boldsymbol{x}}_{\boldsymbol{i}} - \boldsymbol{x}^{+})\right)$$

$i = i + 1$

OUT: $\tilde{\boldsymbol{x}} = \tilde{\boldsymbol{x}}_{\boldsymbol{i}}$

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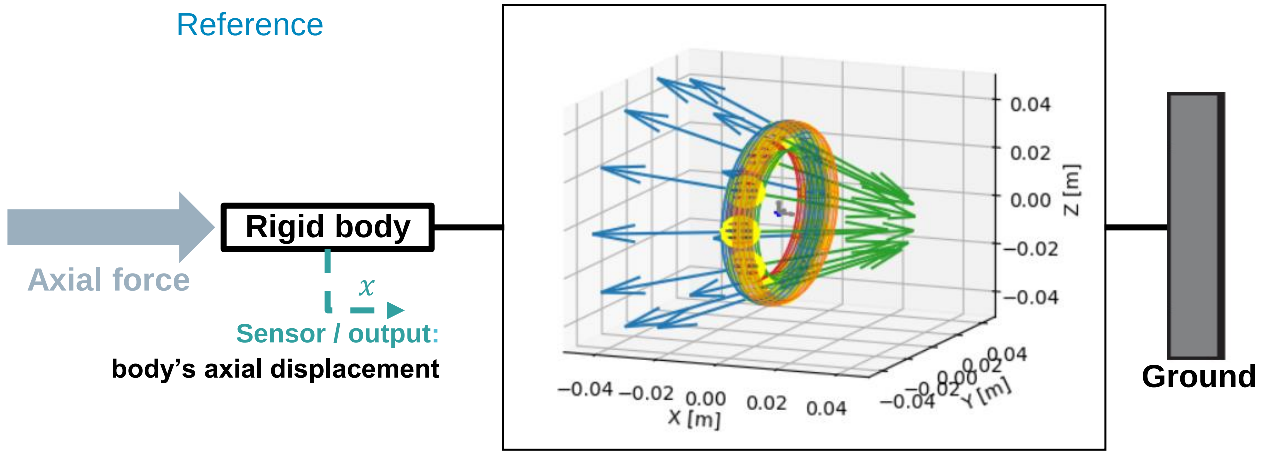
Numerical Validation

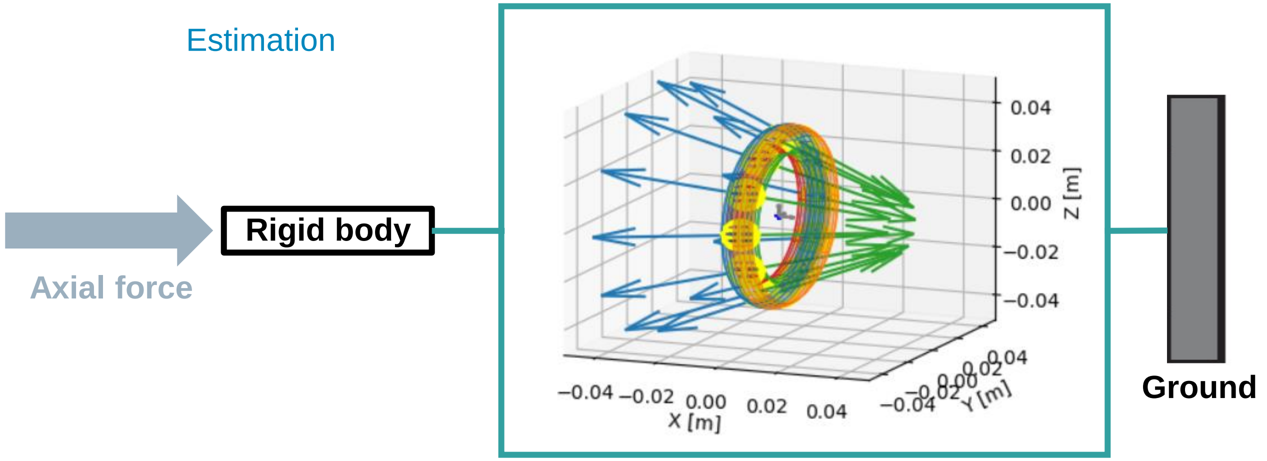
MultiBody case: rolling elements diameter

Reference

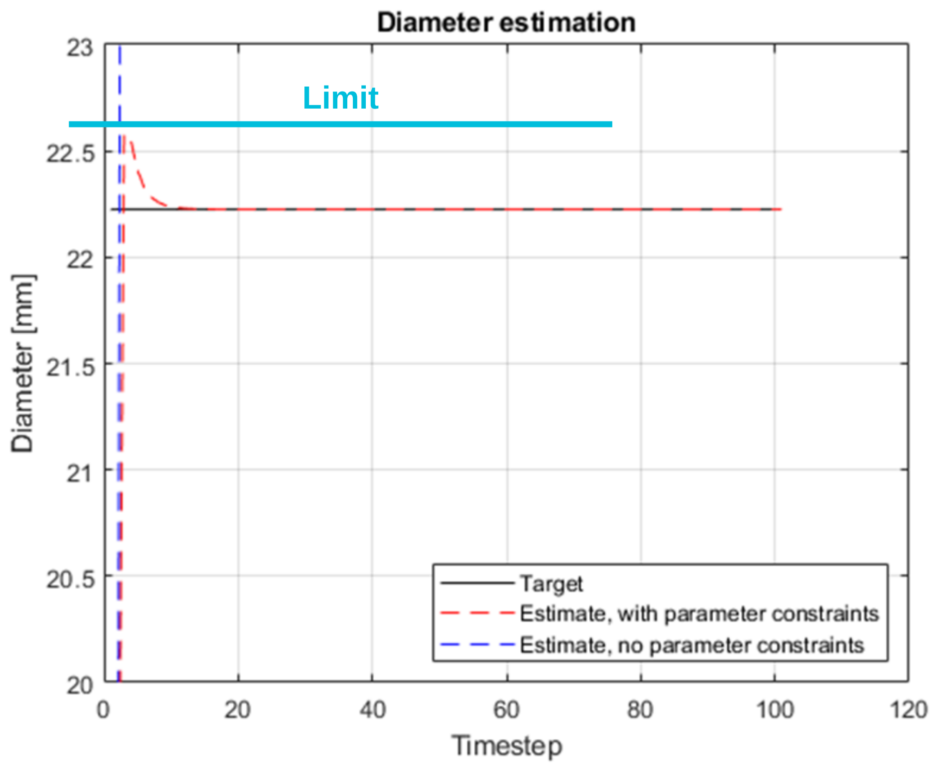


Bearing element
(with correct parameter value)

Estimation



Bearing element
(starting with incorrect parameter value, correcting it during the estimation)



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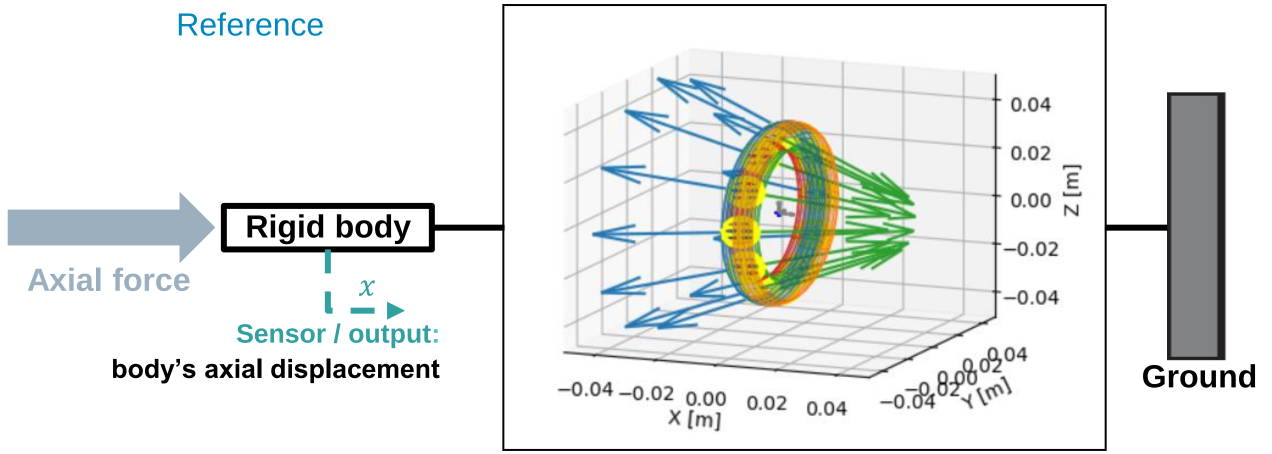
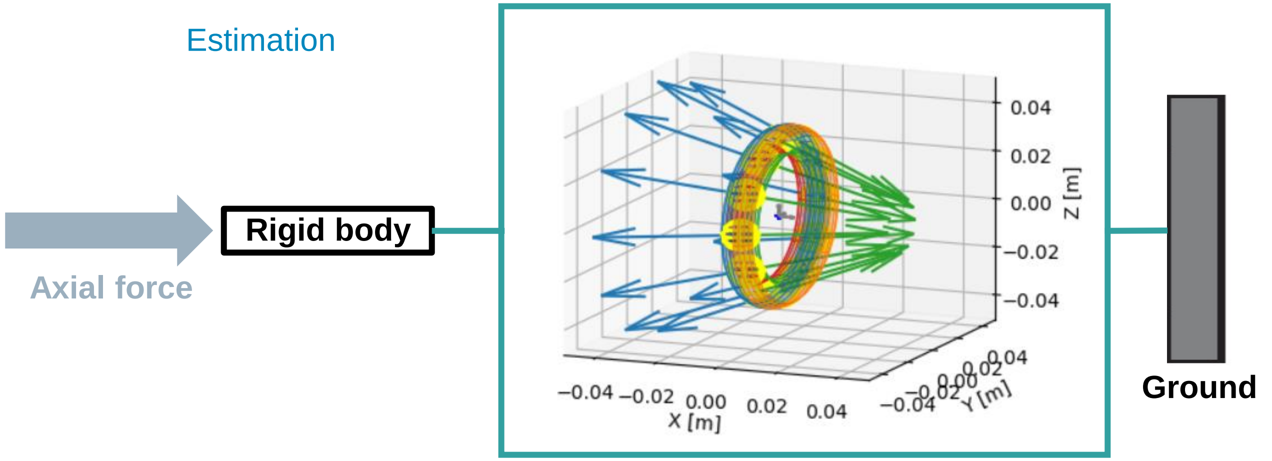
MultiBody case: raceway curvature radius

Reference

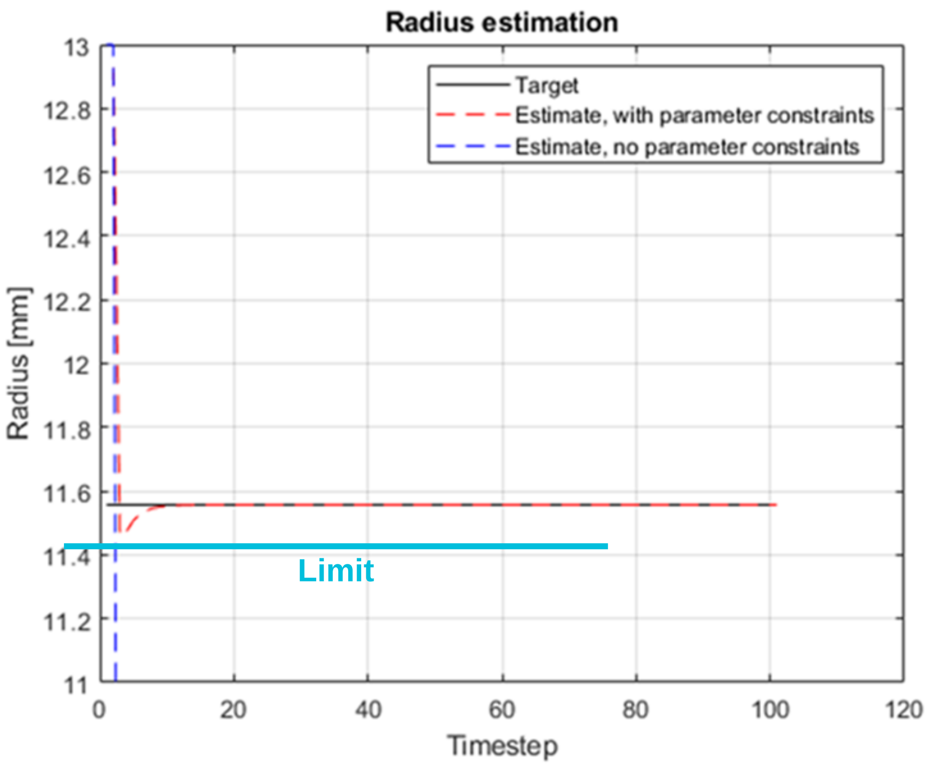


Bearing element
(with correct parameter value)

Estimation



Bearing element
(starting with incorrect parameter value, correcting it during the estimation)



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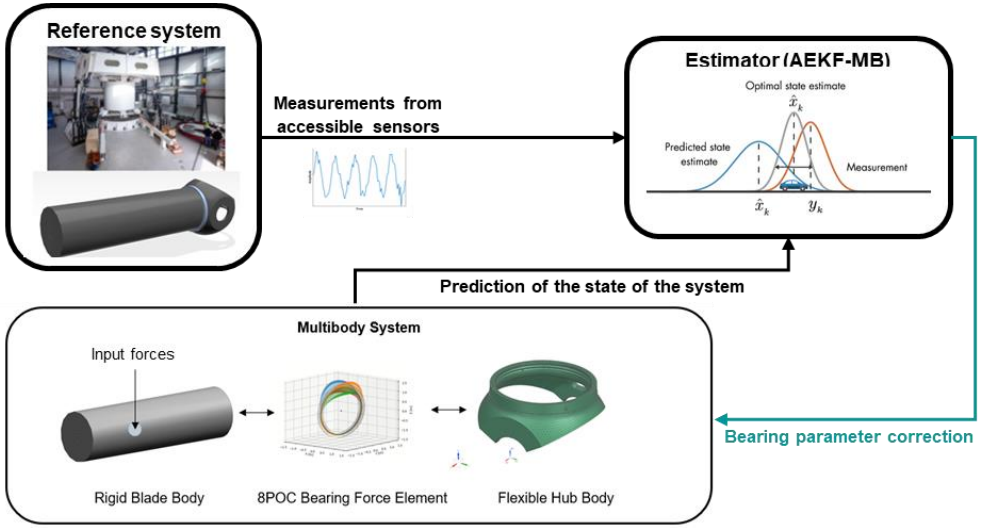
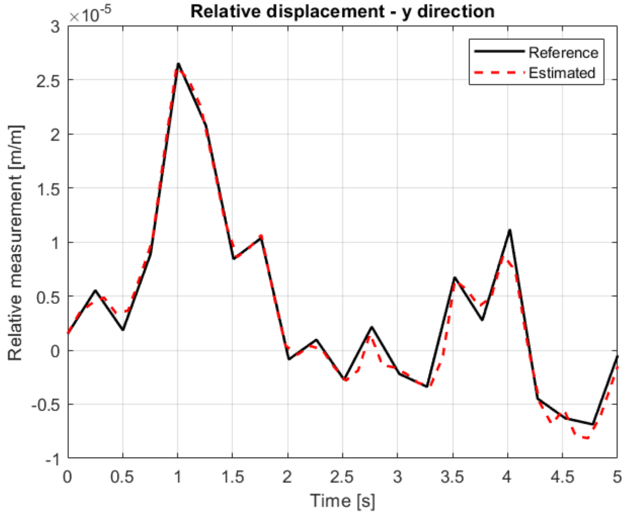
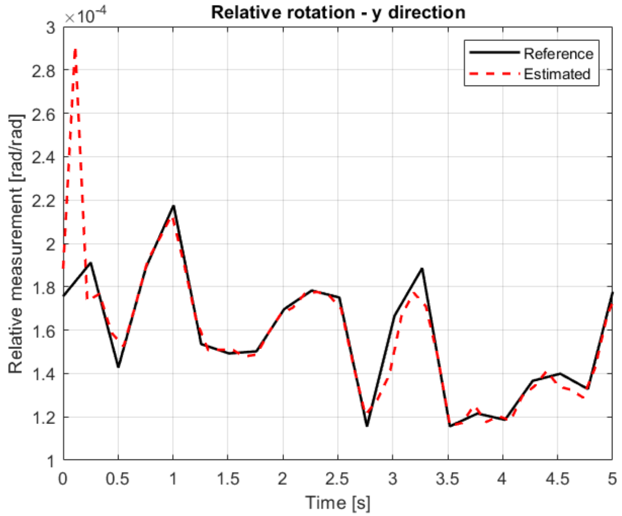
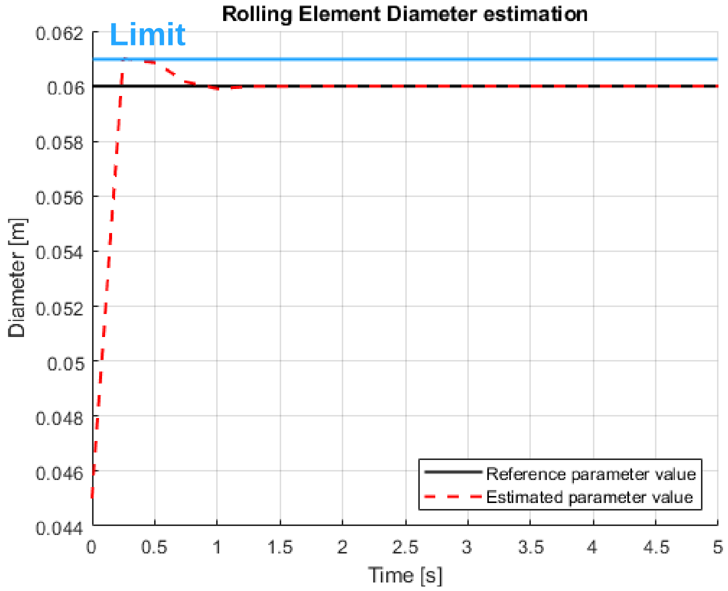
Flexible MultiBody case: rolling elements diameter



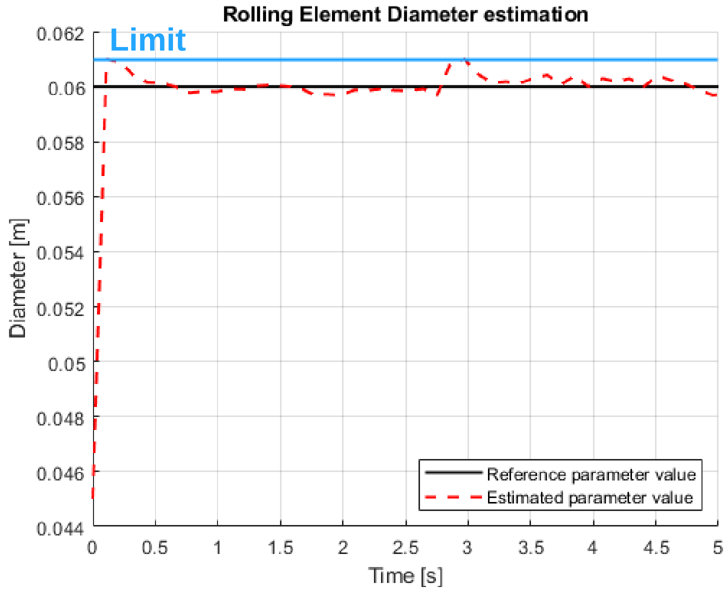




No measurement noise



With measurement noise



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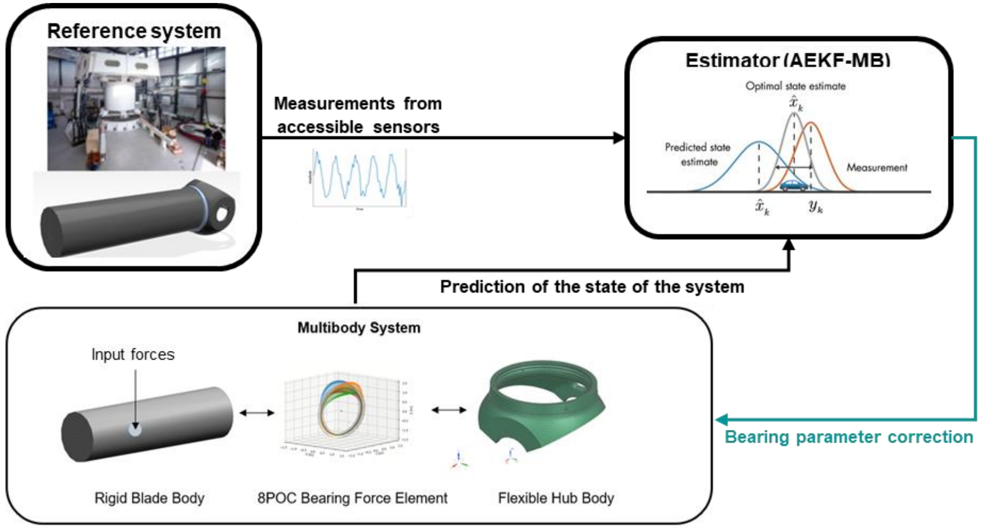
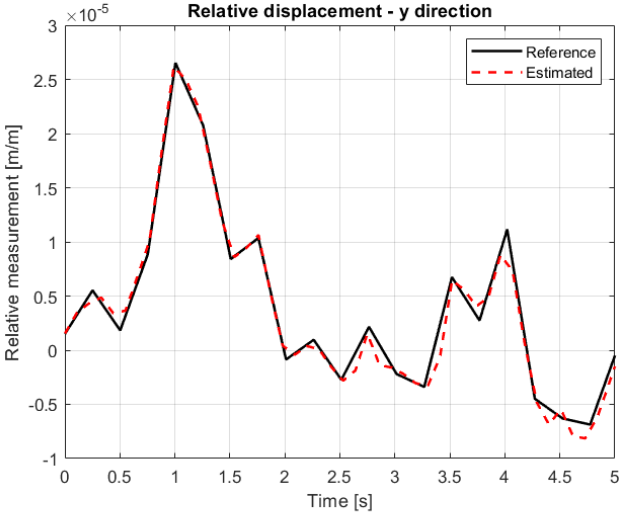
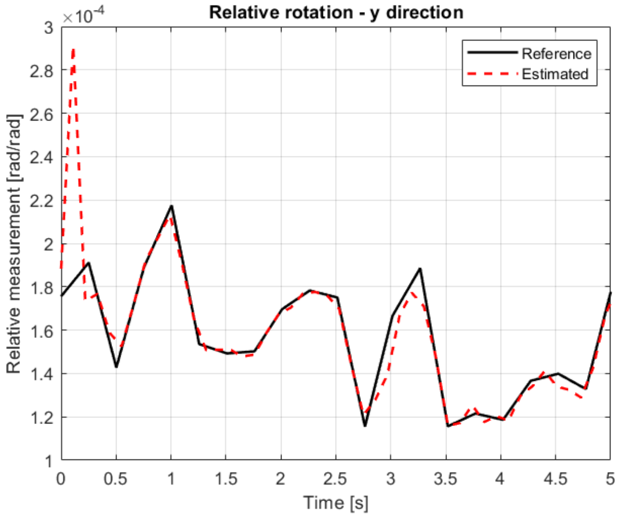
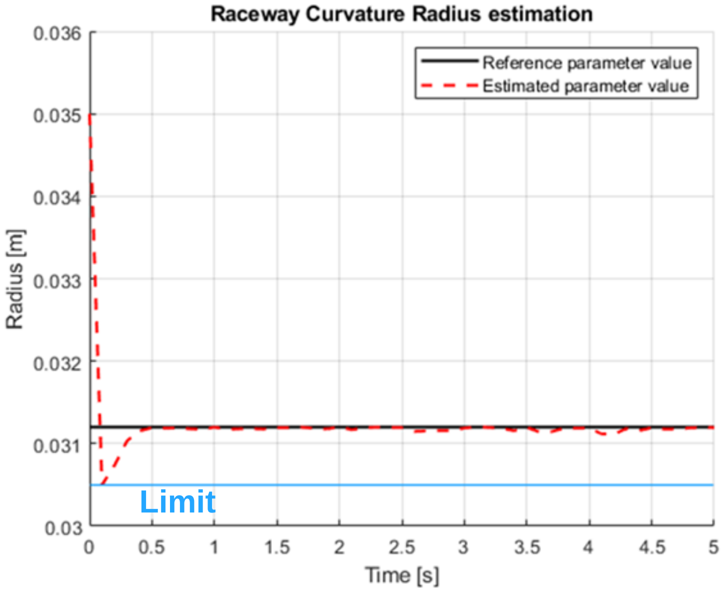
Flexible MultiBody case: raceway curvature radius



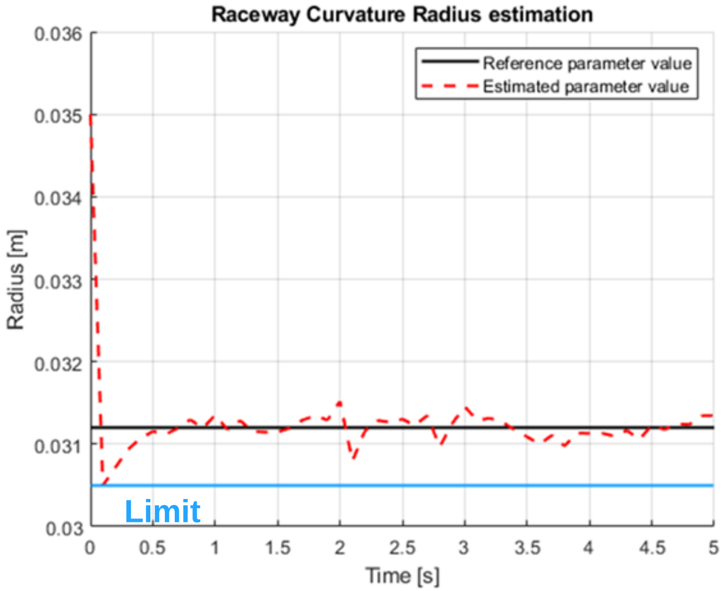




No measurement noise



With measurement noise



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Conclusions

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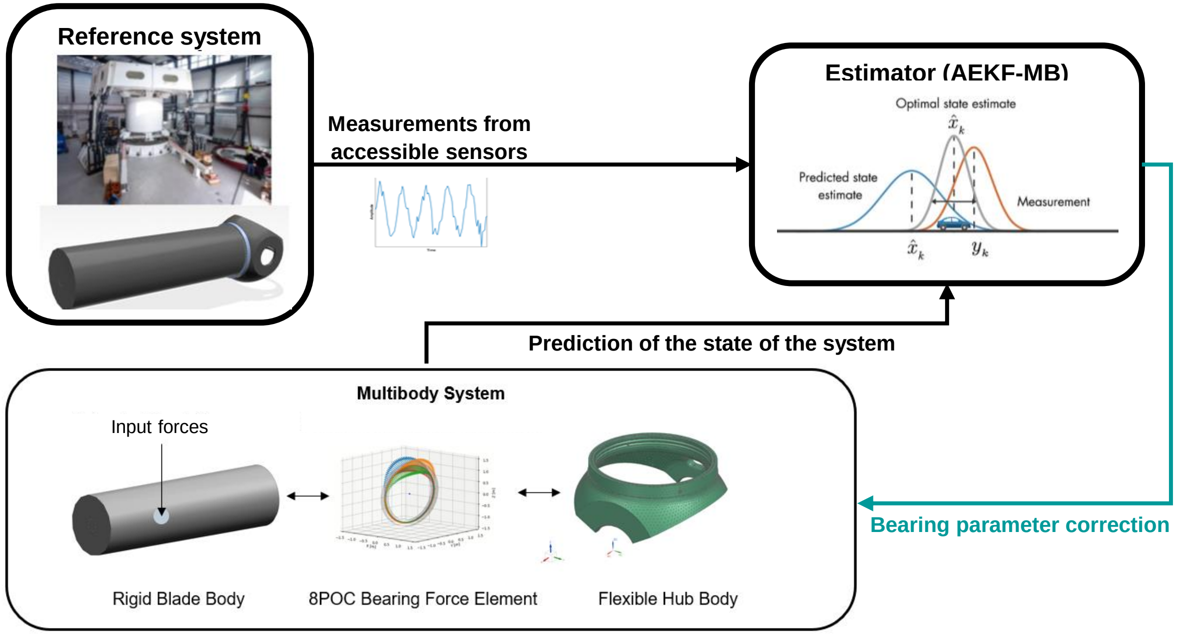
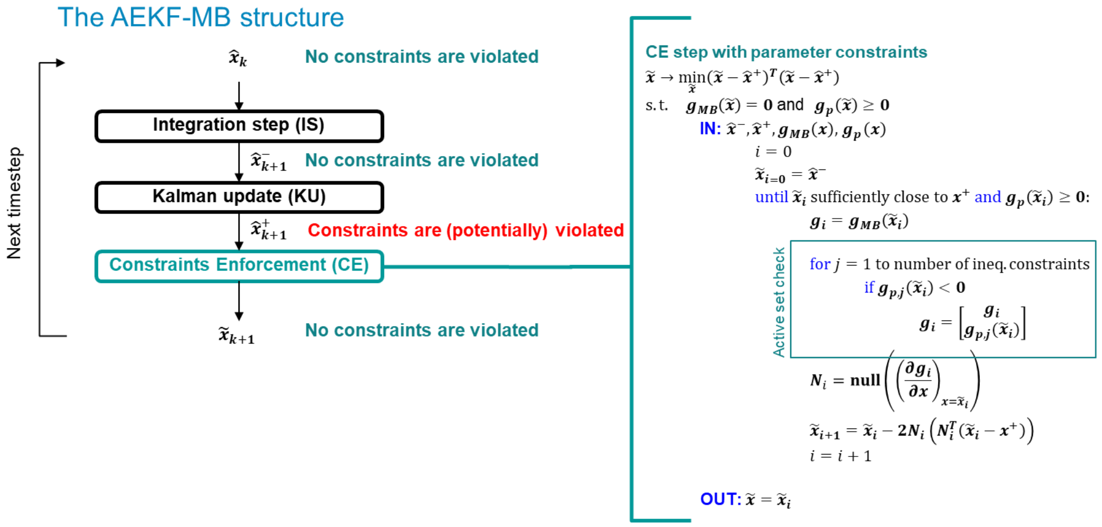
Conclusions

In this work, an Augmented Extended Kalman Filter for MultiBody has been extended to handle enforcement of equality and inequality constraints.

The post-Kalman update estimate is enforced to lie on the constraint manifold using an active-sets approach that checks for the active inequality constraints at every iteration of the algorithm.

The developed approach has been numerically validated using a 4POC/8POC bearing parameter estimation in a (Flexible) MultiBody setting.





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