IFW

Institut für Fertigungstechnik
und Werkzeugmaschinen

Prof. Dr.-Ing. Berend Denkena

State space controller for actuator control of an active jerk decoupled feed drive

euspen Precision Motion Systems & Control 2022

Prof. Dr.-Ing. B. Denkena, Dipl.-Ing. H. Klemme, M.Sc. M.-F. Böhse

Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität Hannover

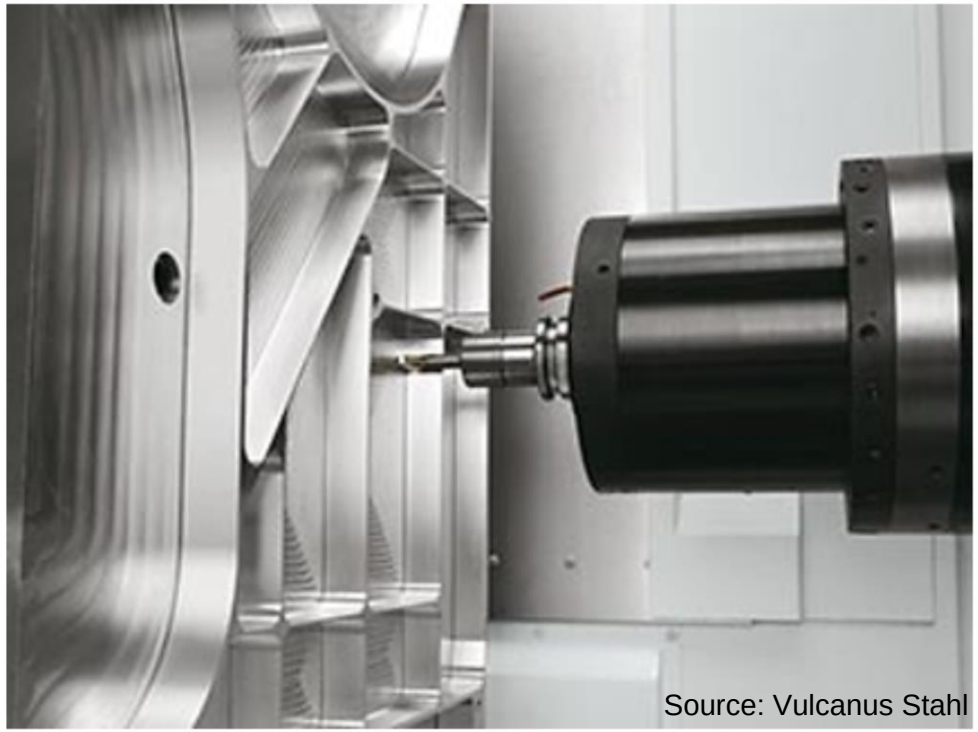
15th November 2022

Leibniz Universität Hannover

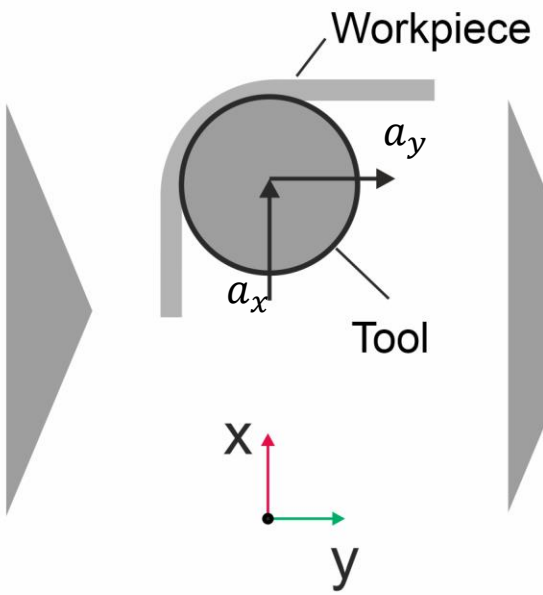
Produktionstechnisches Zentrum Hannover

Motivation

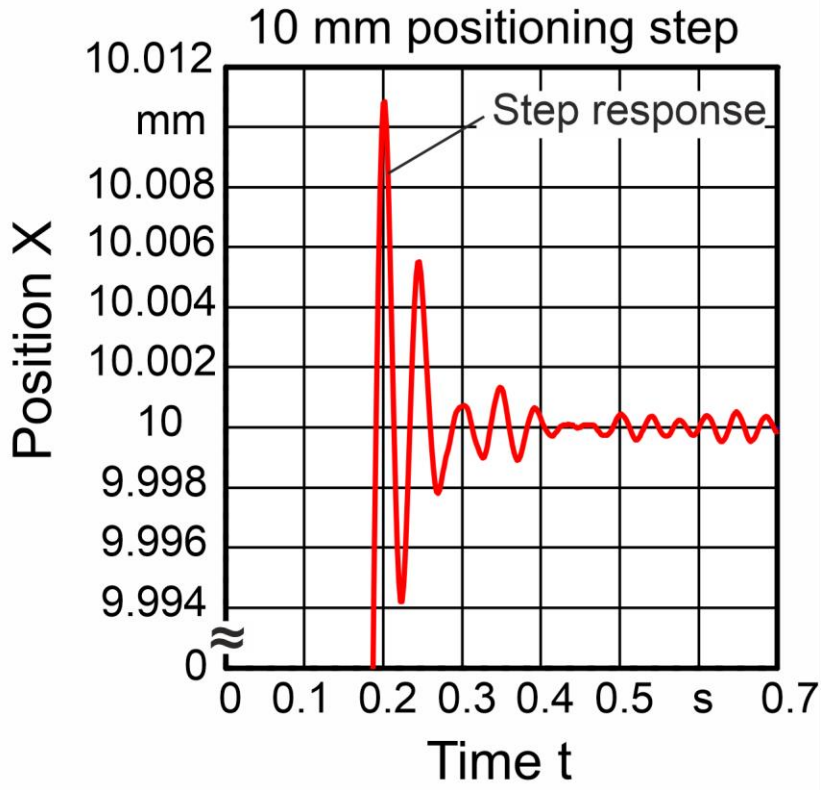
High Speed Cutting



Fast change of direction



Vibration excitation



— High feed rates (20 - 50 m/min)
— Reduced surface quality and positioning accuracy due to machine vibrations
— Target conflict between high dynamics and machine vibrations

$$\dot{F}(t) = m \cdot \dot{a}(t) \rightarrow max$$

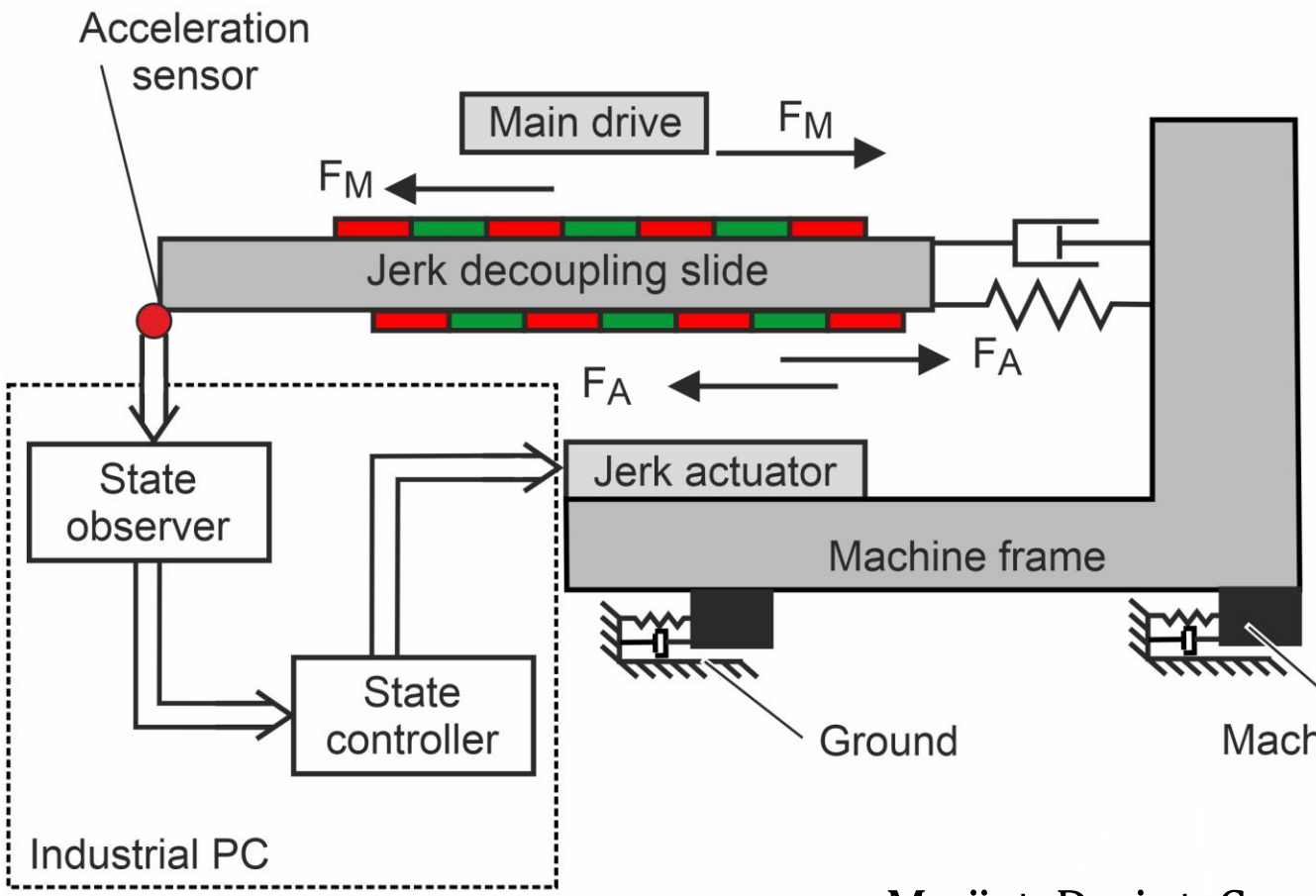
$$\underline{M} \cdot \ddot{\underline{x}} + \underline{D} \cdot \dot{\underline{x}} + \underline{C} \cdot \underline{x} = \underline{F}(t)$$

Bh/ 89265 © IFW

Principle of active jerk decoupling

IFW
Institut für Fertigungstechnik und Werkzeugmaschinen

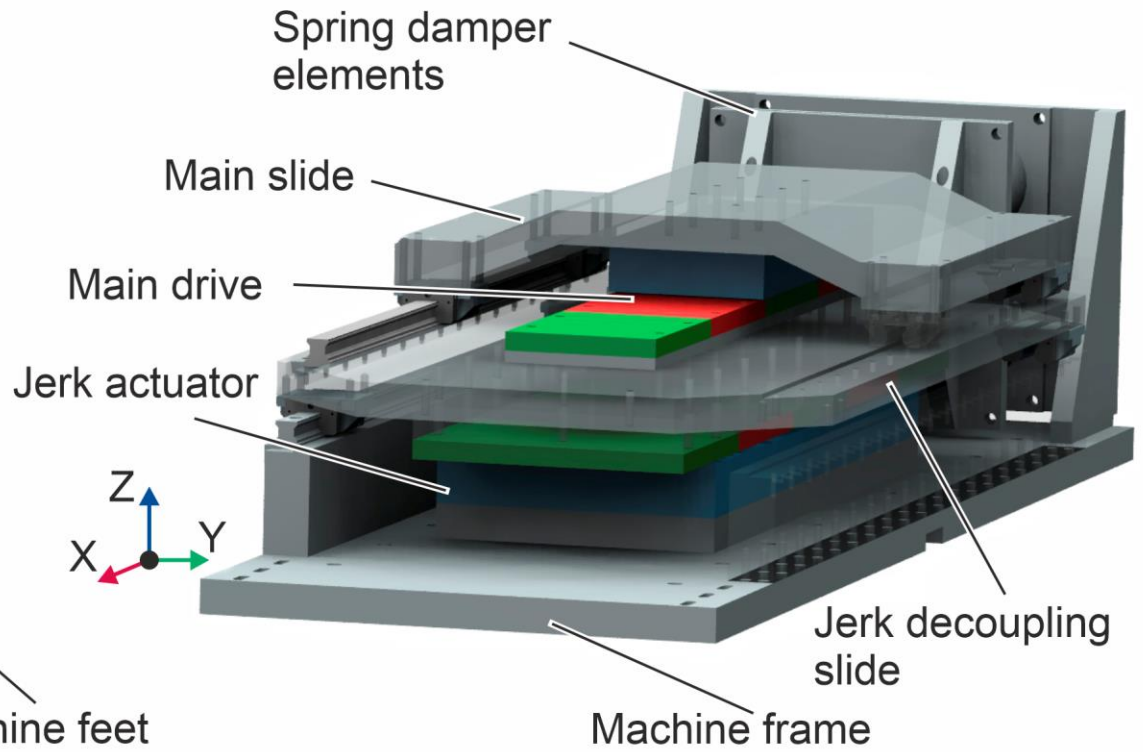
Active jerk decoupling concept



Motor force : F_M

Actuator force: F_A

Active jerk decoupled direct drive



$$\underline{M} \cdot \ddot{\underline{x}} + \underline{D} \cdot \dot{\underline{x}} + \underline{C} \cdot \underline{x} = \begin{bmatrix} -1 & 1 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} F_M \\ F_A \end{bmatrix}$$

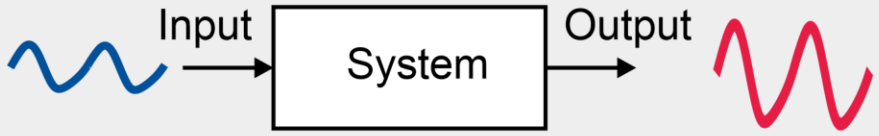
Bh/ 115865 © IFW

Demonstration

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

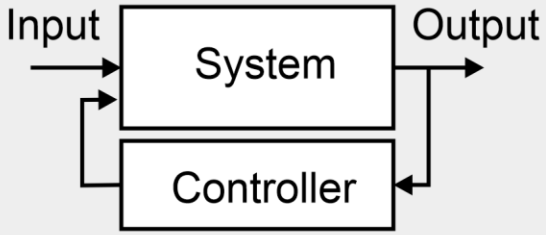
Method

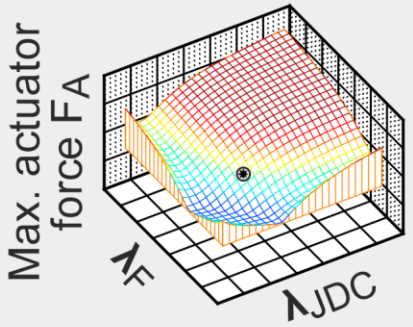
Model building



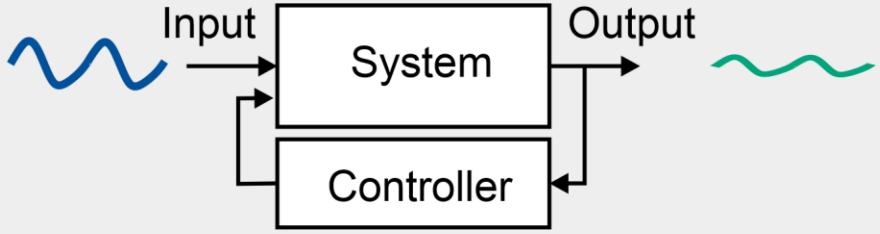
$$\dot{x} = Ax + Bu$$

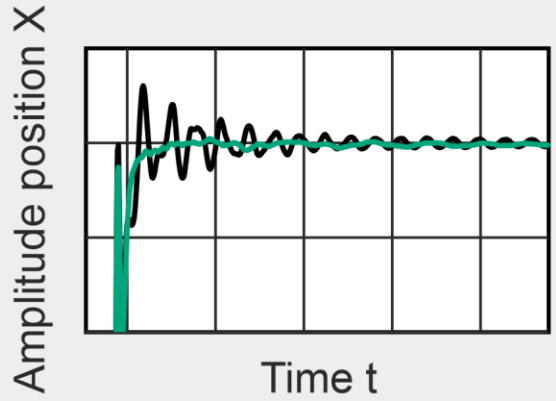
Control parameter selection





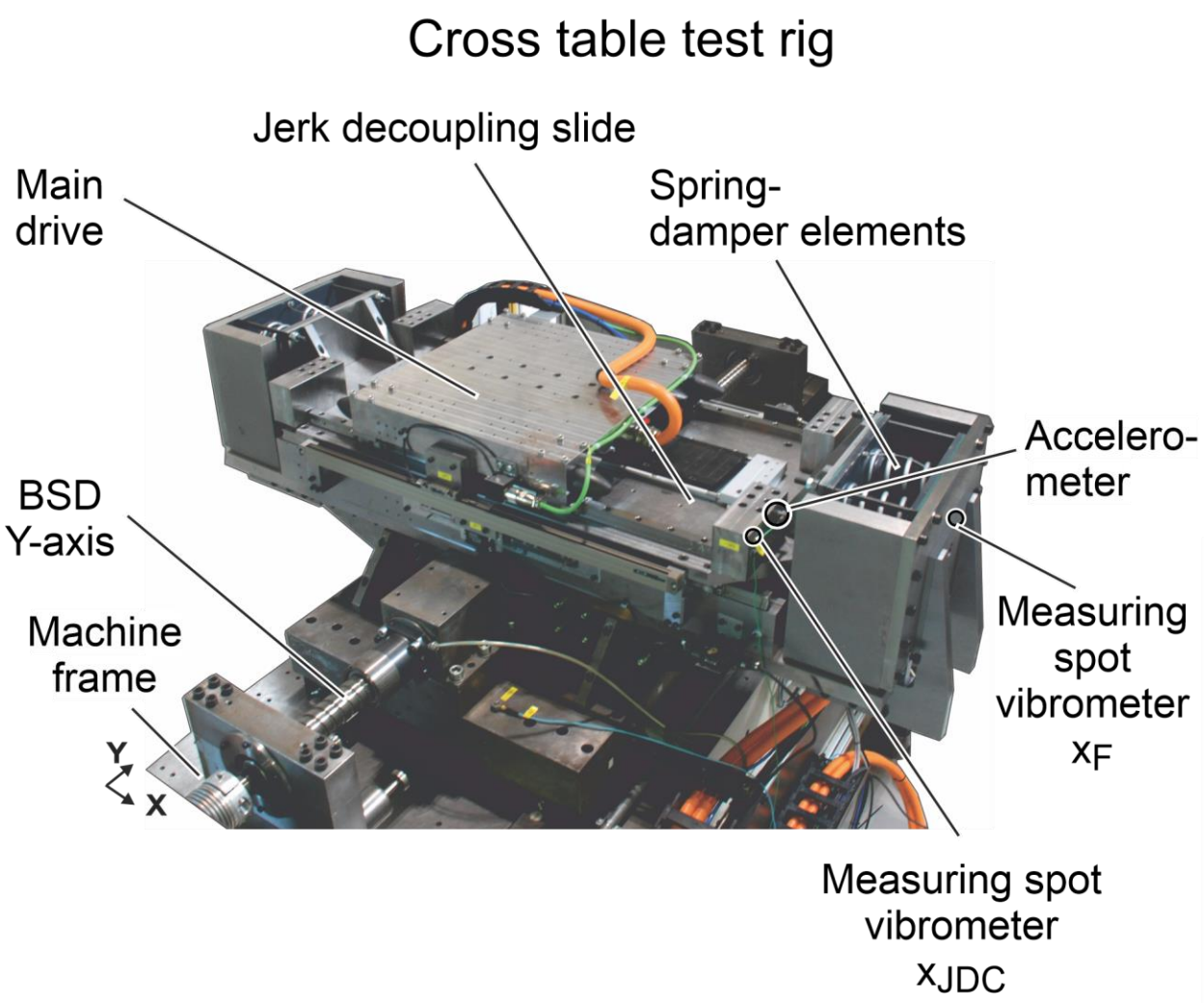
Vibration control

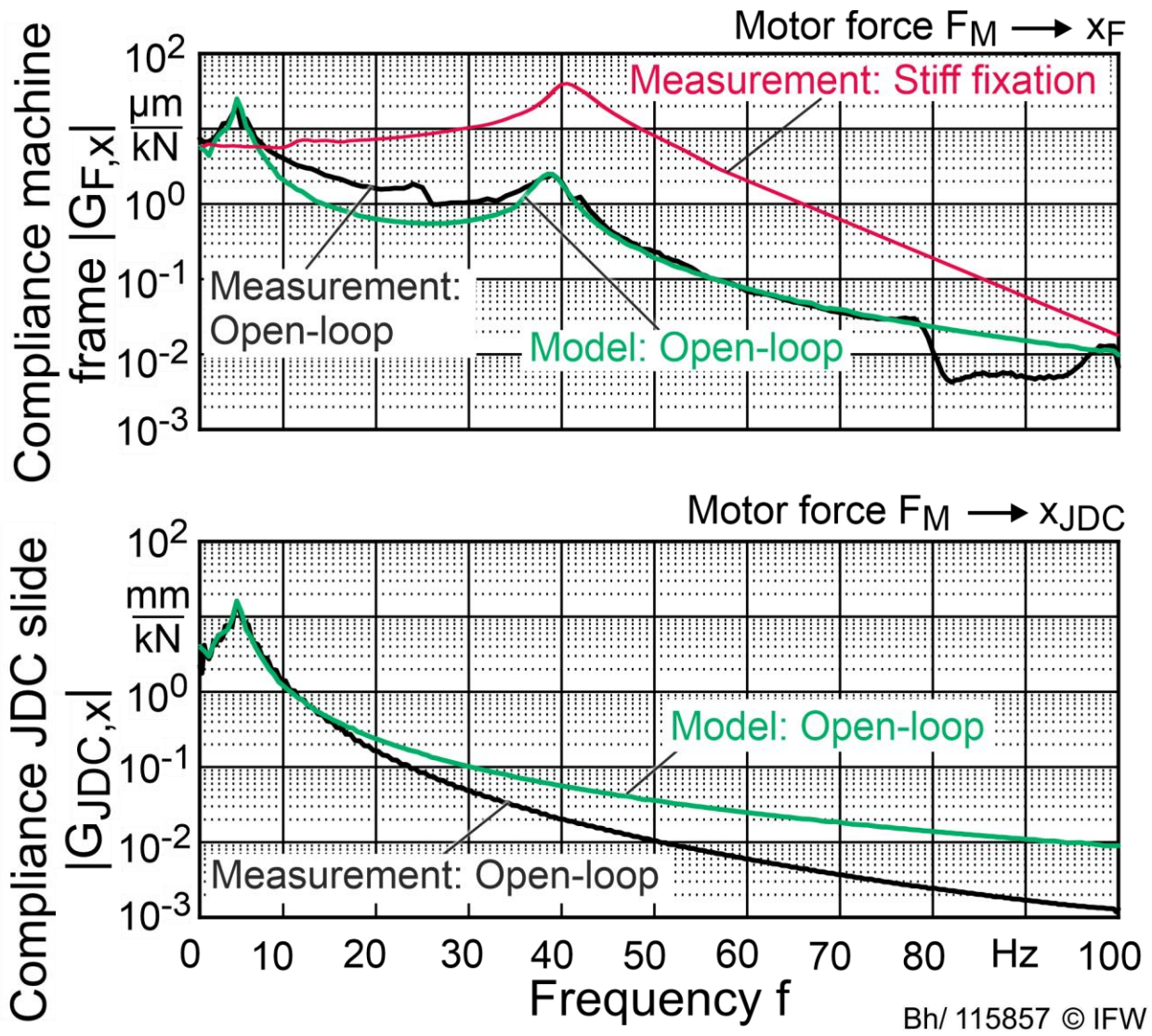




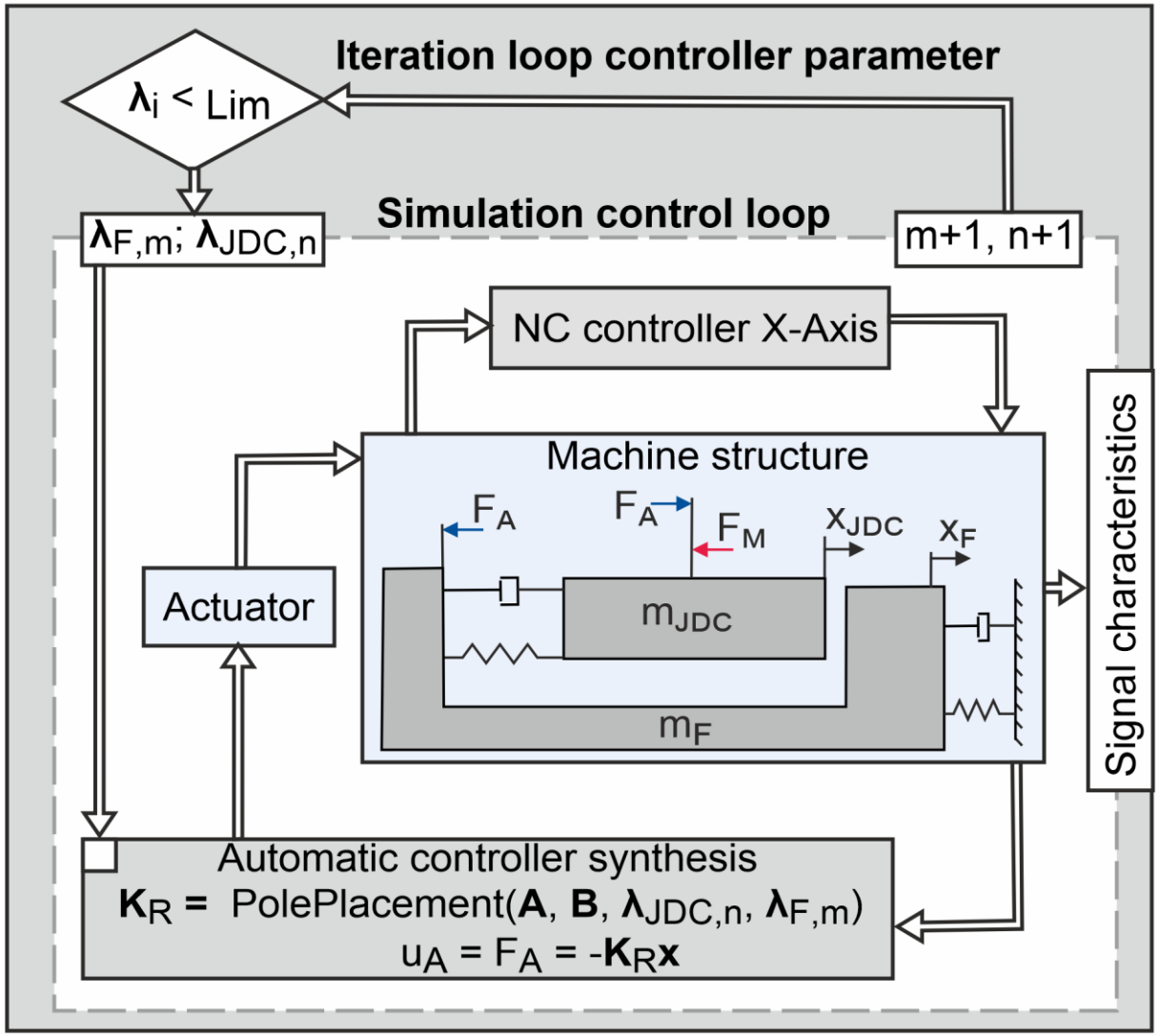
© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Model building





Controller parameter selection/ System dynamics

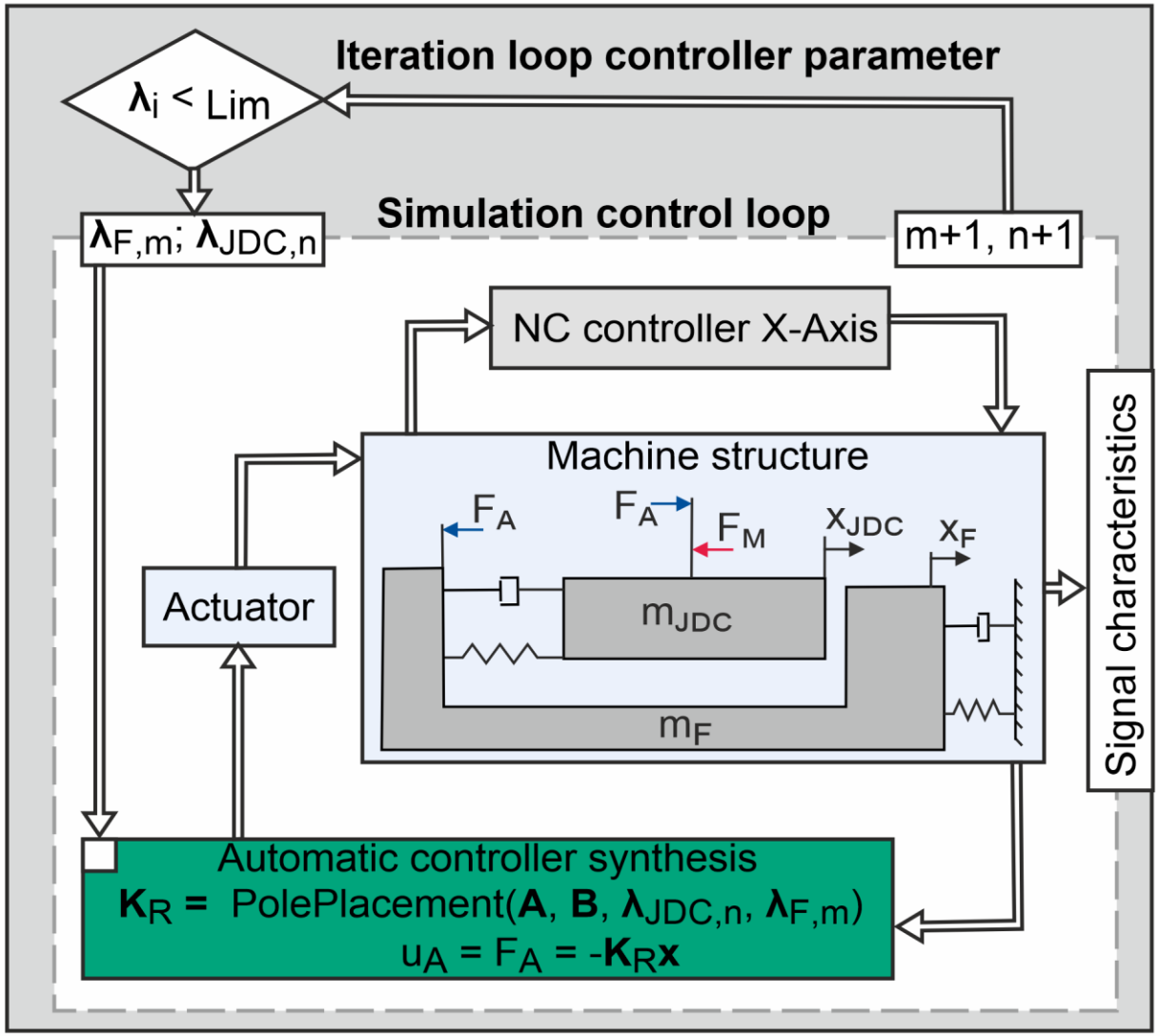


Control parameter selection algorithm

- System dynamics is represented by a state space equation $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$
  - **A**: State matrix
  - **B**: Input matrix
  - **u**: Input vector: $\mathbf{u} = (u_M \quad u_A)^T = (F_M \quad F_A)^T$

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Controller parameter selection/ Pole placement



Control parameter selection algorithm

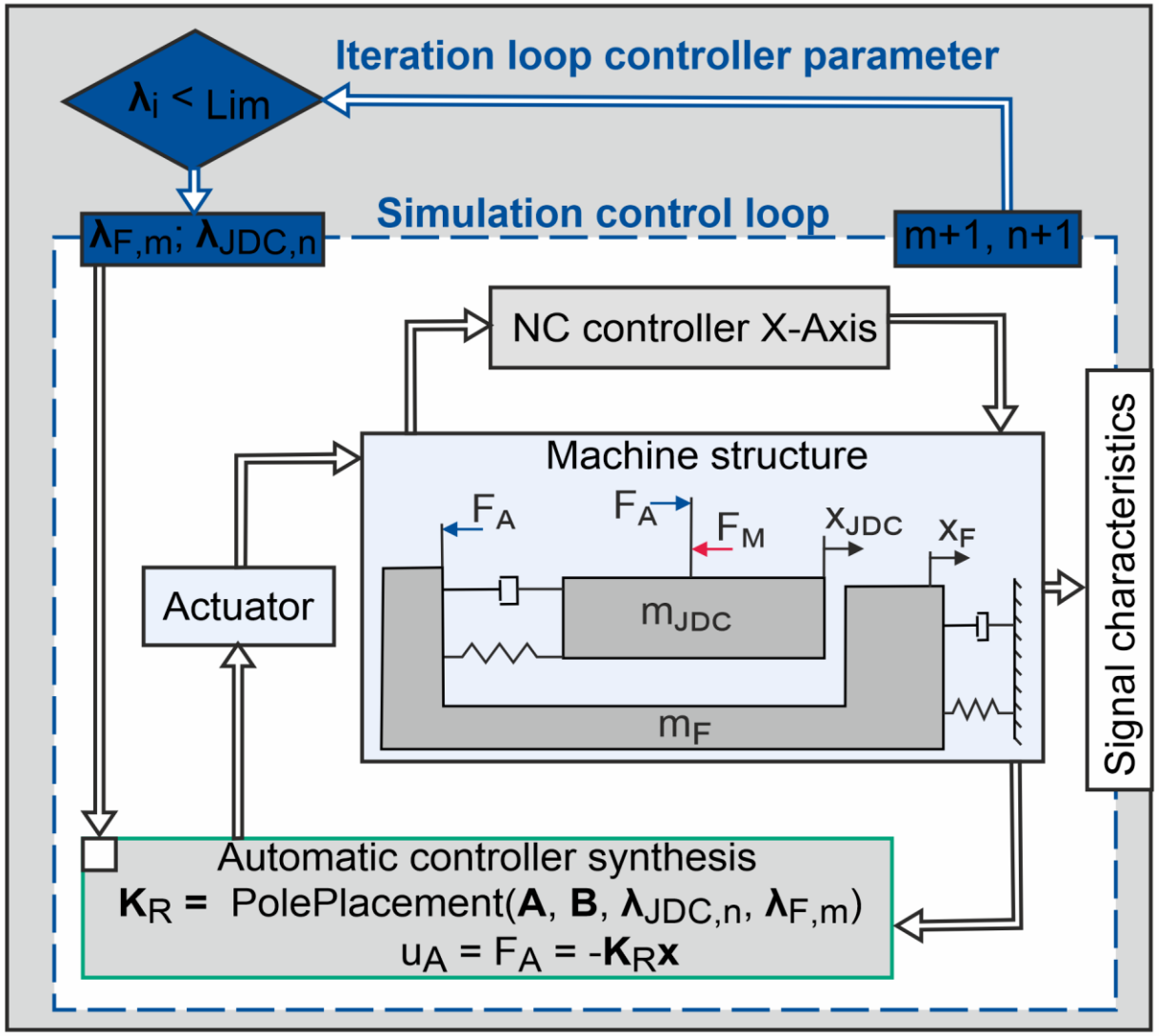
- System dynamics is represented by a state space equation
  $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$
  - **A**: State matrix
  - **B**: Input matrix
  - **u**: Input vector: $\mathbf{u} = (u_M \quad u_A)^T = (F_M \quad F_A)^T$

- State space controller: $u_A = F_A = -\mathbf{K}_R * \mathbf{x}$

- $\mathbf{K}_R$ by the desired eigenvalues of the closed-loop
  - $\boldsymbol{\lambda}_{JDC}$: Eigenvalues of x_{JDC} and $\dot{x}_{JDC}$
  - $\boldsymbol{\lambda}_F$: Eigenvalues of x_F and $\dot{x}_F$

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Controller parameter selection/ Iterative simulation

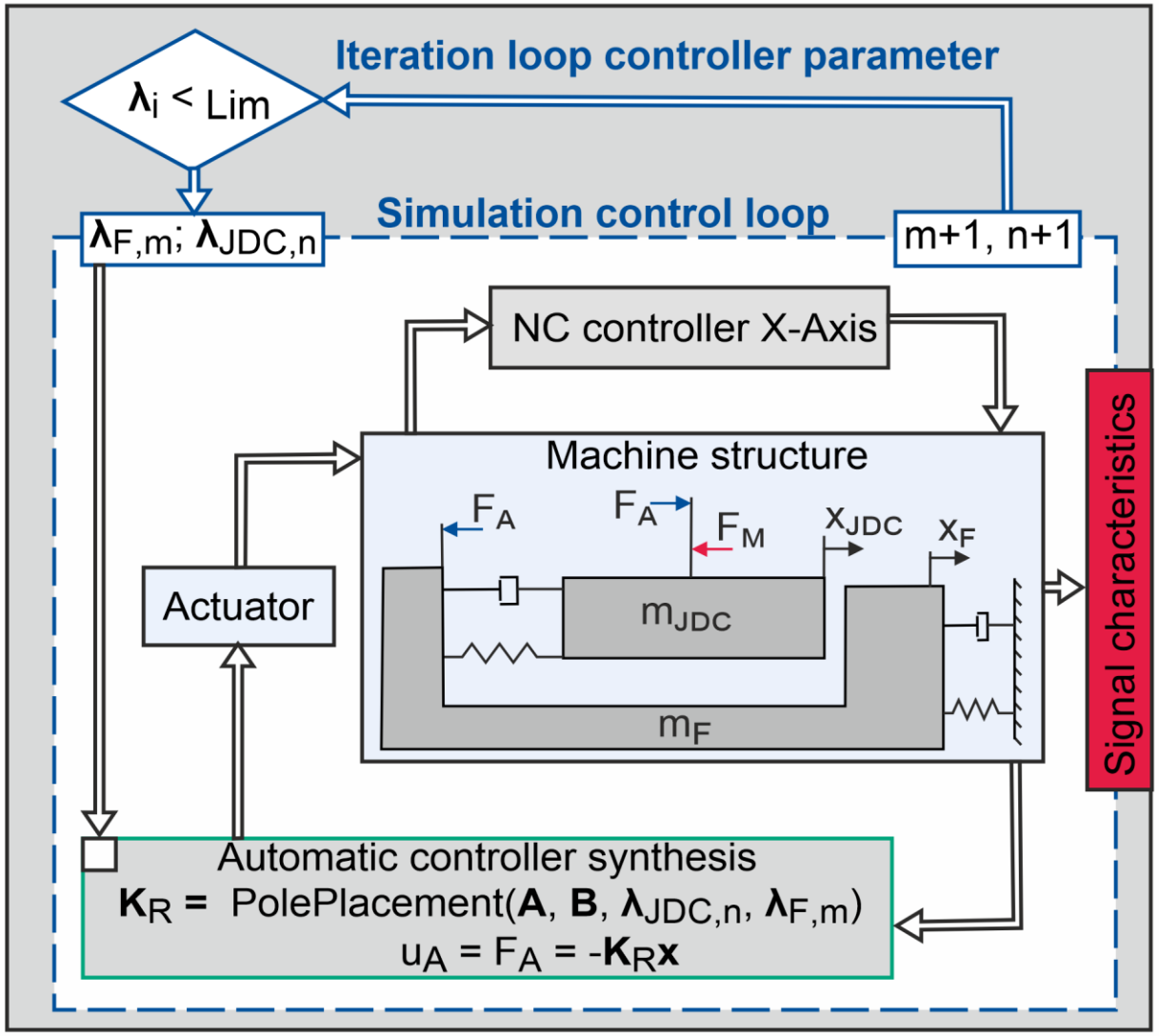


Control parameter selection algorithm

- System dynamics is represented by a state space equation
  $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$
  - **A**: State matrix
  - **B**: Input matrix
  - **u**: Input vector: $\mathbf{u} = (u_M \quad u_A)^T = (F_M \quad F_A)^T$
- State space controller: $u_A = F_A = -\mathbf{K}_R * \mathbf{x}$
- $\mathbf{K}_R$ by the desired eigenvalues of the closed-loop
  - $\boldsymbol{\lambda}_{JDC}$: Eigenvalues of x_{JDC} and $\dot{x}_{JDC}$
  - $\boldsymbol{\lambda}_F$: Eigenvalues of x_F and $\dot{x}_F$
- Iterative control loop simulation for suitable $\boldsymbol{\lambda}_{JDC}$ and $\boldsymbol{\lambda}_F$

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Controller parameter selection/ Satisfying control parameters

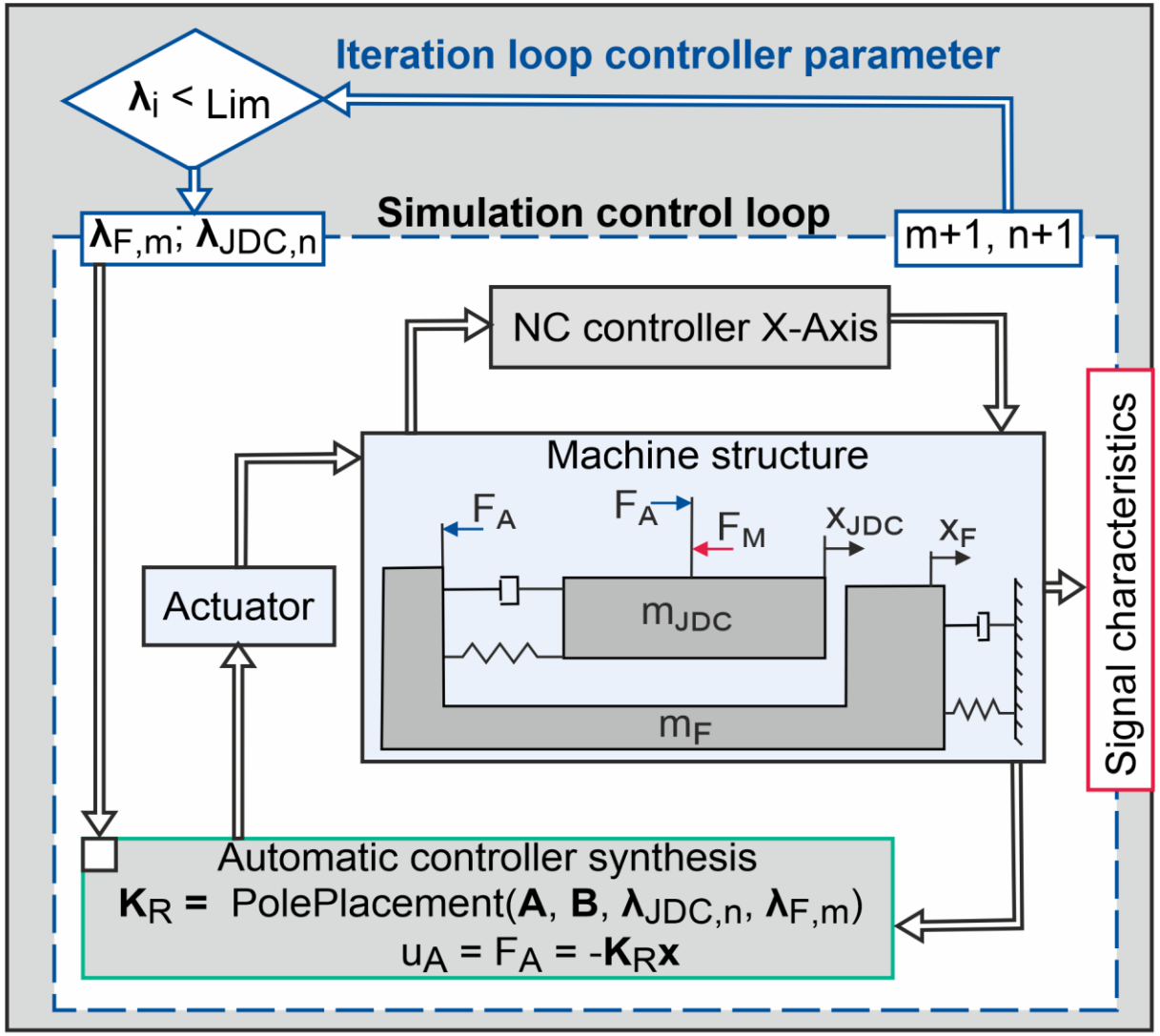


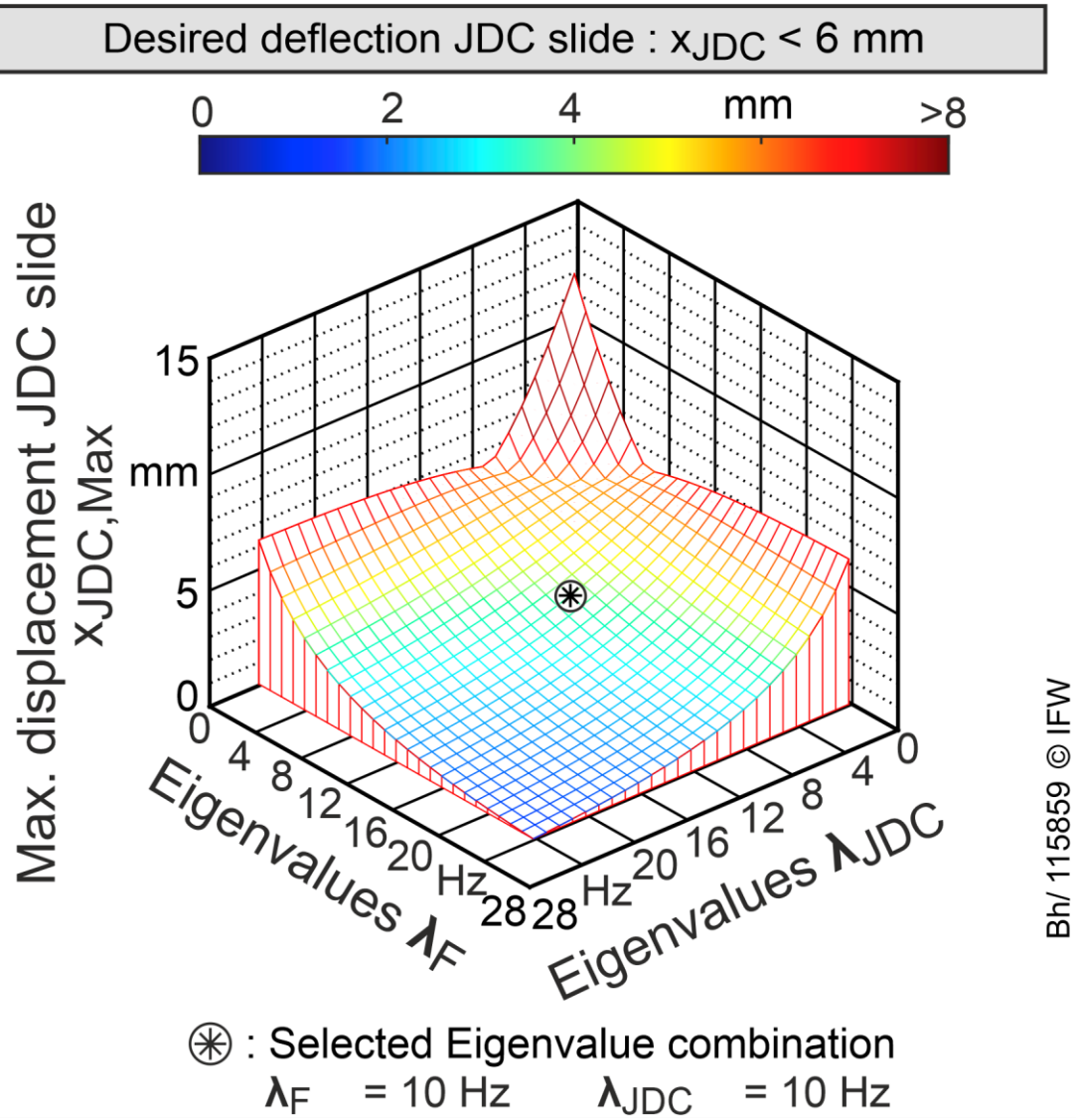
Control parameter selection algorithm

- System dynamics is represented by a state space equation $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$
  - **A**: State matrix
  - **B**: Input matrix
  - **u**: Input vector: $\mathbf{u} = (u_M \quad u_A)^T = (F_M \quad F_A)^T$
- State space controller: $u_A = F_A = -\mathbf{K}_R * \mathbf{x}$
- $\mathbf{K}_R$ by the desired eigenvalues of the closed-loop
  - $\boldsymbol{\lambda}_{JDC}$: Eigenvalues of x_{JDC} and $\dot{x}_{JDC}$
  - $\boldsymbol{\lambda}_F$: Eigenvalues of x_F and $\dot{x}_F$
- Iterative control loop simulation for suitable $\boldsymbol{\lambda}_{JDC}$ and $\boldsymbol{\lambda}_F$
- Selection of the satisfying control parameters $\boldsymbol{\lambda}_{JDC}$ and $\boldsymbol{\lambda}_F$
- System requirements
  - Max. deflection of x_{JDC}
  - Max. deflection of x_F
  - Max. actuator force F_A

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

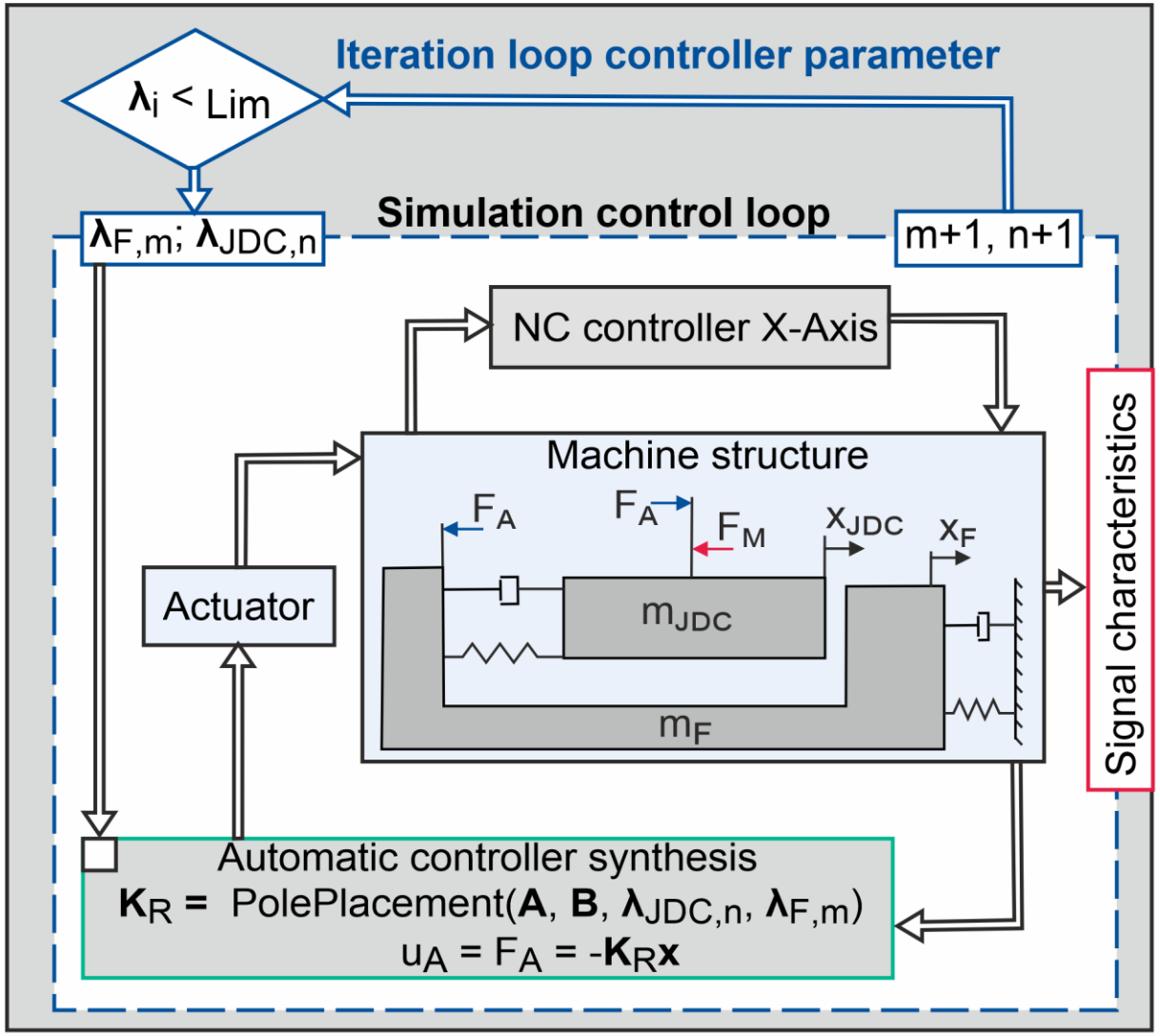
Controller parameter selection/ Requirements

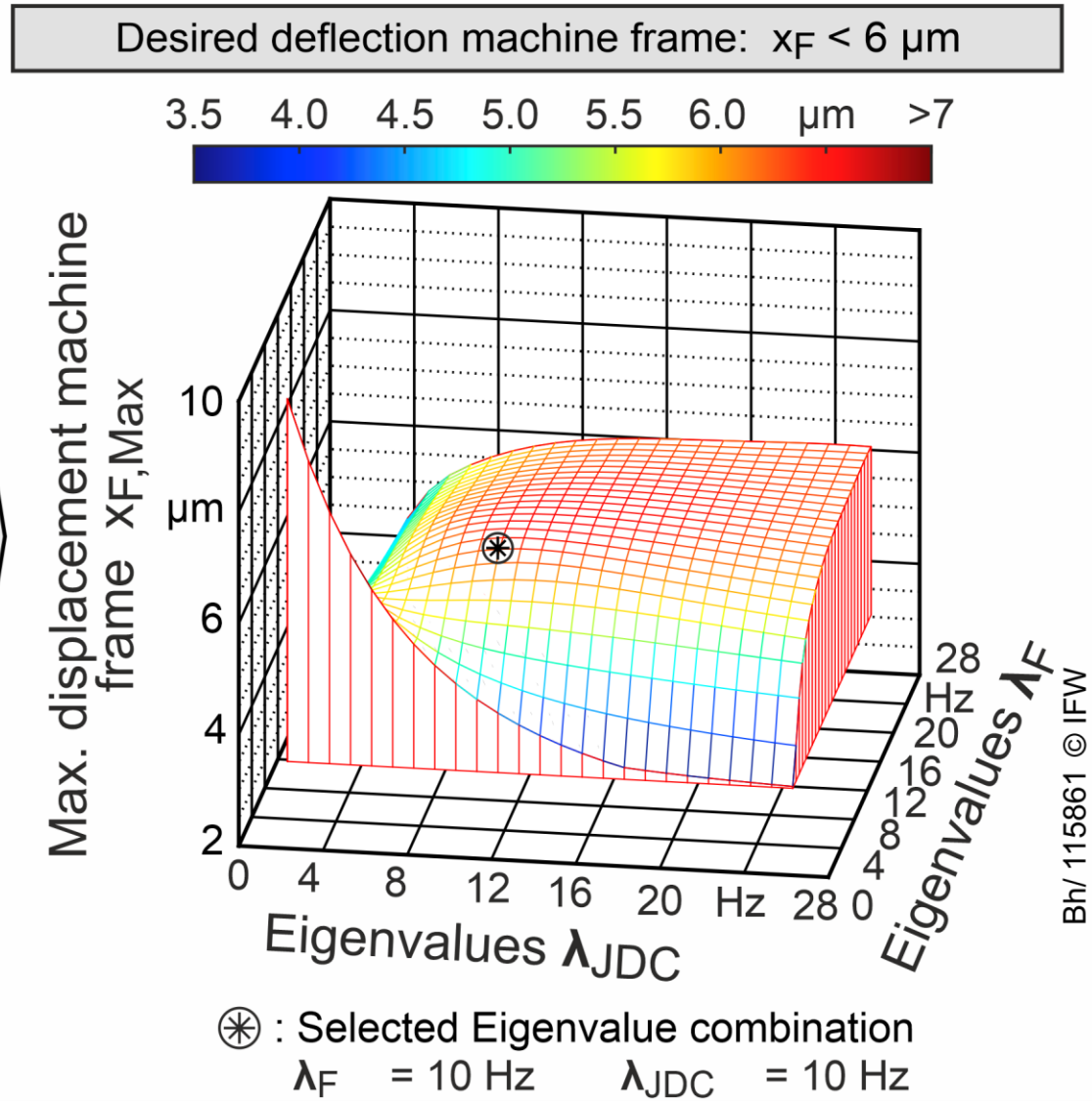




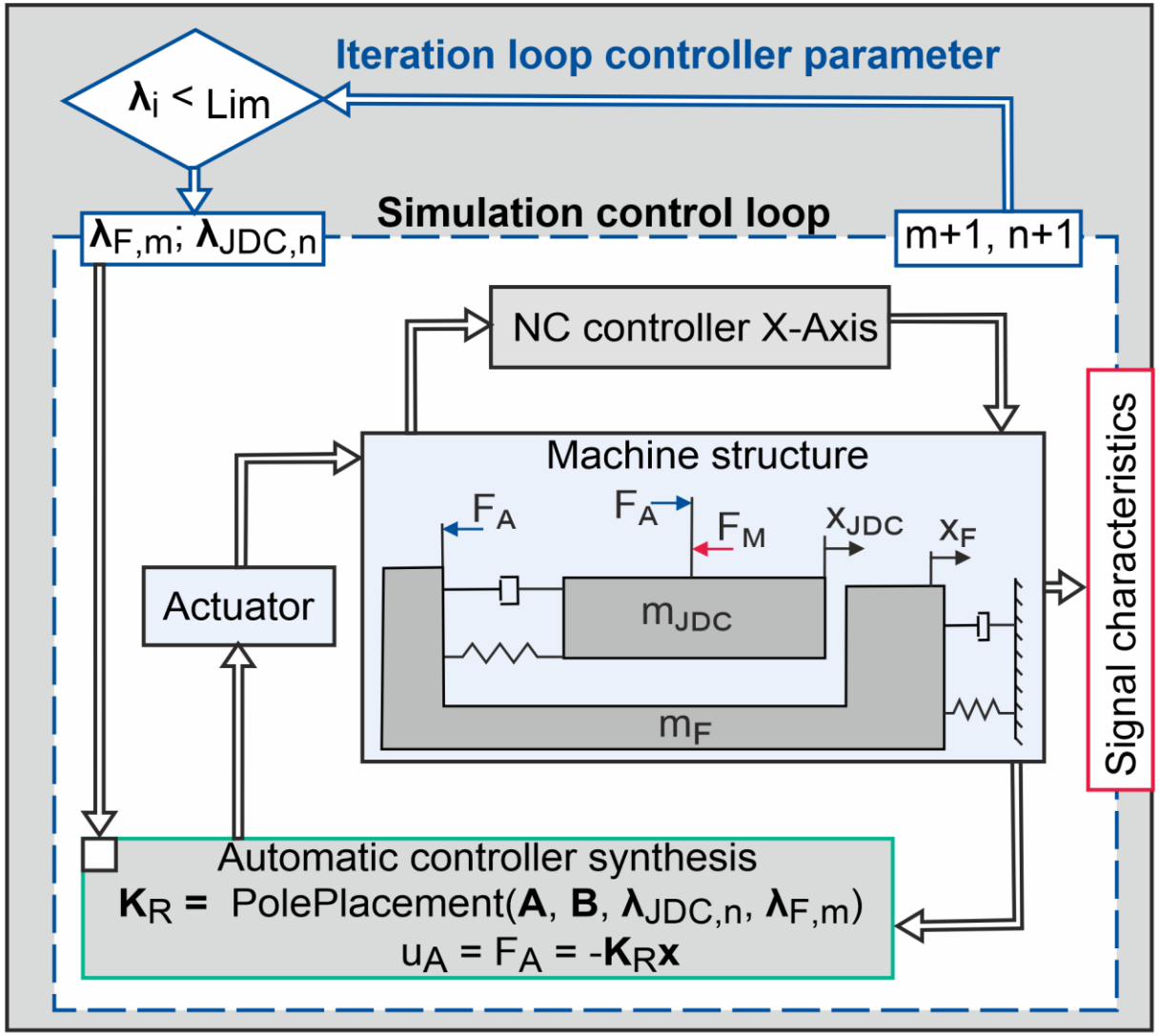
Bh/ 115859 © IFW

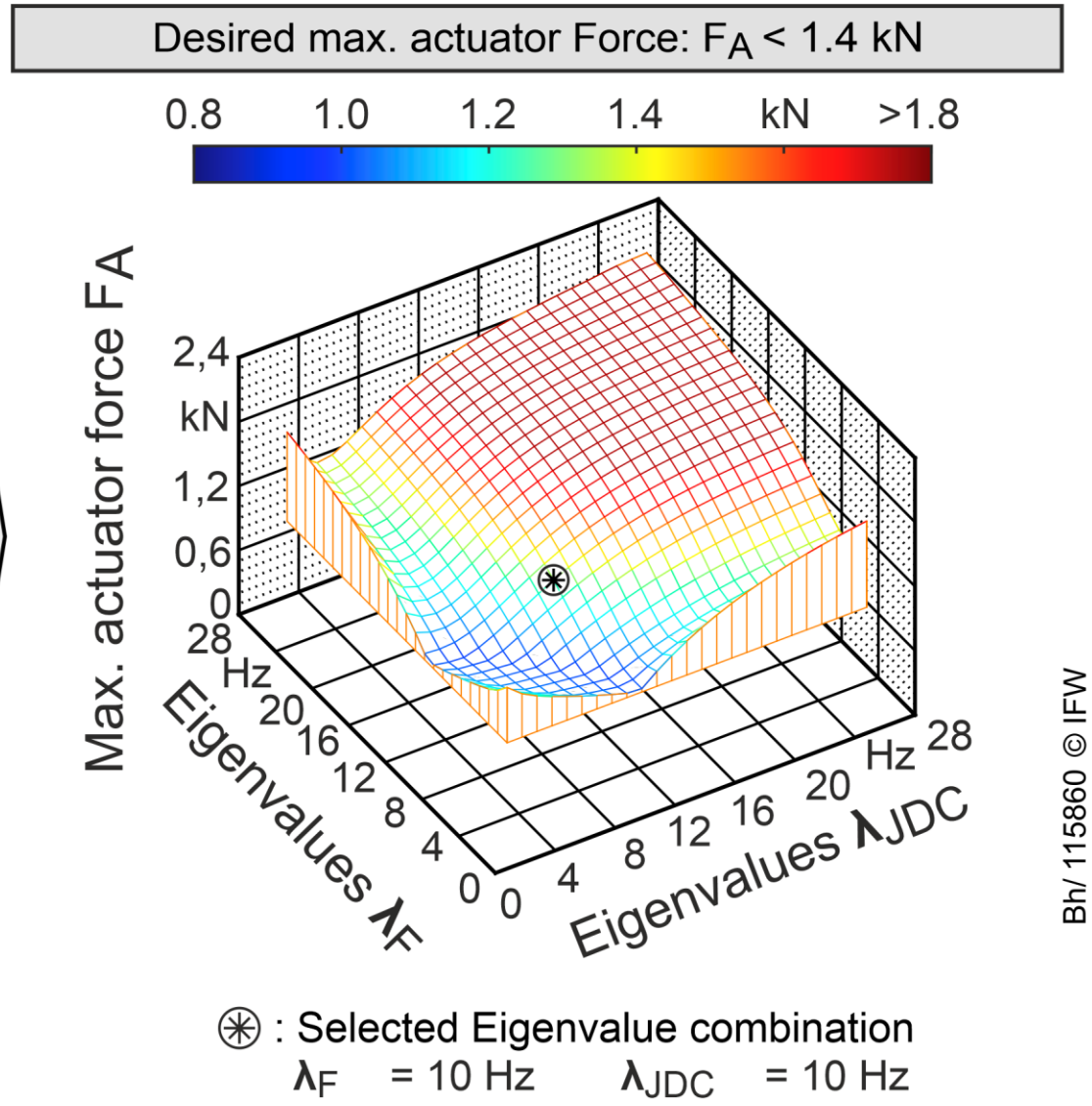
Controller parameter selection/ Requirements





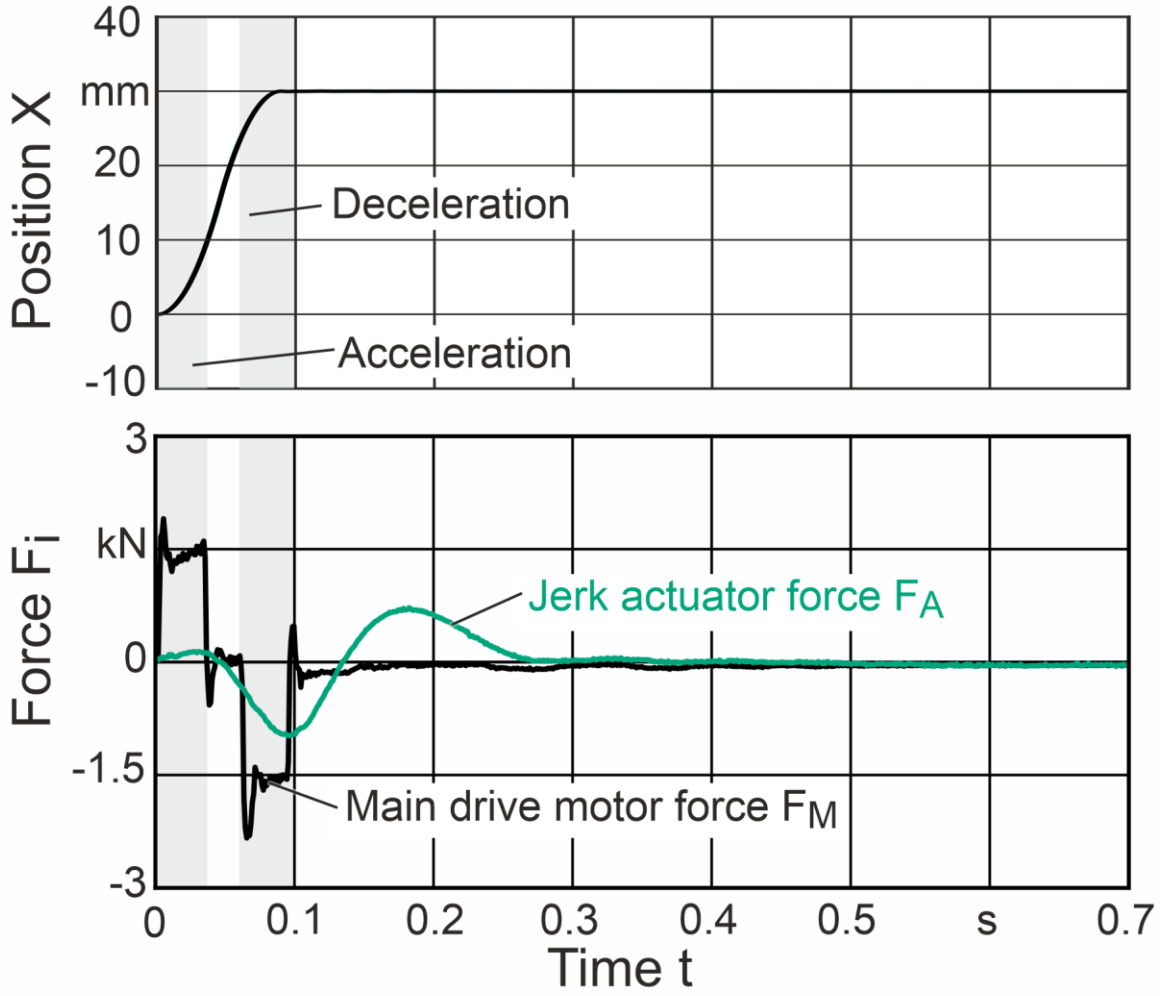
Controller parameter selection/ Requirements



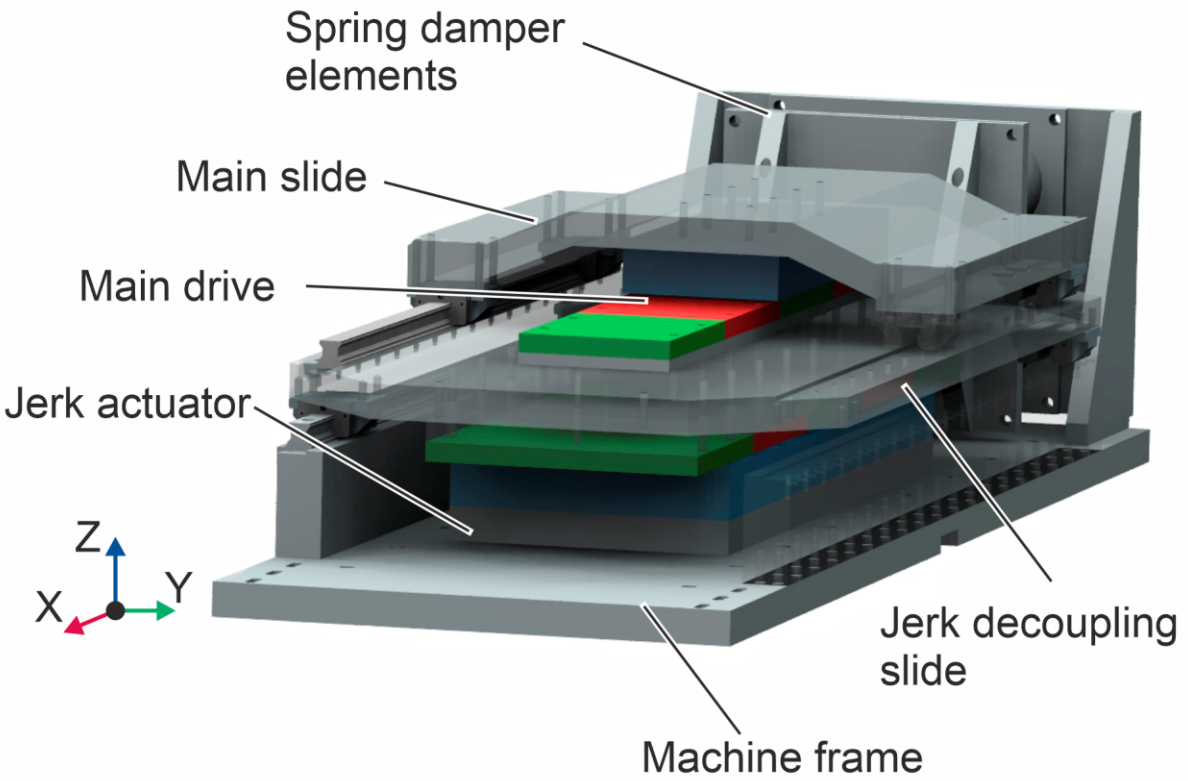


Bh/ 115860 © IFW

System behaviour by positioning step: Actuator and motor force



Active jerk decoupled direct drive

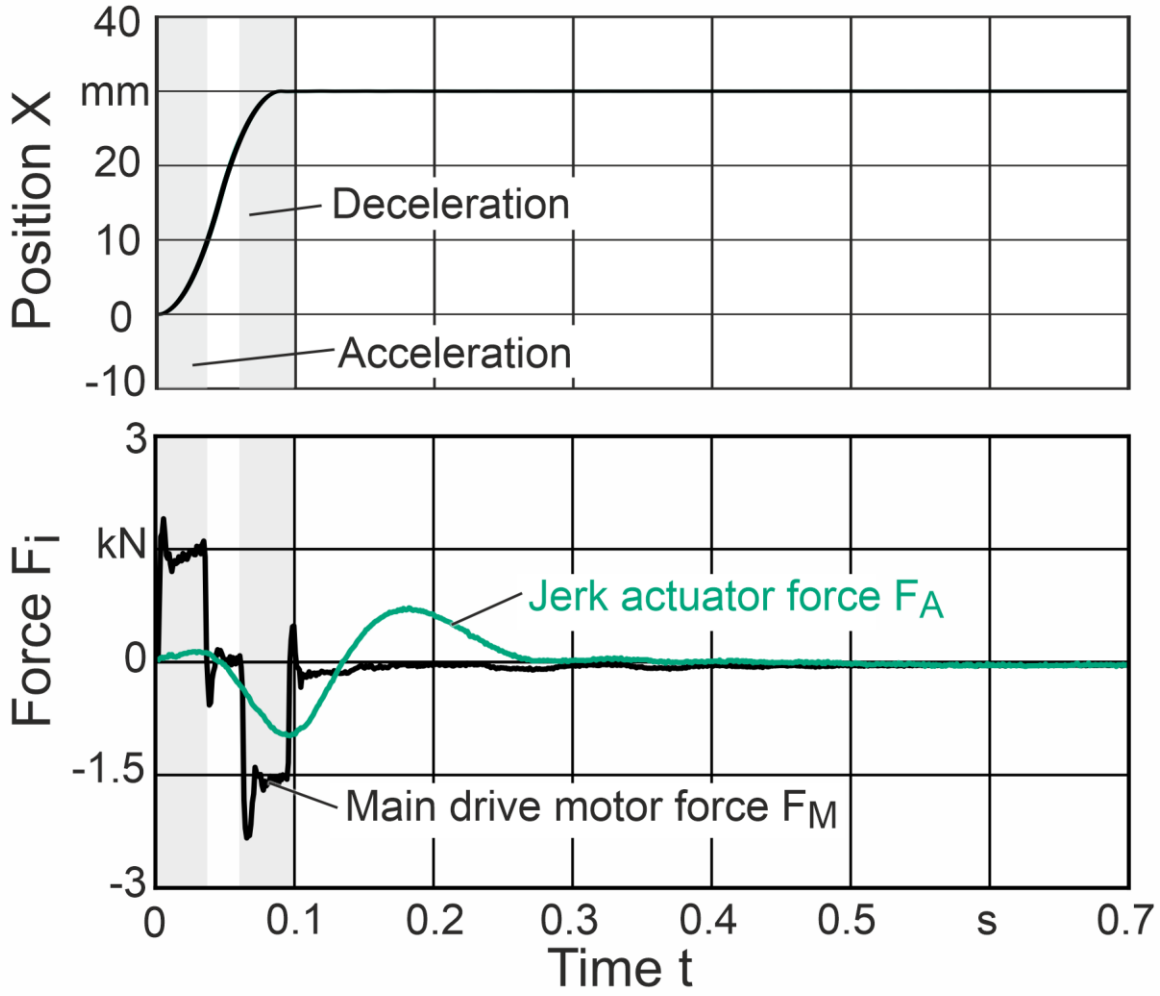


Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

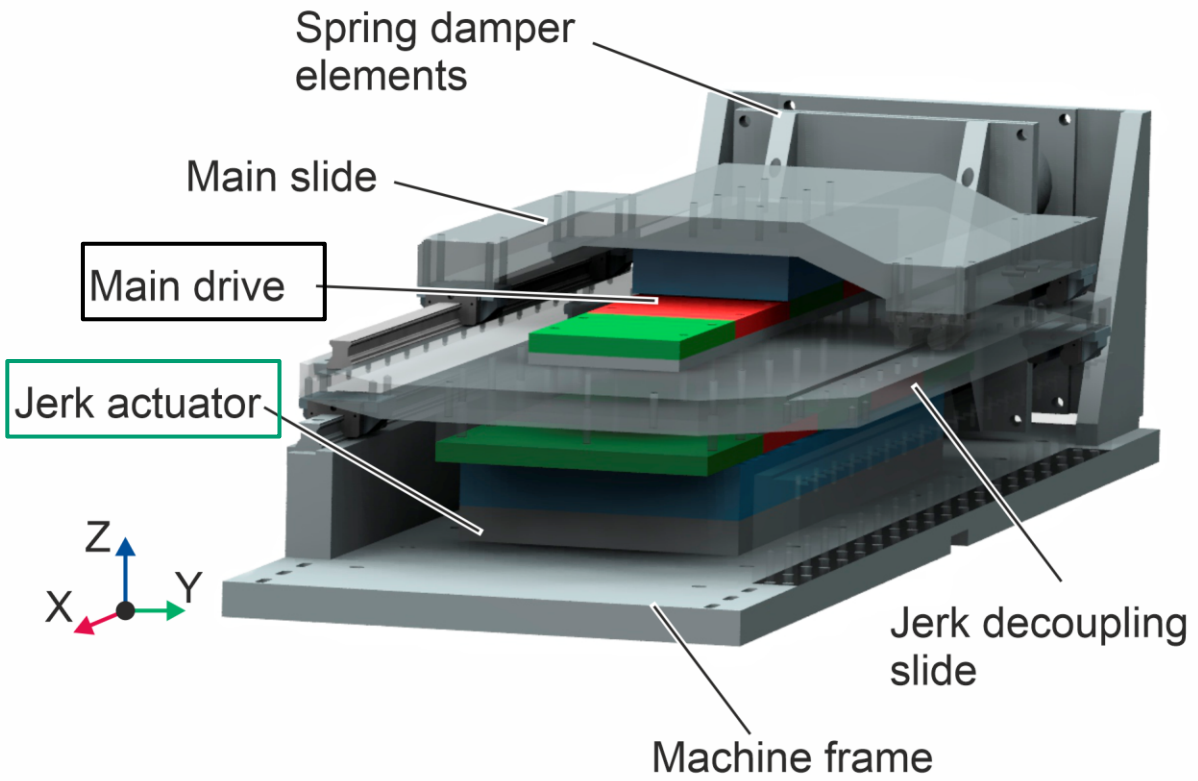
Bh/ 115862 © IFW

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

System behaviour by positioning step: Actuator and motor force



Active jerk decoupled direct drive



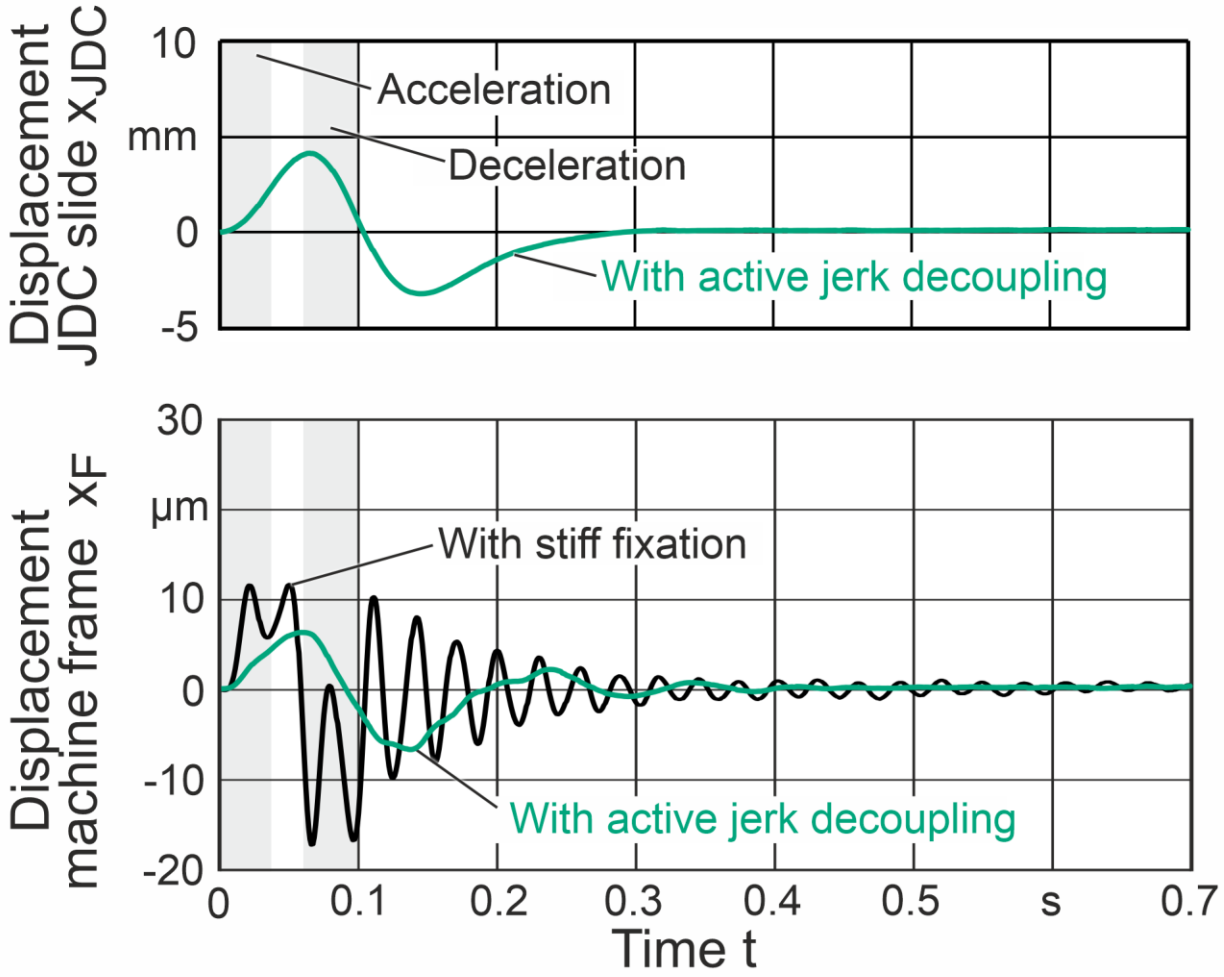
Maximum jerk: r_{max} = 45,000 m/s³
Maximum acceleration: a_{max} = 20 m/s²

Maximum velocity: v_{max} = 1 m/s
Positioning step: X = 30 mm

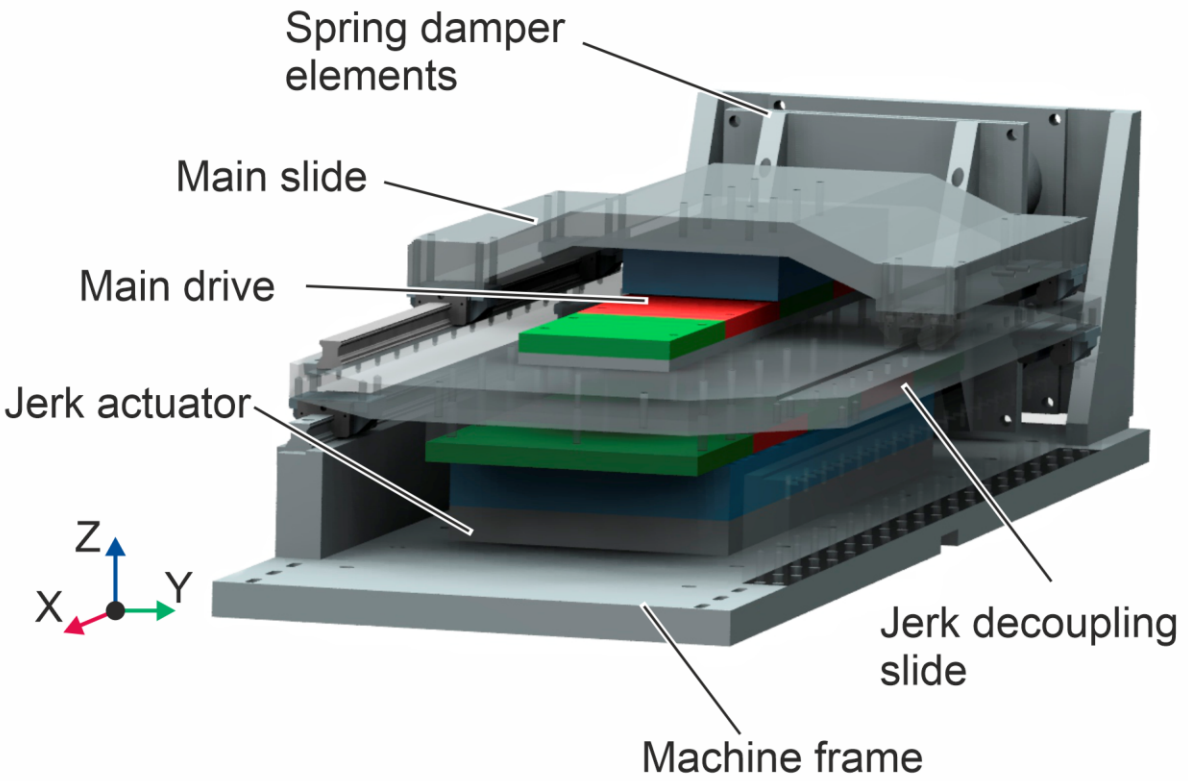
Bh/ 115862 © IFW

System behaviour by positioning step: Deflection of JDC slide and machine frame

IFW
Institut für Fertigungstechnik
und Werkzeugmaschinen



Active jerk decoupled direct drive



Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

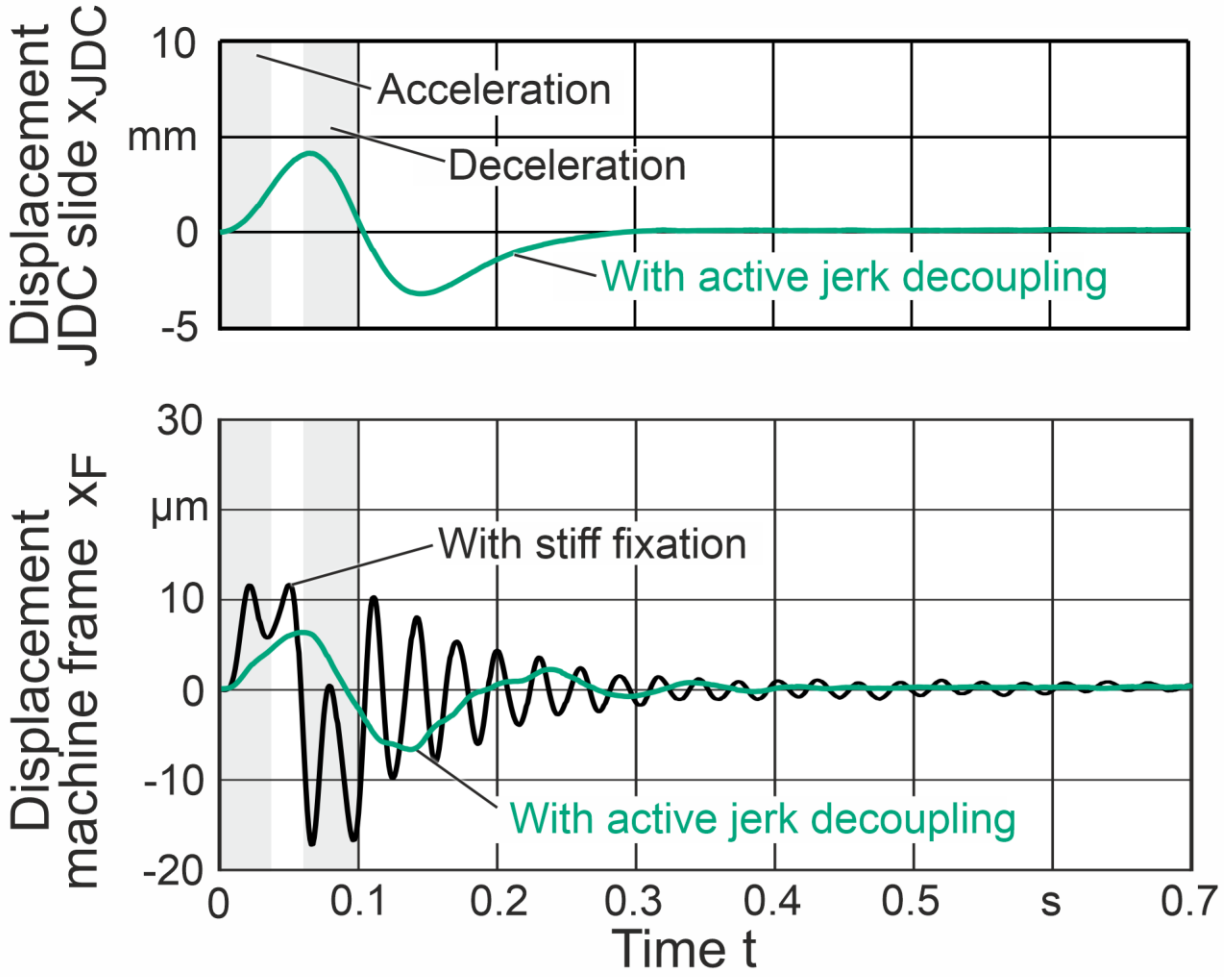
Bh/ 115863 © IFW

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

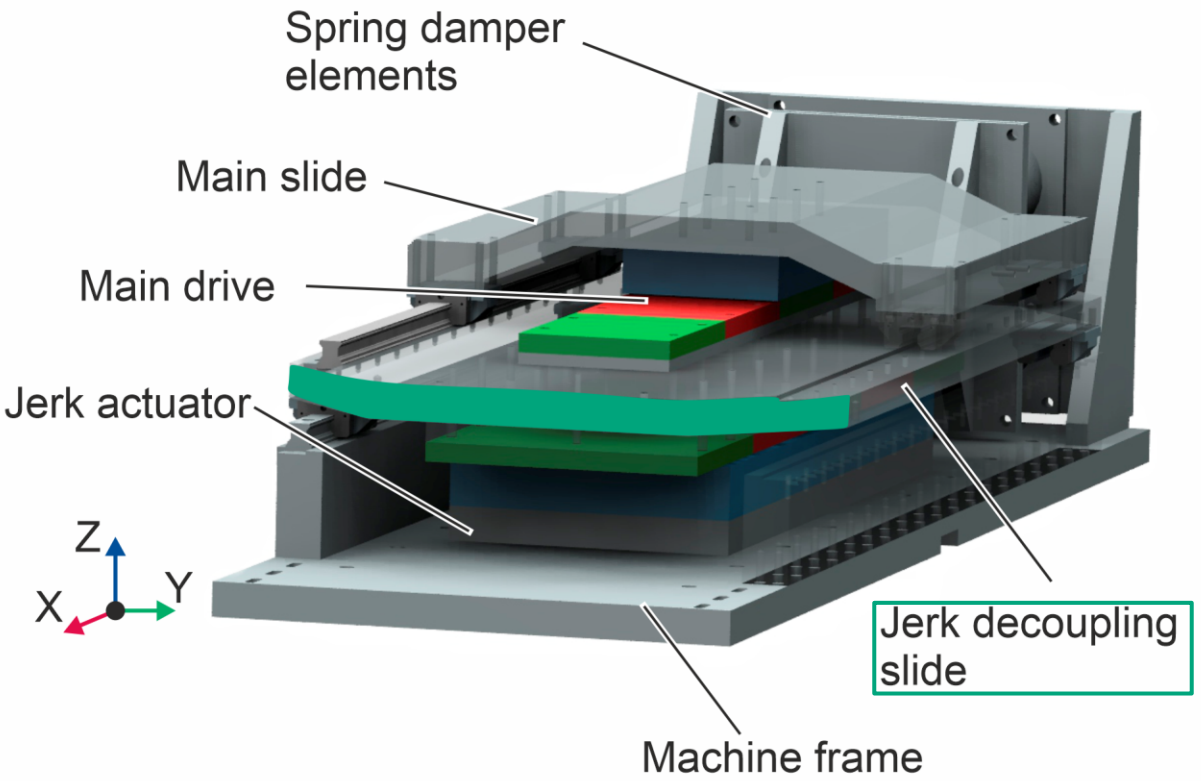
Leibniz Universität Hannover
Produktionstechnisches Zentrum Hannover

System behaviour by positioning step: Deflection of JDC slide and machine frame

IFW
Institut für Fertigungstechnik
und Werkzeugmaschinen



Active jerk decoupled direct drive



Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

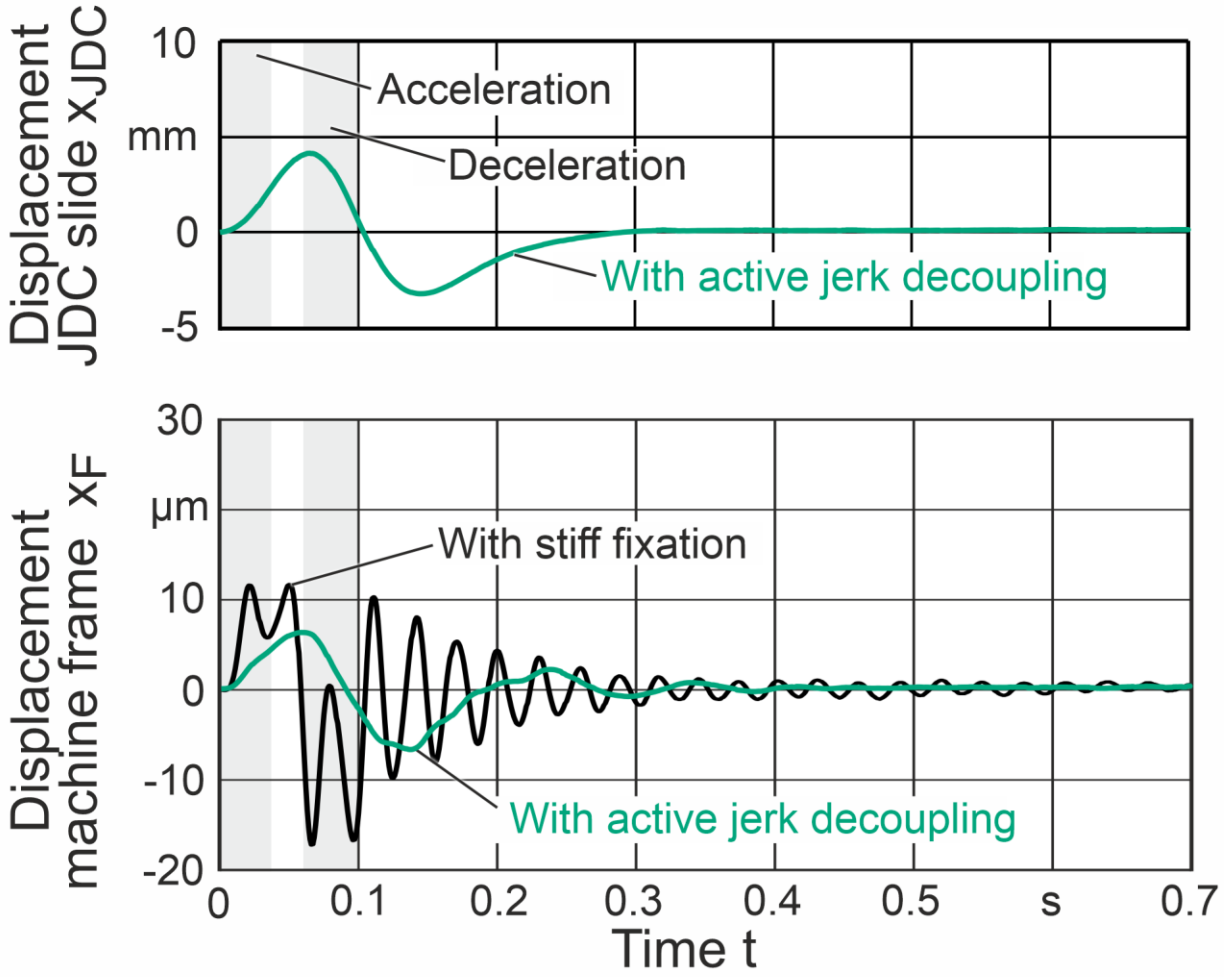
Bh/ 115863 © IFW

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

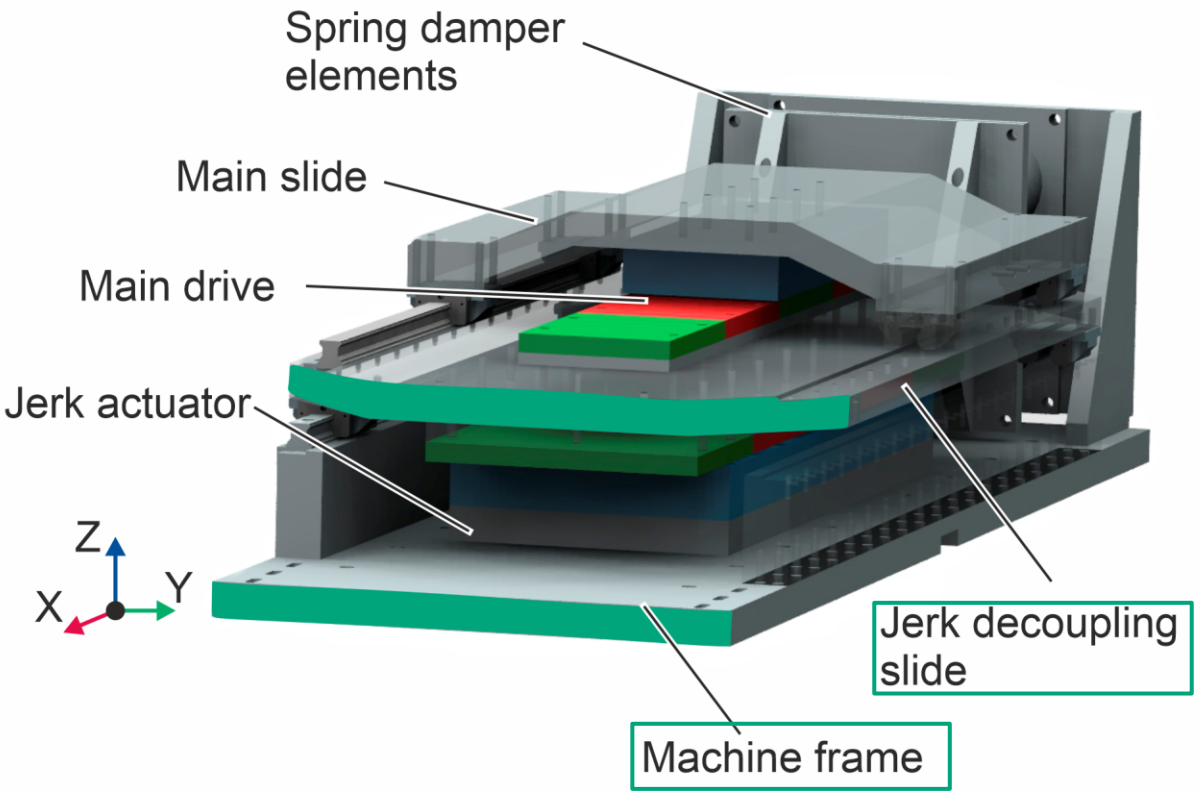
Leibniz Universität Hannover
Produktionstechnisches Zentrum Hannover

System behaviour by positioning step: Deflection of JDC slide and machine frame

IFW
Institut für Fertigungstechnik
und Werkzeugmaschinen



Active jerk decoupled direct drive



Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

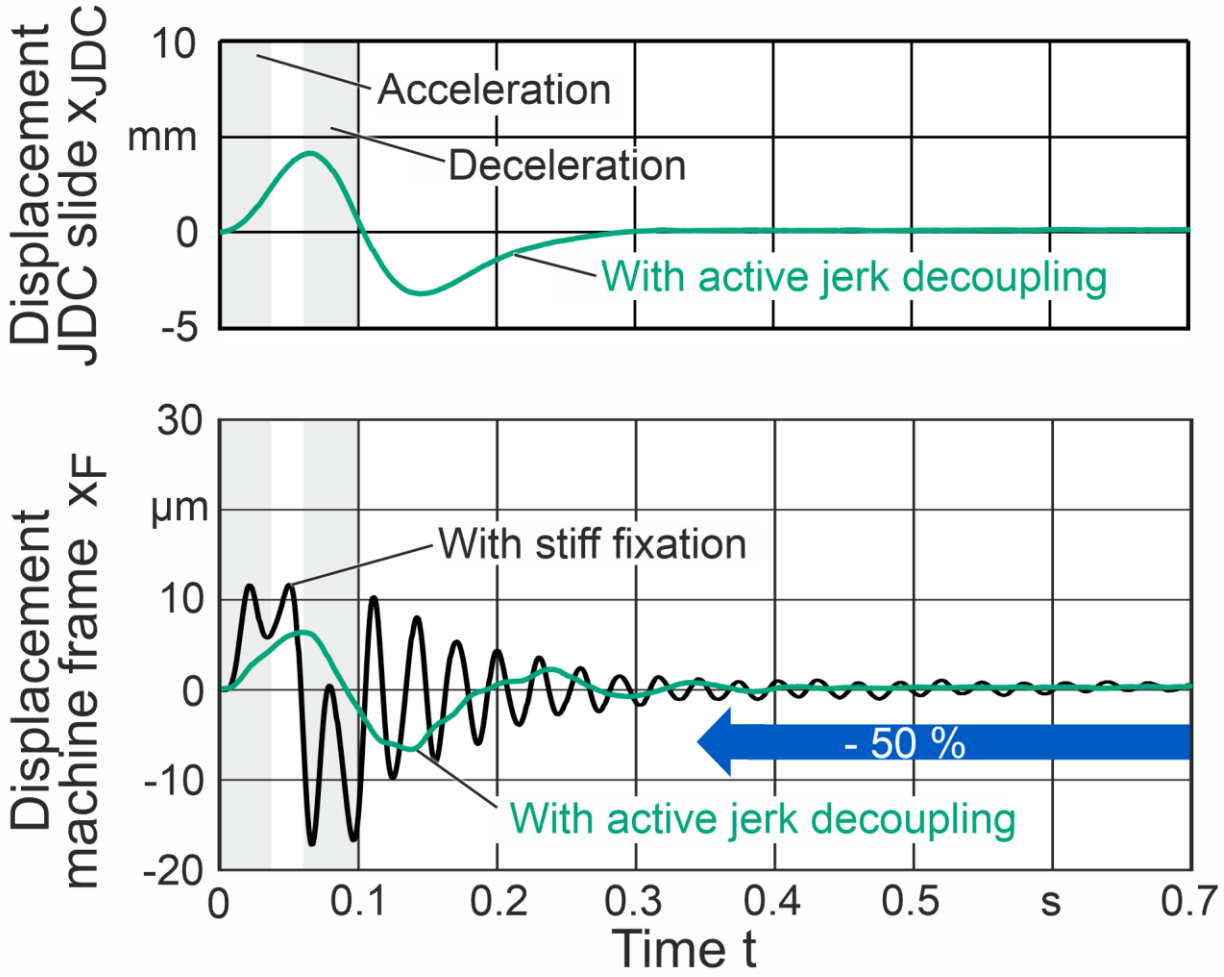
Bh/ 115863 © IFW

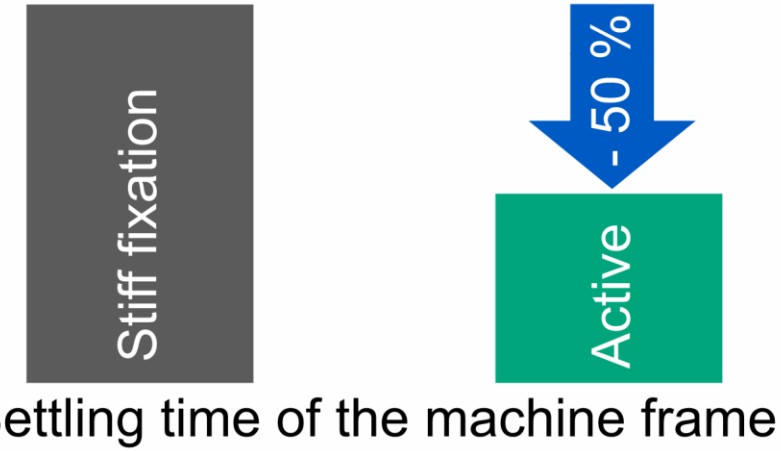
© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Leibniz Universität Hannover
Produktionstechnisches Zentrum Hannover

System behaviour by positioning step: Deflection of JDC slide and machine frame

IFW
Institut für Fertigungstechnik
und Werkzeugmaschinen





Settling time of the machine frame

Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

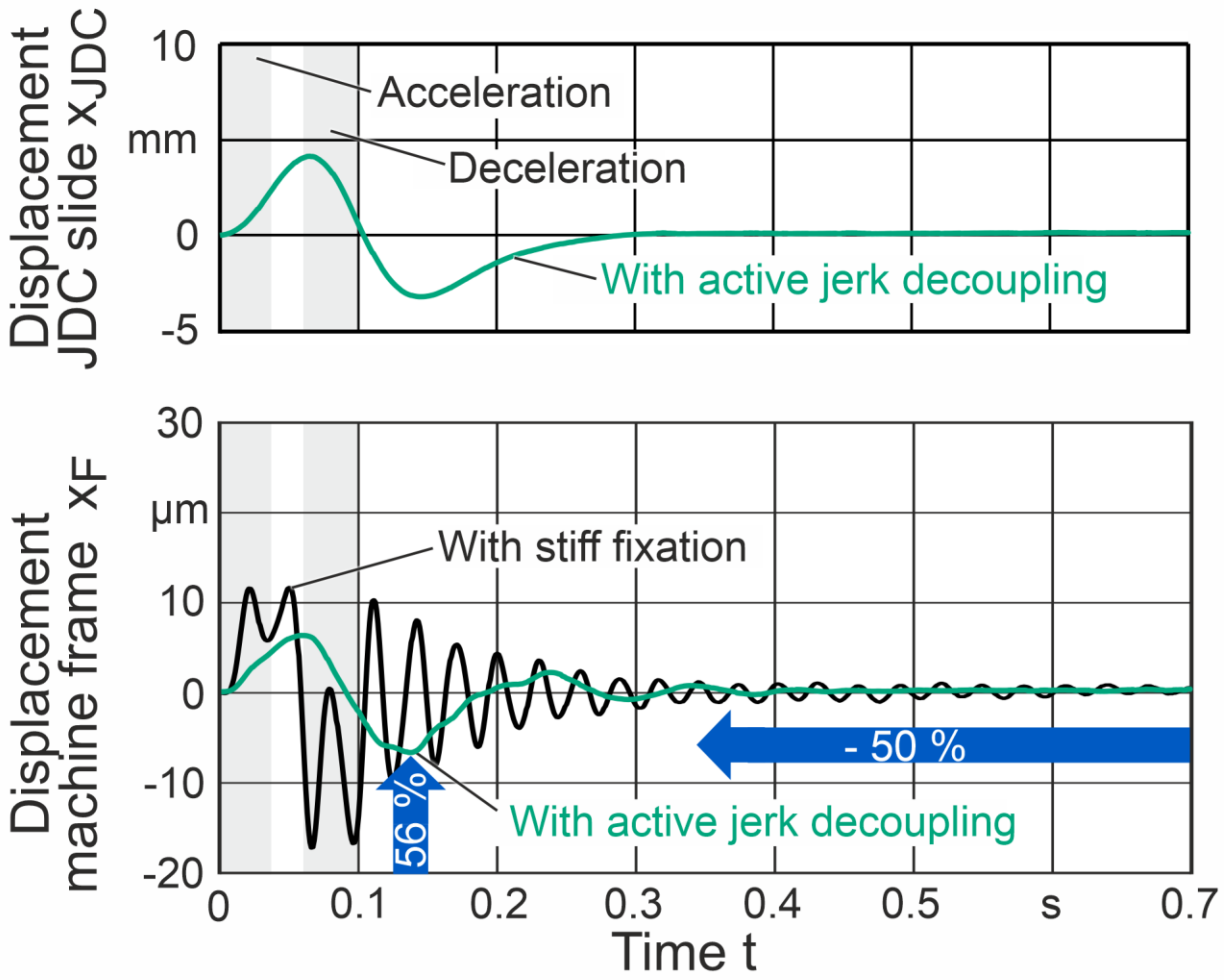
Bh/ 115863 © IFW

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Leibniz Universität Hannover
Produktionstechnisches Zentrum Hannover

System behaviour by positioning step: Deflection of JDC slide and machine frame

IFW
Institut für Fertigungstechnik und Werkzeugmaschinen



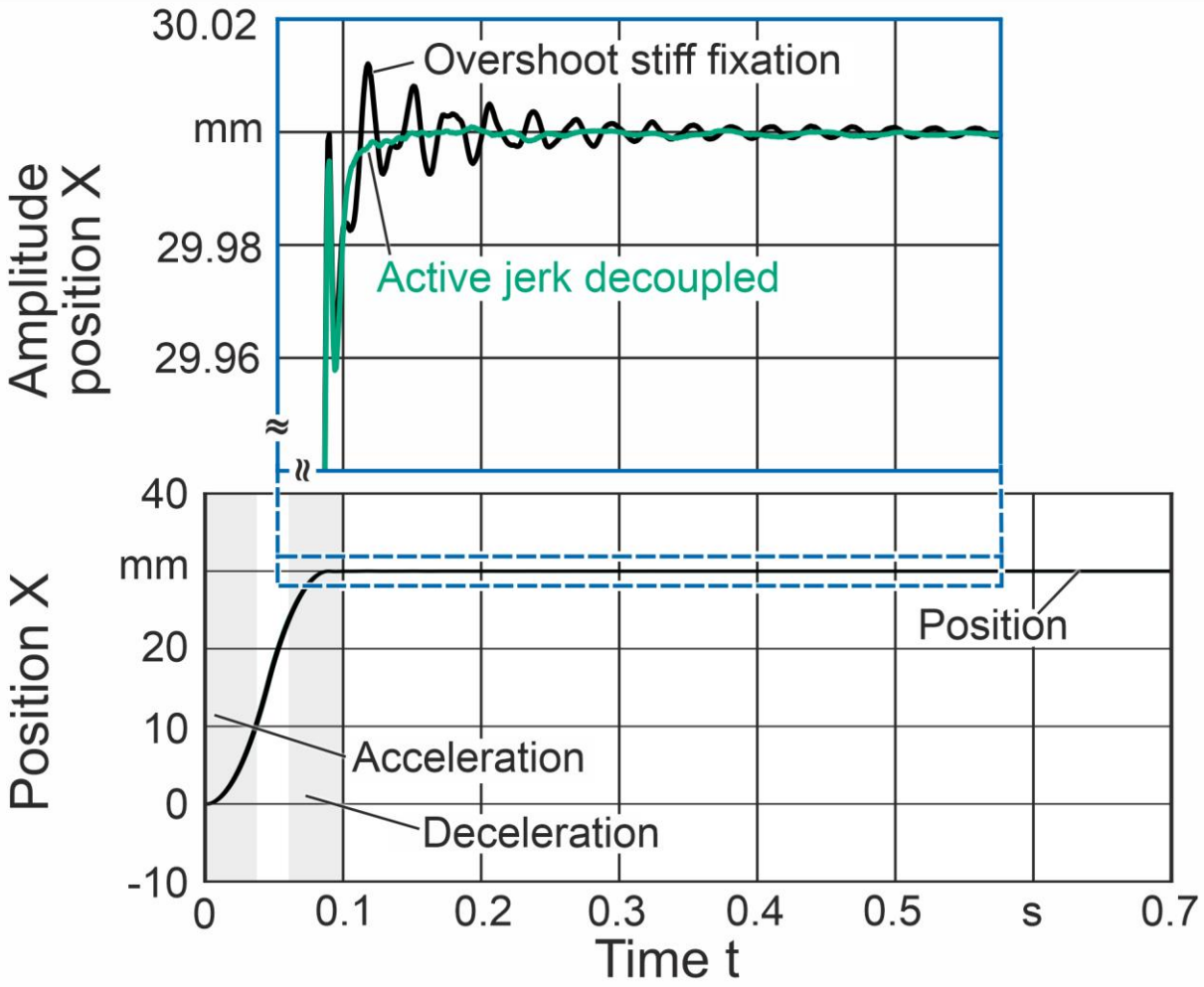
Settling time of the machine frame

Max. Displacement of the machine frame

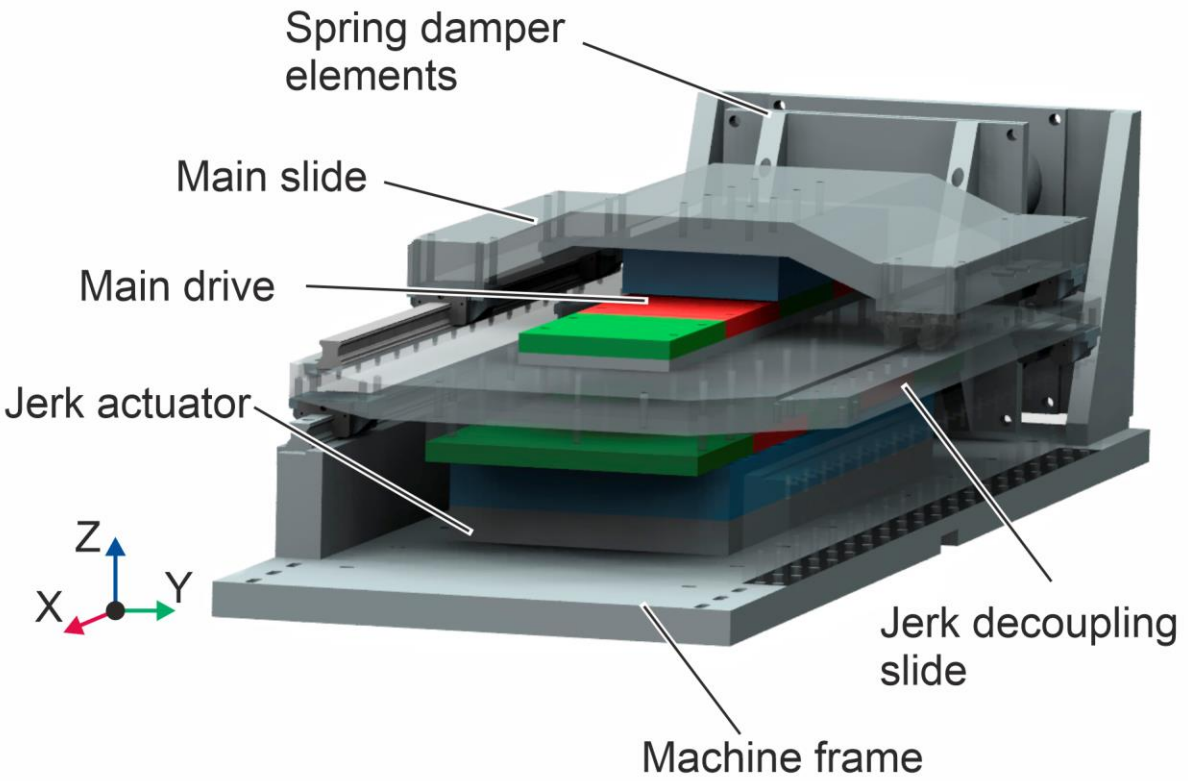
Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

Bh/ 115863 © IFW

System behaviour by positioning step: Positioning accuracy



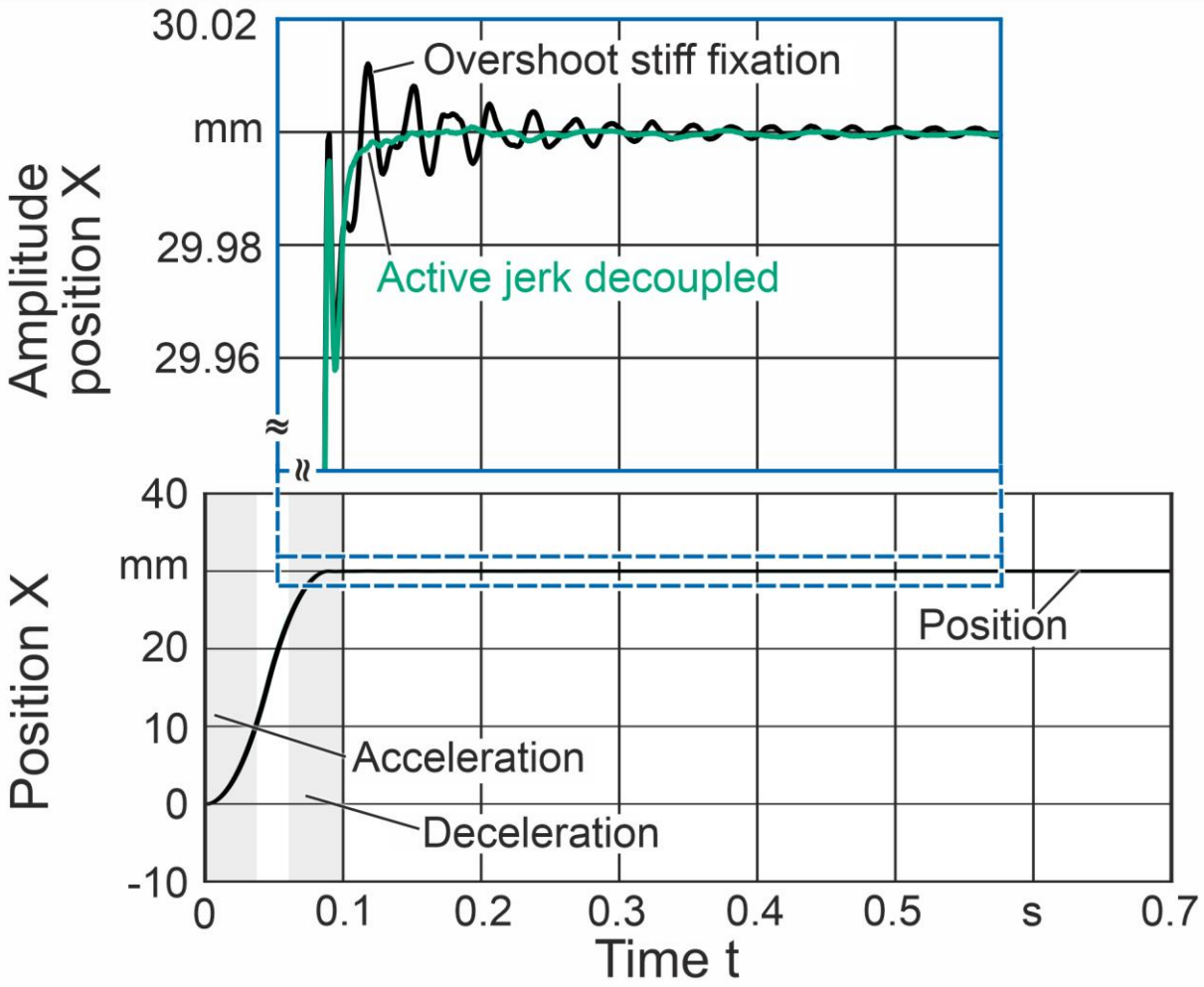
Active jerk decoupled direct drive



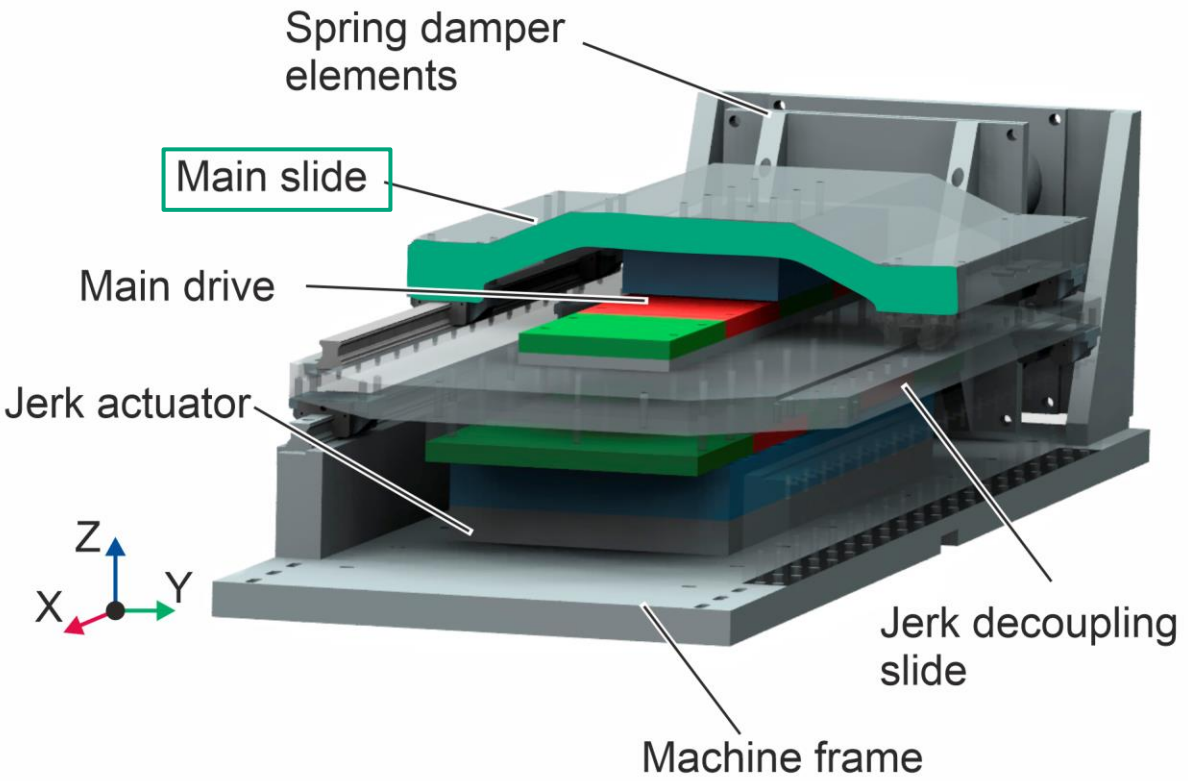
Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

Bh/ 115864 © IFW

System behaviour by positioning step: Positioning accuracy



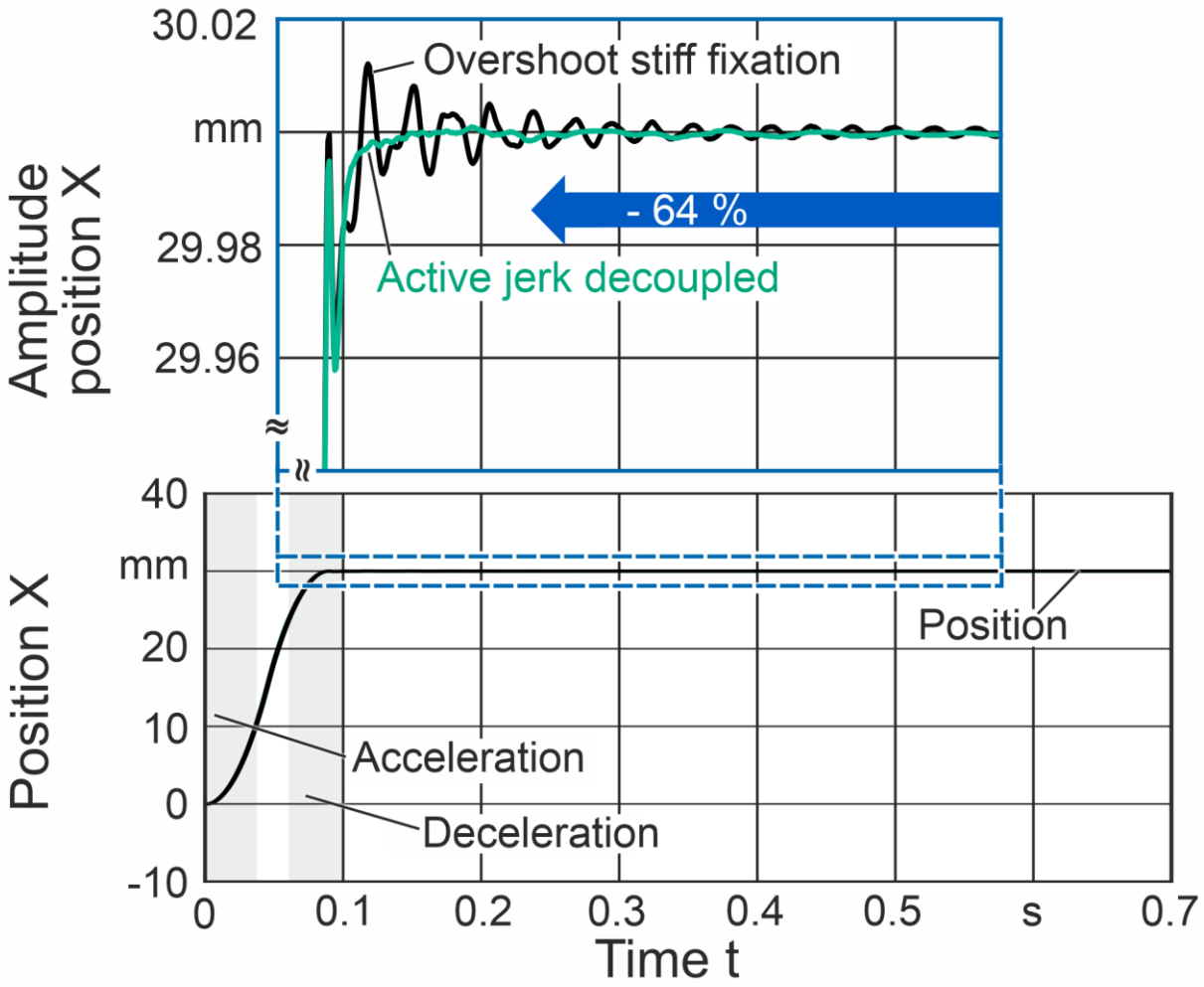
Active jerk decoupled direct drive



Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

Bh/ 115864 © IFW

System behaviour by positioning step: Positioning accuracy

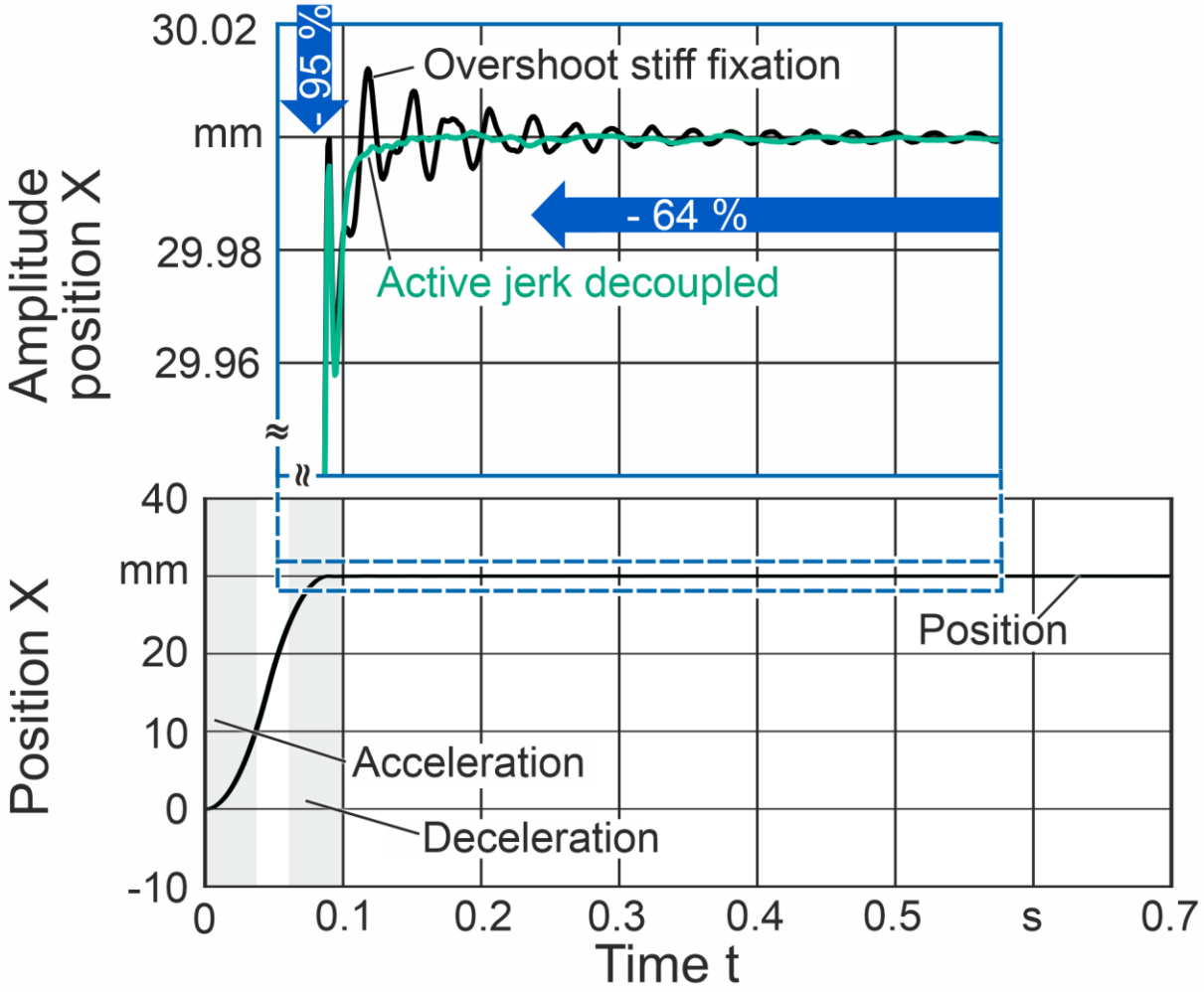


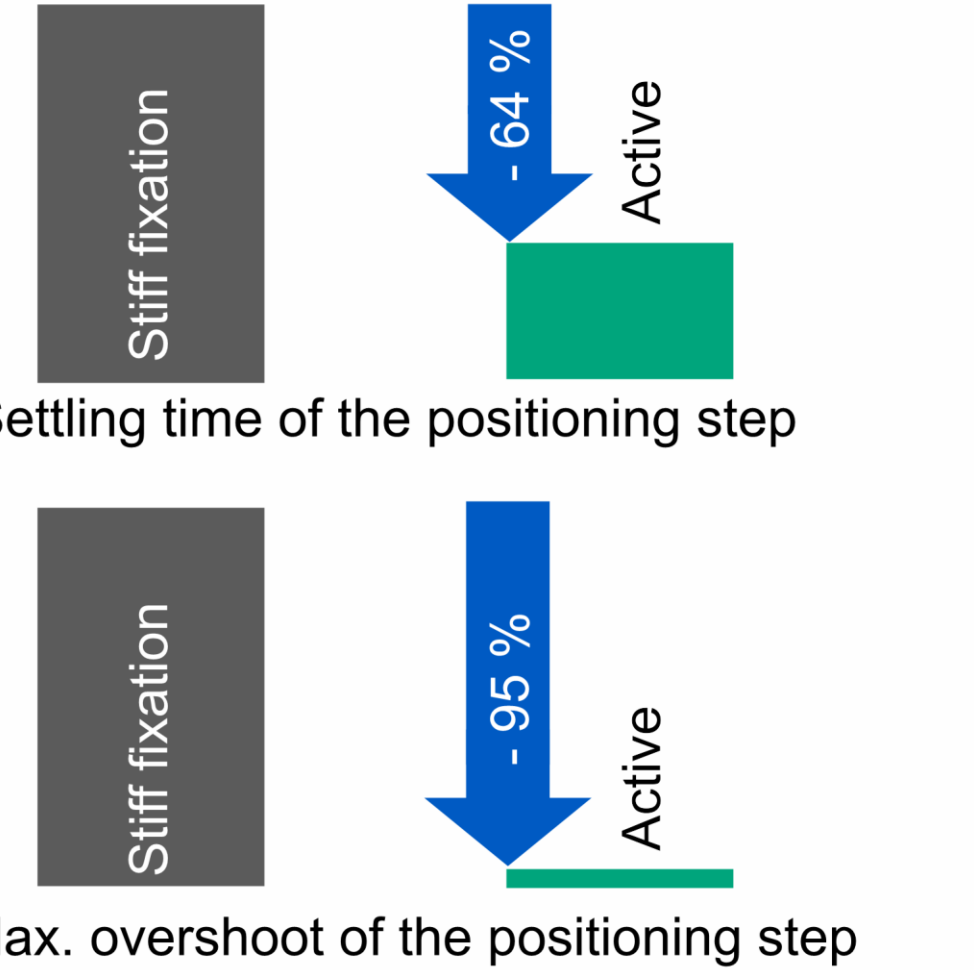
Settling time of the positioning step

Maximum jerk:	r_{max}	= 45,000 m/s³	Maximum velocity:	v_{max}	= 1 m/s
Maximum acceleration:	a_{max}	= 20 m/s²	Positioning step:	X	= 30 mm

Bh/ 115864 © IFW

System behaviour by positioning step: Positioning accuracy

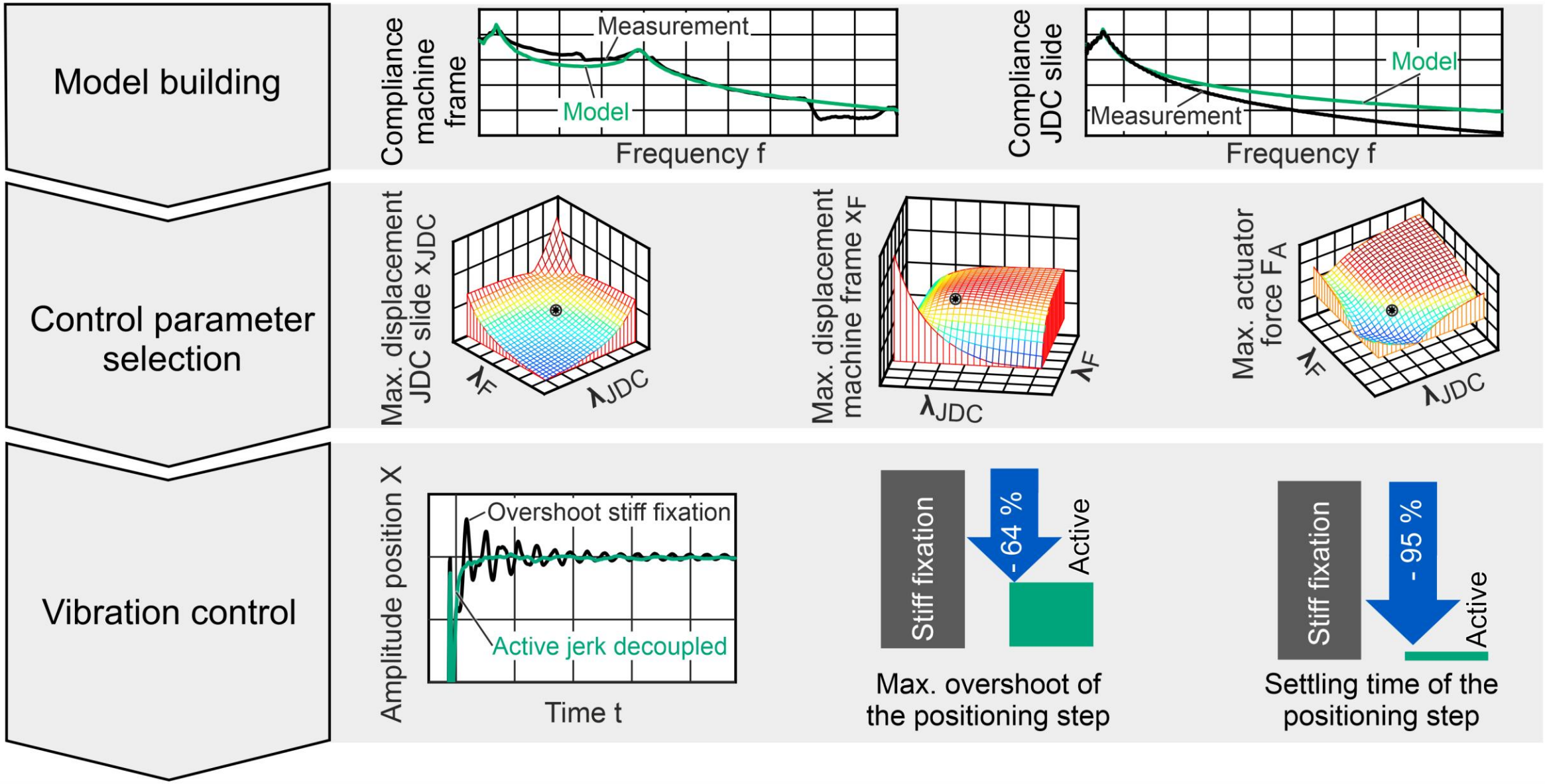




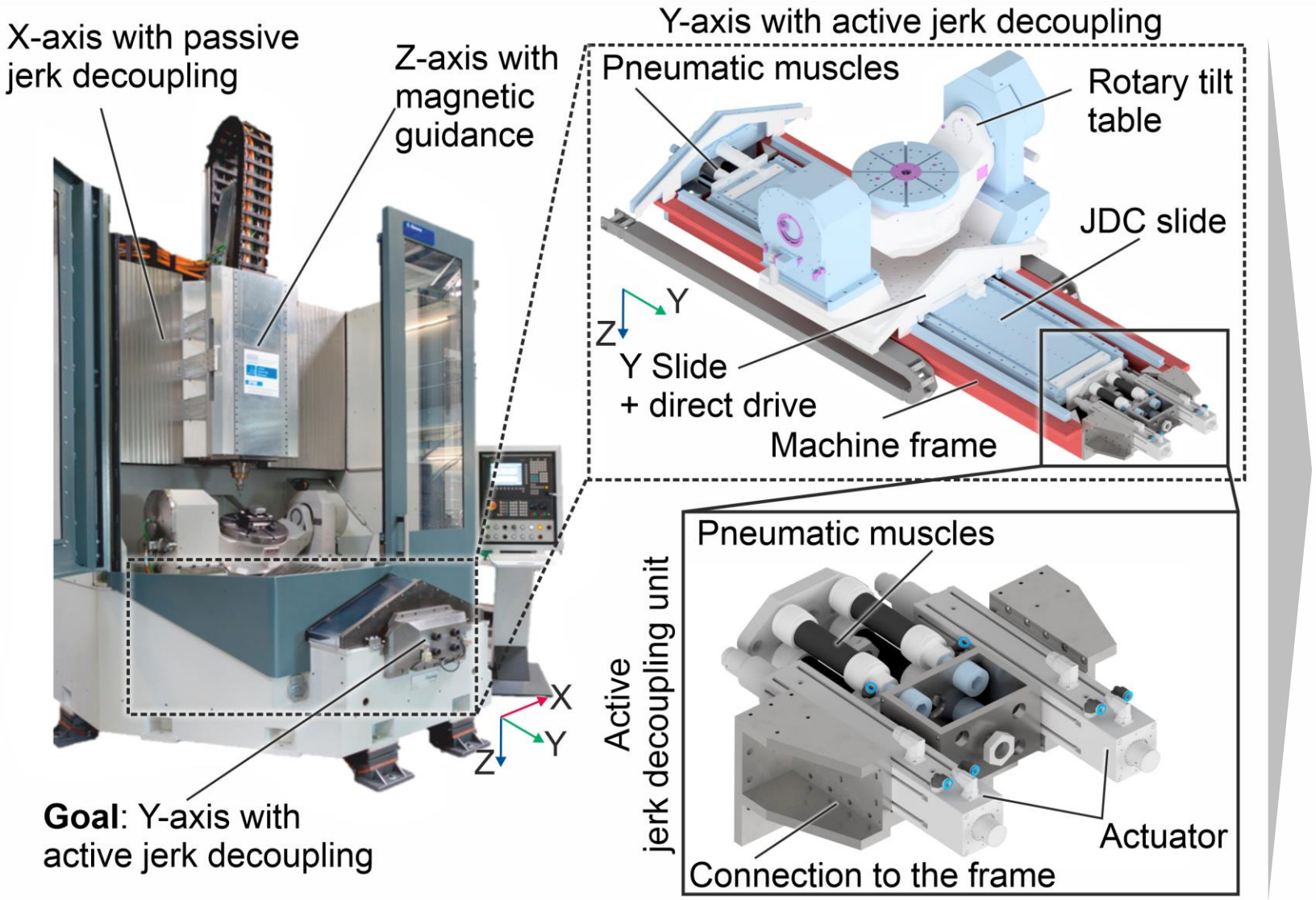
Maximum jerk: r_{max} = 45,000 m/s³
Maximum acceleration: a_{max} = 20 m/s²
Maximum velocity: v_{max} = 1 m/s
Positioning step: X = 30 mm

Bh/ 115864 © IFW

Conclusion


Model building
Compliance machine frame
Measurement
Model
Frequency f
Compliance JDC slide
Model
Measurement
Frequency f
Control parameter selection
Max. displacement JDC slide xJDC
λF
λJDC
Max. displacement machine frame xF
λJDC
λF
Max. actuator force FA
λF
λJDC
Vibration control
Amplitude position X
Overshoot stiff fixation
Active jerk decoupled
Time t
Stiff fixation
- 64 %
Active
Max. overshoot of the positioning step
Stiff fixation
- 95 %
Active
Settling time of the positioning step

Outlook



- **Increase in machining accuracy and workpiece quality**
- **Decrease the processing time**

Bh/ 115866 © IFW

IFW – Your partner for production engineering

IFW
Institut für Fertigungstechnik
und Werkzeugmaschinen

Institute of Production Engineering
and Machine Tools (IFW)

Centre for Production Technology

Leibniz Universität Hannover

An der Universität 2, 30823 Garbsen

http://www.ifw.uni-hannover.de

M.Sc. Marcel-Frederic Böhse

tel. +49 511 762-18311

fax. +49 511 762-5115

boehse@ifw.uni-hannover.de

© Leibniz Universität Hannover, IFW, Prof. Dr.-Ing. Berend Denkena

Leibniz Universität Hannover

Produktionstechnisches Zentrum Hannover