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Seminar | Vibrations in nuclear applications | Stockholm | 10. November 2022

Digital Twin for torsional vibrations of power trains

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Fraunhofer-Institute for Structural Durability and System Reliability LBF

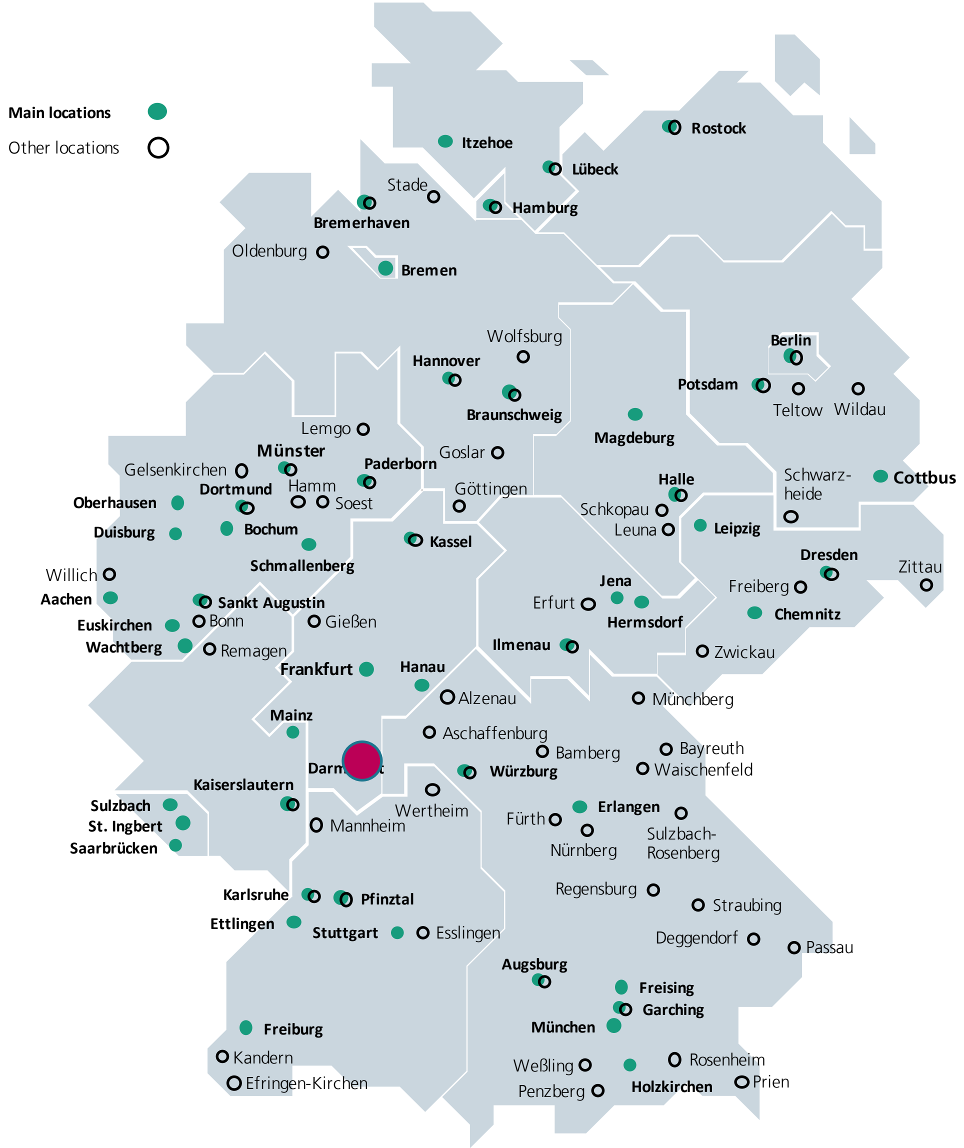
Fraunhofer-Gesellschaft

Locations in Germany

76 institutes and research units

30,000 staff

€ 2.9 bn research volume



Fraunhofer-Gesellschaft

Lead market-oriented Fraunhofer Alliances – Bundling expertise through networking

Institutes or departments of institutes with different areas of expertise work together in Fraunhofer Alliances in order to develop and market solutions for a specific lead market.

- Plant, mechanical and vehicle engineering
- Health care sector
- Digital economy
- Construction industry
- Mobility sector
- Chemical industry
- Energy sector
- Food industry
- Aerospace industry

  - Informationsklassifizierung -

Fraunhofer-Institute for Structural Durability and System Reliability LBF

Fraunhofer LBF

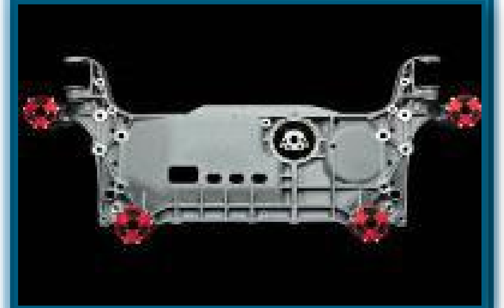
Director: Prof. Tobias Melz

Structural Durability

(Dr. Bleicher)

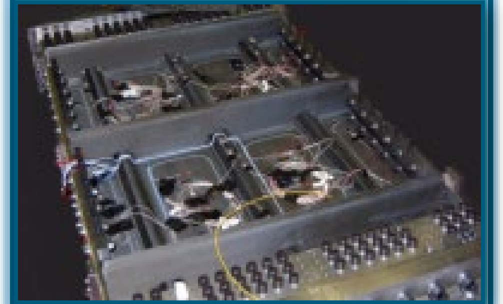
Smart Structures

(Dr. Herold)



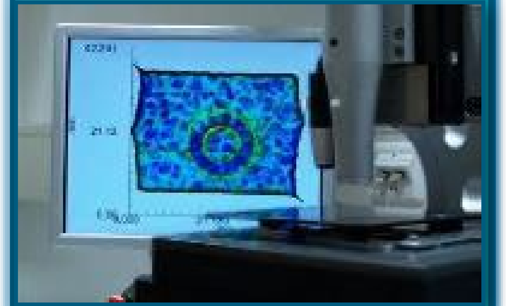
System Reliability

(Dr. Bleicher)



Plastics

(Dr. Pfaendner)



Fraunhofer-Institute for Structural Durability and System Reliability LBF

Facts and figures – Annual report 2021

Employees

- 377 at Fraunhofer LBF
- 39 at TU Darmstadt

Facilities

- Offices: ca. 6.300 m²
- Lab's: ca. 17.900 m²

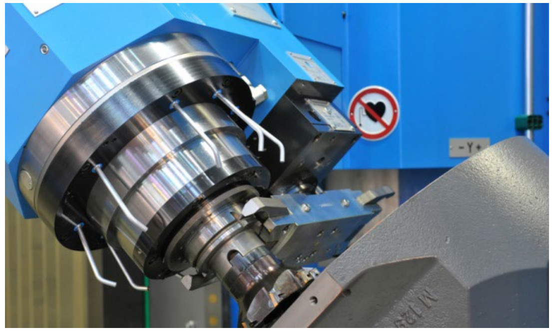
Budget

- Annual budget: 29,2 Mio €
- Budget ratio - Industry: 42,2 %

Fraunhofer-Institute for Structural Durability and System Reliability LBF

Markets

- Mobile systems
  - Automotive
  - Aerospace
  - Shipbuilding
  - Railway
- **Mechanical and plant engineering**
- **Power plant engineering**
- **Processing technology**
- Infrastructure
- Chemical industry
- Testing
- …



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Digital Twin for torsional vibrations of power trains
Outline

Introduction to Digital Twins

Lateral and torsional vibrations of power trains

Models for the design of lateral and torsional vibrations

Models used as Digital Twins for the operation

Simulations by means of the Digital Twin – On line and Off line simulations

- Monitoring
- Identification
- Life time prediction
- Passive and active vibration control measures

Digital Twin example at LBF – High Frequency Testing

Introduction to Digital Twins

What is a Digital Twin?

A **Digital Twin** is a virtual representation that serves as the real-time digital counterpart of a **physical system** or process.

Sensors measure **data** of the physical systems performance, which are relayed to a processing system and applied to a **digital copy**.

Once informed with such data, the **digital twin** can be used to run **simulations**, study **performance issues**, detect **failures** and generate possible **improvements**.

The goal is to generate valuable **insights**, which can be applied back to the original **physical system** or process

Introduction to Digital Twins

Application in the life cycle of a product

Development: Model-based assessment and optimization

Raw Material: Documentation and tracking of sources

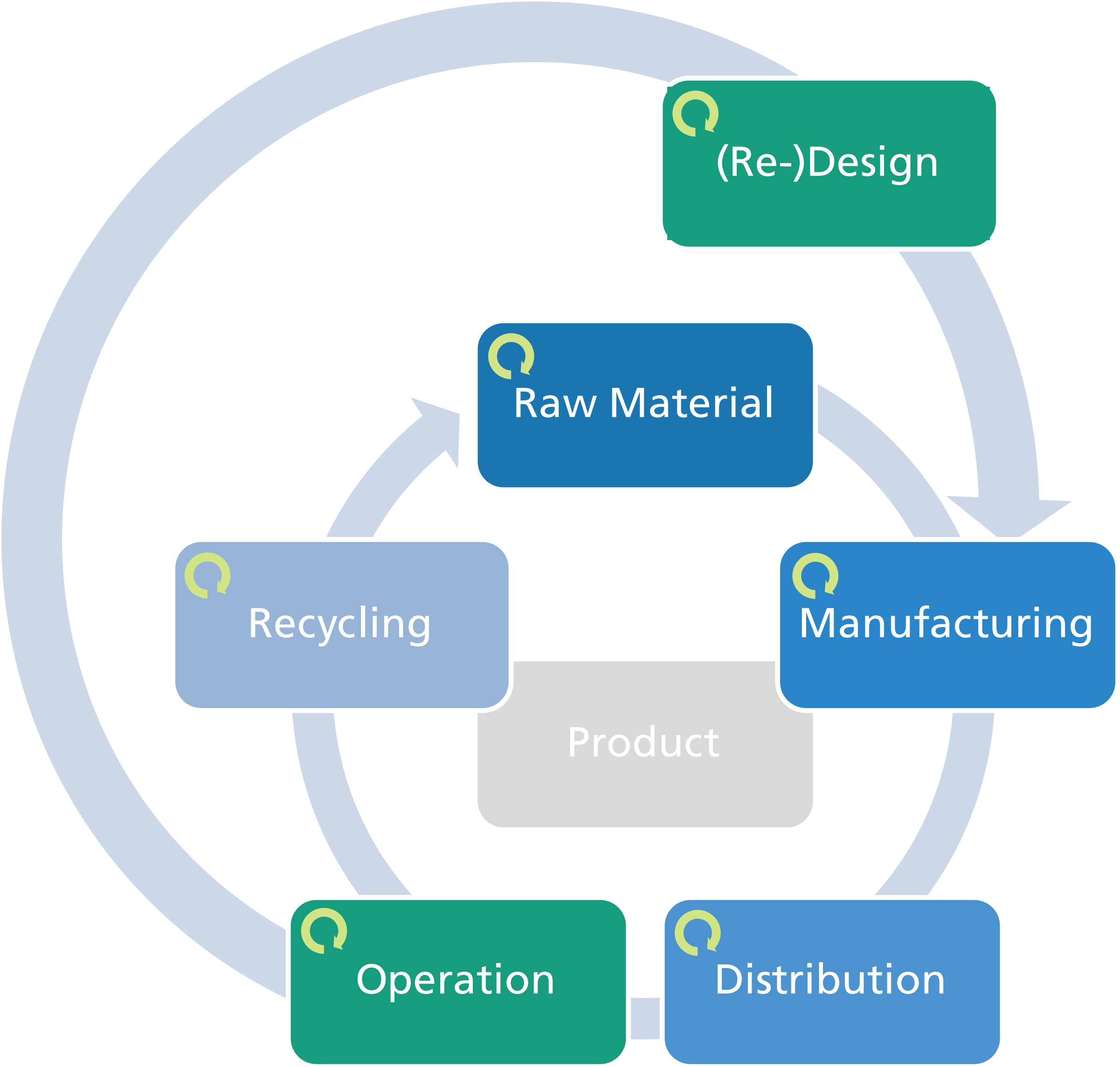
Manufacturing: Process monitoring, quality assurance

Distribution: Sales optimization, track and trace

Operation/Utilization: Data acquisition, operational optimization, predictive maintenance

Disposal/Recycling: Tracking of resources and remains

Re-Development: Usage-based design optimization



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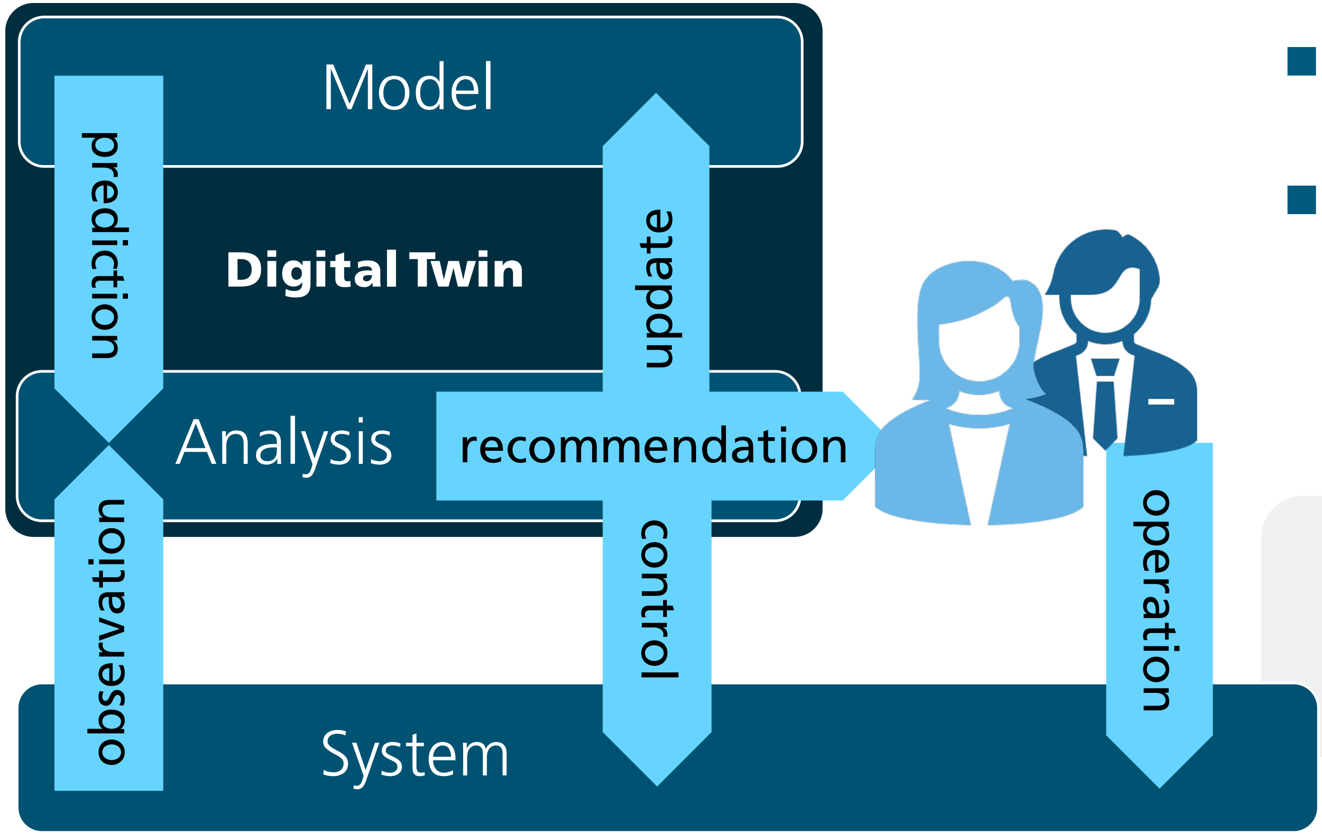
Introduction to Digital Twins
Application for a system at operation

Critical system:



- Digital Twin receives operational conditions and sensor data from the system: Observation
- Behaviour model predicts expected state and behaviour of the system: Prediction
- Based on the deviation between prediction and observation:
  - Update behaviour model, identify system state or operational condition
  - Send signal for active system control
  - Prepare information and recommend activity to experts

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Application: Lateral and torsional vibrations of power trains

Mechanics and other different disciplines of physics

Disciplines: **Thermodynamics** **Mechanics** **Electrodynamics**

- Mechanics
  - Stresses, Strength of material
  - **lateral and torsional vibrations (rotordynamics)**
    - Vibration Response due to Unbalance (lateral) & Air Gap Torques (torsional)
    - Stability

Source: © gui yong nian - stock.adobe.com

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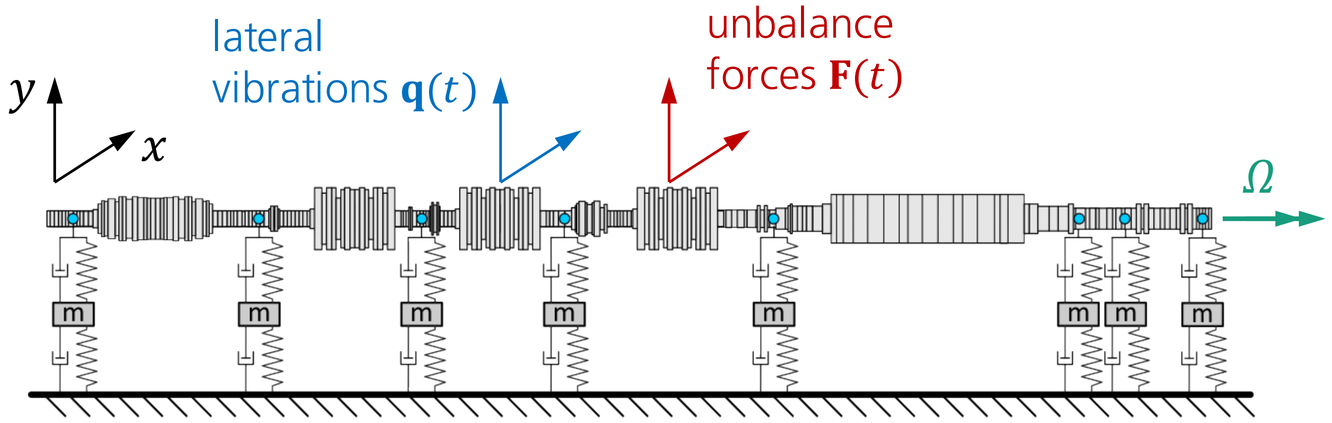
Models for the design of lateral vibrations

Mechanical model and equations of motion

The matrices $\mathbf{M}, \mathbf{D}(\Omega)$, and $\mathbf{K}(\Omega)$ of the equations of motion for **lateral vibrations** of the **power train** contain mainly the stiffness, damping and inertia data of the shaft train, the oil film bearings and the supporting system (pedestals and foundations).
$\mathbf{K}$ and $\mathbf{D}$ depend on Ω due to gyroscopic effects and oil film bearings.

Main excitations are unbalance forces $\mathbf{F}(t)$ along the shaft axis.

Lateral vibrations $\mathbf{q}(t)$ are perpendicular (horiz. x & vert. y) along the shaft axis.



$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{D}\,\dot{\mathbf{q}}(t) + \mathbf{K}\,\mathbf{q}(t) = \mathbf{F}(t)$$

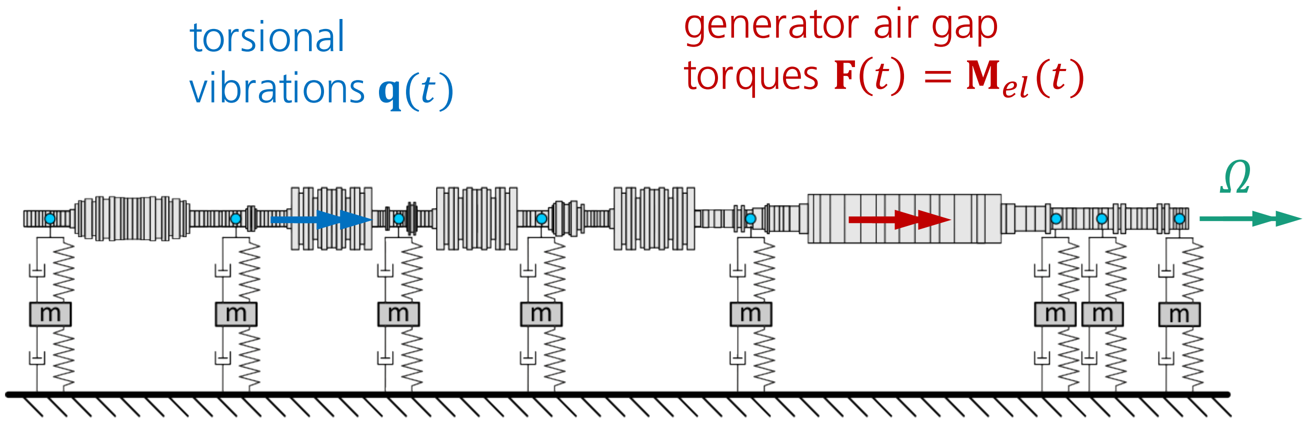
Models for the design of torsional vibrations

Mechanical model and equations of motion

The matrices $\mathbf{M}, \mathbf{D}$ and $\mathbf{K}(\Omega)$ of the equations of motion for **torsional vibrations** of the **power train** contain mainly the stiffness, damping and inertia data of the shaft train. $\boldsymbol{K}$ depends on Ω due to the stiffening of centrifugal forces on blades. The **damping** in the torsional system is **very low**.

The main excitations are **air gap torques** $\mathbf{F}(t) = \mathbf{M}_{el}(t)$ in the generator.

Torsional vibrations $\mathbf{q}(t)$ act around the shaft axis.



$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{D}\,\dot{\mathbf{q}}(t) + \mathbf{K}\,\mathbf{q}(t) = \mathbf{F}(t)$$

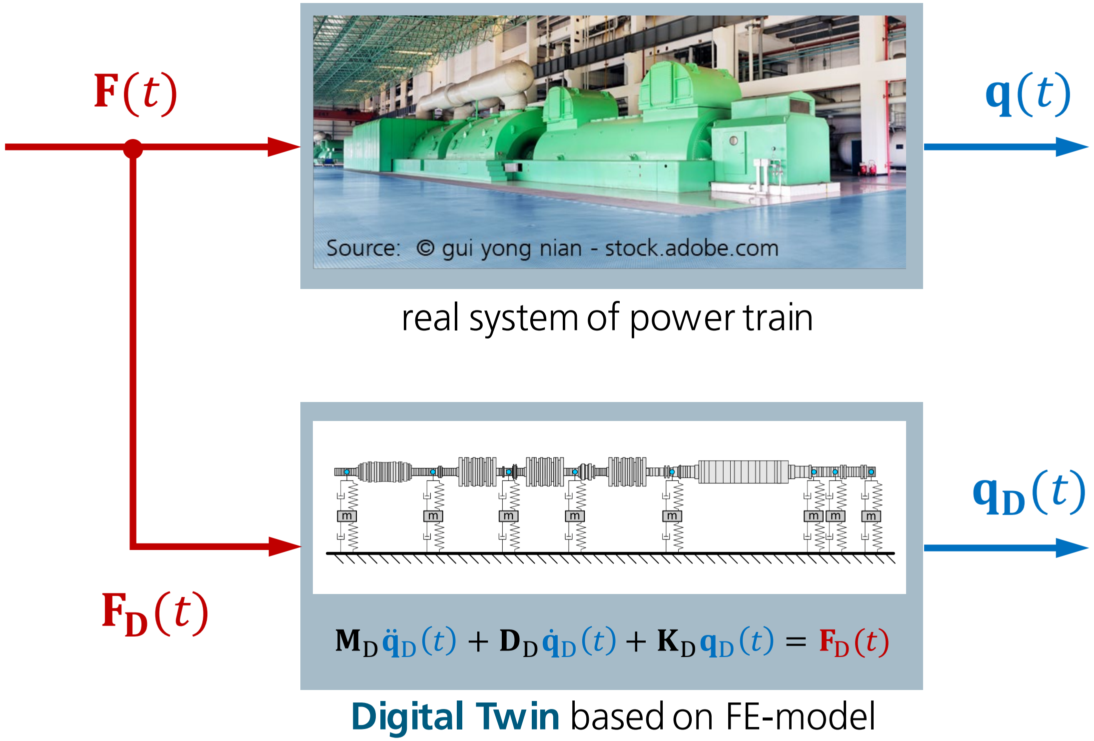
Models used as Digital Twins for the operation

Digital Twin based on a Finite Element (FE) model

The FE-model can be used as a **Digital Twin** for the operation. But a model is never exactly correct to represent the real system.

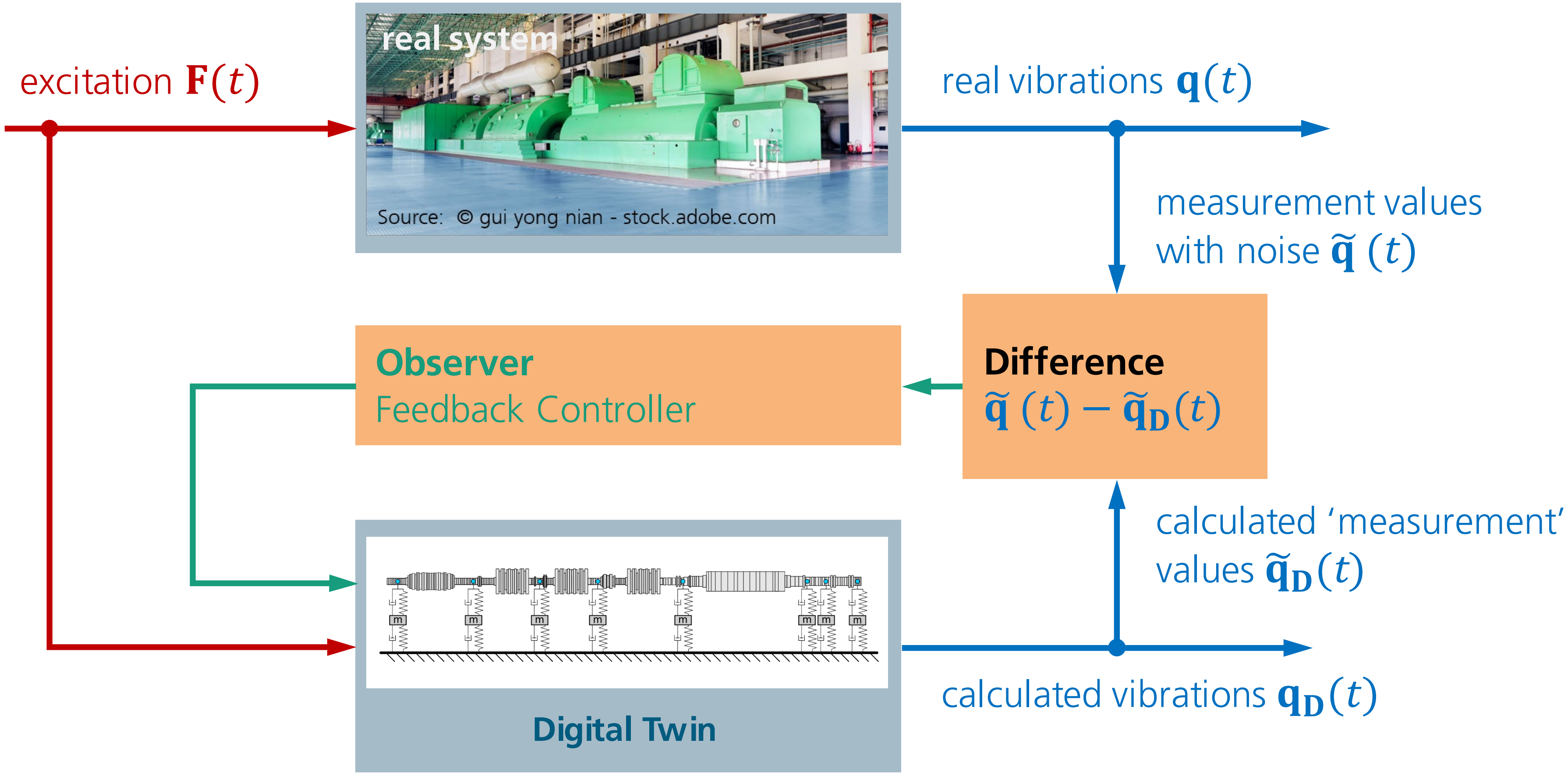
In this case **Observers** or Feedback-Controller can be used in order to adjust the **Digital Twin** continuously.

Input for the **Observers** are some of the differences between measured vibrations $\mathbf{q}(t)$ and corresponding calculated vibrations $\mathbf{q}_\mathrm{D}(t)$ of the **Digital Twin**.



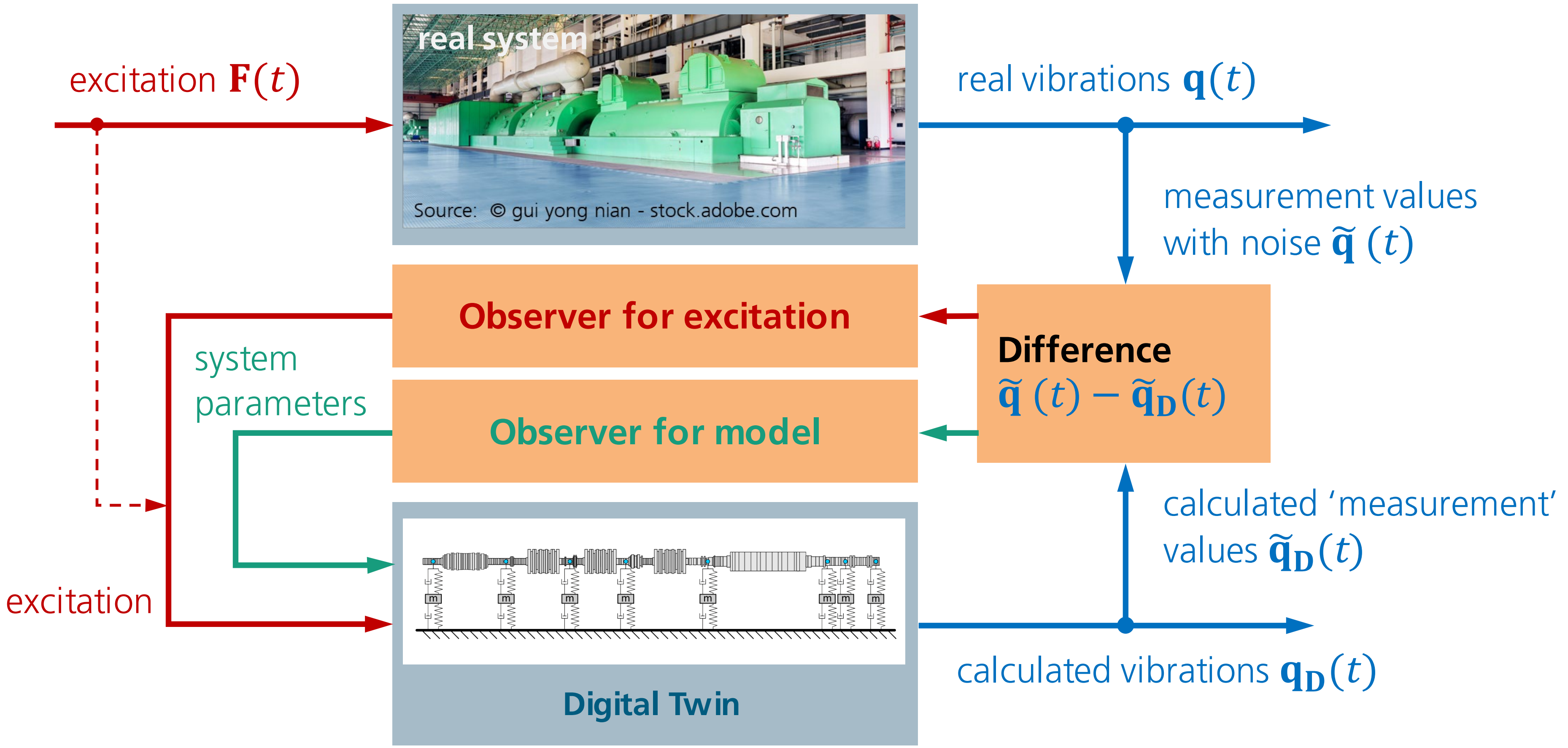
Models used as Digital Twins for the operation

Digital Twin based on a Finite Element (FE) model



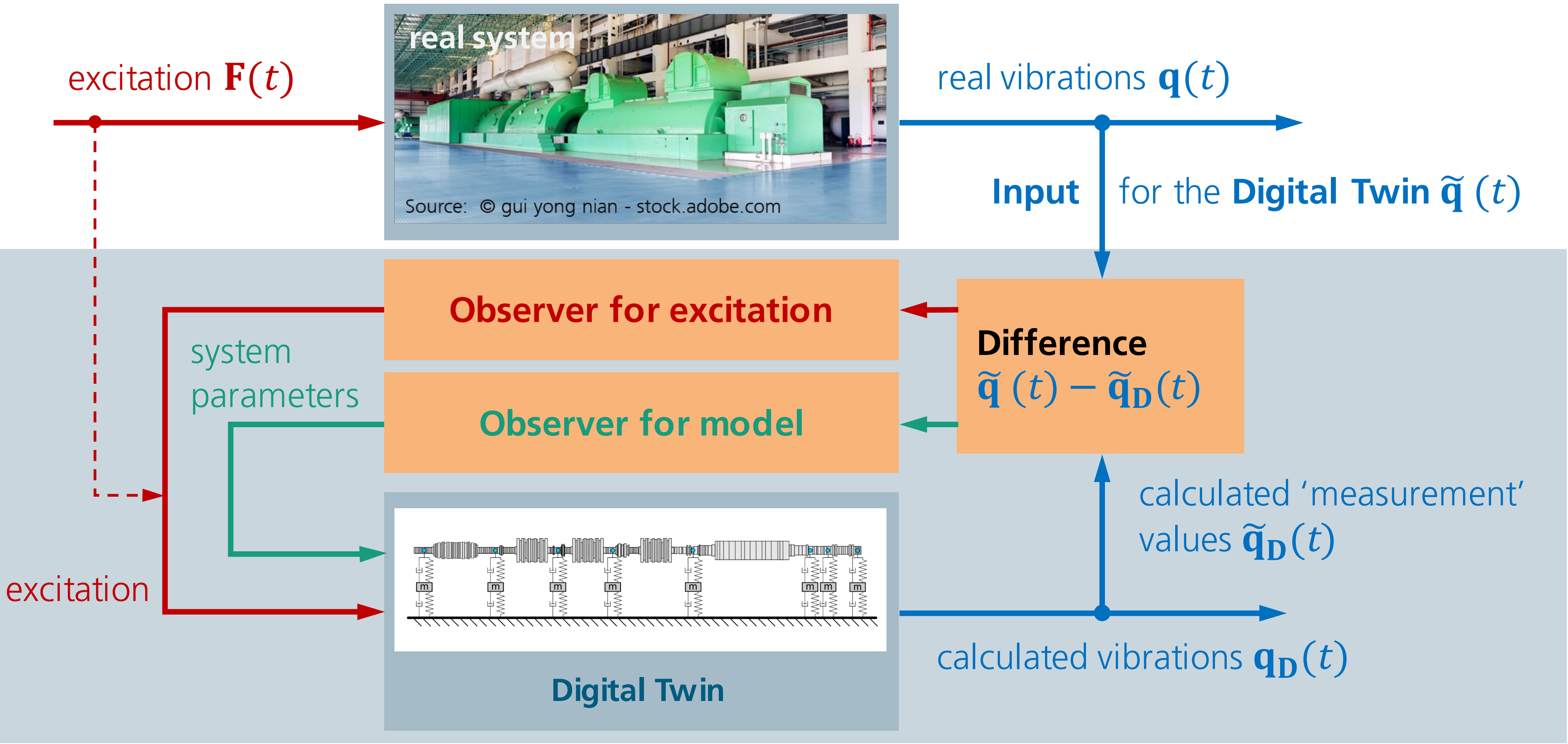
Models used as Digital Twins for the operation

Adjustment of the Digital Twin by observers for the model and the excitation



Models used as Digital Twins for the operation

Sensor information: operational lateral and torsional vibrations



Models used as Digital Twins for the operation

Sensor information: Type of sensors? Sensor locations?

Type of Sensors

- (angular) displacement, velocity, acceleration, strain, stress, pressure …
- voltage, current, …
- temperature, …

→ Do the respective type of sensor deliver the most relevant information to ensure optimal operation?

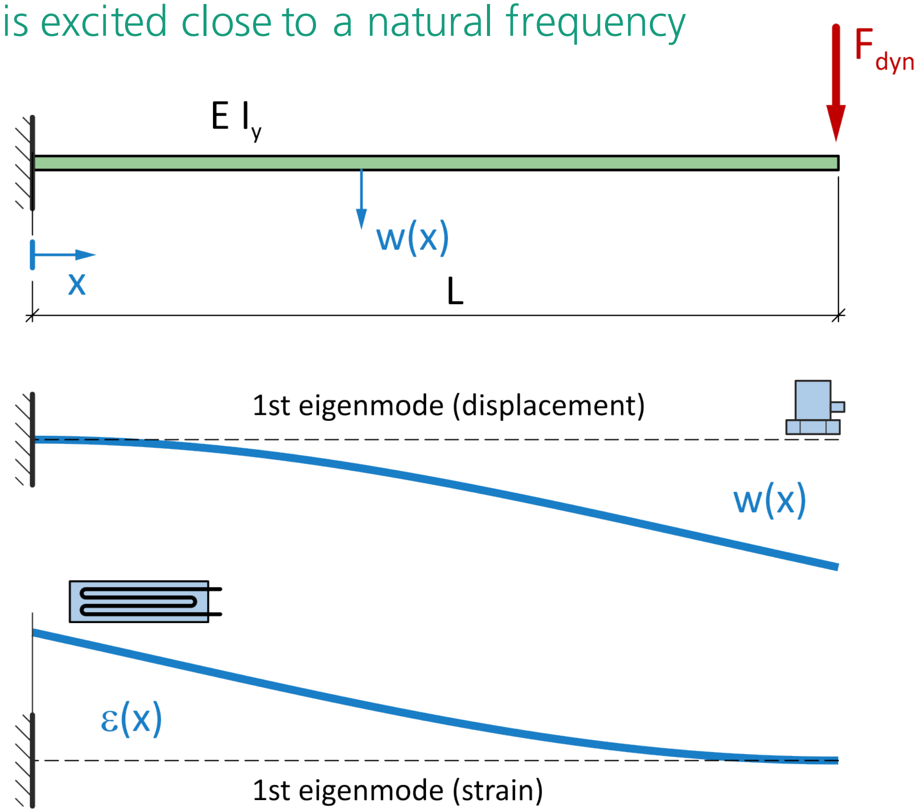
Sensor locations

- good SNR?
- accessible location?

→ Do they deliver relevant and reliable information?

Simple Example:

Structure is excited close to a natural frequency



Simulations by means of the Digital Twin

On line and Off line simulation

On line simulation
(power train and Digital Twin running simultaneously)

Monitoring of the drive train during operation and presentation of measured and calculated vibrations (displacement, strain, stress, …) in the time domain and frequency domain.

Identification of parameter changes and derivation of failures based on predefined and modelled failure modes

Life time prediction based on measured vibrations and/or stresses

Challenge: differentiation between changes of system dynamics, changes of excitation and failures

Off line simulation
(calibrated Digital Twin is used to analyse and evaluate problems)

Evaluation of vibration control measures and **recommendation** of suitable ones for optimal operation (Mitigation)

On line simulations by means of the Digital Twin

Monitoring of the drive train system

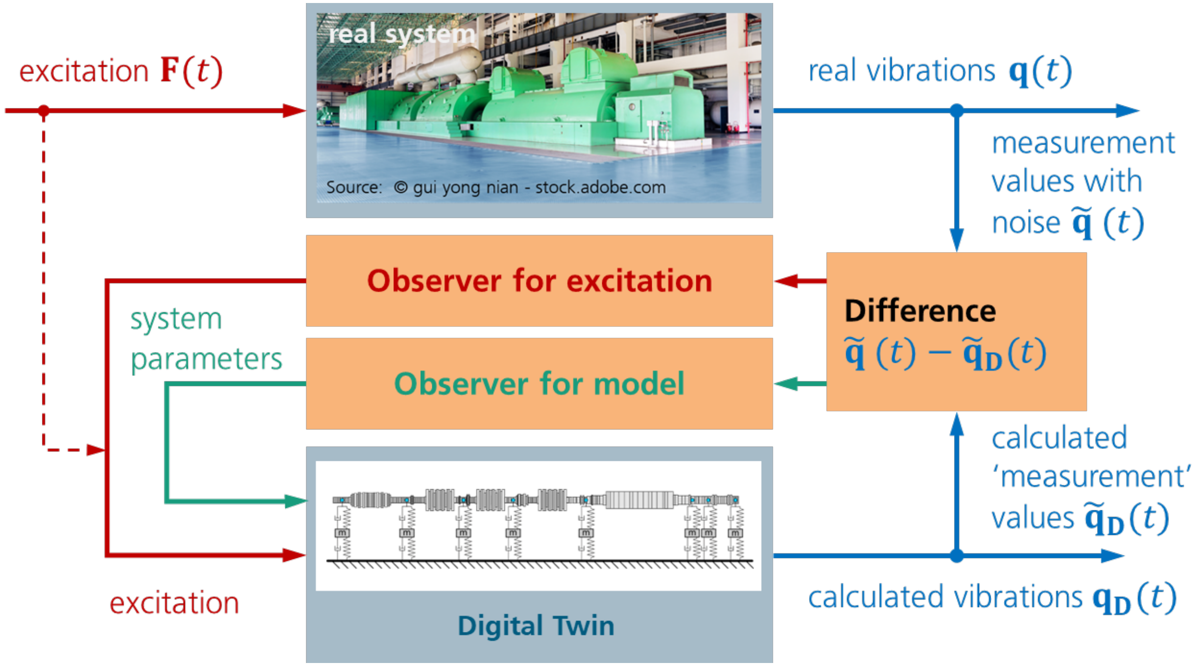
Monitoring of the drive train system during operation and presentation of the

measured vibrations (stresses) and the

calculated vibrations (stresses) by the

Digital Twin.

Measured and calculated vibrations can continuously be presented and evaluated either in the **time domain** and/or in the **frequency domain**.



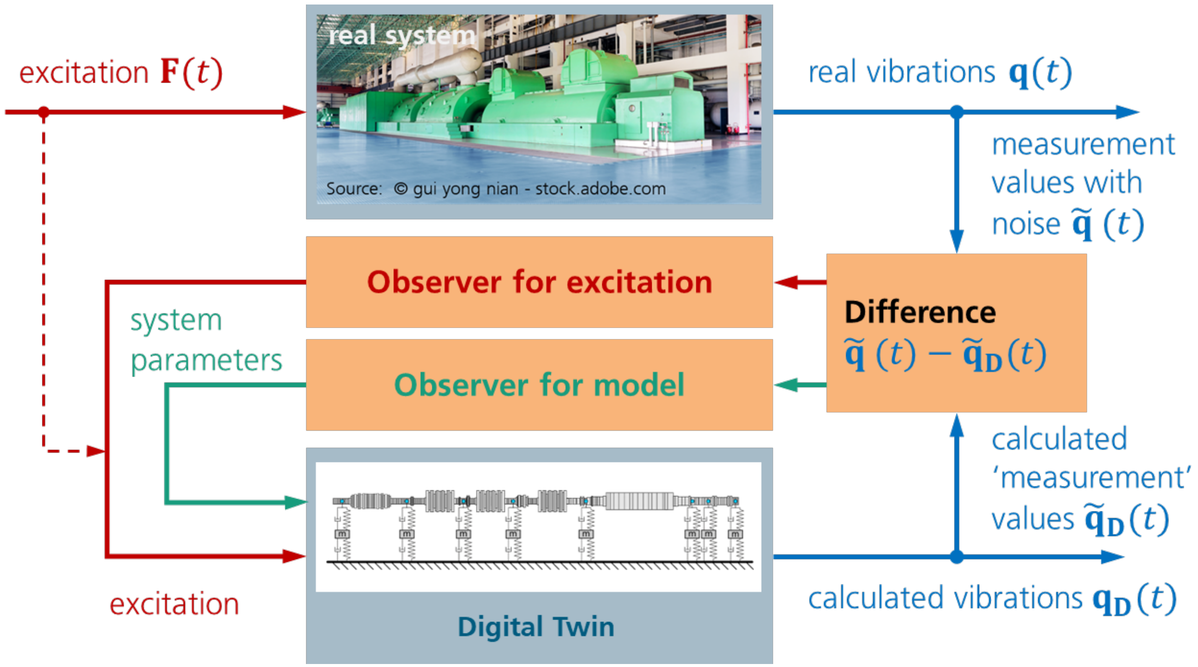
On line simulations by means of the Digital Twin

Identification of Parameters, **Diagnosis** of Failures

From **deviations** between the selected real vibrations $\tilde{\mathbf{q}}(t)$ and the corresponding calculated vibration $\tilde{\mathbf{q}}_D(t)$ possible **parameter changes** or **failures** in the real system can be identified (failure diagnosis).

Examples:

- Increase of air gap torques
- Damping in torsional systems
- Shaft cracks
- Change of bearing stiffness and damping
- Increase of unbalance forces
- Misalignment



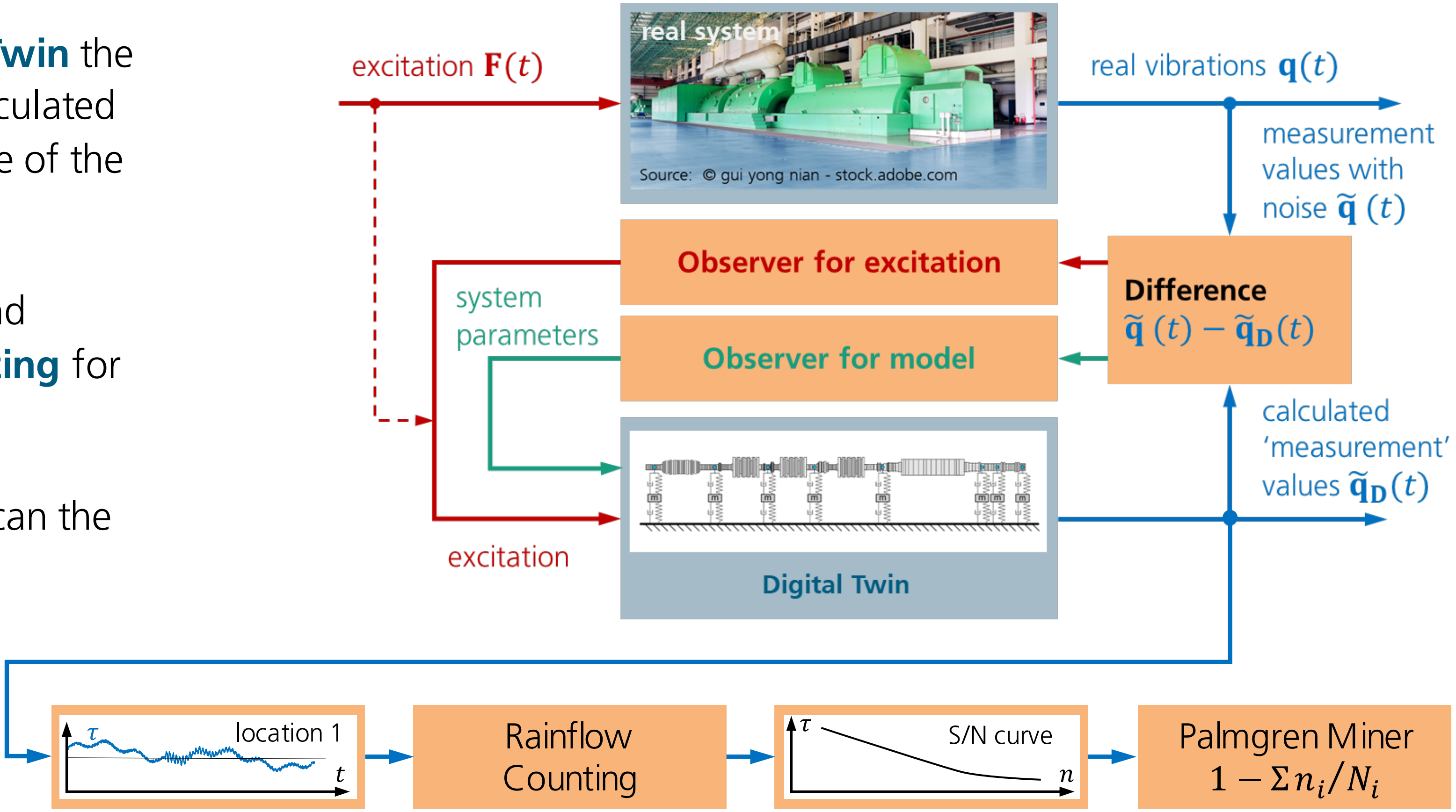
On line simulations by means of the Digital Twin

Life time prediction based on measured shear stresses

By means of continuously adjusted **Digital Twin** the **bending** and **torsional stresses** can be calculated from differences of the vibrations at any time of the operation.

They can be classified by their **amplitude** and **occurrence** (frequency) by **Rainflow Counting** for selected critical locations of the power train.

The remaining **life time** of the power train can the be predicted by a procedure for damage accumulation like **Palmgren Miner**.



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Off Line Simulations by means of the Digital Twin

Passive and active vibration control measures

	without energy conversion	with energy conversion		
	passive		semi-active	active
reduction of excitation				
system tuning				
damping				
vibration absorption				
isolation of sources				
isolation of receiver				

conventional solution space

expanded solution space

In general increase of:

effectiveness, benefit, complexity,
number of possible variants

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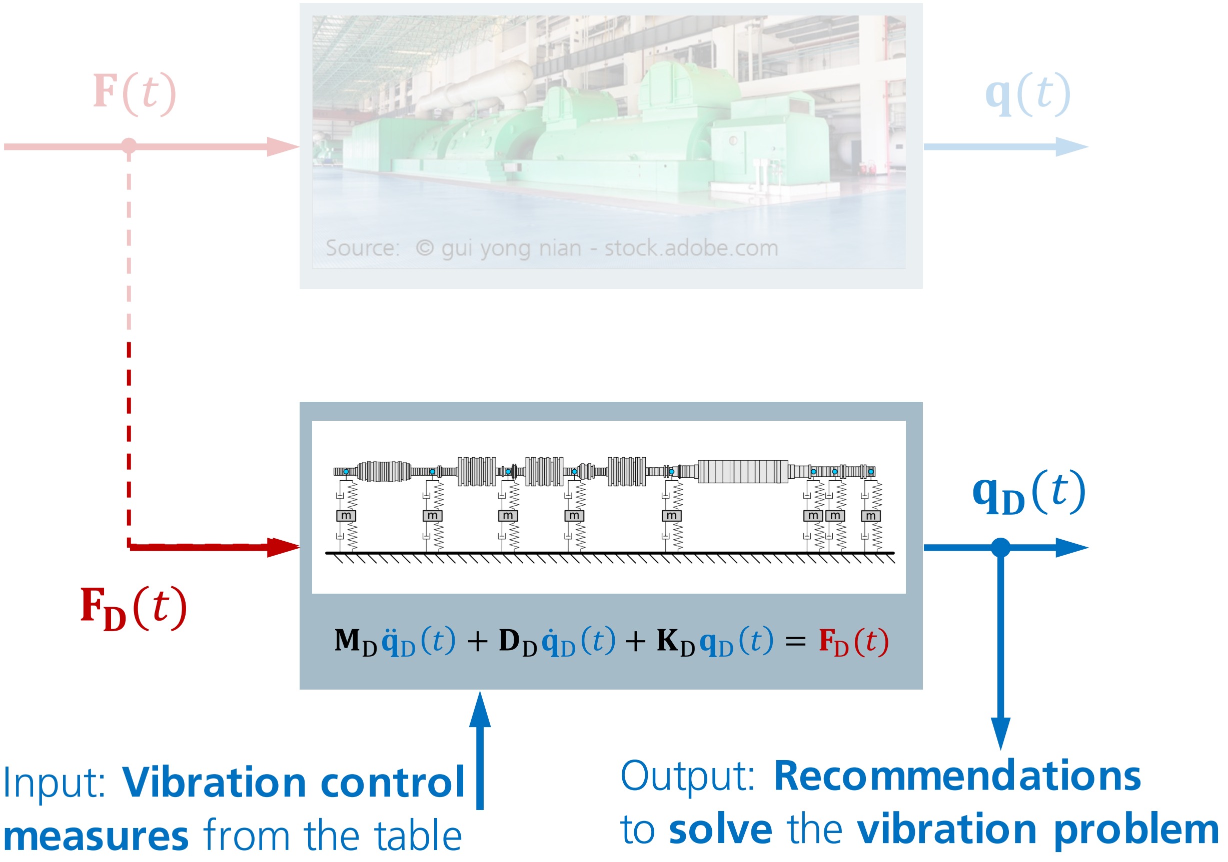
Off Line Simulations by means of the Digital Twin

Passive and active vibration control measures

The selected **vibration control measures** from the table can be introduced into the **Digital Twin**.

The effect of these Control Measures can then be investigated by **off line simulations** with the **Digital Twin**.

Based on the results, **recommendations** for vibration experts can help to **solve the vibration problem**.



Digital Twin example at LBF

High frequency testing

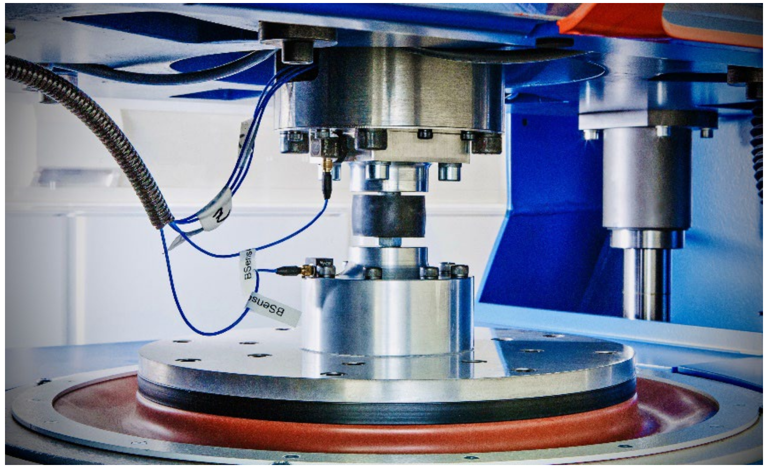
Initial situation

In highly dynamic tests, fixtures significantly falsify the measurement results.

The influence on the overall dynamics of the test setup **must be corrected *offline.***

Test setup for elastomer characterization

- Frequency: 50 - 2000 Hz
- Acceleration: ±3g
- Preload: 1.2 kN
- Sweep: sinusoidal, 1 octave/min
- Temp: Room temperature
- Mass: 5.5 Kg + (412g)



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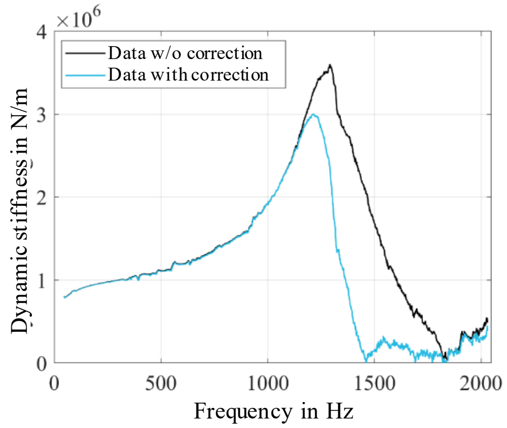
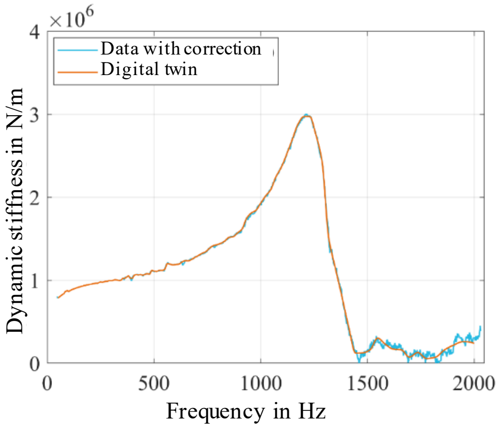
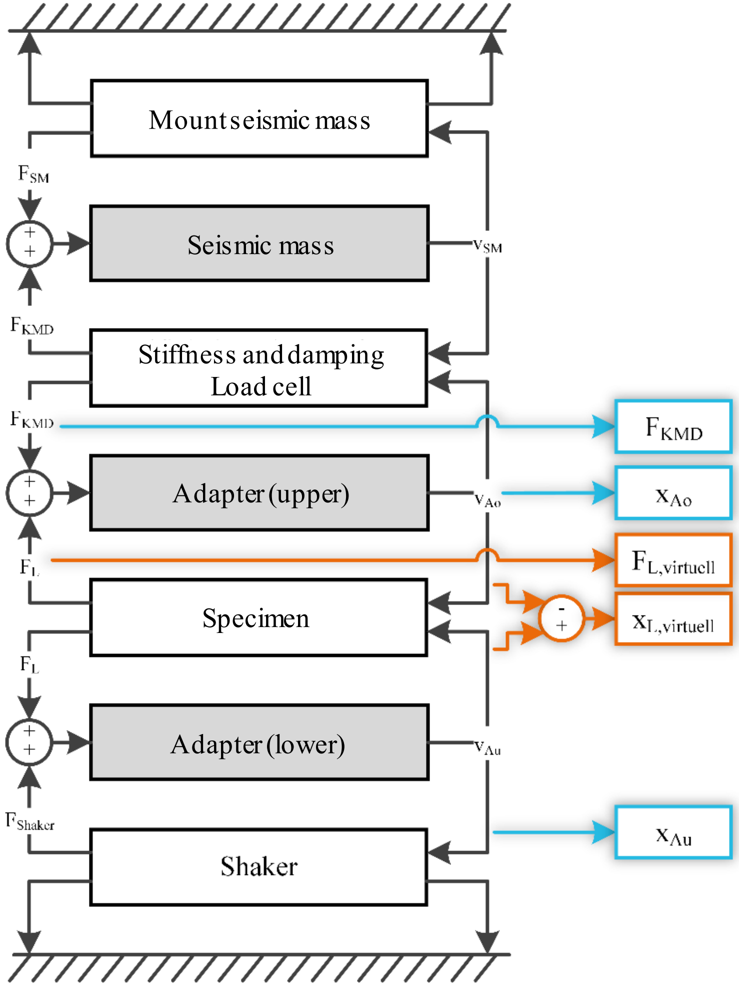
Digital Twin example at LBF

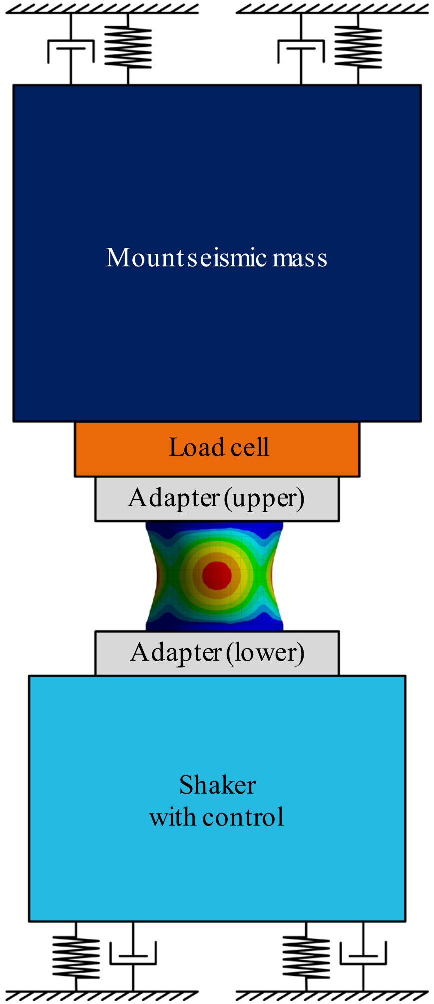
High frequency testing

- Characterization of an elastomer mount with frequency-dependent properties
- Saving of sensors in the test setup
- Determination and compensation of unwanted dynamic effects of the adaptation already in the virtual image
- Determination of further conditions which cannot be measured directly, or which can be measured hardly









Digital Twin for torsional vibrations of power trains

Summary and Outlook

Summary

- An appropriate model of the system, suitable sensor principles/locations and signal evaluation are required to efficiently apply **Digital Twins**
- **Digital Twins** support a more reliable operation and can also be applied to further optimize the system

Outlook

It's proposed to start

- the development of the **Digital Twin** virtually (e.g. by means of recorded data from the real system)
- with a **Digital Twin** containing the torsional vibration behaviour

Thank you for your attention