

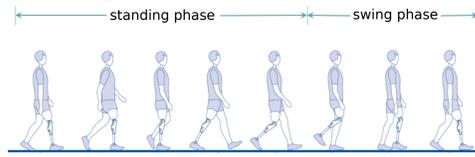
Developing a digital twin of a human knee prosthesis for acoustic analysis

Highlights

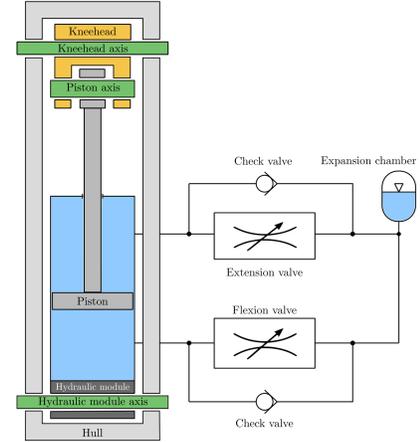
- Flow-Vibro-Acoustic model of a mechatronic knee prosthesis
- Workflow for identification, systematic analysis, and prevention of acoustic sources inside hydraulic system
 - Compressible scale-resolving fluid dynamics model including piston movement, to identify source zones, and source mechanisms
 - Efficient prediction of compressible transfer characteristics by stochastic source model and viscous acoustic simulation
 - Multi-fidelity structural dynamics model
 - Acoustic radiation model

Hydraulic knee prosthesis

- Two-chamber piston damping unit
- Controlled damping rate
- High piston velocity or high damping ratio causes sound emissions



Human gait cycle, separated into standing and swing phase. During each phase the knee joint performs a bending (flexion) and straightening (extension) motion.



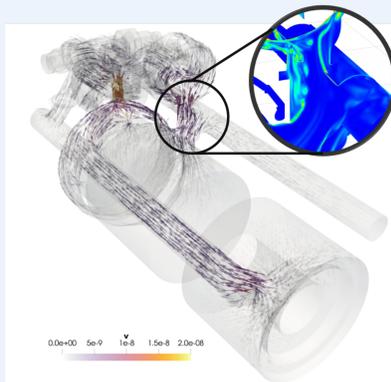
Hydraulic system under investigation.

Turbulent fluctuations

- Low Mach number flow with localized turbulent flow regions
- Hybrid scale resolving method: Stress-blended eddy simulation

Flow instabilities

- Shear layer instability causing vortex shedding
- Nonlinear interaction of vortical flow field with compressible modes
- Evaluation of whistling potential by analysis of compressible modes
- Computationally efficient weakly compressible CFD model using Tait equation of state



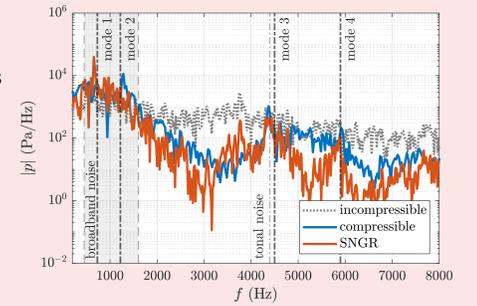
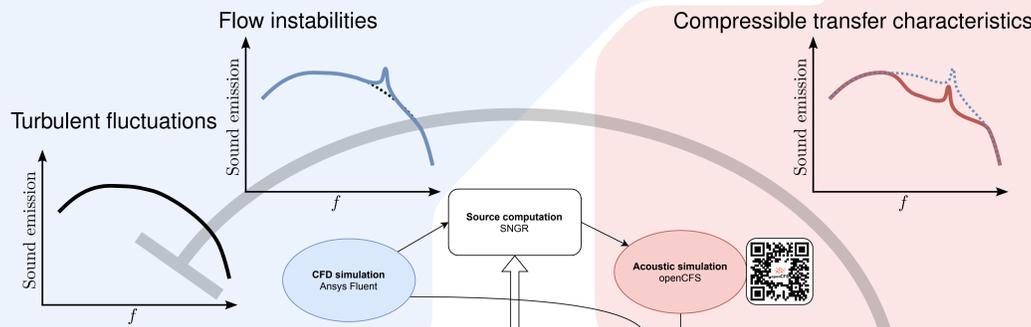
Acoustic particle velocity of acoustic mode 3 interacting with mixing layer instability.

Compressible transfer characteristics

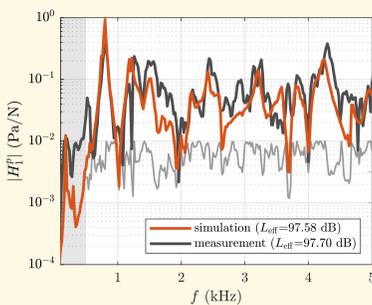
- Finite element model of linear acoustics
- Viscous boundary layer model to account for viscous fluid
- Source distribution based on Stochastic Noise Generation and Radiation (SNGR) from stationary flow field



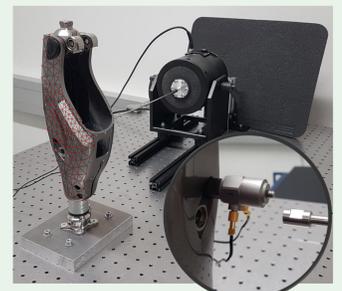
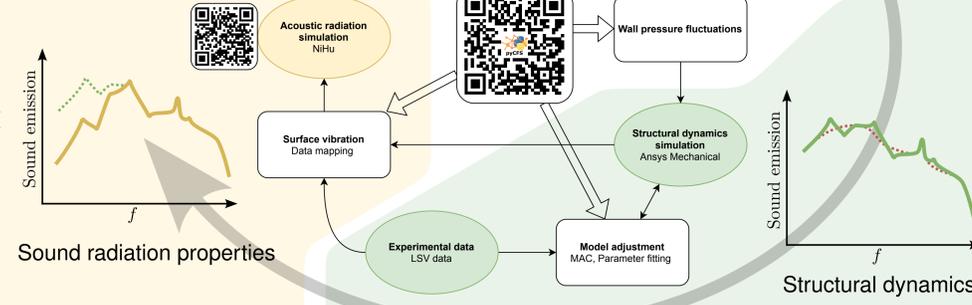
Turbulent kinetic energy during flexion motion highlighting regions of turbulent structures.



Amplitude spectrum of flow pressure based on incompressible and compressible CFD, and SNGR workflow. Highlighted acoustic modes. [1]



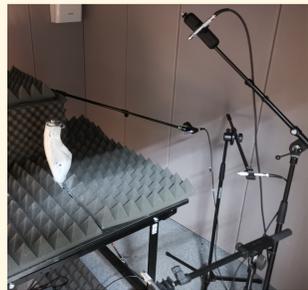
Vibroacoustic transfer function spectrum based on microphone measurements, and sound propagation simulation. [2]



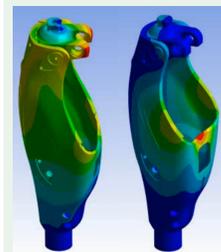
Setup for a laser vibrometer measurement of the frequency response of the prosthesis frame.

Sound radiation properties

- Data transfer from arbitrary surface vibration data
- Boundary element model with Neumann boundary condition (forward coupling)
- Burton-Miller approach to mitigate spurious modes



Measurement setup for validation of the sound propagation model.



Two oscillation modes of the prosthesis frame.

Structural dynamics

- Multi-fidelity model of the structural transfer path
- Finite element model and frequency response data from Laser scanning vibrometry of the frame body
- Lumped element model of the hydraulic unit, and auxiliary components

[1] Wurzinger, A., Schoder, S., Mayr-Mittermüller, B., Kaltenbacher, M. and Sima, H., Hydrodynamic and Flow-Acoustic Simulation of a Two-Chamber Piston Hydraulic System Prone to Whistling. Available at SSRN 5088432. DOI: 10.2139/ssrn.5088432

[2] Wurzinger, A., Kraxberger, F., Maurerlehner, P., Mayr-Mittermüller, B., Rucz, P., Sima, H., Kaltenbacher, M. and Schoder, S., 2024, January. Experimental prediction method of free-field sound emissions using the boundary element method and laser scanning vibrometry. In Acoustics (Vol. 6, No. 1, pp. 65-82). MDPI. DOI: 10.3390/acoustics6010004

