Acoustic monitoring of superconducting magnet component test and shock simulation of coils

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Abstract

Monitoring of critical components is becoming a more and more important task especially in complex multidisciplinary systems as e.g. the Wendelstein 7-X [1,2]. Here especially the superconducting magnetic coil system – comprising, i.a., narrow support elements (NSEs) and bolted connections - is considered. These had been tested in a full-scale test set-up with multi axial loading in the MN range at 77K and vacuum [3, 4]. A smooth sliding of coated surfaces is a major requirement, as non-smooth sliding (stick-slip) excites high mechanical shock loads, which may cause a quench of the superconductor. For an early detection of stick-slip an acoustic monitoring system has been developed and installed. Three sensor types have been compared and data analysis procedures have been developed. It has been shown that acoustic monitoring is possible under such environmental conditions at complex test set-ups and is complementary to standard sensor systems. For the development of the mechanical quench experiment, in which the actual quench sensitivityl to mechanical shock loads is investigated by impact loads, numerical simulations have been performed. For this a semi-analytical model employing a reduced modal state space model of the coil and Hertz'ian theory for the contact formulation has been set up. Based on experimental and numerical verification it proved to be an appropriate and efficient tool for simulating complex mechanical systems under transient dynamic loading. Finally, a statistical energy based model has been set up for simulating the propagation of stick-slip shocks within the complex coil system. Concluding, with the developed acoustic monitoring as well as the numerical simulation models two valuable tools for the W7-X development-test projects have been developed.

Key words: acoustic monitoring, state space, shock simulation, stick-slip, Wendelstein 7-X, narrow support elements

1. Introduction

This paper describes the development and performance of an acoustic monitoring system as well as a simulation procedure for complex mechanical systems under transient loading. Both developments arose from investigations of stick-slip effects that have been observed during qualification testing of support elements of W7-X. Stick-slip developes after the coating of the sliding surface wears and means a non-smooth sliding due to alternating of sticking and sliding of the two surfaces in contact. Due to the elasticity of both sliding partners energy is stored during the sticking phase by increase of the externally applied stroke/force. This energy is released spontaneously if the force exceeds the static coefficient of friction (COF) and excites a shock wave that may lead to a quench of the superconducting (sc) coil.
For the experimental identification and localization of a worn support element coating by acoustic emission due to stick-slip effects, a monitoring system has been developed and tested. For evaluating the effects of this transient load on a coil, numerical simulation have been performed. The numerical models have further been applied to the development of another experiment investigating the actual quench sensitivity of the coil to mechanical shock loads.

The development and specification of the monitoring and simulation procedure will be described in the following.

2. Acoustic monitoring

An extensive development and qualification test program of the narrow support elements (NSEs) [3,4] and the bolted connection (BC) of sc magnet system ([7]) has been performed by KRP-Mechatec. The test set-ups used have been specifically developed and are able to apply biaxial loads in the MN range under cryo (77K) and vacuum (10^{-6}mbar) condition, see Fig. 1 and Fig. 2.

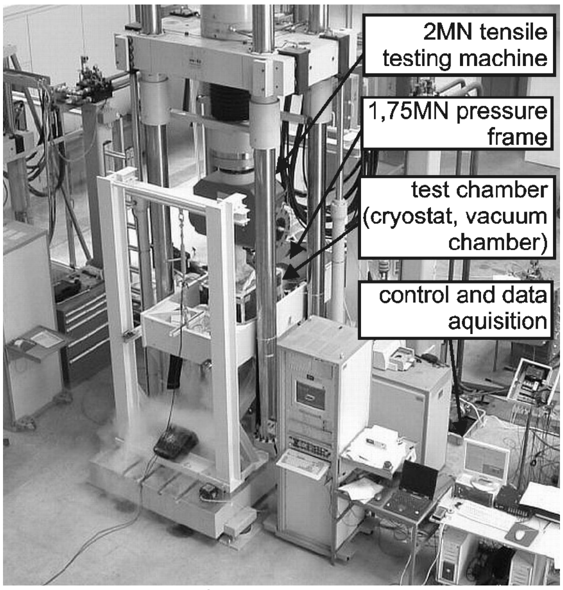

Fig. 1: Test set-up for narrow support elements

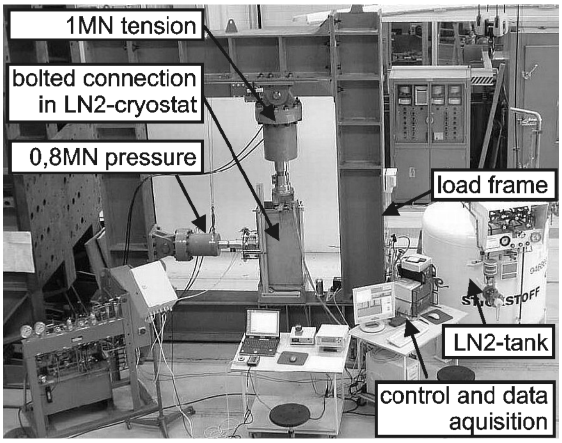

Fig. 2: Test set-up for bolted connection

The nominal instrumentation consists of strain gauges (up to 50), displacement sensors (10-15) and thermocouples. Becoming aware of the risk of stick-slip effects, an acoustic monitoring system has been installed at both test set-ups. In Fig. 3 and Fig. 4 the loads, acoustic excitations / sources and the acoustic instrumentation are shown.

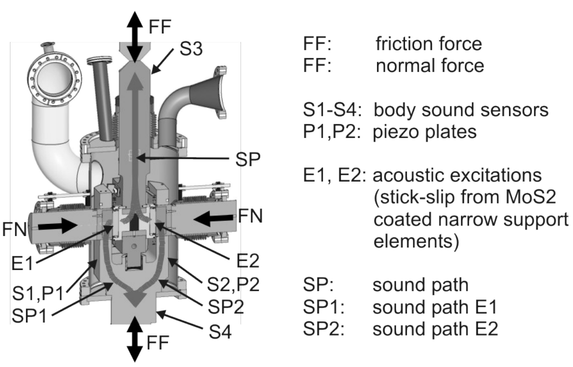

Fig. 3: Acoustic sensors and excitations of NSE test

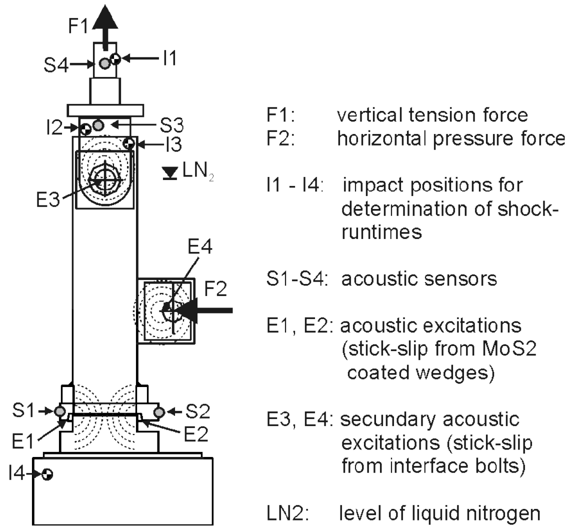

Fig. 4: Acoustic sensors and excitations of BC test

Three types of acoustic sensors have been compared. They have been distributed within the set-up such that several sources (components / sliding surfaces) can be monitored and distinguished. The sensors are located as close as possible to the source and within the path of the sound wave. Material variation and contact between individual parts may lead to reflections due to impedance mismatches. The sensors have been compared with respect to noise (RMS), signal level (RMS), bandwidth and application procedure as shown in Tab 1.

Tab. 1: Sensors for acoustic monitoring

sensor	BSS [a)]	piezo plates [b)]	strain gauge [c)]
noise	3 [mV]	6 [mV]	0,2 [mProm] [d)]
signal	2 [V]	3-4 [V]	1,2 [mProm] [d)]
bandwidth	300 [kHz]	150 [kHz]	1000 [kHz] [e)]
application	hole clamped	glued	glued

[a)] Body Sound Sensor (ps/ks/11, MARCO GmbH)
[b)] size 20 x 20 x 0,5 mm³, type Sonox 53, supplier CeramTec
[c)] grid length 3mm, type CFLA-1-350-11, supplier TML,
[d)] mProm equals a strain of 10-6
[e)] 6kHz amplifier cut-off1

A typical friction test cycle with already worn coatings and therefore strong stick-slip effects is shown in Fig. 5.

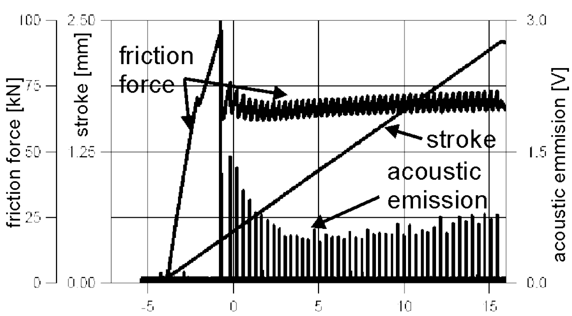

Fig. 5: Friction test cycle with acoustic emission

By means of acoustic sensors a pre-indication of wear on the NSE coating was possible several 100 load cycles before the COF measured by strain gauges increased (Fig. 6). This may allow on time adjustment of loads (adaptation of scenario), reduction of cycles (interruptions of magnetic field), re-lubrication or replacement of the affected components.

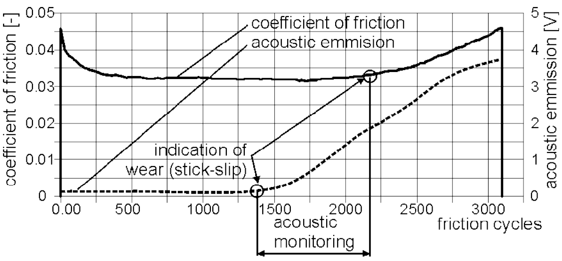

Fig. 6: COF und peak value of acoustic sensors

Before using the sensor array for shock source / defect component localization, the time-of-travel differences from the sources to the sensors has to be determined experimentally, e.g. by impulse hammer excitation. The time offsets observed are typically in the 10 µs to 100 µs range and shall correlate with the analytically determined values according to

$$dt = dl/c \qquad (1)$$

c = sound speed (steel ~5000m/s)
dl = difference of sound path length
dt = time-of-travel difference

Using a data acquisition system with a sampling frequency 10 times higher as the expected time-of-travel difference, a localization of the defect component is possible (Fig. 7). The time offset has been calculated to ~34 µs and correlates well with the observed time offset of 35µs. As can be seen, the piezo plate signal comes first, thereby identifying the NSE on side 1 (E1) to be worn. Having a look at the coatings after test this can clearly be verified (Fig. 8).

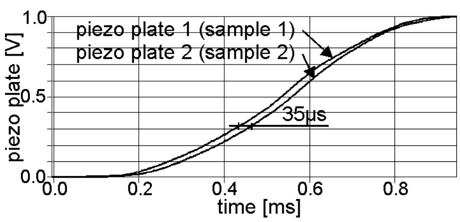

Fig. 7: time-of-travel difference of stick-slip

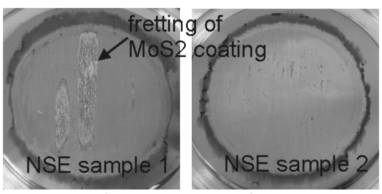

Fig. 8: Coatings of the tested NSEs

Besides the tested components also the test set-up itself may excite shock waves by stick-slip. For example the bolted connection was loaded by interface bolts which also induced stick-slip. To clearly refer observed stick-slip events to the tested component, a numerical evaluation of the time of travel is necessary. The result of such a computation is shown in Fig. 9 with the computed time-of-travel differences and the thereby identified sources. It indicates that the tested component shows stick-slip from high load cycle 300 (total cycle number since then: about 3000) by wear of the MoS_2 coating on the wedges whereas the test set-up (interface bolts) shows stick slip quite from the beginning.

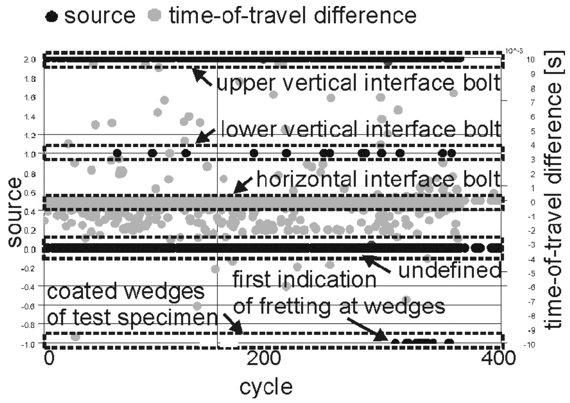

Fig. 9: procedure for localisation of stick slip during high load experiment, after 3000 cycles with standard load

Lessons learned:

At first identify the acoustic sources (the components to be monitored and also secondary structural components, e.g. test set-up). Use a transient recorder with a sampling frequency at least 10 times higher than the reciprocal of the shortest difference of the time-of-travel. Try to minimise signal noise and secondary acoustic sources. Analytically and experimentally determine the time-of-travel from all identified sources to all acoustic sensors. Prepare a data analysis procedure for source localization and verify it by external hammer excitation at the identified sources (use metal hammer tip). Ensure not to miss the initiation of acoustic emission during the operation by false trigger levels. Use standard sensors to check the results of the acoustic monitoring

3. Numerical simulation

Numerical simulation of dynamic coil response to shock loads

Complementary to the full-scale life-cycle qualification test of the NSE elements, an additional experiment will be performed by IPP investigating the actual sensitivity of the superconducting coils to quench under mechanical shock loads potentially caused by these stick-slip events. In this so called MQ-test (mechanical quench) the coil will be subjected to mechanical impacts by a pendulum based hammer during operation under cryo-vacuum conditions. A sketch of the experimental set-up of the MQ-test can be seen in Fig. 10. The rod (dia. 30, length 2.7m) is on one side rigidly connected to the coil and has a spherical contact area (radius 25mm) on the other side. It is impacted by the hammer (dia 0,2m, length 0.122m, mass 30kg) that has also has a spherical contact area (radius 1000mm) with a velocity of 2m/s.

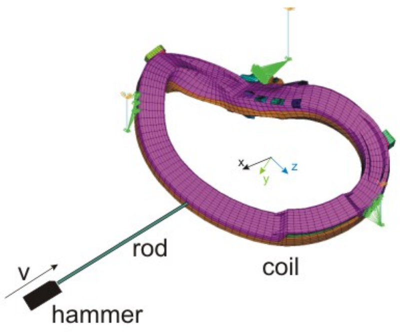

Fig. 10: FEM model of MQ-test

For the design of MQ-test, numerical simulations of the planned test set-up have been performed to assess different configurations, define suitable impact parameters, and evaluate the coil response to experimental contact force profiles determined from MQ-breadboard test.

3.1 Modelling

Two simulation concepts have been employed, a full 3D FE-model in LS-DYNA and a semi-analytical modal state space model in Matlab/Simulink. The full 3D FE-model (see Fig 10) is based on the IPP model [8] for the coil and has been adapted for explicit analysis in LS-Dyna.
In addition to the FE model a semi-analytical model has been developed. In this model a reduced modal state space representation [9] has been applied for representing the coil and the transfer rod dynamics. The modal data of the coil has been computed by a foregoing modal analysis using the coil FE-model in ANSYS. For modelling contact between hammer and rod Hertz'ian contact theory [10] has been implemented. The complete model has been set up as a non-linear time integration model in Matlab/Simulink (see Fig. 11).
For covering the necessary frequency range (~4000Hz), the first 400 Eigenmodes of the coil proved to be sufficient. So by employing the proposed modal state space concept, it has been possible to reduce the number of DOF from ~180.000 of the FEM model to less then ~1000. Thus the semi-analytical model has the great advantage of requiring significantly less computation time compared to the explicit FE-model (see Table 2) and thus offering the possibility to run parameter studies for the impact parameters (hammer mass and velocity) in a time and cost efficient way.

Tab. 2:Comparison of the two modelling concepts

	FEM (LS-Dyna)	Reduced modal
Domain	Physical domain	Modal domain
CPU-Time	>2h	15s
DOF (coil)	180.183	2*400

With respect to model verification, on the one hand the results of the semi-analytical model have been compared with the results for the FE-model, on the other hand the modelling approach has been applied to known problems in literature and the respective results have been compared. In both cases good compliance could be observed.

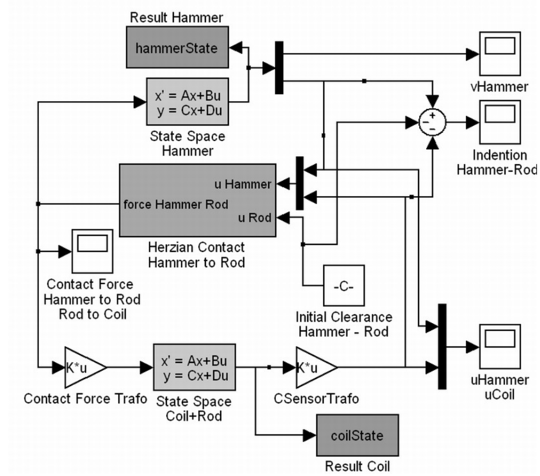

Fig. 11: Flowchart of semi-analytical model (meaning of variables can be found in [9])

3.2 Selected Results

In the following, selected results are shown for the impact simulations.

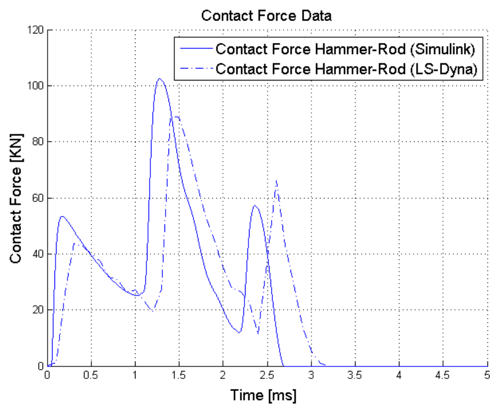

Fig. 12: Comparison of contact forces between FEM model and reduced model (hammer mass of 30kg and an impact velocity of 2m/s)

In Fig. 12 the contact forces between hammer and rod are shown for the reference configuration for both models. A good compliance can be observed. The reduced set of Eigenmodes in the semi-analytical model leads to a slightly stiffer behaviour resulting in slightly higher contact forces and a shorter contact time.

In Fig. 13 the modal constants of the transfer matrix for the first 400 Eigenmodes are plotted for an excitation at the impact locations and sensor locations along a circumferential line on the inner side of the winding pack (keypoints 1-96, see also Fig. 14). It can be observed that high frequency modes in the range of 3400-3700 Hz will play a dominant role with respect to the peak acceleration experienced in the winding pack. Thus for the impact configuration it is important that the corresponding contact force spectrum covers this frequency range.

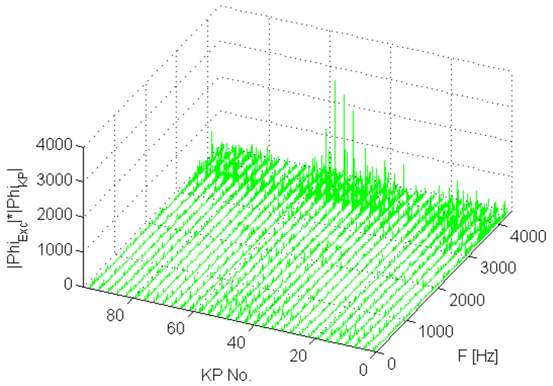

Fig. 13: Modal constants $A_{i,j}(k)$,i=impact node, j=KP1-96 (~line on inner winding pack) for modes k=1-400

Based on the results of parameter studies with the semi-analytical model a breadboard test (using the impact device, pendulum and rod, but hitting on a wall, not the coil) with a selected set of impact configuration has been performed. The measured contact forces have been used as input to the semi-analytical model to compute the dynamic coil response.

In Fig. 14 the peak acceleration along a circumferential line on the inner side of the winding pack is shown for the different impact parameter sets. The maximum winding pack accelerations are observed close to the impact locations, but accelerations above 500m/s² (critical acceleration level as provided by IPP) is reached over a wide section.

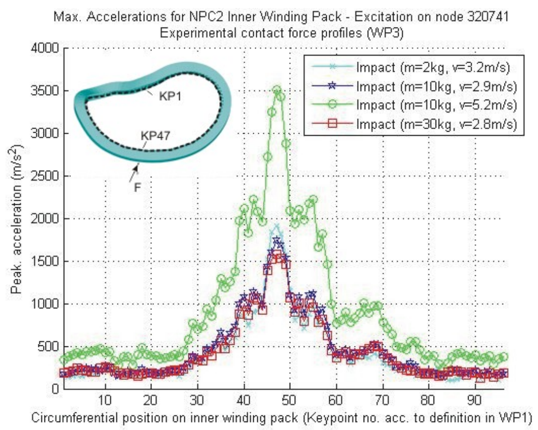

Fig. 14: Peak acceleration within the first 5ms along a circumferential line along the inner side of the winding pack

It shows that the maximum accelerations are reached for a relatively low hammer mass and a high impact velocity. The variation of hammer mass does not have significant influence on the acceleration. The explanation for these results can be seen in the corresponding spectra of the contact forces (Fig. 15). The spectral content of the respective contact force in the important hight frequency range can be directly linked to the achieved acceleration level.

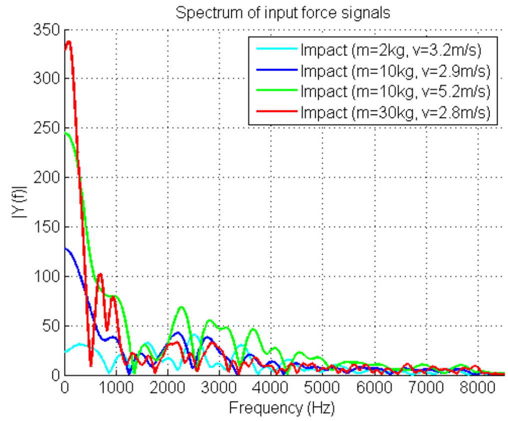

Fig. 15: Contact force spectra for different impact configurations

Lessons learned:

A semi-analytical model employing a reduced modal state space model and Hertz'ian contact theory achieved similar results as an explicit FE-model. By using the reduced model broad parameter studies could be performed in a time and cost efficient way. For achieving high winding pack accelerations the contact force spectrum of the hammer to rod contact is decisive and has to match the important frequency range of the coil. For the MQ-test the impact configuration should be chosen accordingly, i.e. a relatively low hammer mass and a higher impact velocity

3.3 Statistical Energy Analyses

Independent of the work for the above mentioned IPP projects, a statistical energy analyses (SEA) based simulation tool has been developed to evaluate the propagation of a shock loads within mechanical structures. As a first example a the magnetic coil system has been modelled with approximated material properties, assumed to be independent of frequency and loaded with an approximated shock load. The coils are discretised by statistical elements with internal (ILF, 2% damping) and coupling loss factors (CLF, constant at 0.005), the NSEs are implemented as coil couplings with COF-equivalent coupling loss factor (friction coefficient used is 0.03). The classical SEA has been modified for transient shock simulation by using the shock response spectrum (SRS) as energy equivalent parameter [5,6].
In Fig. 16 a preliminary result of this ongoing work is shown. For a reduced 10 coil system, stick-slip has been assumed for two NSEs (Source 1 and 2), the calculated peak response (maximum = 9g) and more imported its distribution within the coil system for a selected frequency (1000Hz) is shown. One can clearly see the three main processes: shock input at a worn NSE, propagation to neighbouring coils, and dissipation within each coil. The objective of this work is to develop an efficient tool for

predicting shock propagation in complex systems with multiple contacts.

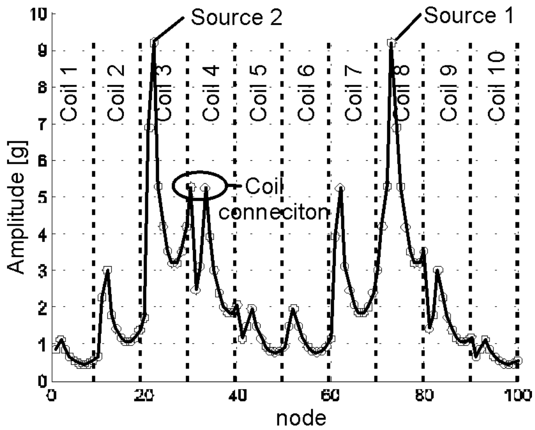

Fig. 16. SEA-result of shock propagation

4. Conclusion

Acoustic monitoring has been shown to be a valuable complement to the standard mechanical instrumentation. It can either be used for an early identification of specimen defects or for the localisation of defects if multiple components or components with multiple failure modes are tested. Sensors have been compared, and piezo based sensors (e.g. body sound sensors and piezo plates) show good performance even under cryo-vacuum condition. Nevertheless, when installing an acoustic monitoring system, preparatory experiments and calculations are suggested (see list of guidelines).
For the development of the mechanical quench experiment investigating the actual quench sensitivity of the sc coil to mechanical shock loads, a semi-analytical model has successfully been developed which employs a reduced modal state space representation of the coil dynamics and Hertz'ian contact theory. Compared to a fully FEM based modelling it allowed for extensive parameter studies at significantly reduced time and costs.

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