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HIGH FIDELITY NUMERICAL MODELLING AND CONDITION MONITORING APPLIED TO SEPTUM MAGNETS AT CERN

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Abstract

The CERN Accelerator Beam Transfer group has recently launched a study to investigate the life cycles of pulsed septum magnets. The development is aiming to enhance the prediction of anomalies, leading to reduced life cycles of these beam transfer equipment. For this reason, the standard vacuum operated, direct drive septa magnet has been chosen to investigate critical design features. In the initial project phase, a so called High-Fidelity (HF) numerical simulation has been carried out, providing insight on critical components, like brazed joints, reducing the fatigue life. In parallel a dedicated test setup with state-of-the-art instrumentation has been developed, allowing to confirm the predicted system response. The novel approach for the beam transfer equipment will allow to review presently established design criteria. In a further iteration, the project is now aiming to demonstrate an anomaly detection and their prediction based on novel machine learning techniques. This paper presents the initial phase of developing the HF model, as well as the results of the instrumented magnet tests which will be compared to results from the numerical simulations.

INTRODUCTION

The CERN Accelerator Beam Transfer group in a frame of tripartite collaboration, has recently launched a study to investigate the life cycles of pulsed septum electromagnets. The development aims to build real-time monitoring system for beam transfer devices being capable of detecting anomalies and predicting failures. A direct drive septum electromagnet – the SMH58 has been chosen to develop High-Fidelity (HF) simulation workflow based on Finite Element (FE) models to investigate critical design features and generate datasets for a reduced order model development.

The selected electromagnet was designed for the extraction of electrons from the Proton Synchrotron (PS) accelerator at CERN (Fig. 1). The analyzed unit was an operational spare, so it has never been used in the accelerator. It is not irradiated and have not experienced large number of stress cycles. This is so-called “virgin” state of the device. It also incorporates common design features and materials. That is why it will serve as a representative example.

The single-turn coil, which consists of several oxygen-free copper bars and stainless-steel cooling channels, is the main component of the magnet. The components were joined using the vacuum brazing technology. A thin part of the coil is called the septum blade. It separates high- and low-field regions. A front side the blade is supported by the stainless-steel clamps, and a back side, by a system composed of levers and flat beryllium copper springs. The magnetic yoke is made of 0.35 mm thickness electrical steel laminations of 3% silicon content with insulating coatings on both sides. Additionally, the assembly includes electrically insulating components made of Kapton or an aluminum oxide. Further details can be found in the article [1].

Figure 1: The SMH58 septum magnet out of the vacuum tank (length x width x thickness of the septum blade [mm]: 803 x 25 x 3).

PROJECT METHODOLOGY

Figure 2 represents the parameter space and the analysis structure chosen to investigate the performance of the SMH58 magnet. The parameter space consists of four domains of investigation. Each of them is composed of analytical, numerical and measurement campaign. This article focuses mainly on the mechanical domain. Electromagnetic characteristics have been validated prior to launching the mechanical analysis. Although the magnet was designed to operate in a vacuum, the initial study is carried out at ambient pressure conditions. The analyzed structural and magnetic phenomena will not be impacted by this simplification. It will be of importance for the next modeling iteration related to the heat transfer analysis. With respect to irradiation, the impact on material properties will be investigated in the future [2, 3]. Although the analyzes and measurements were done for several operating conditions, presented work focuses on the selected case (Table 1).

Table 1: Test Conditions

Parameter	Value	Unit
Electric current (peak)	25.47	kA
Pulse duration	2.6	ms

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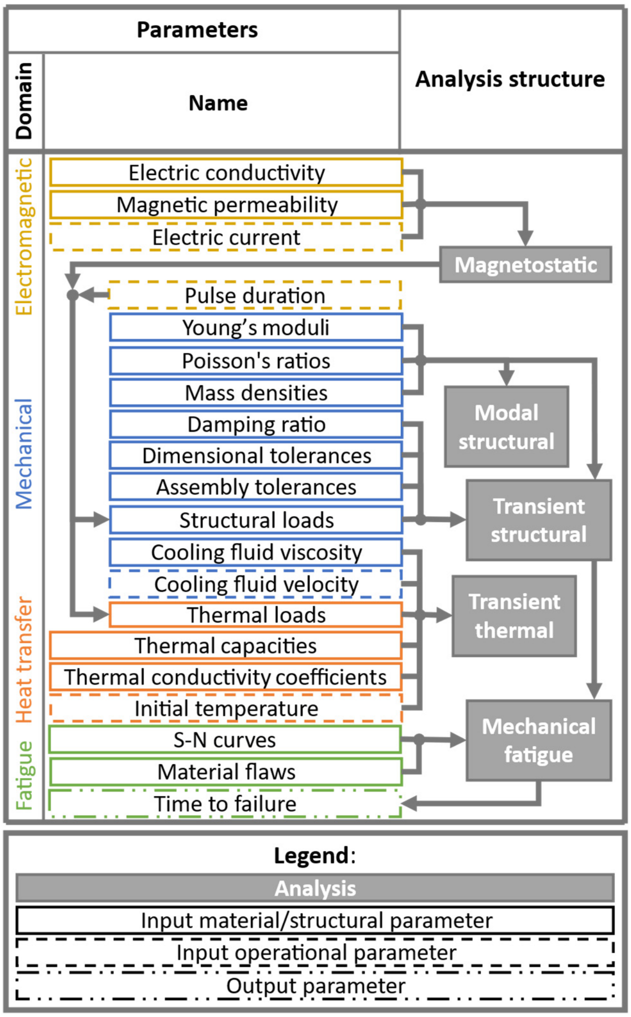

Figure 2: Parameter space and analysis structure.

ELECTROMAGNETIC DOMAIN

The magnetic flux density in the gap of the SMH58 was calculated analytically and numerically as well as measured with the magnetic probe. During the measurement, the magnet was driven with the half-sine pulse (Table 1). The analytical, numerical and measurement results are 1.28, 1.28 and 1.27 T respectively. The measured value was used to calculate the Lorentz force acting on the septum.

MECHANICAL DOMAIN

In the initial phase, the inherent dynamic behavior of the coil was determined. Modal analysis has been carried out for Boundary Conditions (BCs) free and a constraint model. Subsequently a High-Fidelity (HF) numerical model was developed to capture a complex response of the SMH58 assembly. The analyzes were followed by the experimental campaign.

Modal Analysis

In analytical calculations, it is assumed that the septum blade is a prismatic beam of a rectangular cross-section. It has homogeneous, isotropic material which obeys Hooke's law. The general solution of the function X which determines the normal mode shapes of lateral vibrations is shown in Eq. (1) [4]:

$$X = D_1 \sin(kx) + D_2 \cos(kx) + D_3 \sinh(kx) + D_4 \cosh(kx) \quad (1)$$

where:

$$k^4 = 4\pi^2 \frac{\rho S f_n{}^2}{E I_b},$$

E – is the Young's modulus,
ρ – is the mass density,
S – is the area of the cross-section,
I_b – is the area moment of inertia of the cross-section,
f_n – in the n-th natural frequency.

Due to the geometry transition at the ends of the septum blade, no displacements and no rotations BCs are assumed at these locations. Equation (2) shows the specific solution that was derived:

$$\cos(kl)\cosh(kl) = 1 \quad (2)$$

where:
l – is the length of the septum blade.

Two Finite Element (FE) numerical models of the coil were developed. The first one so-called "free-free" model is free of loads and free of boundary conditions. The numerical and analytical results are shown in Table 2. The 1st lateral mode of the septum blade is shown in Fig. 3.

Table 2: Free-Free Modal Analysis - Verification

Mode	Frequency [Hz]	
	FE model	Analytical model
1st lateral	18.1	17.3
2nd lateral	49.0	47.8
3rd lateral	102.6	93.7
4th lateral	158.3	154.9

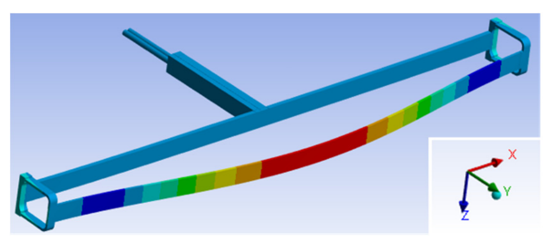

Figure 3: Free-free modal analysis – the 1st lateral mode.

The second modal analysis includes constraints to reflect the measurement setup. During the measurements the structure was excited with the electrodynamic shaker. The model includes the clamping of the cooling pipes and the fixation to the electrodynamic shaker. A 3D Laser Doppler Vibrometer (LDV) measurement has been carried out. The comparison showed strong agreement (Table 3).

Table 3: Constrained Modal Analysis - Validation

Mode	Frequency [Hz]	
	FE model	LDV measurement
1st lateral	14.7	15.0
2nd lateral	48.9	51.2
3rd lateral	100.5	107.5
4th lateral	157.3	166.9

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Transient Analysis

A High-Fidelity (HF) transient structural model was developed to capture the transient structural response of the septum magnet. The FE model, composed of 700 thousand linear elements, has two symmetry planes. The frictional contacts are defined between several contact pairs: blade-clamps, blade-levers and (return conductor)-springs. The spring-lever pairs are bonded. The BCs, other contact regions and loads are shown in Fig. 4. The analysis steps are given in Table 4. The time integration is present in 2nd, 3rd and 4th step.

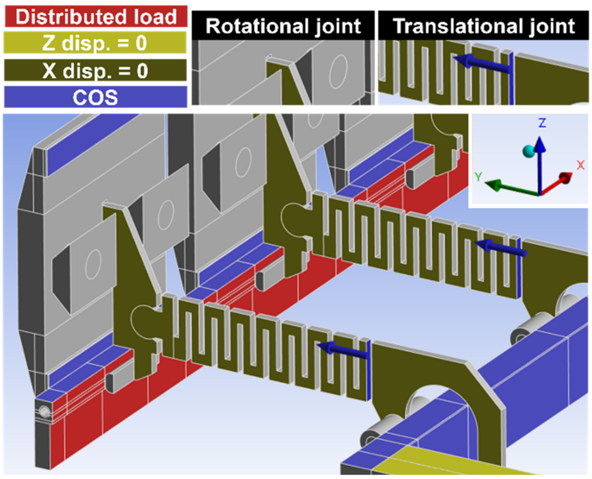

Figure 4: HF model (COS - "compression only support", X disp. = 0 – no displacement in the X-axis).

Table 4: Transient Analysis Steps

Step	Description	Stabilization
1st	Spring pretension	N/A (static)
2nd	Spring stabilization	Yes
3rd	Electric pulse	No
4th	Structural response	Yes

The numerical results showed the deformation patterns in the time domain. They provide insight into the stress cycles which are crucial for the lifecycle prediction. In Table 5, the maximum velocity and displacement over time in the center of the septum have been compared. An influence of the damping, contact and solver settings will be investigated in the subsequent step.

Table 5: Transient Analysis – Validation

Parameter	HF model	LDV (averaged)
Max. disp.	39.5 µm	32.7 µm
Max. velocity	0.10 m/s	0.26 m/s

The punctual vibration measurements on several locations have been carried out using the single-point LDV as shown in Fig. 5. The electric pulse was triggered every 10 seconds to avoid a significant overlap of vibrations (the overlap was seen for shorter durations - 1 s and 2 s). The measurements were studied in different frequency ranges. The results from the campaign are shown in Fig. 6, for the frequency up to 350 Hz. The pulse response waveform has been split in four 1-second timeframes. Fast Fourier Transform (FFT) for each of these frames was calculated and then averaged over three consecutive pulses. In Fig. 6, the waveform split of the first pulse was shown as an example. Future LDV measurements are also considered under vacuum conditions, an initial performance demonstration based on measurement through a standard vacuum feedthrough window has shown satisfactory results.

Figure 5: Vibration measurement setup.

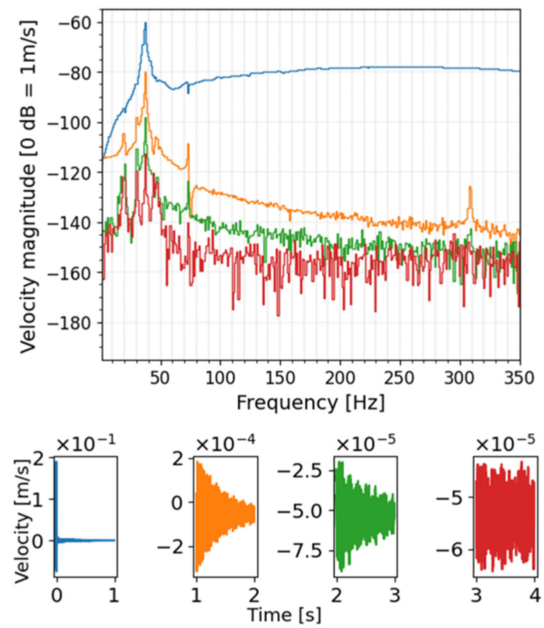

Figure 6: Dynamic response of the SMH58 magnet (each color indicates specific time frame).

CONCLUSIONS

The methodology for reduced order modelling, aiming to detect anomalies and predict failures in septum magnets, has been presented. The numerical and measurement results showed strong agreement. The model is suitable for the development of the anomaly detection and life cycle prediction system. The 1st and 2nd lateral modes of the septum blade are clearly visible in the dynamic response both on the level of the coil and the assembly. This characteristic is foreseen to be used for the septum condition monitoring.

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