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Carbon Fiber Reinforced Polymers for High-Dynamic Testing Machines

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Abstract

Main design objective of high-dynamic multiaxial testing machines is a high fundamental frequency. Carbon fiber reinforced polymers (CFRP) offer outstanding weight-specific properties and high design freedom. They are thus a promising choice for the development of novel testing machines. This paper investigates the challenges which are decisive for a successful implementation of the FRP technology. In order to assess the potential of the approach, an optimized CFRP testing machine is compared to a state-of-the-art metal design. Significantly improved performance at comparable costs indicates that the CFRP technology is a valuable asset to the design of complex low volume special-purpose machines.

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Keywords: CFRP; high dynamics; testing machines; eigenfrequency; freedom of design; laminate optimization; direct tooling

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1. Motivation

High-dynamic multiaxial testing machines (MATM) are used for hardware-in-the-loop (HWIL) simulations of inertial navigation systems, gyroscopes and accelerometers. Although these machines are complex and expensive, their advantages are predominating. Once a HWIL test rig is developed, it can accompany the whole development process of aerospace and defense guidance systems without the need of performing expensive real-life tests. Moreover, MATMs allow for the test of components under extreme conditions that are hard to achieve in real-life application. They are thus a very important tool for the development of guidance systems.

However, the advancement of these guidance systems is driving the demand for improved testing machines. They must be able to achieve higher angular accelerations and velocities without losing stability and precision. As the tests must not be influenced by natural vibrations of the machine, strict requirements for the fundamental frequency of the system must be fulfilled. Improved stiffness and reduced mass of the machine lead to an increased fundamental frequency and hence to a higher usable bandwidth of the system. At the same time, the structure should possess low moments of inertia in order to minimize the required drive power.

Up to now, the moving machine axes are predominantly made as classic box beam designs from magnesium or aluminum. Previous developments veered towards optimization of the magnesium and aluminum alloys with respect to the design requirements. Also, increase of eigenfrequencies was bought by more stiff designs of structural components to the price of higher inertias and the need of more powerful drives.

This article investigates the potential of carbon fiber reinforced polymers (CFRP) as material for the moving structural parts of a MATM. First, a simple material substitution is carried out. Next, more complex structural concepts are investigated that take profit of the freedom of the design of FRP materials. In a final step, a laminate optimization aims at full exploitation of the potential of the material. The manufacturing route for a demonstrator part is presented. The paper concludes with a cost assessment of the optimized MATM.

2. Reference Machine

The testing machine under study consists of a steel base structure on which three aluminum cardanic axes (CA) are mounted as can be seen in Fig. 1. The axes are sized in a way that a 60° field of view cone pointing in Z-direction and originating in the center of rotation is kept free. The outer and middle axes are driven hydraulically, the small inner axis is driven by an electric motor. In order to analyze the dynamics of the machine, a parameterized rigid body model was created and calibrated by experimental modal analysis data. A subsequent sensitivity analysis revealed the outer cardanic axis (OCA) to be the most influencing substructure for the lowest eigenfrequencies of the machine. As a consequence, the OCA is primary target for the machine optimization that is presented in the following.

A simplified FEM model of the outer cardanic axis is used

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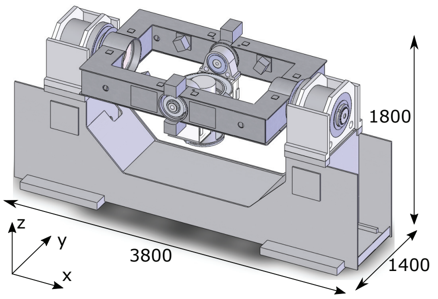

Fig. 1. Reference aluminum testing machine. Dimensions in [mm].

with the middle and inner axis substituted by a point mass of 305 kg. It is attached to the OCA by rigid body elements. Fig. 2 shows the aluminum reference model. The colors indicate the wall thicknesses of the structure. The material properties can be found in Tab. A.7.

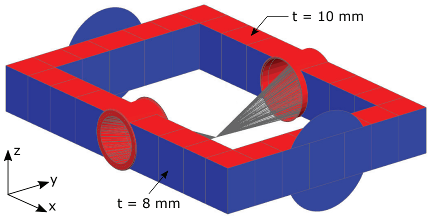

Fig. 2. Simplified model of reference machine

In order to assess the performance of the system the following simulations are carried out:

- Modal analysis: Calculation of the fundamental frequency f_1
- Stiffness analysis: Calculation of the total deformation δ of the structure when maximum angular acceleration $\ddot{\omega}_x = 15.000\ °/\mathrm{s}^2$ is applied
- Strength analysis: Calculation of the margin of safety (Ψ) against failure when counteracting drive torques of 29 000 Nm occur on each side of the outer axis. The margin of safety is obtained from

$$\Psi = \frac{R_{p,0.2}}{\sigma_{Mises,max}} - 1\,. \qquad (1)$$

Additionally, inertia I_{xx} and mass m of the OCA are determined.

The results of the analyses of the simplified FE model for the reference machine are summarized in Tab. 1. The fundamental eigenmode of the structure is depicted in Fig. 3.

Table 1. Results overview

	Reference
f_1 [Hz]	78.6
I_{xx} [kgm^2]	51.8
f_1/I_{xx} [Hz/kgm^2]	1.52
m [kg]	172.0
δ [mm]	0.54
Ψ [-]	6.1

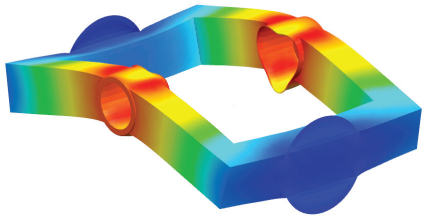

Fig. 3. First eigenmode of reference structure at 78.6 Hz

3. Material Substitution

As a first optimization measure, a material substitution for the OCA is carried out. Fiber Reinforced Polymers (FRP) appear as a promising choice for improving the performance of the system. Due to the common fiber and matrix materials having a low density, good weight-specific mechanical properties of FRPs arise. Especially carbon fiber reinforced polymers (CFRP) are able to achieve weight-specific properties in fiber direction up to one magnitude higher than those of metals, whereas the properties transverse to the fibers are governed by the matrix material and thus are relatively low. Therefore, layers are typically stacked with different fiber orientation angles. By regularly distributing the fiber orientation in all directions, quasi-isotropic (QI) laminates can be achieved. Fig. 4 shows a polar plot of the Young's moduli of a laminate of T300 standard fibers in an epoxy matrix (Tab. A.7) in unidirectional (UD) and $(0/45/-45/90)_s$ QI configuration. They are compared to aluminum. The moduli are normalized by the one of aluminum.

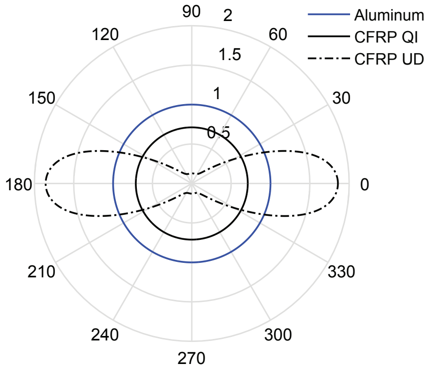

Fig. 4. Young's moduli of aluminum, CFRP QI, and CFRP UD normalized by $1/E_{alu}$

The most anisotropic UD laminate is able to achieve a stiffness in fiber direction about 1.8 times higher than aluminum. On the other hand, the more relevant QI laminate has an elastic modulus that is significantly lower than that of aluminum. As it appears, aluminum is able to compete with CFRP as a lightweight material without any difficulty. However, the material densities have not been considered so far. Fig. 5 shows the same content but normalization also contains the respective material densities. Now it can be seen that even the QI laminate surpasses the weight-specific stiffness of aluminum. Hence, a