Guest Forum

High Performance Shafts for Engine and Powertrain Test Beds based on Glass or Carbon Fiber Polymer Composites.

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In engine, powertrain or e-motor test applications electrical dynamometers connected by shafts to the specimen have to simulate or replicate the load the specimen would see in the real world. Increasing demands on measurements signal quality, speed range and acceleration rates on one side and significant improvements in dynamometer performance on the other side caused the shaft connection becoming a key limiting factor. Therefore HORIBA Europe GmbH has started a research project together with the Institute of Lightweight Design of the TU Darmstadt with the support of public funding by the Hessen Agentur GmbH. The article gives a short introduction to the application and to fiber polymer composites and reveals some differences to metal constructions. Furthermore it discusses the main aspects of the carbon shaft design as well as the construction of the first prototype.

ダイナモメータは，試験対象のエンジン，パワートレイン，電気モーター等と連結軸で繋がり，実際の負荷をシミュレートし確実に再現しなければならない。一方で測定信号品質，速度範囲，および加速率に対する応答性の要求が高まり，他方ではダイナモメータの性能の著しい向上により連結軸が，負荷の再現を阻害する主要な制限要因となってきた。そのためホリバ・ヨーロッパ社(ドイツ)はダルムシュタット工科大学の軽量設計研究所と共に，Hessen Agentur GmbHからの公的資金の支援を得て研究プロジェクトを立ち上げた。本論文ではこの用途および繊維・ポリマー複合材料についての簡単な説明を行い，金属構造とのいくつかの相違について明らかにする。さらに，カーボン軸の設計ならびに最初のプロトタイプの構造に関する主要な点について述べる。

Application Requirements

When testing powertrain components the loads of the missing parts in the environment of a test bed compared to the real world vehicle have to be replicated or simulated. In case of an engine test bed an electrical dynamometer is connected to the flywheel of the unit under test by a shaft connection. The dynamometer has to simulate the load the engine would see in the real world. In case of a transmission test bed multiple dynamometers are connected by shafts to the input and outputs of the transmission. The unit under test, the dynamometers and the elastic shaft connections are forming a multiple mass-spring system with a number of natural frequencies with low damping. It cannot be avoided that these natural frequencies are excited by the firing frequency of the combustion engine, rotational frequencies of the dynamometer, not ideal balanced test bed components, pitch errors or just gear shifting. This will at least cause low quality measurements results of torque and speed signals, but may also result in unrealistic wear of the specimen or in the worst case will cause damage of the specimen and/or test bed components. When designing a test bed it is targeted to move the natural frequencies into "not dangerous" operating ranges by selecting the right shaft connections with dedicated spring rate and damping rate. For example engine test beds are designed in a way that the natural frequency is excited only in the range between starting speed and idle speed, which was not really a normal operating range. However with the introduction of start-stop systems starting and stopping the engine has become a regular test scenario as well. Additionally improvements in the dynamometer technology allow manufacturing of very low inertia dynamometers. These dynamometers provide an extended operating range of test beds with increased demands on measurement signal quality and the inertia of the existing shaft technology is no longer negligible compared to the dynamometer inertia. The shaft inertia is in the same range as the dynamometer inertia. E-motor and hybrid applications require testing at a high speed of more than 15000 rpm. At these speeds the allowed overhang masses are very limited and high weight shafts cannot be used.

Therefore it is a must to develop a new generation of shafts which meets the future requirements and allow HORIBA to remain competitive.

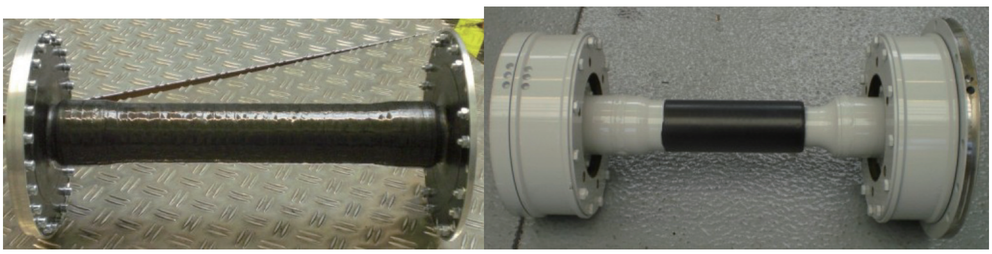
State of the art is using shafts made of steel, Titan or aluminum combined with rubber plates which define stiffness and damping. The rubber plates do have significant damping, but caused by the production process the variance of the stiffness is quite high. Target of the research project together with the University of Technology of Darmstadt is to develop shafts with defined damping and stiffness and at the same time low weight and inertia.

Key to meet the design targets was to use a carbon fiber reinforced shaft combined with a diaphragm coupling flange. (Figure 1) Carbon fiber reinforced shafts already exist on the market however together with steel couplings at the end which have to provide the flexibility. The weight of these shafts is therefore still quite high. The main targets of the project were:
- minimizing the weight by designing the flexible coupling as well out of fiber polymer composites
- defined low stiffness
- high damping rate

The project is supported by the Hessen Agentur GmbH an organization of the Hessen Government to promote the local economy.

Short introduction to fiber polymer composites

Fiber polymer composites provide very high stiffness and strength in relation to their mass density, which is known to be one of the main characteristics of lightweight



(a) (b)

Figure1 (a) Carbon Fiber Shaft and (b) Küsel Coupling

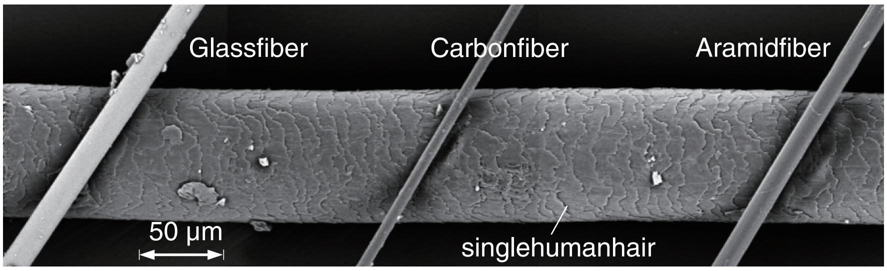


Figure 2 The commonly used fiber types in comparison to a single human hair[1]

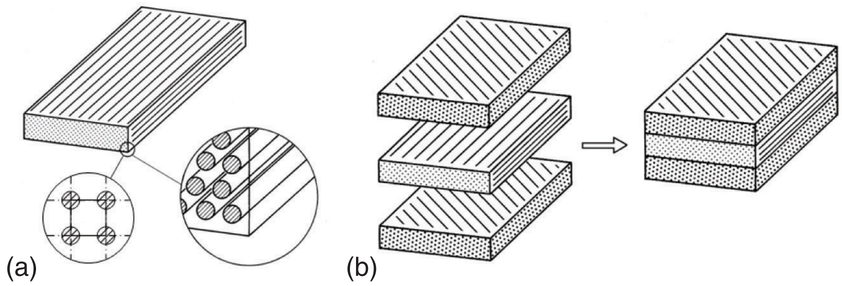


Figure 3 (a) Unidirectional layer (b) Multi-layer composite consisting of single layers[1]

construction materials. This is achieved by combining fibers and matrix in a way that yields material properties which the single components by themselves could not attain. Most commonly carbon or glass fibers are used glued together with an epoxy resin. (Figure 2)

The designer of fiber polymer composites has to handle much more parameters than the designer of metal parts, which makes design much more complex. For example: In a single layer or unidirectional layer (UD) the fibers are oriented parallel in one direction as shown in Figure 3(a). As a result the UD shows, in contrast to metals, orthotropic material properties. In this case there are 3 plains of symmetry that are orientated orthogonally to each other. Instead of 2 engineering constants - stiffness modulus (E) and Poisson's ratio (ν) as for isotropic metals, there are 9 engineering constants - 3 stiffness moduli (E_1, E_2, E_3), 3 shear moduli (G_{12}, G_{13}, G_{23} and 3 Poisson's ratios (ν_{12}, ν_{12}, ν_{23}) - needed to fully describe the fiber polymer constitutive law. Due to the fact that load cases are mostly multiaxial, the load-bearing fibers need to be arranged in different directions, which are quantified by angles. These can be achieved by stacking several UD-layers together building a multi-layer composite, called laminate (Figure 3(b)). These different angles represent another important design parameter.

Choosing different angles between the UD also varies the stiffness and strength of the composite. Hence, the outer strains of the laminate do not line up with the orthotropic coordinate system any longer; therefore 2 coordinate systems are used as shown in Figure 4. The x,y-coordinate system shows the laminate coordinate system which is fixed. The 1,2-coordinate system of the UD-layer is orientated in an angle α in relation to the laminate

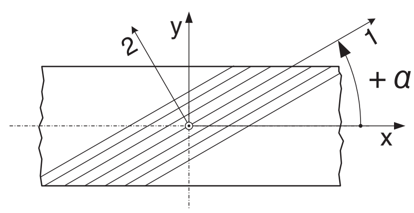


Figure 4 1,2-coordinate system of the UD-layer and x,y-coordinate system of the laminate[1]

coordinate system.
Mechanical properties and strains of the laminate can be calculated using the Classical Laminate Theory (CLT). For further details please see [2] and [3].

Shaft construction

Shaft construction includes several aspects that need to be considered and which can cause conflict of objectives:
1. Strength
2. Stiffness: torsion stiffness and bending stiffness
3. Buckling stability
4. Damping
5. Natural harmonics: torsion harmonics and bending harmonics

The following discusses each aspect of the previously mentioned objectives:

Strength: Highest composite strength can be achieved by placing the fibers in the main load case direction I, II. The load case of the shaft is torsional shear. Figure 5 shows an element under shear load. In this case the main axes lie in an angle of 45°. From this it is determined that using a ±45° ply is the best construction in terms of lightweight design.

Stiffness: The highest torsional stiffness can be reached by using a fiber angle of 45°. The more angles differ from 45° the lower the torsional stiffness will be. On the other hand a fiber orientation of 0° which is the axial direction of the shaft provides the highest bending stiffness.

Torsional buckling: Besides strength failure, shafts can also show buckling failure. To prevent a shaft from buckling a steep fiber angle around 65°-85° should be used in the outer layer.

Damping: Fibers are very stiff and therefore do not provide good damping properties. In contrast the matrix with its viscoelastic properties shows good damping properties. In order to attain damping in the laminate loads have to be guided through the matrix. This can be achieved by choosing fibers angles which are not too close to 45°.

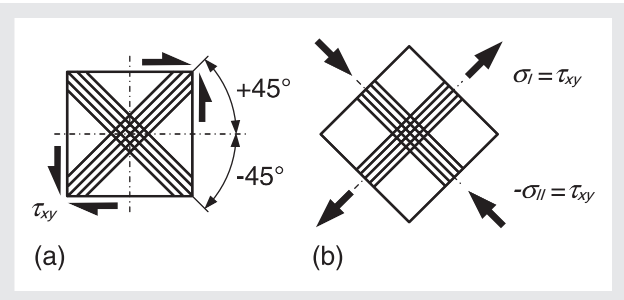


Figure 5 (a) Element under shear load
(b) Shear load transformed to the main axes[1]

Natural harmonic: Especially bending harmonics can limit the revolutions per minute. Therefore it is important to provide sufficient bending stiffness.

Taking all the above mentioned aspects into consideration the optimal construction of the carbon shaft turns out to be as shown in Table 1. Fiber angles differ from 45° to provide damping and low torsional stiffness. The layer with a 15° angle produces bending stiffness and the layer with 65° yields a high buckling moment.

Table 1 Carbon fiber shaft laminate design and lay up

Layer thickness	Fiber angle
0.8 mm	±65°
1.0 mm	±15°
0.8 mm	±65°

The shaft is connected by a carbon fiber diaphragm coupling to the engine and the dynamometer. The diaphragm design is based on specific fiber arrangement which allows the diaphragm to be flexible in axial direction as well as angular movement. Table 2 summarizes the result of the shaft including diaphragm and aluminum adapters for centering on the engine and the dynamometer. Weight and inertia are about 10 times lower as conventional steel shafts.

Table 2 Results in Summery

Parameter	Value
max. torsional impact moment M_{max}	2400 Nm
torsional failure moment M_F	3000 Nm
axial movement U	1.2 mm for 20 kg
	1.8 mm for 40 kg
crit. revolution per minute n_{crit}	> 12000 rpm
torsional stiffness c_T	13723 Nm/rad
mass m	2030 g

Status

The first prototype based on this design was manufactured and tested in 2011 (Figure 6). Based on the results an improved 2nd generation was designed and manufactured. Testing is still in progress.

Especially the design of the diaphragm has turned out to be critical as there is only a small window which provides sufficient strength on one side and elasticity to

Figure 6 Handover of the carbon shaft

compensate misalignment and axial movement on the other side. Furthermore other constructions for optimized damping properties in the shaft are in the planning process. It can be also imagined instead of running the shaft supercritical to increase torsional stiffness in a way which allows having it work subcritical. In this case the shaft does not go through resonance.

References

[1] SCHÜRMANN, Helmut: Konstruieren mit Faser-Kunststoff-Verbunden. Berlin Heidelberg New-York: Springer Verlag, 2007

[2] CHAWLA, Krishan Kumar: Composite Materials: Science and Engineering. New York: Springer Verlag, 1987

[3] PHILLIPS, Leslie N: Design with Advanced Composite Materials. London: The Design Council, 1989