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MODAL ANALYSIS OF HYBRID 'STEEL–COMPOSITE' DISC OF THE INDEXING GEARBOX TURRET FOLLOWER

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Abstract: *The indexing gearbox is used in dynamic applications. To improve its dynamic performance, the hybrid indexing gearbox turret follower disc consisting of a composite body with the steel inserts for pins and a steel shaft flange has been introduced. Such a hybrid disc composite body is made of long-fiber epoxy composite using fiber in place (FIP) technology. That allows integration of inserts into the part during the lamination process. Newly designed hybrid discs have undergone modal analysis in this work to determine their natural frequencies and assess their dependency on composite fiber volume ratio. Results of modal analysis show that 35 % of fiber volume ratio is the limiting value under which natural frequencies of FIP hybrid disc are lower than frequencies of steel disc. The first two modes have similar frequencies which can lead to their superposition. Typical values of 50 % of fiber volume ratio FIP composite shows 11 % increase of frequencies in comparison with steel disc and these frequency values are out of operating frequency range. FIP technology is suitable for hybrid "steel-composite" disc in turret follower application as it contributes to improvement of dynamic performance of the mechanism or its individual parts.*

Keywords: Indexing gearbox, Carousel body, CFRP, FIP technology, FEA

1. Introduction

The indexing gearbox transfers uniform rotary motion of the input camshaft to unidirectional rotary motion with clearly defined dwell portions of the mechanism output shaft. A three-member mechanism contains at least one radial or axial cam connected to the driven member by at least one general kinematic pair. The shape of the transmission function – stroke dependence has a direct effect on the dynamic behavior and mechanical properties of the system. The active surface of the cam is usually determined by kinematic synthesis, which is based on the knowledge of the relevant stroke dependence of the given cam mechanism and its dimensional parameters. Indexing gearboxes are widely used in production and handling machines with so-called 'hard' automation. They are used in highly dynamically loaded applications and where the problem of service life and transmission of large, variable and impact torque with the key requirement of high positional accuracy arises. (Ondrášek, 2019)

Dynamic performance optimization of mechanisms is feasible by material structure modification. In the case of replacing steel with composite, it usually involves changes in geometry as composite material is anisotropic. The possibility to create composite material from microstructure allows us to fully control laminate mechanical properties and customize them right to application demands and technological limitations.

2. Turret follower assembly

An indexing gearbox assembly consists of a camshaft input part and a turret follower output part of the mechanism. (Fig. 1) There is a shaft, four discs (disc A and B differ only in thickness), number of pins and a roller in the turret follower assembly. A sub-assembly consisting of a shaft and discs is called a carousel body. All parts of the gearbox are traditionally made of steel. Dynamically loaded steel parts have a big mass and moment of inertia. Therefor further material optimisation can reduce these characteristics and improve dynamic performance of the whole assembly.

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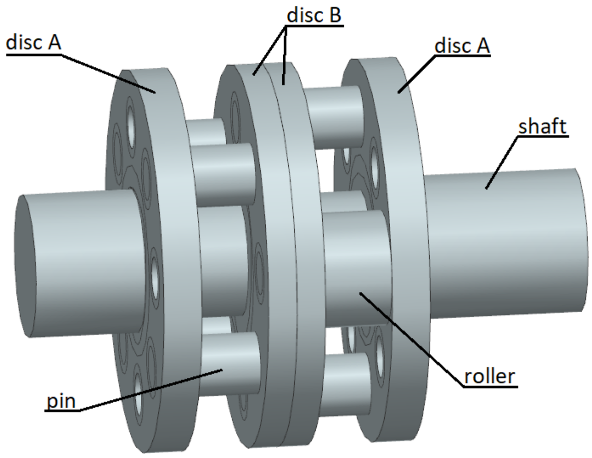

Fig. 1: Turret follower assembly

The shaft and discs used to be machined as one piece. Current patented solution of a camshaft and cams (Patent CZ 306709) enables their separate manufacturing and thus assembling and disassembling. (Ondrášek, 2023) It creates opportunity for a reduction of turret follower assembly's mass and disc's moments of inertia by disc's material optimization.

3. Disk re-design

Discs A have diameter of 80 mm and thickness of 8 mm. Discs B have the same diameter and thickness of 6 mm. There are holes for pins on which a roller is placed. The mass of steel disc A is 0.19 kg and mass of disc B is 0.14 kg. The moment of inertia of steel disc A is 188 kg/mm^2 and the moment of disc B is 140 kg/mm^2. Used steel designation is X155CrVM012.

Composite material has its specifics which must be followed during the design process. Geometry optimization is necessary to reduce stress concentration in specific regions such as bonding areas in hybrid structures. For that reason, several geometries shown in Fig. 2 have been analyzed. Analysis results showed that for selected technology the convex shape of pin insert is the best "mechanically oriented" solution and regular shape insert is the acceptable "simple way" solution of pin insert. (Zbončák, 2024)

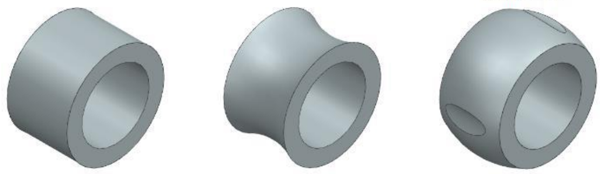

Fig. 2: Steel inserts for pins (regular – concave – convex with notches)

Using composite material for a disc reduces the mass of a single disc by 60 %. The mass of the entire turret follower assembly is reduced by 35 %. Moment of inertia depends on a mass distribution around the axis of rotation. As the geometry of the discs (A and B) stay the same, the only parameter with influence on the value of the moment is the density of used material. Using hybrid "steel-composite" discs reduces discs' moment of inertia about 65 % and entire turret follower assembly's moment of inertia about 44 %. (Zbončák a Ondrášek, 2024)

4. Composite material

The manufacturing technology for this application is a "forged carbon" technology, also called "forming in place" (FIP). This process uses long fibers (up to 20 mm) instead of continuous fibers or weaved fabrics mixed with epoxy resin. It allows manufacturing of the hybrid "steel-composite" disc with inserts in one step. The benefits of this technology are its efficiency, possibility of using recycled fibers, manufacturing of complex shapes or the use of mechanical locks of inserts for increasing joints strength.

HR carbon fibers such as T300 and epoxy resin are used in this application. The forged carbon fiber weight ratio is usually 40 – 60 %, which means 30 – 50 % of fiber volume ratio using this technology. Higher fiber volume ratios are achieved with optimized manufacturing conditions. For comparison, fiber volume ratio with continuous fibers is about 70 %. Technology and application are under utility model no. CZ 38182 U1 protection.

Modal analysis is used to determine natural frequencies, mode shapes and damping of the structure. Using this method can help to adjust fiber orientation and constituents' ratio in laminate design optimization process. Monitoring changes in dynamic properties may help to indicate cracking, delamination, or material degradation in non-destructive damage detection process. Composite material is anisotropic which means that mechanical properties are direction dependent. That affects the modal analysis results by factors such as geometry, layup, damping or defects. (Treviso, 2015)

Higher modulus of the fibers helps to reach higher natural frequencies of the laminate. Composite materials exhibit higher damping than metals due to energy losses in the polymer matrix. This affects the amplitude of vibrations. Voids as "third" constituent of the laminate play a significant role in laminate dynamic performance as they reduce laminate stiffness. The reduction in stiffness leads to a downward shift of the natural frequencies, since natural frequencies are proportional to the stiffness and inversely proportional to the mass of the structure. Porosity causes asymmetrical mode shapes. If porosity is unevenly distributed, it can cause local resonant frequencies to arise. (Pramod, 2023)

5. Hybrid disk modal analysis

Finite-element model consists of three parts: steel flange for a shaft, composite body and steel inserts for the pins. Hexa20 elements are used in 3D mesh. Forged laminate has 32 symmetrical layers where each layer is rotated by 22.5° to neighboring one which represents "idealized" homogenization of material properties for forged carbon composite.

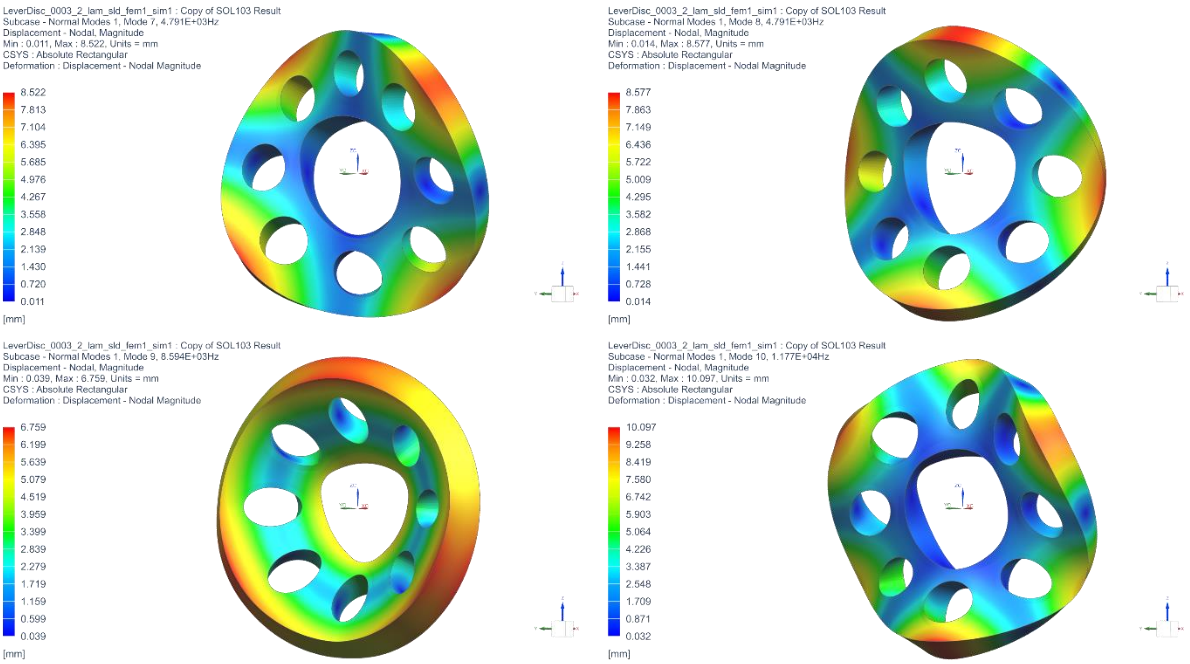

Fig. 3: Hybrid (Forged 50 %) disc mode shapes.

Material properties are specified especially by steel elastic modulus of 200 GPa, reinforcement modulus of 230 GPa and resin modulus of 4 GPa. Steel density is 7 740 kg/m^3, reinforcement density is 1 760 kg/m^3 and resin density is 1 200 kg/m^3. Simulated mode shapes of hybrid "steel-composite" disc (V_f = 50 %) are shown in Fig. 3. Other material properties are calculated according to the micromechanical models. (Zbončák, 2018)

6. Discussion

Natural frequencies of the first four modes are summarized in Tab. 1. There are simulation results of steel disc and 5 different "fiber volume ratio" composite discs distributed in 5 percent increments. The first two modes have higher natural frequency from 35 % fiber volume ratio. All modes have higher values of natural frequencies from 40 % fiber volume ratio. As operating frequency is up to 1 000 rpm which is 16.67 Hz, even the steel disc is not going to reach the resonance in normal operation.

Tab. 1: Natural frequencies (Hz) of hybrid "steel-composite" disc.

	Steel	**Forged**	**Forged**	**Forged**	**Forged**	**Forged**
Vf	**-**	**30 %**	**35 %**	**40 %**	**45 %**	**50 %**
1st mode	4 303	4 249	4 405	4 546	4 673	4 791
2nd mode	4 303	4 250	4 405	4 546	4 673	4 791
3rd mode	7 705	8 095	8 240	8 369	8 486	8 594
4th mode	10 860	10 290	10 710	11 100	11 450	11 770

The higher natural frequencies are, the higher operational excitation frequency can be applied. The 1st and 2nd mode have similar or same frequencies. That can result in the two mode shapes being merged into one (superposition) and consequently it can cause the combined loading leading to failure. The natural frequencies are far from the operating frequencies, so it can be assumed that frequencies will not be excited.

7. Conclusions

The new opportunity of optimization of turret follower parts has occurred after a change in carousel body construction based on patent CZ 306709. The improved concept allows redesign of geometry and material. Using "forged carbon" composites brings benefits like mass reduction, or dynamic performance improvement. Performed modal analysis has shown a small increase of natural frequencies from about 2.3 % for V_f = 35 % to about 11.3 % for V_f = 50 % which means that using composites does not worsen dynamic behavior of the carousel hybrid parts (discs).

"Forged carbon" composite has randomly oriented fibers with high resin content. That gives room for improving mechanical properties by using woven or continuous UD reinforcements with higher modulus. That would need technological modifications of the manufacturing process, but it is good to have some potential space for further improvement. Next step in development process will be manufacturing of a disc prototype and experimental determination of its natural frequencies.

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