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FEM analysis of the options of using composite materials in flexsplines

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ABSTRACT

Purpose: In the present study, as the structural material for toothed flexsplines of harmonic drivers, a composite material based on an epoxy resin matrix reinforced with glass or carbon fibres was used. A preliminary numerical analysis of the material and structural solutions for the harmonic driver flexsplines assumed to be applied was conducted.

Design/methodology/approach: Under the studies performed, geometrical models of flexsplines being manufactured for the HFUC and HFUS type harmonic drivers were developed based on their actual structures and geometrical dimensions. In order to enhance the data preparation process, the model geometry was recorded in a parametrical form. By altering the individual properties of the models, it is possible to automatically generate finite element grids for flexsplines of various geometrical and structural properties. The calculations prepared for the sake of the study by application of the finite element method (FEM) were conducted using the MSC Patran/Nastran and Femap/NX Nastran software.

Findings: Using composite materials in production of flexsplines enables increasing the values of their fundamental vibration frequencies. Using composite materials based on an epoxy resin matrix reinforced with glass fibres causes an increase of the fundamental frequency values by ca. 20%, and if the reinforcement is made with carbon fibres, the values increase by up to 35% compared to flexsplines made of steel.

Research limitations/implications: The technological problem involved in production of flexsplines from composite materials comprises the difficulties related to manufacturing of their rim teeth. A solution to this problem may be fabrication of steel-composite flexsplines.

Originality/value: The results discussed apply to application of new structural (composite) materials for harmonic driver flexsplines that are currently manufactured using alloy steels assumed to be quenched and tempered.

Keywords: Composite materials; Flexspline; Harmonic drive; Finite Elements Methods

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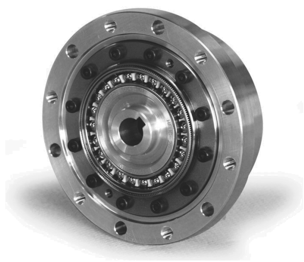
METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Flexsplines of harmonic drivers are used in various spheres of life in a more and more extensive scope of applications. They are currently used for a growing number of purposes in the automotive industry, aviation, medicine, automatic control and robotics [1]. In transmission gears installed in the most important automatic control systems, the problems of their high kinematic accuracy, smoothness in moment transmission and dynamic characteristics (rigidity, damping, moments of inertia and natural frequencies) are becoming increasingly relevant. A toothed harmonic driver (Fig. 1) is a specific toothed mechanism which consists of three fundamental components: an internal gear (the circular spline), a flexspline with an indented toothed ring and a deforming wave generator.

a)



b)

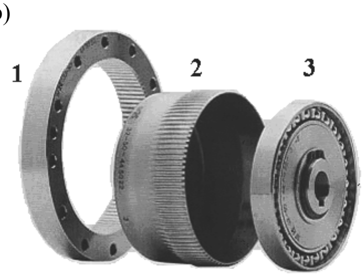


Fig. 1. a) Harmonic drive, type HFUC [1], b) 1 – the circular spline, 2 – the flexspline, 3 – wave generator

The operating principle of harmonic drivers is that the relative motion of the cooperating splines results from a deformation of one of them. The spline being deformed is known as a flexspline, whereas the one cooperating with it is referred to as a circular spline. The generator, usually being a set of mechanical components (e.g. special rolling bearings), generates elastic waves to deform the flexspline. Depending on the number of deformation waves, one may speak of single- or double-wave harmonic drivers.

Harmonic drivers are known of numerous advantages, but they also have certain disadvantages as compared with classical toothed transmission gears. The basic advantages include high torque on relatively small weight and compact structure, coaxiality of the drive shaft and the driven shaft, smooth operation and high kinematic accuracy, whereas the disadvantages of harmonic drivers include high elasticity and minimum gear ratio value as well as nonlinear rigidity and damping.

In harmonic drivers, the external moment is transferred by means of the flexspline cyclic deformation with a wave generator causing a complex state of stress to emerge in this harmonic driver subunit. Therefore, the most heavily loaded, the weakest and the main element of toothed harmonic drivers is actually the flexspline. It is the design of this component and the choice of its material that determine the fundamental properties of the harmonic driver. While choosing the flexspline material, one must consider the deformations and stresses occurring in the flexspline operating in the driver, both unloaded and loaded by the torsional moment. The heat treatment method to be applied to a spline must be determined entailing the criterion of ensuring its elastic properties as well as the service life assumed. Due to the fatigue strength and the permissible hardness necessary for the teeth to be able to cooperate and for the sake of their running-in, flexsplines are subject to the process of quenching and tempering. Then the mechanical working is conducted and the teeth are being indented. The stresses occurring in the circular spline, caused by the torsional moment transferred by the driver, are far lower than in the flexspline. A selection of materials used in manufacturing of harmonic driver flexsplines is provided in Table 1 [2].

Table 1.
Materials used in manufacturing of harmonic driver splines [2]

	Materials
The flexspline	42CrMo4, 35CrMo4, 34CrNiMo6, 40NiCrMo6
The circular spline	C45, C55, 28Cr4

Within the recent years, various attempts have been undertaken to use different structural materials for flexsplines, other than those commonly applied in quenching and tempering [3-5]. An example of such an approach may be a flexspline made of composite materials based on an epoxy resin matrix reinforced with carbon fibres [3]. A flexspline should ensure the capacity for vibration damping, high radial flexibility and torsional rigidity. The authors of paper [3] conducted experimental studies on a prototype of a composite flexspline and compared the results obtained with a traditional steel flexspline. The results obtained evidenced numerous advantages of a composite flexspline compared to a steel one [3]. Using composite materials for harmonic driver flexsplines enables reduction of the wheel weight. Composite flexsplines are characterised by higher radial flexibility and damping capacity. The authors of papers [4-5] performed preliminary tests upon the application of composite materials in production of flexsplines for harmonic drivers.

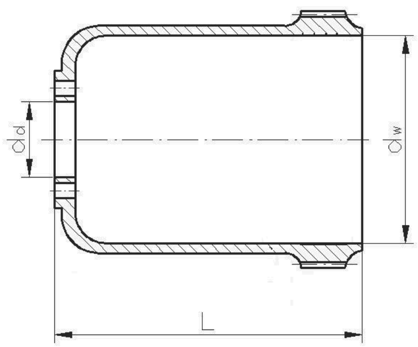
2. FEM models of flexsplines

Under the study discussed herein, an attempt was made to perform a preliminary numerical analysis of flexsplines made of composite materials based on the epoxy resin matrix reinforced with glass and carbon fibres. References to application of the finite element method (FEM) for the analysis of the state of stress in the toothed rims of flexsplines as well as complete gears may be found in publications of numerous authors [6-10]. These works mainly concern two-dimensional models of flexsplines and particularly the analysis of the state of stress in a rim tooth root [6-8] as well as the cooperation between a wave generator and a flexspline [8-9]. The authors of publication [10] conducted numerical calculations for a flexspline by application of a tree-dimensional model. The general interest in using composite materials in various spheres of life has recently been rapidly growing. Numerous theoretical and experimental investigations have been performed to study the use of composite materials, the purpose of which is to increase the number of potential practical applications of those materials [11-15].

Under the studies performed, geometrical models of flexsplines being manufactured for the HFUC and HFUS type harmonic drivers were developed based on their actual structures and geometrical dimensions. The structure and the most important geometrical dimensions of the flexsplines being analysed have been depicted in Figure 2 and described in Table 2. The FEM models developed for flexsplines featuring a base (HFUC) and with an external flange (HFUS) have been shown in Fig. 3. While creating the numerical models of flexsplines, the following assumptions were made:

1. A flexspline is a statically loaded thin-walled axial and symmetric shell;
2. In order to determine the distribution of the load acting on a flexspline, one is to use the results of calculations obtained based on a flat FEM model of a flexspline and a wave generator featuring contact elements [8-9];
3. While modelling the flexsplines, their toothed rims were disregarded. The impact of the rim teeth was taken into account by locally increasing the rigidity of the flexspline wall under the toothed rim by increasing its thickness accordingly.

a)



b)

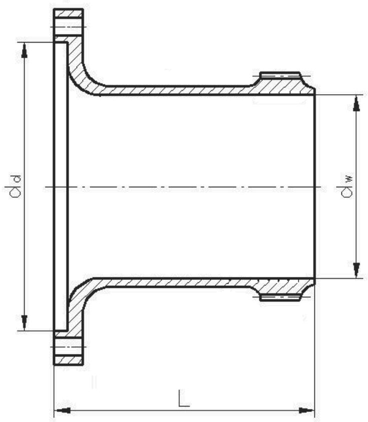


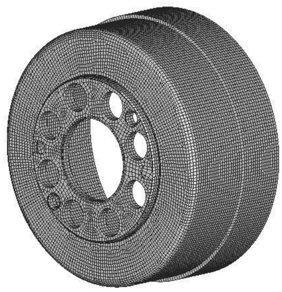
Fig. 2. Basic geometrical dimensions of the following flexsplines: a) the flexspline type HFUC, b) the flexspline type HFUS

In order to enhance the data preparation process, the model geometry was recorded in the form of a processor's macro-commands owing to which, by changing the properties of models, one could automatically generate grids of finite elements for flexsplines of various geometrical and structural properties. The calculations prepared for the sake of the study were conducted using the MSC Patran/Nastran and Femap/NX Nastran software.

Table 2.
Sample basic geometrical dimensions of flexsplines: HFUC 40-100 and HFUS 40-100

L, mm	51
d_w, mm	107
d_d, mm (the flexspline type HFUC)	25
d_d, mm (the flexspline type HFUS)	140

a)



b)

Fig. 3. Three-dimensional FEM models of flexsplines: a) featuring the HFUC base, b) featuring the HFUS external flange

The geometry of the models examined was then recorded using the Femap/NX Nastran system. Tables 3 and 4 contain material characteristics for the steel and composite materials used for the calculations.

3. Calculation results

The modal analysis requires solving an internal problem for the structural model assumed for the structure examined. The established sets of natural periodicities and the forms of vibrations and damping coefficients enable simulation of the structure's behaviour under any chosen input functions. It is applicable in the designing process when it is impossible to conduct tests on the object of study. Knowing the vibration frequencies of flexsplines becomes particularly useful when designing their structures, since it enables avoiding the resonance phenomenon.

Table 3.
Properties of the steel 42CrMo4

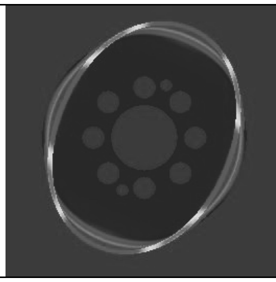
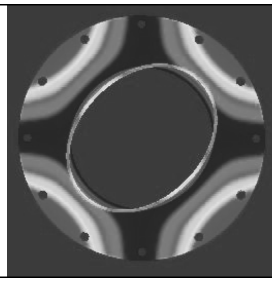
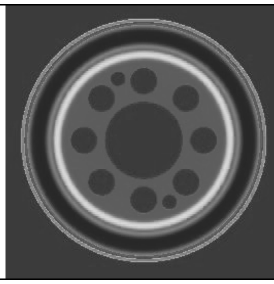
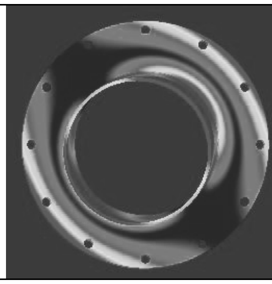
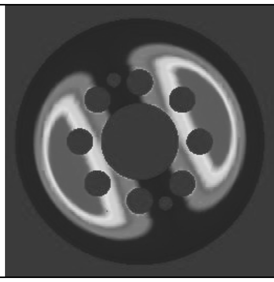
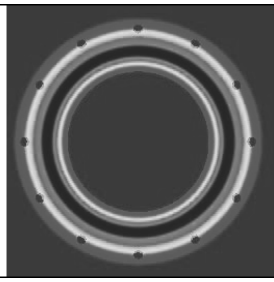
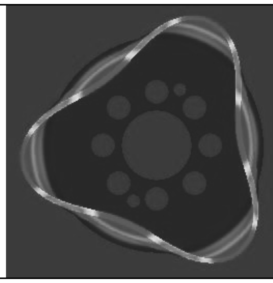
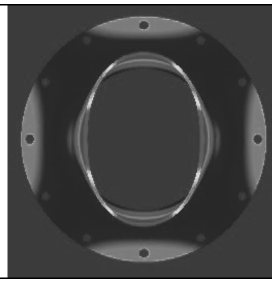
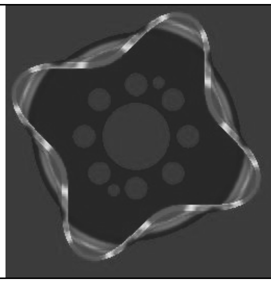
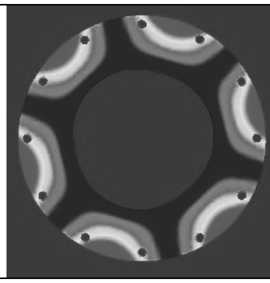
Tensile modulus, GPa	210
Shear modulus, GPa	80
Poisson's ratio	0,3
Tensile strength, MPa	1000
Density, kg/m^3	7850

Table 4.
Properties of the composite materials

Properties of the epoxy resin		
Tensile modulus, GPa	1.3	
Shear modulus, GPa	0.45	
Poisson's ratio	0.40	
Tensile strength, MPa	45	
Shear strength, MPa	29.5	
Density, kg/m^3	1200	
Properties of the fibre	Glass fibre	Carbon fibre
E_L, GPa	43.5	130
E_T, GPa	5.0	8.0
G_{LT}, GPa	5.0	6.0
ν_{LT}	0.25	0.28
Density, kg/m^3	2150	1750

Under the studies in question, four spatial models were developed representing two flexspline design solutions assumed to be analysed, namely one of the HFUC type and one featuring the HFUS type external flange. For each of the structural solutions, two models were assumed differing in geometrical dimensions. Flexsplines of sizes 32 and 40 were analysed on the assumed gear ratio of 100 marked correspondingly HFUC 32-100, HFUC 40-100 as well as HFUS 32-100 and HFUS 40-100 [1]. For the sake of the calculations, three material solutions were assumed for the flexsplines being analysed: flexsplines made of steel (Table 3) and composite materials (Table 4) based on an epoxy resin matrix reinforced with glass and carbon fibres. In the course of the calculations performed by application of the finite element method, basic forms and natural frequencies for the flexspline models in question were established. Table 5 contains sample forms of vibrations for steel flexsplines of the HFUC and HFUS types for size 40 and gear ratio of 100. In Figures 4 and 6, five sample vibration frequency values have been depicted for flexsplines with the HFUC 32-100 and HFUC 40-100 bases made of steel and composite materials. In Figures 5 and 7, the initial five vibration frequency values have been shown for flexsplines with the HFUS 32-100 and HFUS 40-100 bases made of steel and composite materials.

Table 5.
Sample forms of vibrations of the flexsplines analysed

	The flexspline	
	HFUC 40-100	HFUS 40-100
1		
2		
3		
4		
5		

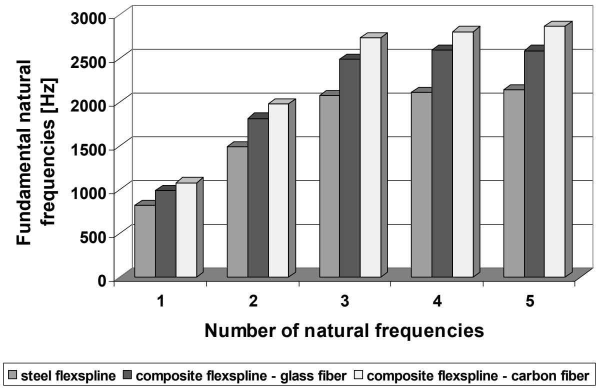


Fig. 4. Fundamental natural frequencies of a flexspline with a base HFUC 32-100

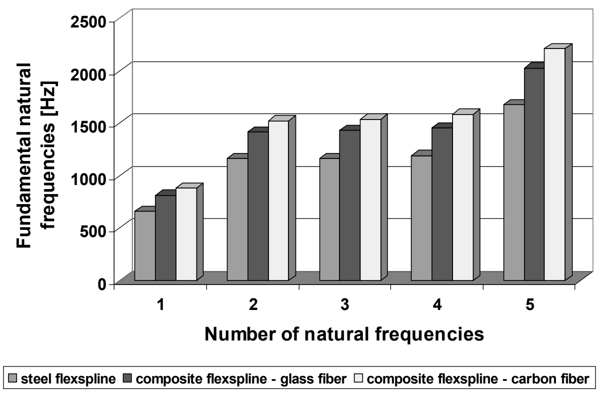


Fig. 5. Fundamental natural frequencies of a flexspline with an external flange HFUS 32-100

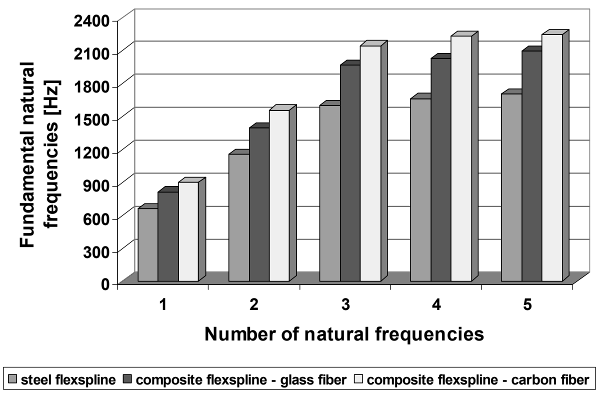


Fig. 6. Fundamental natural frequencies of a flexspline with a base HFUC 40-100

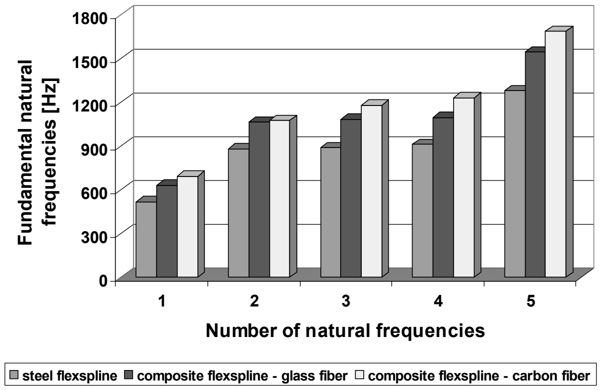


Fig. 7. Fundamental natural frequencies of a flexspline with an external flange HFUS 40-100

Based on the numerical calculation results obtained, one may reach the following conclusions:

1. The influence of flexspline dimensions on the results obtained is relevant. Reducing the geometrical dimensions in the same type of flexsplines causes a decrease in the vibration frequency value (Figs. 4 and 6 and Figs. 5 and 7).
2. In type HFUC flexsplines, compared to type HFUS flexsplines of the same size (Figs. 4 and 5 and Figs. 6 and 7), higher vibration frequency values were observed.
3. Using composite materials in production of flexsplines enables increasing the values of their fundamental vibration frequencies as compared with steel flexsplines. Using a composite material based on an epoxy resin matrix reinforced with glass or carbon fibres caused an increase in the vibration frequency values by ca. 20% and 35% respectively.

4. Conclusions

Using new structural materials in manufacturing of harmonic driver flexsplines may significantly contribute to improving the mechanical and strength properties of these elements. Manufacturing the flexsplines entirely of composite materials enables considerable reduction of the spline weight and increase of the fundamental natural frequency values (Figures 4-7). Using a composite material based on epoxy resin reinforced with glass fibres in flexsplines causes the fundamental vibration frequency values to increase by ca. 20%, and when the reinforcement is provided with carbon fibres, the increase is up to 35% compared to steel flexsplines. In order to fine tune the numerical models developed, an experimental modal analysis of the structural and material solutions assumed for flexsplines is to be conducted.

The problem encountered while manufacturing flexsplines of composite materials is in the difficulties related to fabrication of the teeth of toothed rims that would have similar toothing properties as the traditional involute teeth profiles. This problem may be solved by using flexsplines made of steel and composite materials [16]. A definite advantage of such a solution is that the steel flexspline featuring indented rim teeth can be fabricated according to the traditional technological process, whereas the composite material is laid on the external surface of the steel flexspline thus improving its mechanical properties. Therefore, it seems definitely necessary to perform further experimental tests and numerical analyses concerning application of composite materials in production of harmonic driver flexsplines.

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