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Multibody simulations of a distributed-compliance helical transmission joint for largely misaligned shafts

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Abstract. The manuscript presents the development of a flexible multibody model to study the behavior of a distributed-compliance helical transmission joint. This kind of joint has not already been studied in literature and its simulation challenges with complexities. The flexible multibody approach breaks through these and provides some interesting results. It's exposed first upon the kinematic behavior of the joint; then a stress analysis is provided; and lastly the results of dynamical tests are shown.

Introduction

Transmission joints allow the transfer of mechanical power between generally misaligned rotating shafts [4,6,7,8]. Their design confronts Applied Mechanics with two main tasks, it is:

a) the regularity of the transmission of motion, i.e. obtaining or approximating the optimal transmission ratio of the angular velocities, which is equal to one.
b) the power efficiency, i.e. to reduce the passive work of friction actions. Contact forces and consequently friction tend to be large, due to the necessity of transmitting a high torque through a minimized radial extension.

Concerning both points, rigid-link transmission joints are moreover extremely sensitive to construction and assembly errors [6,8]. Relevant lubrication is needed, and wearing deteriorates the quality of the kinematic operation. A good solution for the task (b) may be the adoption of compliant mechanisms as transmission joints. These kinds of mechanisms work in fact without contacts, save when they are specifically designed, for they are monolithic deformable structures, or made of integrated parts, in which the deformation of some of their portions allows for the desired displacement of others [1,6]. This anyway makes them intrinsically load-sensitive, and so their fitness to task (a) needs to be evaluated. Severe fatigue issues may arise and, further, the dynamics of the compliant-jointed system will exhibit critical frequencies in which resonating effects are produced.

Compliant kinematic-equivalent joints. Compliant transmission joints had insofar been designed generally to reproduce rigid-links kinematic pairings [2,3,5]. In [2] there are examples of several flexures to reproduce revolute joints. In [5] torsional prisms are used to simulate the functional couplings of a Hooke-Joint.

Compliant helical joint (CHJ). Another kind of compliant joint is not based on some rigid-links ideal or actual counterpart but on helical machined springs [9]. The structural concept of CHJ's is to join a high torsional stiffness with a low flexural. These kinds of devices may work as couplings for small axes misalignments, or transmission joints for large, either angular, parallel, or skewed. The manufacturing of machined springs enjoys all the common advantages for compliant mechanisms, it is no necessity of assembly thus integration with other elements, and high precision. It has some advantages even with the common manufacturing of extruded wire springs, while the machined coil has negligible residual stress. CHJ's are produced and can be purchased. To the knowledge of the authors, there is no existing literature on the subject, despite this kind of compliant joint is interesting from a mechanical point of view, and possibly economical too.

Cases of study

Multibody simulations. Multibody dynamics simulations represent a very useful approach to study transmission joints because thanks to this approach it is possible to consider the behaviour of the joint in several operating conditions. [10].

In this case, a sample CHJ is modelled in CAD and employed in full-flexible multibody simulations. In these, the coil is treated as a flexible component discretized as FEM, and it's analyzed along with the computation of the general multibody dynamics. The purpose is to highlight the basic features of a generic CHJ about its kinematic, dynamic, and structural performances. At this earlier stage of the study the influences of variations in the coil geometry had not been investigated.

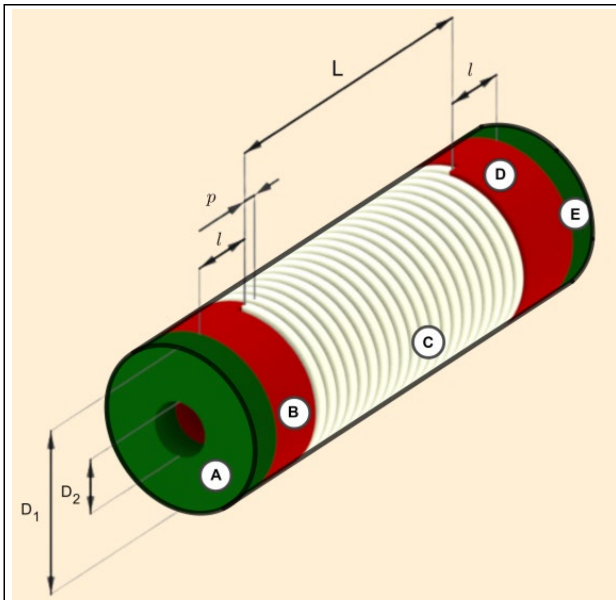


Fig. 1. CAD model of the sample CHJ.

Table 1. Nomenclature and sizes.

A	Input bearing	D_1	19,2 [mm]
B	Input rigid end	D_2	6,35 [mm]
C	Flexible coil	l	8,50 [mm]
D	Output rigid end	p	1,98 [mm]
E	Output bearing	L	39,6 [mm]

Model description. The sample CHJ is featured and sized according to a joint of the kind at [11]. This is an inox-steel single coil and single coil-start monolith, actually designed for angularly misaligned shafts. Two rigid ends are integral to the coil and the two input and output shafts bearings are added in the model.

Simulations environment and setups. In a full-flexible multibody simulation environment, the helical coil is modelled in shell Quad4 elements. With reference to Fig.2, the bearings are joined by a cylindrical pair at their middle point along the line of the aligned axes, with allowed perpendicular translations S and rotations R. It has to be noticed that this is a *particular* condition of kinematic constraints, although not unrealistic. That is, a more complete study on CHJ's shall account for different conditions too, like for instance possibility for one or both of the rigid ends of the joint to slide along the respective shaft. The model is completed with a massive body M integral to the output rigid end, with parametric moments of inertia J in the direction of the output axis.

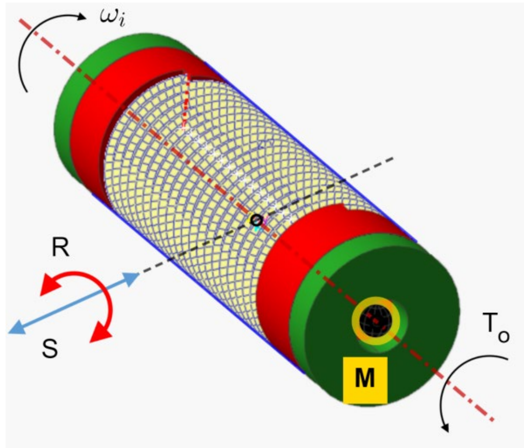


Fig.2 Flexible Multibody modelling and simulations setup.

Tests are generally with skewed misalignments, even if the sample joint is declared to be specifically designed for angular ones. In fact, the purpose of the simulations is to detect general tendencies, apart from the definition of some optimal designs. Tests are of quasi-static kinds to measure the error of transmission and stress peaks and magnitudes of oscillation; and of dynamical kind to find the resonating frequencies and factors of amplification.

Results

Quasi-static tests had been carried out varying angular misalignments R from 0° to 45° with 9° step; and translational S by multiples of $r = D_1/2$, ranging from 0,0 to 1,0 with 0,2 step.

Transmission error. The main results on transmission error, calculated on smoothed data, demonstrate that: i) it depends *only* on misalignment parameters; ii) is anyway very limited, it is $O(10^{-3})$. This from an engineering point of view confirms the producers' claim of an *effective constant-velocity* performance of these joints.

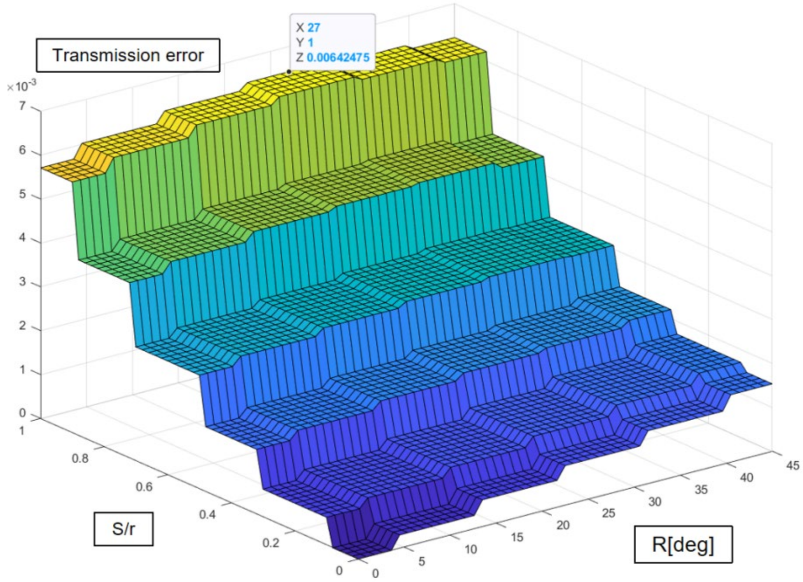
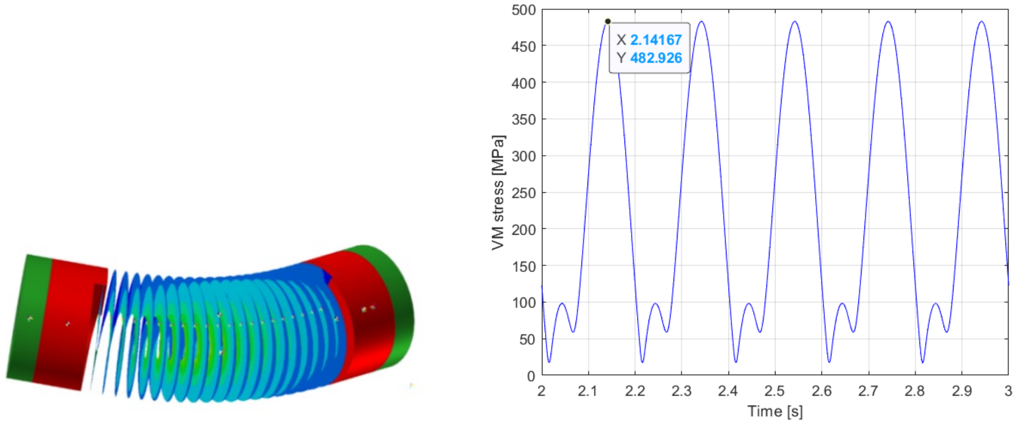
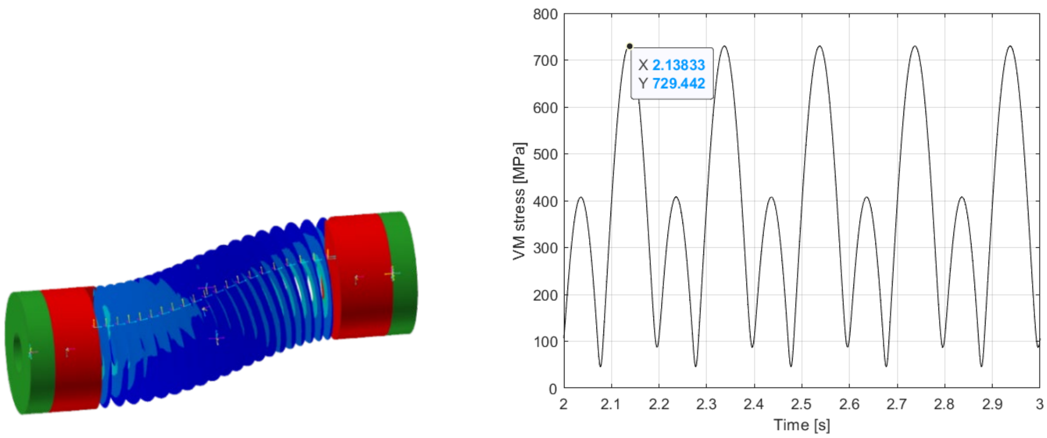


Fig.3 Transmission error at varying parameters of misalignment.

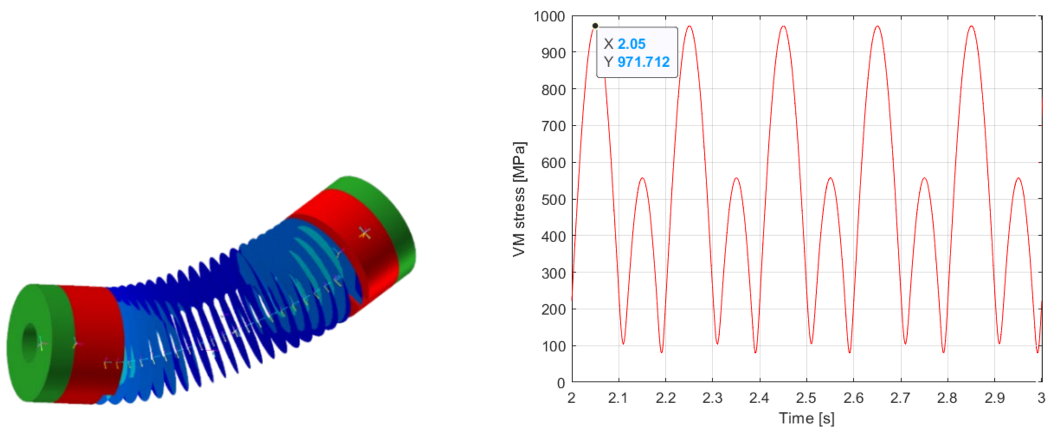
Stress distributions and severities. The behavior of the coil at different kinds of misalignment can be appreciated in Fig. 4 *a) b) c)*. These show the distributions of Von Mises stress at the extreme points of pure rotation, of pure translation and in the major skewing, with an applied output torque T_o=500 Nmm.



a) R=45°, S/r = 0;



b) R=0, S/r = 1;



c) R=45°, S/r = 1;

Fig.4 Von Mises stress distributions in the coil and developments at more stressed points in different conditions of misalignment.

In all the cases the distributions remain quite constant in the control volume. In the cases of pure rotation stress increases axially from the ends to the middle; in the cases of pure translations instead, it decreases axially from the ends to the middle; in skewed misalignments it has a hybrid behaviour. In all the cases stress increases radially from the external to the internal edge of the coil. This is consistent with the theory of beams with high curvatures, that predicts a non-homogeneous distribution of stiffness on the cross-sections, and more specifically increasing toward the centre of curvature. This implies a greater stress on the same deformations.

Dynamic tests. Resonating frequencies had been obtained through simulations at different values of misalignments, torque, and moments of inertia J. A nonlinear behavior had been detected and it's shown in Fig.5 on normalized variables. The values f_0 of the frequencies at aligned axes seem to scale in inverse ratio with $\sqrt{\mathrm{J}}$ as in the linear theory. These values decrease with the translational misalignments, and not with the rotational *if* there is no applied output torque. If the torque is applied a greater decrease it's observed with the translational, and then with the rotational too. For this behavior it had been hypothized a law which is *trilinear* in the parameters of misalignment and output torque. Coefficients had been established on the data obtained for J=400[kgmm^2], and the hypothetical laws thus reads as:

$$f = \frac{20}{\sqrt{\mathrm{J}}}\left\{18.5 - \frac{\mathrm{S}}{\mathrm{r}}\left[2.7 + \frac{\mathrm{T_o}}{500}\left(1.44 + 0.24\frac{\mathrm{R}}{45°}\right)\right]\right\},$$

where R is expressed in degrees.

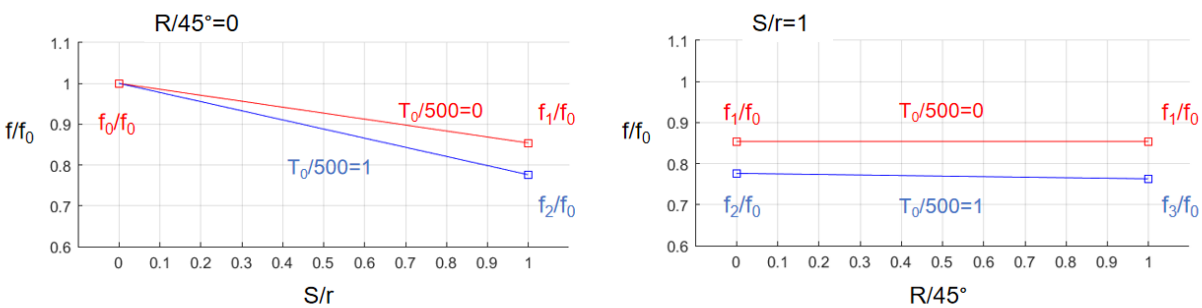


Fig.4 Adimensional variations of the frequencies of resonance in dependence of:
(left) translational misalignments, and output torque;
(right) translational misalignments, output torque, and rotational misalignments.

The formula gives some good predictions, the results of some of which are shown in Fig.6 in terms of the difference between output and input angular velocities. In the case on the right side the prediction of 5.29 Hz is not truly remote from the actual resonance, which had been detected at ab. 5.50 Hz. The error is thus less than 4%. A more refined model may be developed in further work.

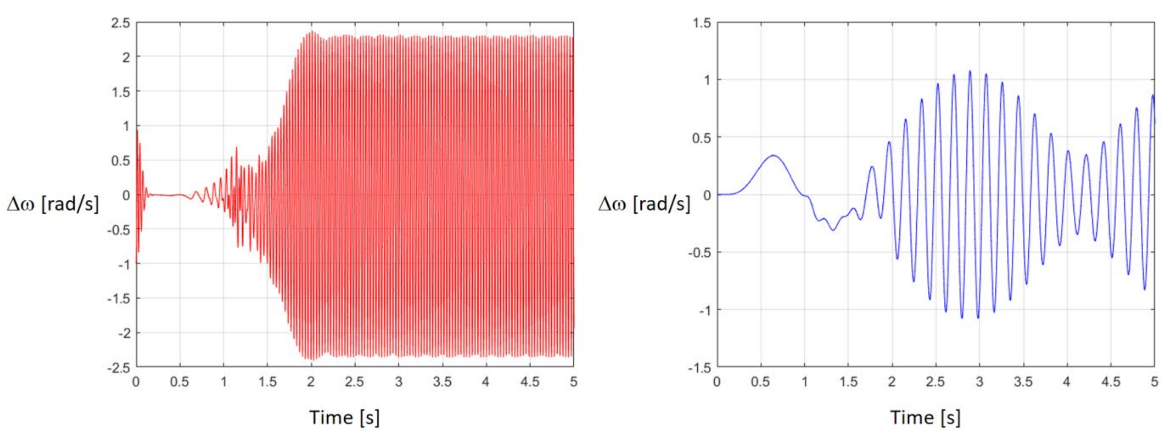


Fig.6 Validation of predictions on frequencies of resonance:
(left) J=100.0 [kgmm^2], S/r=1.0, R=45°, f = 30.9 [Hz];

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(right) J=3600 [kgmm^2], S/r=0.6, R=45°, f= 5.29 [Hz].

Conclusions

This paper deals with study of a distributed compliance helical transmission joint through a methodology of flexible multibody simulations. The compliance of the coils is considered by the adoption of a shell FEA model of same thickness of the reference geometry, in order to speed up the simulations. The results demonstrate that the transmission error is very limited and depends only on misalignment parameters. Moreover, the stress distribution appears to agree with the stress theory of deformed beams. Dynamic behavior exhibits some nonlinearity, expressed in a first hypothesis as a multilinear relation.

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