Author's accepted version of the paper entitled "Numerical and Experimental Analysis of the Transmission Error in Hybrid Metal-Composite Gears", published in Composite Structures, 2022, 298,116012
https://doi.org/10.1016/j.compstruct.2022.116012

# Numerical and Experimental Analysis of the Transmission Error in Hybrid Metal-Composite Gears

Ali Rezayat[1], Piervincenzo G. Catera [2], Cristian Capalbo[2], Francesco Cosco[2], Domenico Mundo [2]

[1] Siemens Industry Software NV, Interleuvenlaan 68, B-3001 Leuven, Belgium
e-mail: ali.rezayat@siemens.com

[2] Department of Mechanical, Energy and Management Engineering, University of Calabria, Cubo 45C, 87036, Rende, Italy
e-mail: {piervincenzo.catera, cristian.capalbo, francesco.cosco, domenico.mundo} @unical.it

## Abstract

The aim of this work is to provide a numerical analysis and an experimental characterization of the meshing behaviour of hybrid metal-composite gears, manufactured by press-fitting a carbon fibre reinforced polymer (CFRP) web into a steel gear structure. Hybrid gears have been recently proposed as an answer to the quest for lighter mechanical transmissions, with improved meshing performance in comparison to conventional lightweight gears. Numerical and experimental studies at single-gear level as well as gear-pair testing demonstrated a huge potential for such a technology to contribute to system-level weight reduction.
In this paper, the meshing behaviour of a hybrid gear, manufactured by interference fitting and engaging with a conventional steel gear, is analysed numerically by using a hybrid gear contact model that combines, in a multibody simulation environment, an analytical description of the non-linear contact phenomena with a Finite Element (FE) formulation of the overall gear compliance. An experimental characterization of the Static Transmission Error (STE) is also given by using a high-precision gear test-rig, where quasi-static tests have been carried out under different load conditions. Important indications on how the manufacturing process must be implemented to prevent from poor meshing performance are illustrated.

**Keywords**: hybrid metal-composite gears, gear meshing, Finite Element analysis, Transmission Error

## 1. Introduction

The level of technological advancement in today's world would have been unreachable without the existence of gears. From the industry of recreational equipment to all sectors of transportation technology, gears play a crucial role in almost all applications where mechanical power transmission is required. After millennia of technology development, nowadays gears are by a large amount the preferred technology for mechanical power transmission in a wide application range, from small clock mechanisms to huge wind turbine gearboxes, from sport equipment to industrial machinery. In spite of such a widespread diffusion of gears, the gear industry has recognised that significant technological challenges lie ahead and must be overcome to have such a technology aligned with the general paradigm of sustainability enhancement, while satisfying the market demand for increased performance.
One of the main innovation drivers in several industrial sectors is identified in mass reduction as a means for the achievement of system lightweighting and efficiency enhancement. The concept of

lightweight gears originated in the aerospace sector, where mass reduction is of paramount importance, and extended to other areas. Automotive manufacturers are forced to comply with increasingly stricter regulations on fuel efficiency and emissions. Recent literature shows that weight reduction is highly beneficial to system efficiency in automobiles [1] and in aircrafts. In the latter, gearboxes can account for up to 15% [2] of the total weight and mass saving allows to lower fuel consumption significantly [3].
A common approach to gear lightweighting is based on material removal from the body, but thin rims or holes in the gear blank increase the structural flexibility and possibly deteriorate noise and vibration (N&V) performance [4]. Gear lightweighting is then a challenging problem, where a variety of factors must be handled to achieve design targets and meet performance criteria. A different approach to gear lightweighting is based on the employment of lighter materials. Polymer gears, eventually reinforced by glass or carbon fibres, can replace metal gears in low-power transmission applications [5,7].

A recent approach for weight reduction of mechanical systems with high-load capacity is based on hybrid metal-composite design, which exploits the excellent stiffness-to-weight ratio of Carbon Fibre Reinforced Polymers (CFRP) as a replacement of metal parts to achieve the goals of meeting structural performances while reducing weight and damping N&V during dynamic events. The use of composite materials in multi-material components is reported in several industrial applications. In 2006 Kim et al. [8] proposed the design of a hybrid steel-composite circular plate as a structure for a cutting tool. In 2011, Cho et al. [9] employed polymer composites to the table-top machine tool components with the aim of increasing the stiffness and reducing the weight.
The application of composites in the automotive sector has been proposed for the manufacturing of hybrid aluminium-composite drive shafts with enhanced dynamic performances [10] and for the development of a hybrid metal-composite wheel with a friction layer that enables enhanced noise and vibration performance [11]. Other examples of multimaterial design applied to mechanical power transmissions are reported in [12], where Lin and Poster proposed the development of a braided composite drive shaft, and in [13], where Cecil et al. describe application and configuration issues of composite material in the transmission housing.
In the last decade, efforts have been spent to extend the use of composite materials to the geared bodies in a mechanical power transmission and a new concept of hybrid metal-composite gear was proposed by Handschuh et al. in [14]. In the proposed design, the gear can be considered as divided in three main regions: the rim (i.e., the toothed part of the gear), the web (the central part) and the hub (the inner part that connects the gear to the shaft). In the first and in the third regions, the hybrid gear is made of steel, which provides the component with the required wear and fatigue resistance, while the web is made of triaxial braided composite material that enables a weight reduction of about 20% with respect to the steel gear with the same macro-geometry. Such an innovative multimaterial approach to gear design and manufacture was extended to a full-scale bull gear by LaBerge et al. in [15], while in [16] static, dynamic and endurance test results for a bull gear with a variable thickness of the composite part in the gear body were illustrated.

Starting from the concept of hybrid gear presented in [14], Catera et al. [17] proposed a multiscale modelling approach for FE-based modal analysis, while Finite Element (FE) models of hybrid gears were generated and analysed in [18] to simulate the meshing behaviour of hybrid transmissions. In [19], two joining technologies for metal-composite gear manufacturing, namely adhesive bonding and interference fitting, have been compared by prototyping and testing the two different hybrid gears. Numerical and experimental results demonstrated that the proposed multimaterial design enables a higher stiffness and a better damping capacity in comparison to an all-steel gear with the same mass.

For hybrid gears assembled by adhesive bonding, Yilmaz et al. [20] analysed the effect of rim thickness on the root and joint stress, tooth stiffness, natural frequency and dynamic behaviour by using an FE-based approach. Their results confirm that hybrid gears have substantial potential to enable lightweighting in geared mechanical power transmissions. By using FE analysis and experimental material characterization, Gauntt and Campbell [21] investigated the modal behaviour of a hybrid gear with different composite materials and various layup sequences.

In the present paper, the meshing behaviour of a hybrid metal-composite gear, engaging with a solid steel gear, is analysed and the Transmission Error (TE) curves are derived for different operating conditions through multibody simulations and compared to the experimental testing. As shown in [22], the TE, which represents the difference between the perfectly kinematic transmission of motion and the real one, is an indicator of the transmission's N&V performance. Different types of models and methods have been investigated to analyse the TE and the mesh stiffness of gears. In a recent work [23], Marafona et al. provided a detailed review of analytical, finite element and hybrid models that allow to establish the mesh stiffness of parallel axis cylindrical gears, including a section dedicated to tooth contact analysis of polymer gears. By exploiting finite element simulations, Gauntt et al. [24] and Catera et al. [18-19] analysed the Static Transmission Error (STE) and the time-varying mesh stiffness of a hybrid spur gear drivetrain.

In the work presented here, the virtual prototype of a gear pair consisting of a solid steel gear and a hybrid gear was built and analysed by using a hybrid FE-analytical gear contact model [25]. In fact, as shown in [26], a combination of analytical formulations with distributed parameter models of the transmission in a multibody environment allows to reach a trade-off between predictive accuracy and computational efficiency, paving the wave to simulation-driven design and optimization of hybrid geared transmissions, with increasing complexity and under variable operating conditions. Moreover, in the work presented here a physical prototype of the transmission, built using interference fitting as joining technology for the hybrid gears, is presented. The transmission prototype was tested by using a high-precision test-rig and the TE of the transmission was measured under tightly controlled operating conditions [22] with the aim of analysing the meshing behaviour of the hybrid gear. The experimental study has been executed twice. In a first campaign, the hybrid gear was tested as resulting from the proposed interference fitting process. The achieved results showed the effects of gear body distortion due to the pressure applied during the interference fitting process and suggested to amend teeth geometry by a second grinding process aimed at restoring the nominal profiles. The hybrid gear with amended teeth profiles was then tested and a detailed comparison between the two gear pairs in terms of the STE was achieved.

The remainder of the paper is as follows. In Section 2.1 the specifications of the test gears are illustrated along with the description of the interference fitting process employed to manufacture the hybrid gear. The hybrid FE-analytical gear contact model, which is detailed in [25], is summarized for sake of clarity in Section 2.2, while Section 2.3 provides a description of the test-rig used for the experimental campaign. Section 3.1 and 3.2 describe the achieved numerical and experimental results after quasi-static testing. Concluding remarks are reposted in Section 4, along with an outlook of future developments.

## 2. Materials and methods

### 2.1 Specifications and prototyping of the test gears

The test gear set consists of two gears with the same macro-geometry, the specifications of which are listed in Table 1.

| Parameter | Value |
|---|---|
| Teeth number | 59 |
| Module | 2.5 mm |
| Pressure angle | 20 deg |
| Face width | 24 mm |
| Tip diameter | 154 mm |
| Root diameter | 142.75 mm |
| Theoretical pitch diameter | 147.50 mm |
| Base diameter | 138.60 mm |
| Addendum | 1 x module |
| Dedendum | 1.25 x module |
| Tooth thickness (ref. circle) | 4.47 mm |
| Hob tip radius | 1 mm |

Table 1. Macro-geometry of the test gears

In the experimental setup, a solid gear (Figure 1-a), made of 18NiCrMo5 alloy steel and case-hardened, engages with the hybrid gear (Figure 1-b). For both gears, teeth have been manufactured by using a high-precision CNC grinding process that allowed to meet ISO1328 Quality 5 standard.



**a)** **b)**

Figure 1: Prototypes of the steel (a) and of the hybrid metal-composite (b) test gears.

The hybrid gear was manufactured by following a multi-step process. First, rim and hub, connected by a 2mm thick metal layer were machined by using the same material and process specification of the solid gear (Figure 2-a). The thin metal layer in the central region of the gear serves the twofold purpose of guaranteeing co-axiality between the toothed part and the connection hub, while leaving space in the axial direction to accommodate a 10.5mm thick composite layer on each side of the gear. The composite layers were manufactured by manual overlapping of pre-impregnated composite plies (pre-preg) produced by SHD composites. The pre-preg plies are composed of an epoxy matrix (DT102T) and M40J carbon fibres with enhanced tensile strength and modulus. Among the most common reinforcements in composite materials, carbon fibres offer excellent mechanical properties

in terms of stiffness, strength and low density. In particular, the composite material used to manufacture the gear body has been chosen with the aim of maintaining an adequate stiffness of the gear body. Indeed, the selected material is capable to withstand the high loads coming from gear meshing during operational conditions, as demonstrated by the experimental results described in Section 3. On the other side, the matrix chosen for the composite material used to manufacture the hybrid gear is an epoxy resin, which has an optimum thermal stability at high service temperatures, up to 180 °C. The physical and elastic properties of matrix and reinforcement materials are listed in Table 2. The fibres are combined with the epoxy in a ply with a percentage in weight of 34%. A quasi-isotropic layup, $[0/30/60/90/120/150]_{3s}$, with thickness of 10.5 mm and homogeneous in-plane properties, was manufactured by autoclave curing. More information on the curing process can be found in [19].

| Property | Fiber | Matrix |
|---|---|---|
| Material type | Carbon M40J | Epoxy |
| Longitudinal Modulus [GPa] | 377 | 2.7 |
| Transverse Modulus [GPa] | 15 | 2.7 |
| Shear Modulus [GPa] | 24.7 Long./ 5.0 Transverse | 1 |
| Poisson's ratio [-] | 0.41 | 0.35 |
| Density [g/cm^3] | 1.77 | 1.2 |

Table 2. Physical and elastic properties of the fibre and matrix

With the aim of enabling the fulfilment of tight tolerances needed to prevent from assembly issues and to avoid possible thermal degradation, the two web layers were cut out of a composite panel by precision waterjet (Figure 2-b).



a) b)

Figure 2: Metal (a) and composite (b) parts of the hybrid gear before assembly

The hybrid gear was assembled by a process of interference fitting, which was performed by using an Instron® electromechanical universal machine, employed under displacement control. During the process, which is schematically represented in Figure 3, the two composite layers are coaxially and gradually pressed into the rim, in such a way that pressure-induced deformation of the web at the

interface with the rim and with the hub produces inter-locking between the steel and the composite parts. Small pins, 3 mm thick and 6 mm long, were manufactured by CNC milling on both sides of the connection areas to facilitate the assembly process and improve the mechanical interlock between the steel and the composite parts

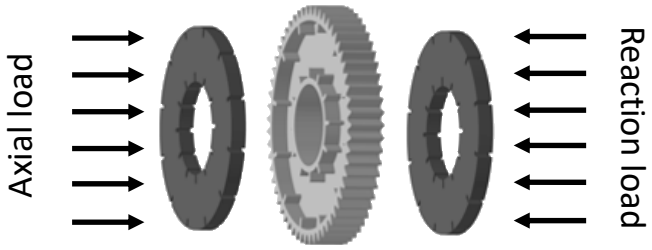



Figure 3: Assembly process based on interference fitting.

### 2.2 Hybrid FE-analytical gear contact model

With the aim of simulating the meshing behaviour of the hybrid gear and analysing the load dependency of the TE, a hybrid FE-analytical gear contact model was used. This method solves the contact problem in a computationally efficient way by keeping a high level of fidelity. A detailed description of the method is reported in [25], while this sub-section summarizes its main features and describes how it was applied to the presented case-study.

This method uses a modified penalty formulation to solve the contact problem and at the same time to compute the contact forces. The software implementation of the problem can be described by two main steps: (i) contact detection phase and (ii) force computations.

The first step of the method is an initial contact detection process, which identifies the lines along which the contact occurs in a given position of the gears. A tailored efficient contact detection strategy is thus achieved, which is based on the following main assumptions: (i) the method assumes contact between cylindrical spur/helical internal/external gears and profile shapes that are involute or close to involute; (ii) the tangent and normal vectors to the contact surfaces are computed assuming perfectly involute profiles; (iii) the contact points along the gear flank remain located along the line of action defined by the involute profiles. Thanks to the above assumptions, it is possible to exploit well know analytical formulas that describe the teeth geometry and allow to predict the locations of potential contact between the gear teeth.

After the contact lines are detected, a second computational step is performed to translate the penetrations into contact forces acting along the teeth normals and caused by stiffness-related effects. The proposed method uses a hybrid analytical/numerical penalty approach, which is detailed in [27]. As shown in Figure 4, the overall contact deformation is decomposed in two components: (1) a local non-linear deformation caused by locally non-linear Hertzian-like effects; (2) a global linear deformation caused by the tooth bending and shear as well as by complex effects due to the gear body geometry and coupling between different teeth. In order to capture the first contribution, it is possible to rely on analytical formulas available in the literature. In the method used in this work, a formula derived by Weber and Banaschek based on Hertzian theory is used [27]. The second contribution includes global effects that, despite being linear with respect to the applied loads, are generally not representable by any closed-form analytical expression. This second contribution is taken into account in the contact model through a compliance matrix that is computed, for each gear, by applying

unity loads on the potential contact points and by estimating the global tooth deflection through linear FE simulations.

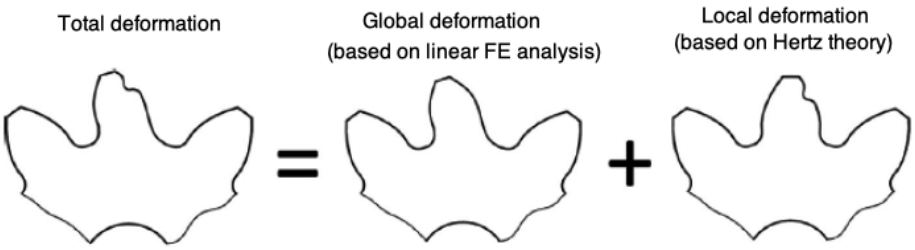
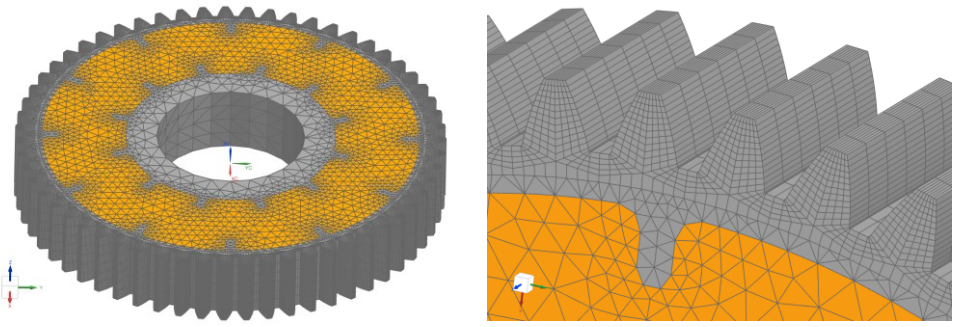



Figure 4: Decomposition of the total gear deformation.

The described hybrid approach has the advantage of considering the non-linear hertzian effects in the contact area, without requiring computationally expensive non-linear FE analyses. The implemented model order reduction schemes bring robustness and less computation effort to the solver.

It is noteworthy that for hybrid gear blanks, the FE formulation allows to represent the global deformation of the gears including modification of geometry (holes) and material (composite), provided that proper geometric and material properties are set in the FE model. For this reason, the FE model of the hybrid gear, shown in Figure 5 along with a zoomed view on the toothed region, was first built from the CAD model. The FE model of the hybrid gear consists of the combination of multiple regions: (1) the gear crown mesh (shown in grey) is automatically generated using hexahedral elements; (2) the transition zone between the crown and the composite is made of tetrahedral elements; (3) the composite region (shown in orange) is made of tetrahedral elements. The final mesh is obtained by combining all three regions using the mesh mating condition. In such a way, the duplicated nodes at the interfaces are merged into one, ensuring the continuity of the mesh elements across the gear blank. The gear body mesh is generated in Simcenter 3D Pre/Post using user-defined constraints in the edges, depending on the accuracy requirements. The minimum element size overall corresponds to the tooth root area with an approximate size of 0.055 mm. The mesh density follows the geometrical curvatures and it gradually decreases until the gear hub, where the maximum element size of 7.470 mm is achieved.



a) b)

Figure 5: FE model of the hybrid gear (a) and zoomed view on the toothed region (b).

The material properties were computed using the homogenization approach described in [18] and assigned to the FE model composite web region. Table 3 provides the estimated homogenized properties of the composite component.

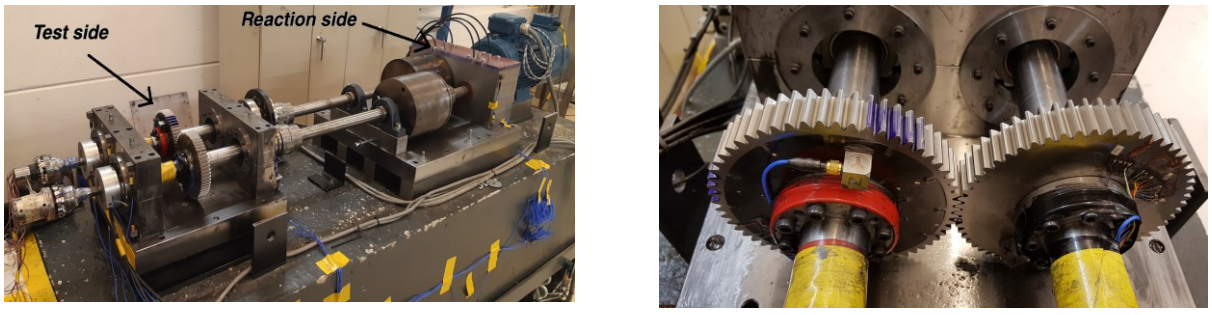
| **Homogenized properties** | $E_1$ [GPa] | $E_2$ [GPa] | $E_3$ [GPa] | $\nu_{12}$ _ | $\nu_{23}$ _ | $\nu_{13}$ _ | $G_{12}$ [GPa] | $G_{13}$ [GPa] | $G2_3$ [GPa] |
|---|---|---|---|---|---|---|---|---|---|
| Material | 77.1 | 77.1 | 8.3 | 0.32 | 0.27 | 0.27 | 29. 1 | 2.9 | 2.9 |

Table 3. Elastic properties of the homogenized laminate used in the FE model

The prediction of equivalent (or homogenized) material characteristics of the carbon fibre component was conducted using the Virtual Material Characterization (VMC) ToolKit in Simcenter 3D. This tool relies on the detailed material modelling that goes down to the micro-scale and sequentially builds up knowledge in terms of material mechanical behaviour towards the macro/component application-scales.

### 2.3 High-precision test-rig for TE measurement

In a geared transmission, the real relationship between the angular speed of the output shaft and the one of the input shafts generally deviates from the kinematic law, due to a number of factors, including tooth profile deviations from the nominal ones, teeth and shaft deformation under load, assembly errors and gear misalignment. With the aim of enabling STE measurements for the gear pair described in section 2, along with the related and relevant physical quantities, a high-precision test rig has been employed [22]. A picture of the test rig is shown in Figure 6, where the gears under investigation are hosted in the test-side, while a pair of helical identical gears are placed in the reaction side in order to enable recirculation of the mechanical power entrapped in the system.




a) b)

Figure 6: High-precision test-rig for TE measurement (a), and zoomed view on the instrumented test side (b).

The test rig is operated by a 9 kW asynchronous motor controlled by a frequency inverter, which allows to test the gears up to a speed of 4000 rpm. By using a torque wrench and a set of weights, the gears can be pre-loaded with a specified value of torque in the range 0 – 400 Nm. Bearings in the test

side are embedded in eccentric caps, which enable a tight control of the operating angular misalignment in an arbitrary plane and parallel misalignment in the transverse plane.
The test-rig is equipped with two high-resolution optical TTL encoders (Heidenhain ERN 120) with 5000 divisions, which are mounted on the two shafts supporting the test gear pair and they allow to measure the TE signal.
Strain gages are attached on the edge of the metallic segment, in the transition region between the teeth crown and the composite part, in the proximity of the tooth root. A triaxial accelerometer (PCB 356A02) is attached to the gear body in order to measure the in/out-of-plane vibrations of the gear. Both the strain and acceleration signals are conducted by wires through the hollow shaft towards the slip ring (Michigan Scientific SR20M). All the signals are conducted through wires to the acquisition device (SCADAS Mobile). The SCADAS device allows to acquire all channels with a sample rate of 50 KHz, for a duration of 60 s.
Additional accelerometers are mounted on the supporting structure to measure the vibrations transmitted by the shaft. A microphone is employed to analyse the emitted noise by measuring the pressure level in proximity of the test side.

## 3. Results and discussion

The deviation of the real behaviour of the transmission from the kinematic one can be quantified by defining the TE as:

$$TE = r_{b2}\theta_{b2} - r_{b1}\theta_{b1} \tag{1}$$

where $\theta_{b1}$ and $\theta_{b2}$ are the rotations of the driving gear and of the driven one respectively, while $r_{b1}$ and $r_{b1}$ are their base radii. In the present work, the solid, full metal, gear is gear 1, while gear 2 represents the hybrid metal-composite gear.
The following subsections describe how the STE was estimated through numerical analyses using the multibody (MB) simulation environment Simcenter 3D Motion & Transmission Builder [28, 29], in which the hybrid FE-analytical gear contact model described in Section 2.2 is implemented. Additionally, by using the test-rig described in section 2.3, TE curves were measured in quasi-static conditions for different values of applied torque.
Figure 7 shows the MB model of the two gears, which are supported by infinitely rigid shafts. To estimate the TE in quasi-static conditions, a velocity driver was attached to the shaft of the solid gear with the aim of providing it with a constant speed value. With the aim of making dynamic effects negligible, a constant speed of 10 rpm was set for the velocity driver, as to achieve quasi-static conditions. A resistant torque, varying in the range 50 – 250 Nm, was applied to the output shaft. For each value of torque, a simulation was run, from which the rotation of the two gears were estimated. Due to gear teeth and body deformations, the rotation of the driven gear deviates from the theoretical one, which is equal in absolute value to the rotation of the driving gear for a pair of identical gears. From the instantaneous value of rotation imposed by the driver to the solid gear and from the rotation predicted by the MB simulation for the hybrid gear, the numerical STE curves can be calculated by using eq. (1).

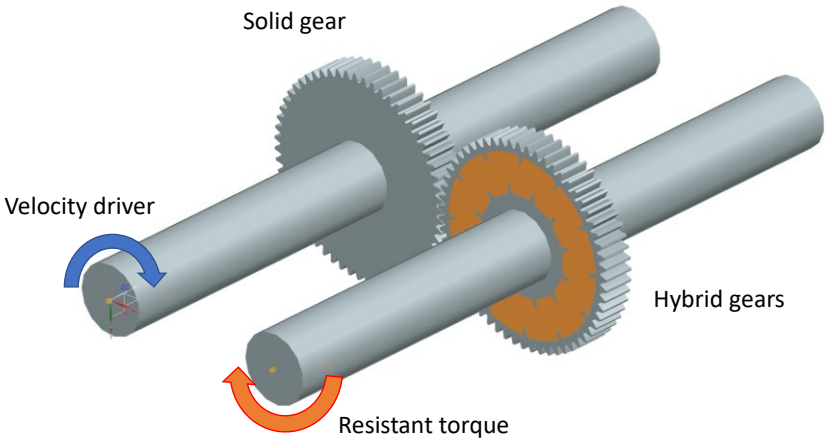



Figure 7: MB model of the engaging gears.

In parallel to the numerical analysis, the STE was also measured by using the test-rig described in Section 2.3 and operated at a constant speed of 10 rpm to enable quasi-static conditions that make dynamic effects, such as inertia forces/moments and mode excitation, negligible. For the experimental study, two sets of tests were carried out. In a first stage, the hybrid gear was tested as resulting from the proposed interference fitting process (hybrid gear 1). The achieved results are illustrated in Figure 8 in terms of Harris maps, generated by measuring the quasi-static TE curves for different values of the applied torque. From these results, the effects of gear body distortion, due to the pressure applied during the interference fitting, appear clear from the modulation of the curves due to low-order harmonic content. For this reason, a second grinding process was executed on the hybrid gear to restore the nominal teeth profiles. In a second set of tests, the amended hybrid gear (hybrid gear 2) was tested and new, more consistent Harris maps were achieved, as shown in Figure 9. A further comparison between the meshing behaviour of the two hybrid gears is achieved by analysing the orders content of the measured STE curves for two different torque values, namely for 50 Nm and for 250 Nm. The results are shown in Figures 10 and 11, from which significant differences appear. Specifically, in the low-order range (Figures 10-a and 11-a), a much broader distribution of the harmonic content is noticed for the hybrid gear 1. For the hybrid gear 2, instead, the first order, due to runout errors caused by the gear-to-shaft locking system, is the only significant one. Figures 10-b and 11-b show the first three meshing orders for the transmissions with the two hybrid gears. Also here, a relevant difference is noticed in that side-bands are visible in the graphs calculated for the hybrid gear 1, which are explained by the modulation effects produced by the low orders.

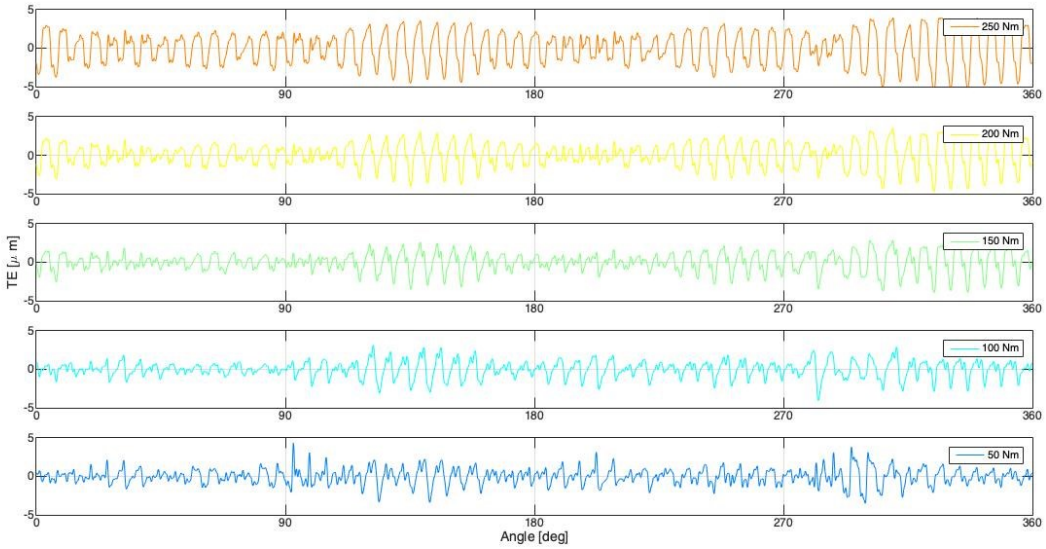



Figure 8: Harris maps for the solid gear engaging with hybrid gear 1.

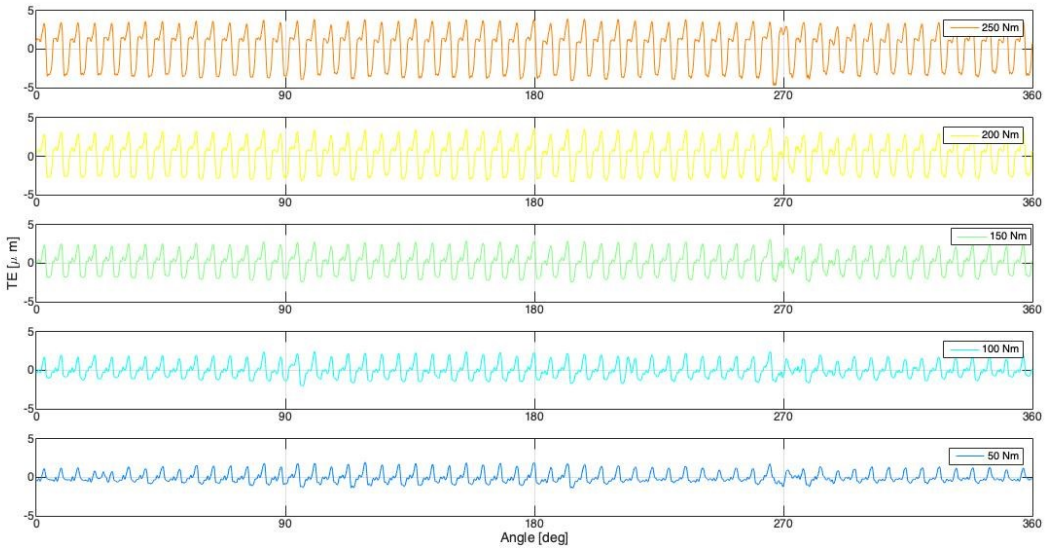



Figure 9: Harris maps for the solid gear engaging with hybrid gear 2.

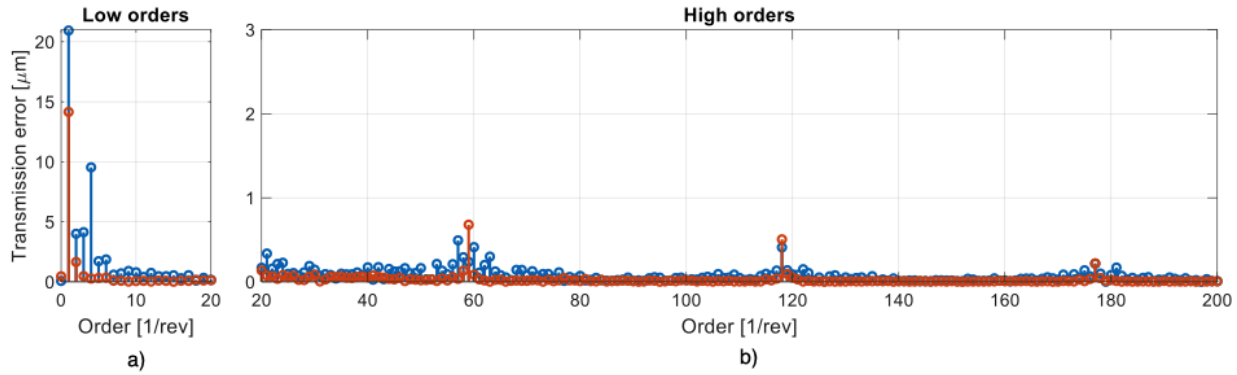



Figure 10: Order analysis for the hybrid gear 1 (blue curve) and for the hybrid gear 2 (red curve) under a torque of 50 Nm.

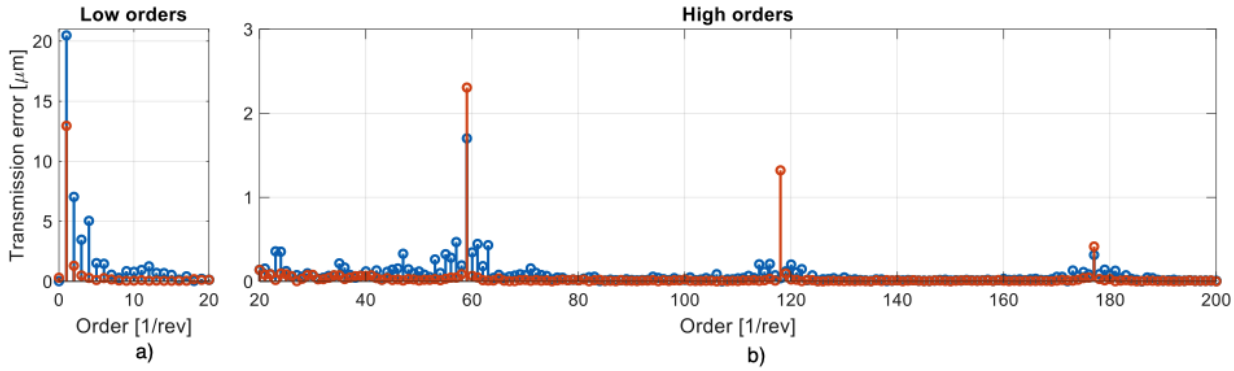



Figure 11: Order analysis for the hybrid gear 1 (blue curve) and for the hybrid gear 2 (red curve) under a torque of 250 Nm.

To compare numerical and experimental results, the STE curve estimated in angle-domain for the simulation model under a torque of 100 Nm is shown in Figure 12, along with the experimental curve measured for the hybrid gear 2. The experimental curve was generated by implementing the following post-processing procedure. The raw data, measured in time domain, is converted to angle domain. Measured tacho signals coming from both incremental encoders allow to divide the TE signal into corresponding gear (or shaft) revolutions. The TE data of each revolution is converted to order domain using the Fourier transform. After being filtered using a band-pass filter, the signals are finally averaged together in order domain. The averaged TE is converted back to angle domain using the inverse Fourier transform. In the particular case of Figure 12, the signal has been filtered below order 20 and above order 500 [1/rev], as the essential part of the TE characteristics was mostly observed between orders 20 and 500 [1/rev].

It is noted that the simulation model is reasonably capable of capturing the STE trend along one meshing cycle, even if the experimental curve suggests that the mesh stiffness of the transmission is overestimated, being the peak-to-peak value of the STE 24.3% lower in the numerical curve. The reasons for such an approximation are easy to explain, if it is considered that the MB model neglects the compliance of the shafts and of all the other components that, in the real test-rig, reduce the torsional stiffness of the system.

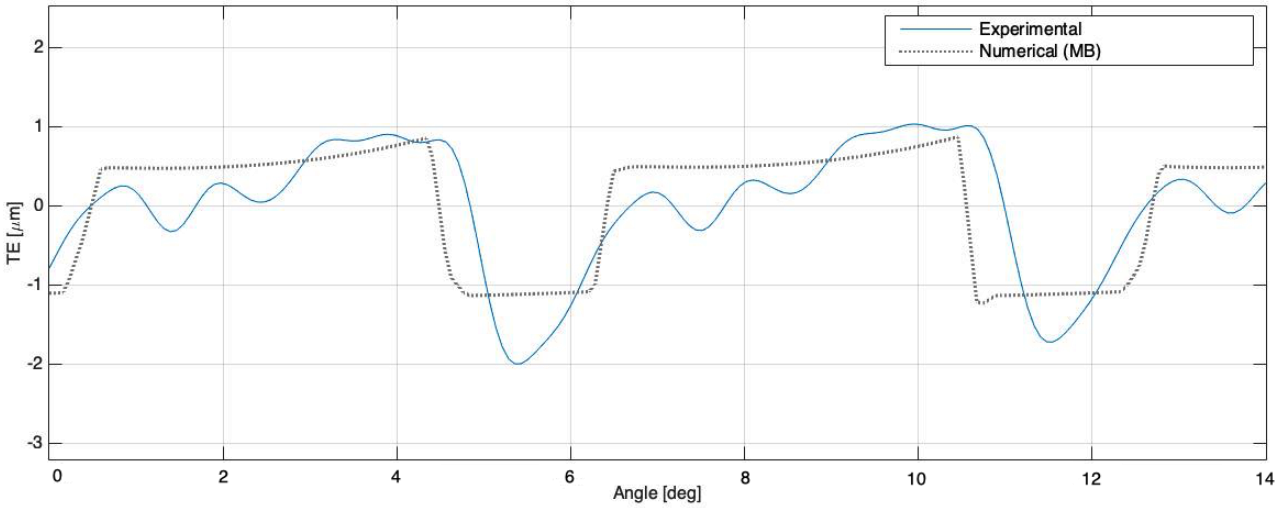



Figure 12: STE curves for an applied torque of 100 Nm.

A further analysis is done by computing the harmonic content of the first three meshing orders for the numerical STE curve and for the one measured for hybrid gear 2. The results are shown in Figure 13.

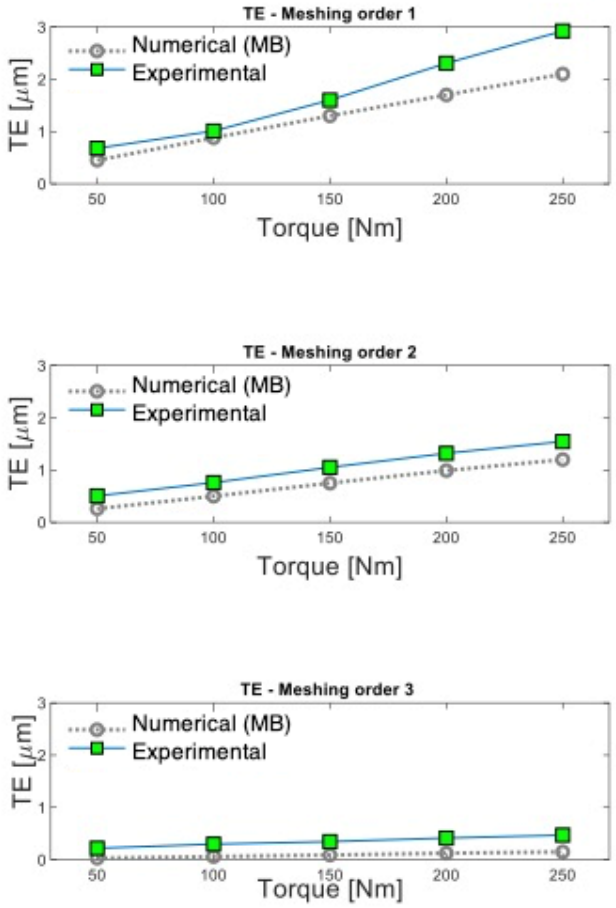



Figure 13: Meshing orders for the numerical and for the experimental STE curves.

The results shown in Figure 13 confirm that the MB model overestimates the meshing stiffness for all the torque values, resulting in trends for the first three meshing orders that are consistent for the hybrid gear 2, with a maximum difference between the predicted and the measured order contents equal to 28.3%. The observed differences are explained by two main limitations of the predictive model. First, the multibody model of the system is represented by a pair of gears, one of which with a hybrid blank. The surrounding components are considered to behave as rigid bodies at this stage of the research. By omitting the bearings, shaft and housing (plates) deflections, the model will systematically overestimate the overall stiffness of the test rig. Thus, the amplitudes of the predicted meshing orders are lower than the corresponding values obtained by experiments. Furthermore, the friction occurring between the teeth shows to have an effect in the meshing order amplitudes. As the friction phenomenon is mostly observable near the pitch contact points, the variation in the sliding velocity direction of the teeth produces a jump in the TE signal in angle domain. This effect is mostly contributing to the second meshing order amplitude. The current experimental setup does not allow the measurement (estimation) of the real friction coefficient, as in the operating conditions used in these tests the lubricant has not yet achieved a developed regime (no oil film).

It is noteworthy that the measurements were performed in a controlled way using the precision gear test rig, the components of which were manufactured within a high accuracy. The confidence intervals of the measured TE signals are shown in the following table.

| Confidence intervals [$\boldsymbol{\mu m}$] | Torque level [Nm] | | | | |
|---|---|---|---|---|---|
| Meshing order [-] | 50 | 100 | 150 | 200 | 250 |
| $\boldsymbol{O_{m_1}}$ | 0.1007 | 0.0995 | 0.1333 | 0.1330 | 0.1394 |
| $\boldsymbol{O_{m_2}}$ | 0.0242 | 0.0244 | 0.0228 | 0.0349 | 0.0416 |
| $\boldsymbol{O_{m_3}}$ | 0.0176 | 0.0237 | 0.0244 | 0.0205 | 0.0262 |

Table 4. The 95% confidence interval of the experimental TE meshing orders

## 4. Conclusions

This paper presented the results of numerical and experimental analyses, executed with the aim of studying the meshing behaviour of a gear pair comprising a hybrid metal-composite gear manufactured by an interference fitting process.

Two variants of the hybrid gear were analysed: the gear as resulting from the proposed manufacturing process and the same gear with teeth profiles amended at the end of it. The experimental results achieved on the hybrid gear 1, in fact, showed that the high pressure-values generated during the interference fitting have produced a distortion of the gear body that has a negative impact on the meshing behaviour of the transmission. By analysing and comparing simulation and experimental results, the following findings can be highlighted: the simulation model proved capable of capturing the torque dependence of the first three meshing orders as measured on the amended hybrid gear, paving the way to simulation-driven design and N&V optimization of such mechanical power transmissions. Moreover, the experimental analysis of hybrid gear 1 showed the appearance of low-order harmonics in the STE curves, which are expected to generate a broadband parametric excitation

of the transmission during the meshing process. In addition, a poor correlation was found between measured and predicted STE orders. From such experimental evidence, it is concluded that hybrid gears, generated by interference fitting, require a tooth surface finishing as the last step of the manufacturing process to eliminate the effects of the body distortion due to the fitting process on tooth flanks.

As future development of the research presented here, the vibroacoustic performance of hybrid transmissions will be analysed by comparing the meshing behaviour of two lightweight gear pairs, one comprising a hybrid gear and the other with a thin-rim metal gear with the same mass. The outcome of the foreseen research will provide an experimental evaluation of the benefits deriving from the higher stiffness and vibration damping capacity of the hybrid gear.

**Acknowledgements**

The research was partially funded by the European Commission, with the support of the European social fund (ESF) and the European regional development fund (ERDF), and the Ministry of Education, University, and Research (MIUR), through the National Operational Program for Research and Innovation, PON R&I 2014–2020, Action I.2 Attraction and International Mobility, AIM1857122.

**References**

[1] L.A. Dobrzanski, L.A. Dobrzańskia, T. Tańskia, L. ČížekbZ, Brytana., Structure and properties of magnesium cast alloys J. Mater. Process. Technol., 192-193 (2007), pp. 567–574

[2] NASA's Revolutionary Hybrid Gear Lightens Your Load, accessed online at https://www.newequipment.com/research-and-development/article/22058083/nasas-revolutionary-hybrid-gear-lightens-your-load on 18/01/2022

[3] K.E. Ohrn, Aircraft Energy Use, Encyclopaedia of Energy Engineering and Technology (first ed.), 1, CRC Press Taylor & Francis Group, Florida (2007), 24–30

[4] S. Shweiki, A. Palermo, D. Mundo, A study on the dynamic behaviour of lightweight gears, Shock and Vibration journal, Article ID 7982170 (2017)

[5] A. Pogacnik, M. Kalin: Parameters influencing the running-in and long-term tribological behaviour of PA against POM and steel. Wear, 290-291, 2012.

[6] M. Mbarek, S. Rhaiem, M. Kharrat, Experimental simulation of the friction, temperature, and wear distributions for polyamide–steel gear contact. Proc IMechE Part J. 230 (2016)

[7] D. Zorko, J. Tavčar, R. Šturm, Z. Bergant, Investigation of the durability and performance of autoclave-cured, woven carbon fiber-reinforced polymer composite gears in mesh with a steel pinion, Composite Structures, Volume 273, 1 October 2021, 114250

[8] B.J. Kim, H.S. Kim, D.G. Lee, Design of hybrid steel/composite circular plate cutting tool structures, Composite Structures, volume 75, 2006, 250-260, doi: 10.1016/j.compstruct.2006.04.028.

[9] S.K. Cho, H.J. Kim, S.H. Chang, The application of polymer composites to the table-top machine tool components for higher stiffness and reduced weight, Composite Structures, volume 93, 2011, 492-501, doi: 10.1016/j.compstruct.2010.08.030.

[10] D.H. Cho, D.G. Lee, J.H. Choi, Manufacture of one-piece automotive drive shafts with aluminium and composite materials, Composites Structures, vol 38, 1997, 309-319, doi: 10.1016/S0263-8223(97)00065-2.

[11] J.H. Bae, K.C. Jung, S.H. Yoo, S.H. Chang, M. Kim, T. Lim, Design and fabrication of a metal-composite hybrid wheel with a friction damping layer for enhancement of ride comfort, Composites Structures, volume 133, 2015, 576-584, doi: 10.1016/j.compstruct.2015.07.113.

[12] Lin, S. and Poster, S.: Development of a Braided Composite Drive Shaft with Captured End Fittings, 60th Annual Forum of the American Helic. Soc. Int., 2004

[13] Cecil, T., R.T. Ehinger, C. Kilmain: Application and Configuration Issues of Resin Transfer Molded Composite Transmission Housings – A Program Review, the 63rd Annual Forum of the American Helicopter Society International, May 2007

[14] R.F. Handschuh, G.D. Roberts Gary, R. Sinnamon, D.B. Stringer, B.D. Dykas, L.W. Kohlman: Hybrid Gear Preliminary Results—Application of Composites to Dynamic Mechanical Components, NASA/TM—2012-217630

[15] K. E. LaBerge, R. F. Handschuh, G.D. Roberts, S. Thorp, Performance Investigation of a Full-Scale Hybrid Composite Bull Gear, AHS 2016 Forum; 72nd, 17-19 May 2016, West Palm Beach, FL, United States.

[16] K. E. LaBerge, J. P. Johnston, R. F. Handschuh, G.D. Roberts, Evaluation of a Variable Thickness Hybrid Composite Bull Gear, AHS 2017 Forum; 73rd, 14-17 May 2018, Phoenix, Arizona, United States.

[17] P. G. Catera, F. Gagliardi, D. Mundo, L. De Napoli, A. Matveeva, L. Farkas, Multi-scale modeling of triaxial braided composites for FE-based modal analysis of hybrid metal-composite gears, Composite Structures 2017, volume 182, 116-123, doi: 10.1016/j.compstruct.2017.09.017.

[18] P. G. Catera, D. Mundo, A. Treviso, F. Gagliardi, A. Visrolia, On the design and simulation of hybrid metal-composite gears, Applied Composite Materials, 2018, doi: 10.1007/s10443-018-9753-6.

[19] Catera, P. G., Mundo, D., Gagliardi, F., Treviso, A., A comparative analysis of adhesive bonding and interference fitting as joining technologies for hybrid metal-composite gear manufacturing, 2020, International Journal of Interactive Design and Manufacturing, 14(2), pp. 535-550

[20] T.G. Yılmaz, O. Doğan, F. Karpat, A numerical investigation on the hybrid spur gears: Stress and dynamic analysis. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. December 2021. doi:10.1177/0954406220982007

[21] S.M. Gauntt, R.L. Campbell, Characterization of a Hybrid (Steel-Composite) Gear with various composite materials and layups. AIAA SciTech Forum, 7-11 January 2019, San Diego, California

[22] Palermo, A., Britte, L., Janssens, K., Mundo, D., Desmet, W., The measurement of Gear Transmission Error as an NVH indicator: Theoretical discussion and industrial application via low-cost digital encoders to an all-electric vehicle gearbox, Mechanical Systems and Signal Processing, 110, 2018, pages 360-389

[23] Marafona, J.D.M., P.M.T. Marques, P.M.T., Martins, R.C., Seabra, J.H.O, Mesh stiffness models for cylindrical gears: A detailed review, Mechanism and Machine Theory, Volume 166, December 2021, 104472

[24] Gauntt, S.,;McIntyre, McIntyre S., Campbell, R., Static transmission error analysis of a hybrid spur gear drivetrain, Vertical Flight Society's 76th Annual Forum and Technology Display, 5 October 2020 through 8 October 2020, Code 164757

[25] S. Shweiki, A. Rezayat, T. Tamarozzi, D. Mundo, Transmission Error and strain analysis of lightweight gears by using a hybrid FE-analytical gear contact model, Mechanical Systems and Signal processing, volume 123, 2019, 573-590, doi: 10.1016/j.ymssp.2019.01.024.

[26] M. Vivet, T. Tamarozzi, W. Desmet, D. Mundo, On the modelling of gear alignment errors in the tooth contact analysis of spiral bevel gears, Mechanism and Machine Theory, (155) 2021, Article n. 104065

[27] Cappellini, N., Tamarozzi, T., Blockmans, B., Fiszer, J., Cosco, F. and Desmet, W. Semi-analytic contact technique in a non-linear parametric model order reduction method for gear simulations. Meccanica, 53(1-2), 49-75 (2018).

[28] Boosting productivity in gearbox engineering using a revolutionary approach to multibody simulation. Siemens PLM Software. URL: https://resources.sw.siemens.com/en-US/white-paper-gearbox-multibody-simulation

[29] Advanced FE-preprocessor, Simcenter 3D Motion: Siemens PLM Software. URL:

https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-3d.html