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Research paper

NVH robust optimization of gear macro and microgeometries using an efficient tooth contact model

Pierre Garambois*, Joël Perret-Liaudet, Emmanuel Rigaud

Laboratoire de Tribologie et Dynamique des Systèmes, UMR CNRS 5513, Ecole Centrale de Lyon · 36 avenue Guy de Collongues, 69130 Ecully, France

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ABSTRACT

This paper presents a methodology for the multi-objective optimization of both gear macro and microgeometry parameters in order to minimize the Static Transmission Error (STE) and the mesh stiffness fluctuations generated by the meshing process. The optimization is performed using a genetic algorithm which allows testing of a high number of gears. As a fast evaluation of the gear excitation sources is required, a analytical tooth bending model is introduced. It computes the gear compliance with an analytical thick plate model evaluating the tooth strain energy and a Ritz–Galerkin approximation evaluating the tooth deflection. For each gear design analyzed, the robustness to manufacturing errors is evaluated by performing Monte Carlo simulations for a thousand random manufacturing errors samples. The Probability Density Functions describing the RMS values of the mesh stiffness and STE fluctuations of each gear are estimated, and their average values are the two objectives of each gear. Standard deviations and maximum values describing the dispersion of results are also evaluated. Finally, the methodology provides a range of gears and a decision help tool, illustrated with a reverse gear.

1. Introduction

Mechanical gear systems involve internal excitations responsible for upsetting vibroacoustic phenomena [40]. It is usually assumed that the Static Transmission Error (STE) is the main excitation source generated by the meshing process and is responsible for the so-called whining noise [20,24,36,40,54]. It is defined as the difference between the actual position of the output wheel and the position it would occupy if the gear drive were perfect and infinitely rigid [24,54]. Its time-evolution depends on the instantaneous situations of the meshing tooth pairs which results from two physical sources. The first source corresponds to the under load gear teeth deflections. The second source correspond to the tooth flank micro-geometry associated with manufacturing errors and/or profile/longitudinal tooth corrections. The misalignment induced by the global deformation of the device can be included in the second source. STE is an excitation source which can be taken into account by its time-evolution $\delta(t)$ (displacement type excitation) and a mesh stiffness fluctuation $k(t)$, origin of a parametric excitation of the mechanical gear system. Under steady-state operating conditions, STE and mesh stiffness fluctuations are periodic functions. In the absence of pitch errors and eccentricity faults, their fundamental frequency corresponds to the meshing frequency ($f_m = Zf$, with f the rotation frequency of a wheel and Z its number of teeth). Under operating conditions, STE $\delta(t)$ and $k(t)$ lead to dynamic mesh forces which are transmitted to the housing through wheel bodies, shafts and

* Corresponding author.
E-mail addresses: pierre.garambois@ec-lyon.fr (P. Garambois), joel.perret-liaudet@ec-lyon.fr (J. Perret-Liaudet), emmanuel.rigaud@ec-lyon.fr (E. Rigaud).

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Nomenclature

a'	Center distance (m)
b	Gear facewidth (m)
C	Gear torque (N.m)
C_β	Parabolic and symmetrical gear crowning (m)
$\mathbf{e}(\theta)$	Vector describing the initial gap between the teeth at the angular position θ (m)
E	Young Modulus (pascal)
f	Rotating frequency of the shaft (Hz)
f_m	Meshing frequency (Hz)
$f_{H\alpha}$	Gear tip relief (m)
F	Gear load (N)
g_s	Specific glide
$\mathbf{H}(\theta)$	Compliance matrix of the teeth in contact at the angular position θ (m.N^{-1})
$\mathbf{h}_{j,AN}(\theta)$	j line of the compliance matrix $\mathbf{H}_{AN}(\theta)$ built with the analytical model (m.N^{-1})
$\mathbf{h}_{j,FEM}(\theta)$	j line of the compliance matrix $\mathbf{H}_{FEM}(\theta)$ built with the FEM (m.N^{-1})
$h(x)$	Thickness of the plate at the heigh x (0 being the tooth foot) (m)
h_a	Tooth addendum coefficient
h_e	Tooth height (m)
h_f	Tooth dedendum coefficient
j	Gear backlash (m)
$k(t)$	Gear mesh stiffness (N.m^{-1})
$L_{f_{H\alpha}}$	Gear tip relief length (m)
m_k	Average value of the PDF describing RMS values of $k(t)$ fluctuations (%)
m_{ste}	Average value of the PDF describing RMS values of STE $\delta(t)$ fluctuations (m)
$(M_x, M_y)^T$	Bending moments (N)
$(Q_x, Q_y)^T$	Shear stress forces (N.m^{-1})
MAC_{def}	MAC-like criterion representing the accuracy of the plate deflection (analytical model/FEM)
$MAC_j(\theta)$	MAC-like criterion representing the accuracy of the j line for a position θ of the matrices $\mathbf{H}_{AN}(\theta)$ and $\mathbf{H}_{FEM}(\theta)$
M_k	Maximum value of the PDF describing RMS values of $k(t)$ fluctuations (%)
M_{ste}	Maximum value of the PDF describing RMS values of STE $\delta(t)$ fluctuations (m)
M_{xy}	Twisting moments (N)
n_{MC}	Number of Monte Carlo simulations
N	Number of angular positions of the driving wheel in a meshing period
$\mathbf{P}(\theta)$	Load distributed along the gear contact line at the angular position θ (N)
P_i	Load at the discretized contact point i (N)
r_b	Gear base radius (m)
r_f	Gear root radius (m)
r_i	Gear reference radius (m)
$s_R(R)$	Tooth thickness at the radius R (m)
s_i	Tooth thickness at the reference radius r_i (m)
S	Surface of the plate (m^2)
$T(x_0, y_0)$	Transverse force applied to the point (x_0, y_0) (N)
$\mathbf{u}(x, y)$	Displacement vector of the plate (m)
$w(x, y)$	Deflection of the plate in the direction z in function of (x,y) the position in the tooth (m)
W_{def}	Strain energy of the plate (J)
x_{ps}	Gear profile shift coefficient
$\mathbf{X}_{AN}$	Deflection vector of the plate obtained with the analytical model (m)
$\mathbf{X}_{FEM}$	Deflection vector of the plate obtained with the FEM (m)
Z	Number of teeth
α_o	Gear pressure angle (°)
α_{oT}	Gear transverse pressure angle (°)
β	Gear helix angle (°)
$\boldsymbol{\epsilon}$	Strain tensor of the plate
$\delta(\theta)$	Static Transmission Error (STE) at the angular position θ (m)
ν	Poisson coefficient
σ_k	Standard of the PDF describing RMS values of $k(t)$ fluctuations (%)