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Requirement-based system-level simulation of mechanical transmissions with special consideration of friction, backlash and preload

J-Charles Maré [a,b,c,*]

[a] Université de Toulouse, Toulouse, France
[b] INSA, UPS, Mines Albi, ISAE, Toulouse, France
[c] ICA (Institut Clément Ader), Toulouse, France

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ABSTRACT

Mechanical transmissions are addressed with a system-level view for preliminary sizing and virtual prototyping. The simulation needs are transformed into requirements that drive the model development. Balanced models, incremental modeling, parameterization from datasheets, admittance to causal cases, fault injection or ageing, and reduction of discontinuities are considered with particular attention throughout. Examples of implementation are given for a nut-screw in the Dymola–Modelica simulation environment. The mechanical transmission is decomposed as a sequence of perfect power transmission, friction and compliance. In the compliance model, a single parameter allows a continuous transition between preload or backlash. The friction model structure enables irreversible transmissions to be simulated, if needed. Friction is decomposed into load-dependent and load-independent effects, for which parameters can be varied versus velocity and temperature. The influence of the preload force on friction is introduced as an additional load-dependent friction in the preload domain. Finally the mechanical transmission model is assembled and analyzed with respect to admittance of causal cases.

1. Introduction

The field of mechanical power transmission has not missed the evolution toward greener, cheaper and safer solutions, chasing energy losses and promoting power-on-demand designs. This is particularly obvious in the automotive and aerospace industries, which have started introducing major step changes. As a side effect, systems are progressively becoming more complex with numerous cross links between technological domains. Therefore, it has become mandatory to resort to systems-engineering (SE) processes and simulation-driven design (SDD) to increase maturity, performance and robustness in a world-wide competitive market.

Simulation-driven design has become pretty well established for 3D analysis through commercial simulation software that can address stress and strain, flow patterns, heat exchanges, electro-magnetics, etc. by using to geometric discretization, including coupling between domains and transients. However, this only provides advanced means to investigate the very local geometrical level that lies at the bottom of the V-shape design cycle [1]. From a more system-level standpoint,

* Correspondence to: INSA Dpt Mécanique, 135 Avenue de Rangueil, 31077 Toulouse, Cedex 4, France. Tel : +33 (0)5 6155 9717/561812608.
E-mail address: jean-charles.mare@insa-toulouse.fr

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Notations

a, b	model coefficients
d	viscous factor
F	force
J	moment of inertia
K	compliance factor
l	lead
M	mass
n	compliance exponent
$\mathcal{P}$	heat power
T	torque
V	translational velocity
x	translational position
z	vector of parameters
δ	deformation
λ	free-run factor
η	efficiency
γ	jamming factor
θ	temperature
ω	angular velocity

Subscripts/superscripts

a	drive side
b	load side
B	bounded
c	compliance
C	contact
d	drive side or damping
D	dependent
e	elastic
f	friction
h	healthy
m	middle
I	independent
j	jamming
l	load side
nld	no-load driving
ndb	no-drive back-driving
p	pseudo, preload
r	relative
s	support
v	velocity
0	reference or backlash
1, 2	index of contact, direct/indirect
'	additional value
$\bar{}$	dimensionless

the situation is not so well established although the amount of commercial system-level simulation software on the market is increasing. However, very few engineering needs are covered for both development and integration activities which include the architecting (functional, conceptual then technological), sizing and specification of sub-systems (preliminary then detailed), and their integration, verification and validation (virtual then real). Unfortunately, it must be admitted that the model libraries of mechanical transmissions are often poor or incomplete and do not meet the engineering needs.

In the field of actuation (e.g. for flight controls or landing gears in aerospace), there is indeed a huge demand for realistic models of mechanical power transmission to support system-level design, integration and monitoring. In particular, the models and their simulations are required to work towards multiplicity of engineering targets, such as thermal balance, performance in closed-loop control, energy saving and weight reduction, back-drivability, damping, soft endstop, tolerance or resistance to jamming, etc. A good illustration of this status can be found in the example of nut-screws models. In recent years, much research work with a component-level view has been published, e.g. [2] for kinematics, [3] for wear, [4,5] for finite element modeling, [6] for friction and [7] for compliance. Although some publications have partly addressed the