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Research paper

Multi-objective spur gear pair optimization focused on volume and efficiency

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ABSTRACT

Besides satisfying the essential strength requirements, gearbox design should ensure additional desirable properties in order to be competitive. For example, a gearbox should be efficient, durable, quiet, compact, and light. Nowadays, as a consequence of rising environmental concerns, high efficiency is a rather desirable feature. In this article, a genetic algorithm was used for conducting a multi-objective optimization of gear pair parameters with a goal of reducing the transmission volume and power losses. Gearing efficiency primarily depends on the normal load, sliding velocities, and the friction coefficient. Gearing efficiency was calculated analytically, using the approximate load distribution formulae and efficiency formulation developed by Schlenk. The resulting formula was included in the genetic algorithm as an objective. To verify it, results were compared to the ones obtained by other authors. Optimization variables consisted of the gear module, the face width, the pinion and wheel profile shift coefficients and the number of teeth of the pinion. Solutions have shown that the trade-off between volume and efficiency is obligatory and a combination of the lower gear module, the lower face width, the higher profile shift coefficients and the higher number of teeth of the pinion yield good results regarding both objectives.

1. Introduction

During the gearbox design phase, gear pair parameters, and consequently gear pair properties, are defined by the calculation standards such as ISO and AGMA [1,2]. Nonetheless, the resulting design is often not competitive on the market even though it satisfies all the necessary strength requirements. For this reason, additional desirable properties are included to improve it, either in terms of higher durability, higher efficiency, or a lighter and more compact design.

Optimization methods provide a fast way of solving the above-mentioned problems by finding the optimal set of parameters for each observed case. In the field of gear optimization, genetic algorithms (GA) have been widely used since they were proposed by Marcelin and Yokota [3–5]. GA is a bio-inspired optimization algorithm that replicates the theory of evolution. By combining the best performing specimens in a generation, all of which satisfy both the obligatory and additional criteria, a solution with the highest fitness value is found. GA has been used for solving a substantial number of tasks in the field, such as the gear train volume minimization, gearbox design, and the optimization of micro-geometric modifications [6–10]. If multiple conflicting objectives exist, searching for the optimal results separately for each objective is not recommended. Konak et al. provide a brief description of GAs used for multi-objective optimization in [11]. They state that the

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Nomenclature

b	face width, mm
b_1	power constant
d_{a1}	addendum diameter (pinion), mm
d_{a2}	addendum diameter (wheel), mm
F_{tb}	normal load, N
F_N	circumferential force at base circle, N
i	transmission ratio
K_A	application factor
m	gear module, mm
n_1	rotational speed (pinion), s^{-1}
P	transmitted power, W
P_{loss}	power loss, W
p_{et}	transverse base pitch, mm
Ra	arithmetic mean roughness, µm
R_m	load sharing ratio along the line of action
T_1	input torque, Nm
t_{st}	starting time, s
v	pitch line velocity, m/s
v_d	dynamic oil viscosity, mPa·s
v_s	sliding velocity, m/s
$V_{\Sigma C}$	sum velocity, m/s
x_1	profile shift coefficient (pinion)
x_{1max}	maximal allowable profile shift coefficient (pinion)
x_2	profile shift coefficient (wheel)
Y_{NT}	life factor for tooth root stress for reference test conditions
Z_L	lubricant factor
Z_{NT}	life factor for contact stress for reference test conditions
z_1	number of teeth (pinion)
z_2	number of teeth (wheel)
α_w	operating pressure angle, rad
ε_1	tip contact ratio of the pinion
ε_2	tip contact ratio of the pinion
ε_α	transverse contact ratio
η	efficiency
μ_m	friction coefficient
ξ	involute profile parameter [30,40]
ρ_{redC}	reduced radius of curvature (point C), mm
σ_{Flim}	nominal stress number (bending), N/mm^2
σ_{Hlim}	nominal stress number (contact), N/mm^2
θ	rotation angle, rad
ψ_i	curvature radius at point i on the line of action, mm

optimal solution with respect to one objective will often result in an unacceptable result with respect to other objectives. The final solution will always be a trade-off between objectives; therefore, Pareto optimal solution sets are preferred. Other optimization algorithms successfully used in the field include particle swarm optimization and simulated annealing [12].

Environmental concerns coupled with constant demands to increase the green energy market share make high efficiency a rather desirable product property. Gearbox losses consist of bearing, seal and gear losses [13], which can be further divided into churning and frictional losses. Gearing efficiency is considered to be a function of the load normal to the gear tooth, sliding velocity, and friction coefficient [14]. Extensive theoretical research has been conducted on gear pair efficiency. Baglioni et al. analysed the differences in spur gear efficiency caused by different friction coefficient formulations [15]. The same authors also assessed variations in efficiency resulting from the changes in addendum modifications. Four often used methods of profile shift distribution have been assessed: design for balanced sliding, design for decreased noise, DIN 3992 method (balanced gears), and Maag guidelines (a compromise between strength and efficiency). The analysed guidelines can be found in the technical literature [16,17]. Marques et al. [18] assessed the effects of using either a local or a constant friction coefficient value on the spur and the helical gear power losses. Two different load distribution models were presented. Power losses of spur gears with tip reliefs were studied by Diez-Ibarbia et al., who assessed the role of friction coefficient formulation [19] and load sharing model [20] by using the method presented in [14]. Velex and Ville proposed