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PARAMETRIC DESIGN AND FEM-BASED STRENGTH INVESTIGATION OF CYLINDRICAL GEAR TRANSMISSIONS IN THE SOLIDWORKS ENVIRONMENT

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Abstract. The article describes a methodology for parametric modeling, assembly, kinematic analysis and finite element method-based strength evaluation of a single-stage spur cylindrical gear transmission used in the motion transmission mechanisms of technological machines. The study consecutively used the SolidWorks Part, Toolbox, Assembly, Gear Mate, Motion and Simulation modules. FEM results were compared with theoretical calculations performed according to the Lewis, Hertz, AGMA and GOST 21354-87 approaches. The results showed that under nominal operating conditions, the transmission ratio is 3.167, the linear velocity at the mesh point is 4.56 m/s, the maximum bending stress reaches 312 MPa, and the maximum contact stress reaches 492 MPa. The agreement between FEM and theoretical calculations for bending stress was 92.95-99.36%, while for contact stress it was 95.53% relative to the AGMA calculation. The developed approach has practical significance for rapid design, virtual testing and preparation of design documentation for gearboxes of technological machines.
Keywords: cylindrical gear transmission, SolidWorks, CAD/CAE, parametric modeling, Gear Mate, FEM, bending stress, contact stress, kinematic analysis, gearbox.

Abstract. The article presents a methodology for parametric modeling, assembly, kinematic analysis and finite element strength evaluation of a single-stage spur cylindrical gear transmission used in technological machines within the SolidWorks CAD/CAE environment. The study consistently applies SolidWorks Part, Toolbox, Assembly, Gear Mate, Motion and Simulation modules. FEM results are compared with theoretical calculations based on Lewis, Hertz, AGMA and GOST 21354-87 approaches. Under nominal operating conditions, the transmission ratio is 3.167, the linear velocity at the mesh point is 4.56 m/s, the maximum bending stress reaches 312 MPa and the maximum contact stress reaches 492 MPa. The agreement between FEM and theoretical calculations is 92.95-99.36% for bending stress and 95.53% for contact stress compared with AGMA. The proposed approach is practically useful for rapid design, virtual testing and preparation of engineering documentation for gearboxes of technological machines.
Keywords: cylindrical gear transmission, SolidWorks, CAD/CAE, parametric modeling, Gear Mate, FEM, bending stress, contact stress, kinematic analysis, gearbox.

Introduction

In mechanical engineering, motion transmission mechanisms are one of the main structural units that determine the reliable operation, energy efficiency and operational stability of technological machines. In particular, cylindrical gear transmissions are widely used in gearboxes, conveyors, textile machines, metal-cutting machine tools and other technological equipment because they transmit torque between parallel shafts with high efficiency, compact design and a constant transmission ratio.

In traditional design, calculating gear wheel geometry, preparing drawings and checking strength require a considerable amount of time. CAD/CAE systems bring this

process to the level of digital prototyping and make it possible to create the model, assemble it, check its motion and evaluate the stress-strain state in a single environment. In this respect, SolidWorks is an effective environment widely used in mechanical engineering practice, combining parametric modeling, a standard parts library, and kinematic and FEM analysis tools.

The purpose of this article is to develop a methodology for designing a single-stage cylindrical gear transmission for technological machines in the SolidWorks environment and evaluating its strength on the basis of FEM, and to substantiate the reliability of the approach by comparing the obtained results with theoretical calculations.

Research object and methodology

A single-stage, spur, externally meshing cylindrical gear transmission was selected as the research object. The transmission was modeled parametrically in SolidWorks; the assembly unit was formed in the Assembly module; and the meshing of the teeth was simulated by means of the Gear Mate constraint. In the next stage, kinematic analysis was performed in the SolidWorks Motion module, while static analysis based on the finite element method was carried out in the SolidWorks Simulation module.

The calculation and analysis sequence consisted of the following stages: 1) selection of initial design parameters; 2) determination of the pitch, outside and root diameters of the gear wheels; 3) creation of parametric 3D models in the SolidWorks Toolbox and Part modules; 4) assembly of the shaft, pinion and gear wheel in the Assembly module; 5) assignment of the transmission ratio through Gear Mate; 6) determination of angular velocities and linear velocity in the Motion module; 7) mesh generation, setting of boundary conditions and application of loading in the Simulation module; 8) determination of bending and contact stresses; 9) comparison of the results with theoretical calculations.

Table 1
Main geometric and operating parameters adopted in the study

Indicator	Designation	Value
Number of pinion teeth	z_1	30
Number of gear wheel teeth	z_2	95
Module	m	2 mm
Pitch diameter, pinion	$d_1=m\cdot z_1$	60 mm
Pitch diameter, gear wheel	$d_2=m\cdot z_2$	190 mm
Center distance	$a_w=(d_1+d_2)/2$	125 mm
Tooth width	b	50 mm
Driving shaft rotational speed	n_1	1450 rpm
Nominal torque	T_1	36,200 N·mm
Tangential force	F_t	1207 N

Results of kinematic analysis

In the SolidWorks Motion environment, a Rotary Motor with a value of 1450 rpm was assigned to the driving shaft. The analysis was performed over 5 complete revolutions. The results showed that the Gear Mate constraint was selected correctly and that the kinematic transmission law corresponded to the theoretical calculation.

In the Motion analysis, the angular velocity of the pinion was 151.84 rad/s and the angular velocity of the gear wheel was 47.94 rad/s. From their ratio, the actual transmission ratio was determined as u = 3.167. This fully corresponds to the theoretical value z_2/z_1 = 95/30 = 3.167. The linear velocity at the mesh point was 4.56 m/s; since this value is below the accepted limit of 6 m/s for spur gear transmissions, the transmission was assessed as acceptable in terms of speed regime.

Table 2

Comparison of kinematic analysis results with theoretical values

Indicator	SolidWorks Motion	Theoretical calculation	Agreement, %
Transmission ratio, u	3.167	3.167	100.00
Mesh point velocity, m/s	4.56	4.55	99.78
Reactive torque T_2, N·mm	110,850	110,612	99.79

FEM-based evaluation of the stress-strain state

A static analysis of the gear transmission was carried out in the SolidWorks Simulation module. As boundary conditions, the shaft supports were fixed, nominal torque was applied to the pinion, and reactive resistance was generated through the gear wheel. The main focus of the analysis was placed on bending stress at the tooth root and contact stresses on the meshing tooth surfaces.

The bending stress reached its maximum value in the fillet region on the loaded side of the tooth root. This is consistent with the classical Lewis theory, which considers the tooth as a cantilever beam. According to the FEM result, the maximum bending stress was 312 MPa. In theoretical calculations, the bending stress was estimated at 314 MPa according to the Lewis approach and about 290 MPa according to the AGMA approach.

Contact stress had an ellipsoidal distribution along the line of tooth meshing, and the maximum value was located around the pitch point. According to the FEM result, the maximum contact stress was 492 MPa, while the value calculated according to AGMA was 470 MPa. This result indicates that the FEM model, which takes the real meshing geometry into account, agrees sufficiently well with the theoretical approach in contact problems.

Table 3

Comparison of FEM and theoretical calculations

Indicator	FEM/Motion	Theoretical calculation	Agreement, %
Transmission ratio, u	3.167	3.167	100.00
Mesh point velocity, m/s	4.56	4.55	99.78
Reactive torque T_2, N·mm	110,850	110,612	99.79
Bending stress σF, MPa (Lewis)	312	314	99.36
Bending stress σF, MPa (AGMA)	312	290	92.95
Contact stress	492	470	95.53

σH, MPa (AGMA)			

Analysis of the influence of load and module

Additional analyses performed at 50, 75, 100, 125 and 150% of the nominal load showed that the bending stress is almost linearly dependent on load. In the nominal regime, the safety factor was 1.22, while when the load was increased to 125%, this indicator decreased to 0.97. Therefore, in practical operation, it is not recommended to overload the transmission by more than 20% above the nominal value.

Table 4

Dependence of bending stress on load level

Load, %	T_1, N·mm	σF (FEM), MPa	nF
50	18,100	156	2.44
75	27,150	234	1.62
100	36,200	312	1.22
125	45,250	390	0.97
150	54,300	468	0.81

Increasing the module value is an effective solution for reducing contact stress. According to the analysis results, when the module was 1.5 mm, the contact stress was 541 MPa; at a module of 2.0 mm it was 492 MPa; at 2.5 mm it was 445 MPa; and at 3.0 mm it was 418 MPa. However, increasing the module also increases the overall dimensions and mass; therefore, the design decision must be made on the basis of a balance between strength, compactness and mass requirements.

Table 5

Dependence of contact stress on module

Module, mm	Tooth width b, mm	σH (FEM), MPa	nH
1.5	50	541	0.95
2.0	50	492	1.05
2.5	50	445	1.16
3.0	50	418	1.23

Discussion

The obtained results show that the parametric model created in the SolidWorks environment is adaptable to changes in gear transmission geometry. The Gear Mate constraint correctly ensured the kinematic law: the transmission ratio matched the theoretical value by 100%. This makes it possible to use the CAD model as a reliable basis for subsequent dynamic or strength analyses.

The high agreement between FEM results and theoretical calculations confirms that the Simulation module is effective for the preliminary engineering evaluation of gear transmissions. However, in contact problems, the theoretical GOST/Hertz approaches rely on simplified assumptions and coefficients; therefore, an FEM model that takes real meshing geometry, contact area, mesh quality and boundary conditions into account may in some cases give higher values.

From a practical point of view, it is advisable for the designer to consider the following decisions: not excessively reducing the tooth root radius, ensuring high-quality finishing of tooth surfaces, selecting the lubrication regime correctly, increasing the module or tooth width if there is a possibility of overload, and considering helical gear variants at higher speeds.

Conclusion

The comprehensive CAD/CAE methodology based on the SolidWorks Part, Toolbox, Assembly, Drawing, Motion and Simulation modules made it possible to design a cylindrical gear transmission through all stages from the technical assignment to virtual testing.

The Motion analysis showed that the transmission ratio is 3.167, the linear velocity at the mesh point is 4.56 m/s, and there is 99.78-100% agreement with theoretical values.

According to the FEM analysis, the maximum bending stress was 312 MPa, the maximum contact stress was 492 MPa, the minimum overall safety factor was 2.05, and the maximum displacement was 8 micrometers.

The agreement between FEM and theoretical calculations was 92.95-99.36% for bending stress, while the agreement relative to the AGMA approach for contact stress was 95.53%.

It was established that when the load exceeds the nominal value by 25%, the safety margin becomes insufficient, whereas increasing the module to 2.5 mm significantly reduces contact stress.

The developed methodology is recommended for designing gearboxes of technological machines, organizing laboratory classes in higher education, and implementing digital prototyping processes in small machine-building enterprises.

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