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Reliability Optimum Design for Bevel Gear Driven Systems Based on Genetics Algorithm

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Abstract. Genetics algorithm is a global group search optimum calculation method based on the natural selections and the genetic variations. Mechanic reliability design makes sure that the reliability indexes can be realized. However, it cannot guarantee that the products have the best working performances and the optimum design parameters. In this paper, genetics algorithm is introduced into the reliability optimum design for bevel gear driven systems, and then the optimum design parameters of driven systems are obtained under the allowable reliability degree. This method can quantificational make optimum analysis for bevel gear driven systems, and is very useful for the engineering application.

Keywords: Bevel gear driven systems; reliability optimum design; random parameters; genetics algorithm.

1. Introduction

With the development of modern industry and machinery science technology, the bevel gear driven system is required to have the characteristics of light-duty, high-speed, large carrying power, long life and high reliability [1-3]. In the era of rapid development computer, compared with the actual situation, the accuracy of calculation parameters is far behind the precise analysis of engineering structures. Therefore, considering the random factors of actual situation have a very significant impact on the reliability optimum design for bevel gear driven systems based on genetics algorithm.

Genetics algorithm describes problems by a single string, makes optimum calculation by using the fitness function without regard to the gradient information such as functional derivatives, etc. Therefore, it is good at solving the complex nonlinear problems that other subjects don't solve or are difficult to solve. Reliability optimum design for bevel gear driven systems based on genetics algorithm can guarantee that the driven systems have the best working performances and the optimum design parameters.

2. Establishing Reliability Optimum Mathematical Model for Bevel Gear Driven Systems

2.1 Establishing Optimum Objective Function.

The least all-in cost of bevel gear driven system design is set for the objective function. It can be written as:

$$\min C_T = C_1(\mu_\delta) + C_2(\sigma_\delta) + C_3(\mu_s) + C_4(\sigma_s)$$

Where, C_T is the all-in cost, $C_1(\mu_\delta)$ and $C_2(\sigma_\delta)$ are respectively the cost functions of strength equalizing value and strength standard deviation, $C_3(\mu_s)$ and $C_4(\sigma_s)$ are respectively the cost functions of stress equalizing value and stress standard deviation.

In many factors, the cost of bevel gear material is an important factor for the all-in cost. Therefore, the cost of material is mainly taken into consideration. C_T is set for:

$$C_T = (V_1 + V_2)\rho$$

Where, ρ is the material density of bevel gear, V_1 and V_2 are respectively the volumes of driving gear and driven gear. The bevel gear drive mechanism is shown in Fig.1. The gear mesh volumes of driving gear and driven gear are respectively obtained, as shown in Eqs.1 and 2.

$$V_1 = \frac{\pi}{3} b \cos\delta_1 \times \left[\left(\frac{mz_1}{2} \right)^2 + \frac{mz_1}{2} \left(\frac{R-b}{R} \times \frac{mz_1}{2} \right) + \left(\frac{R-b}{R} \times \frac{mz_1}{2} \right)^2 \right] \tag{1}$$

$$V_2 = \frac{\pi}{3} b \cos\delta_2 \times \left[\left(\frac{mz_2}{2} \right)^2 + \frac{mz_2}{2} \left(\frac{R-b}{R} \times \frac{mz_2}{2} \right) + \left(\frac{R-b}{R} \times \frac{mz_2}{2} \right)^2 \right] \tag{2}$$

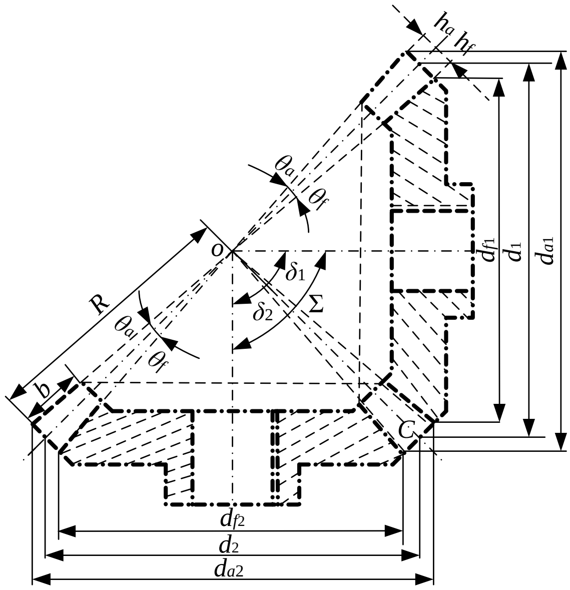

Fig. 1 Driven structure of orthogonal bevel gears

Where, z_1 and z_2 are respectively the tooth numbers of driving gear and driven gear; m is the big end module; R is the cone distance; b is the tooth width; δ_1 and δ_2 are respectively the reference cone angles of driving gear and driven gear.

2.2 Determining Reliability Optimum Constraints.

The contact stresses of driving gear and driven gear are calculated respectively. We selected the smaller value. The contact stress of bevel gear is obtained by Eq. 3.

$$\sigma_H = Z_H Z_E Z_\varepsilon Z_\beta Z_k \sqrt{\frac{K_A K_V K_{H\beta} K_{H\alpha} F_{tm}}{d_{m1} b_{eH}} \times \frac{\sqrt{u^2+1}}{u}} \tag{3}$$

Where, u is the gear ratio;Z_H is the node region coefficient; Z_E is the elastic coefficient and we set $Z_E = 189.8\sqrt{\mathrm{N/mm^2}}$; Z_ε is the overlap ratio coefficient and we set $Z_\varepsilon = \sqrt{(4-\varepsilon_{v\alpha})/3}$; Z_β is the helix angle coefficient of contact strength calculation; we set $Z_k = 0.85$; K_A is the utilization coefficient; K_V is the dynamic load factor; $K_{H\beta}$ is the distribution coefficient of longitudinal form load; $K_{H\alpha}$ is the partition ratio of longitudinal form load; F_{tm} is the nominal shear stress on pitch circle of tooth width midpoint; d_{m1} is the pitch circle diameter of virtual cylindrical gear of bevel pinion; b_{eH} is the effective tooth width and we set $b_{eH} = 0.85b$; u is the gear ratio.

We selected the equalizing values of all parameters in Eq. 3. Therefore, the contact stress equalizing value of bevel gear $\bar{\sigma}_H$ is determined. Meanwhile, according to the literature [2], the variation coefficient of contact stress can be written as [4-6]:

$$C_{\sigma_H} = \left[C_{z_H}^2 + C_{z_E}^2 + C_{z_\varepsilon}^2 + C_{z_\beta}^2 + \frac{1}{4}\left(C_{F_{tm}}^2 + C_{d_{m1}}^2 + C_{b_{eH}}^2 + C_{K_A}^2 + C_{K_V}^2 + C_{K_{H\beta}}^2 + C_{K_{H\alpha}}^2 \right) \right]^{1/2} \tag{4}$$

The standard deviation of contact stress is:

$$s_{\sigma_H} = C_{\sigma_H} \times \bar{\sigma}_H \tag{5}$$

The allowable contact stress is:

$$\sigma_{Hp} = \frac{\sigma_{H\lim}}{S_{H\min}} Z_L Z_V Z_R Z_X \tag{6}$$

Where, $\sigma_{H\lim}$ is the contact fatigue strength limit of experimental gear; $S_{H\min}$ is the least safety factor of contact strength calculation; Z_L is the lubricant coefficient; Z_V is the velocity coefficient; Z_R

is the coefficient of rugosity; Z_X is the dimension coefficient of contact strength calculation; The above parameters can be determined by the corresponding forms of literature [1].

We selected the equalizing values of all parameters in Eq. 6. Therefore, the allowable contact stress equalizing value of bevel gear $\bar{\sigma}_{Hp}$ is determined. Meanwhile, according to the literature [2], the variation coefficient of allowable contact stress can be written as:

$$C_{\sigma_{Hp}} = \left[C^2_{\sigma_{H\lim}} + C^2_{S_{H\min}} + C^2_{Z_L} + C^2_{Z_V} + C^2_{Z_R} + C^2_{Z_X}\right]^{1/2} \tag{7}$$

The standard deviation of allowable contact stress is:

$$s_{\sigma_{Hp}} = C_{\sigma_{Hp}} \times \bar{\sigma}_{Hp} \tag{8}$$

According to the above conditions, the reliability optimum constraint of contact stress can be determined as:

$$G_1(x) = R_H - [R_H] \geq 0 \tag{9}$$

Suppose stress and strength all conform to the normal distribution, the constraint can be written as:

$$z_{R_H} = \frac{\mu_{\sigma_{Hp}} - \mu_{\sigma_H}}{\sqrt{\sigma_{\sigma_{Hp}}{}^2 + \sigma_{\sigma_H}{}^2}} \geq z_{[R_H]}$$

In the same way, the dedendum flexural stress of bevel gear can be written as:

$$\sigma_F = \frac{K_A K_V K_{F\beta} K_{F\alpha} F_{tm}}{b_{eF} m_{nm}} Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta Y_k \tag{10}$$

Where, K_A is the utilization coefficient; K_V is the dynamic load factor; $K_{F\beta}$ is the distribution coefficient of longitudinal form load of flexural strength calculation; $K_{F\alpha}$ is the partition ratio of tooth space load; F_{tm} is the nominal shear stress on pitch circle of tooth width midpoint; we set $b_{eF} = 0.85b$; m_{nm} is the normal module of tooth width midpoint; Y_{Fa} is the stress correction factor; Y_ε is the overlap ratio coefficient; Y_β is the helix angle coefficient; we set $Y_k = 1$.

We selected the equalizing values of all parameters in Eq. 10. Therefore, the dedendum flexural stress equalizing value of bevel gear $\bar{\sigma}_F$ is determined. Meanwhile, according to the literature [2], the variation coefficient of dedendum flexural stress can be written as:

$$C_{\sigma_F} = \left[C^2_{K_A} + C^2_{K_V} + C^2_{K_{F\beta}} + C^2_{K_{F\alpha}} + C^2_{F_{tm}} + C^2_{b_{eF}} + C^2_{m_{nm}} + C^2_{Y_{Fa}} + C^2_{Y_{sa}} + C^2_{Y_\varepsilon} + C^2_{Y_\beta} + C^2_{Y_k}\right]^{1/2} \tag{11}$$

The standard deviation of dedendum flexural stress is:

$$s_{\sigma_F} = C_{\sigma_F} \times \bar{\sigma}_F$$

The allowable dedendum flexural stress is:

$$\sigma_{Fp} = \frac{\sigma_{F\lim} Y_{ST}}{S_{F\min}} Y_{\delta relT} Y_{RrelT} Y_X \tag{12}$$

Where, σ_{Flim} is the bending fatigue limit of experimental gear; Y_{ST} is the stress correction factor of experimental gear and we set $Y_{ST}=2.0$; $S_{F\min}$ is the least safety factor of flexural strength calculation; $Y_{\delta relT}$ is the sensitivity coefficient of relative tooth root fillet; Y_{RrelT} is the condition coefficient of relative heel of tooth; Y_X is the dimension coefficient of flexural strength calculation; The above parameters can be determined by the corresponding forms of literature [1].

We selected the equalizing values of all parameters in Eq. 12. Therefore, the allowable dedendum flexural stress equalizing value $\bar{\sigma}_{Fp}$ is determined. Meanwhile, according to the literature [2], the variation coefficient of allowable dedendum flexural stress can be written as:

$$C_{\sigma_{Fp}} = \left[C^2_{\sigma_{F\lim}} + C^2_{Y_{ST}} + C^2_{S_{F\min}} + C^2_{Y_{\delta relT}} + C^2_{Y_{RrelT}} + C^2_{Y_X}\right]^{1/2}$$

The standard deviation of allowable dedendum flexural stress is:

$$s_{\sigma_{Fp}} = C_{\sigma_{Fp}} \times \bar{\sigma}_{Fp}$$

According to the above conditions, the reliability optimum constraint of dedendum flexural stress can be determined as:

$$G_2\left(x\right)=R_F-\left[R_F\right]\geq 0 \tag{13}$$

Suppose stress and strength all conform to the normal distribution, the constraint can be written as:

$$z_{R_F}=\frac{\mu_{\sigma_{Hp}}-\mu_{\sigma_H}}{\sqrt{{\sigma_{\sigma_{Hp}}}^2+{\sigma_{\sigma_H}}^2}}\geq z_{[R_F]}$$

2.3 Design Variables and Edge-restraint Conditions.

The tooth number of driving bevel gear $z_{1\max}\geq z_1\geq 17\cos\delta_1$;the module of gear pair $m\geq 2$;the tooth width coefficient of gear pair $0.35\geq\psi_b\geq 0.2$;the density of gear material $\rho\geq 0$.

3. Making Fitness Function with Punishment Function Method

According to the exterior point punishment function method, we made the fitness function for the constraint nonlinear programming problem,as follows [7-9]:

$$Val\left(x\right)=f\left(x\right)+L\left(x\right)$$

Where, x represents the chromosome; $f(x)$ is the objective function; $L(x)$ is the penalty term.

For the minimum value, we have:

$$\begin{cases} L(x)\;=\;0,\ \text{the feasible }\ x \\ L(x)\;=\;-s_1\left[G_1(x)\right]^2\;-\;s_2\left[G_2(x)\right]^2\;<\;0,\ \text{the infeasible }x \end{cases}$$

Where, s_1 and s_2 are respectively the penalty factors of two inequality constraint functions. According to the design criteria of encased gear, we set s_1 = 1 and s_2 =0.5, respectively. We regarded Eqs. 9 and 11 as the penalty terms in the fitness function. Meanwhile, we regarded the boundary conditions of design variables as the matrix of variables top and bottom limitation in the genetics algorithm.

4. Model Solution of Reliability Optimum Design for Bevel Gears Based on Genetics Algorithm

In calculation, we selected the orthogonal 90° encased straight bevel gear driven system as the optimum design object. Meanwhile, we set that the gear-driven useful horsepower is 9.8kW; the speed of driving gear is 1000r/min; the gear ratio is 3; the working condition coefficient K is 1.8; the material of small bevel gear is 40Cr, modified treatment, the rigidity is 250HBS; the material of big bevel gear is 35SiMnA, modified treatment, the rigidity is 230HBS; the densities of two bevel gears are set according to their materials; the reliability of allowable contact stress $[R_H]$ and dedendum flexural stress $[R_F]$ are respectively 0.9999.

According to the above calculation conditions, we wrote the programs by MATLAB. By calling the genetics search function and iterative computations, the least optimum result of all-in cost of bevel gear driven system design is obtained.

Table 1 shows the data of search path of population optimum. Fig. 2 shows the trend curve of average changes of each generation optimal sufficiency in genetics algorithm.

Table 1 Search path data of bevel gear pair reliability optimum based on genetics algorithm

hereditary algebra	tooth number of small bevel gear	modulo/mm	coefficient of face width	mass of bevel gear driven system /kg	Hereditary algebra	tooth number of small bevel gear	modulo/mm	coefficient of face width	mass of bevel gear driven system /kg
1	28.0231186647	2.04467151358	0.275670035500	1.438088031306750	53	18.7297380165	2.00000000000	0.250000000000	0.374710945232760
3	17.2836767226	2.00000000000	0.271111329306	0.604524556291095	54	18.7288391897	2.00000000000	0.250000000000	0.374657001485795
4	19.8973428501	2.00000000000	0.274347885569	0.480150955772500	55	18.7287417624	2.00000000000	0.250000000000	0.374651154623675
5	19.1833249969	2.00000000000	0.270891590979	0.426472536958825	57	18.7286519706	2.00000000000	0.250000000000	0.374645766042985
7	19.2572809131	2.00000000000	0.250000000000	0.407273514076675	60	18.7286485740	2.00000000000	0.250000000000	0.374645562211455
8	18.8180708343	2.00000000000	0.270891590979	0.402573063923525	63	18.7286474356	2.00000000000	0.250000000000	0.374645493892905
10	19.0285888848	2.00000000000	0.250234992208	0.393204715819815	66	18.7286472062	2.00000000000	0.250000000000	0.374645480124005
11	18.7516101421	2.00000000000	0.250000000000	0.376025213372810	67	18.7285908895	2.00000000000	0.250000000000	0.374642100479205
16	18.7516024263	2.00000000000	0.250000000000	0.376024749203095	69	18.7285514548	2.00000000000	0.250000000000	0.374639733954620
18	18.7515983265	2.00000000000	0.250000000000	0.376024502563945	70	18.7285486653	2.00000000000	0.250000000000	0.374639566554155
19	18.7515954574	2.00000000000	0.250000000000	0.376024329962070	71	18.7285155871	2.00000000000	0.250000000000	0.374637581502675
21	18.7515934792	2.00000000000	0.250000000000	0.376024210952145	73	18.7285034656	2.00000000000	0.250000000000	0.374636854087135
22	18.7494590795	2.00000000000	0.250000000000	0.375895822728700	75	18.7284934782	2.00000000000	0.250000000000	0.374636254732570
23	18.7462003196	2.00000000000	0.250000000000	0.375699858457710	77	18.7284893052	2.00000000000	0.250000000000	0.374636004308935
25	18.7458119773	2.00000000000	0.250000000000	0.375676510185440	79	18.7284868680	2.00000000000	0.250000000000	0.374635858054800
28	18.7434166926	2.00000000000	0.250000000000	0.375532520072865	80	18.7284858998	2.00000000000	0.250000000000	0.374635799953025
30	18.7422694076	2.00000000000	0.250000000000	0.375463565225415	81	18.7284856693	2.00000000000	0.250000000000	0.374635786115830
31	18.7415117725	2.00000000000	0.250000000000	0.375418033995320	82	18.7284856174	2.00000000000	0.250000000000	0.374635783002520
33	18.7414408156	2.00000000000	0.250000000000	0.375413769921635	83	18.7284856016	2.00000000000	0.250000000000	0.374635782053455
35	18.7414279650	2.00000000000	0.250000000000	0.375412997684165	84	18.7284855993	2.00000000000	0.250000000000	0.374635781920005
38	18.7406091554	2.00000000000	0.250000000000	0.375363794656605	85	18.7284343013	2.00000000000	0.250000000000	0.374632703499330
39	18.7402283103	2.00000000000	0.250000000000	0.375340910781700	87	18.7284152965	2.00000000000	0.250000000000	0.374631563018360
40	18.7399950118	2.00000000000	0.250000000000	0.375326893016290	88	18.7284147099	2.00000000000	0.250000000000	0.374631527822100
41	18.7398545449	2.00000000000	0.250000000000	0.375318453215175	89	18.7283645428	2.00000000000	0.250000000000	0.374628517294505
42	18.7395753099	2.00000000000	0.250000000000	0.375301676058585	90	18.7282463102	2.00000000000	0.250002518400	0.374624176059245
46	18.7379606383	2.00000000000	0.250000000000	0.375204672250535	92	18.7282463102	2.00000000000	0.250000000000	0.374621422224295
49	18.7378178180	2.00000000000	0.250000000000	0.375196092910960	99	18.7282462828	2.00000000000	0.250000000001	0.374621420576580
50	18.7325416367	2.00000000000	0.250000000000	0.374879239803340	100	18.7282462828	2.00000000000	0.250000000001	0.374621420576580
52	18.7315947043	2.00000000000	0.250000000000	0.374822392098025					

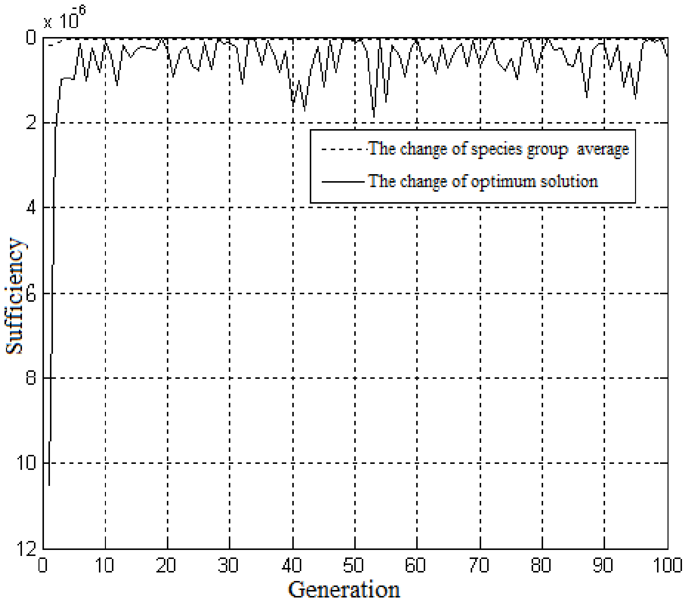

Fig. 2 Search process curve of bevel gear reliability optimum based on genetics algorithm

The calculation shows that breeding to the 89th generation, the optimal solution of reliability optimum design for bevel gear driven system is obtained. The optimal solution is:

$$x^* = \left(x_1^*, x_2^*, x_3^*\right)^T = \left(18.728,2.0,0.25\right)^T$$

C_T=0.375kg

The optimum parameters of bevel gear driven system are obtained under meeting reliability constraints of Eqs.10 and 11 more than 99.99%. Then, the optimum parameters are changed into integers that are final parameters of optimum design.

5. Summary

1) The reliability optimum design model of bevel gear driven system is established. The design parameters of system reliability optimum are obtained based on genetics algorithm.

2) The method is fit for the programming operation. The theory of reliability is introduced into the optimum design of bevel gear to provide the theoretical basis for quantification design in the gear manufacturing process.

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