

# 汽车零件磨损渐变可靠性分析

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**摘 要:** 为研究车辆零件在磨损作用影响下的可靠性问题,将零件结构尺寸最大磨损量考虑到渐变可靠性模型中,得到随时间变化的可靠性状态方程的数学模型,并利用二阶矩和随机摄动法得出动态可靠性指标,进而获得零部件的渐变可靠性及灵敏度的定量分析结果.通过算例与蒙特卡洛相结合验证了该方法的有效性,拟合得到了零部件磨损渐变可靠性分布规律曲线和灵敏度曲线,很好地反映了零部件几何尺寸在磨损状态下危险截面的可靠性变化情况,为车辆零件的磨损渐变可靠性研究提供了理论参考.

**关 键 词:** 车辆零件; 磨损; 渐变可靠性; 蒙特卡洛; 灵敏度

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## Reliability Analysis of Wear Gradient of Automobile Parts

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**Abstract:** To study the reliability of automobile parts under the influence of abrasion, the biggest wear loss is taken into account in the gradual changing reliability model and the model of reliability state with the changing of time is obtained. Then, the secondary moment and the random perturbation method are adopted to give a quantitative analysis of the gradual changing reliability and the sensitivity. Finally, the effectiveness of the proposed method is confirmed by an example and the Monte Carlo. The fitting curves of the regularities of distribution of reliability and of sensitivity with abrasion are obtained, which can well reflect the change of reliability of dangerous sections of automobile parts in wear conditions and provide references for the gradual changing reliability with abrasion.

**Key words:** automobile parts; abrasion; gradual changing reliability; Monte Carlo; sensitivity

随着人们对车辆质量更高层次的追求,可靠性理论方法的研究也需要更深入的探讨.汽车可靠性主要是指在预期的使用时间内和零部件所需的工作条件下汽车零部件能够完成规定的功能的能力<sup>[1]</sup>.由于车辆零部件在使用过程中不断磨损<sup>[2]</sup>,零件磨损量随着使用时间而逐渐增大,一个零部件失效通常是由于磨损导致的.磨损的存在会使零部件几何尺寸(体积)变小,进而导致零部件之间不能够很好地吻合,失去原有人们的期望的功能而失效.车辆零件剧烈磨损的磨损量与工作时间之间具有一定的渐变性<sup>[3-4]</sup>.零部件失效以后就不能完成预定的功能,如果继续使用甚至会产生一定的危险.因此,零部件的可靠性是时间的函数,并呈现出显著的渐变性<sup>[5]</sup>.

本文采用随机摄动方法、二阶矩技术、可靠性理论等,讨论了车辆零件在考虑磨损时的动态可靠性.在知道零部件尺寸、初始强度等基本随机变量的概率特性下,能够准确地得出随时间变化的车辆磨损零件动态可靠性.这对以后车辆零件磨损的渐变可靠性的研究具有重要意义.

### 1 随时间变化的可靠性分析方法

在静态可靠性中,由应力-强度干涉理论可

知,其零部件临界失效状态方程为

$$g(\boldsymbol{Y}) = r - \delta. \tag{1}$$

式中: $r$  为材料强度; $\delta$  为附加载荷; $\boldsymbol{Y}$  为参数向量, $\boldsymbol{Y} = (Y_1, Y_2, \cdots, Y_n)^T$ .

可将零部件的状态函数表示为

$$\left. \begin{aligned} g(\boldsymbol{Y}) \leq 0, & \text{为失效状态;} \\ g(\boldsymbol{Y}) > 0, & \text{为安全状态.} \end{aligned} \right\} \tag{2}$$

根据可靠性设计的随机摄动法,可求出静态可靠性指标 $\beta^{[6-8]}$ :

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{E[g(\boldsymbol{Y})]}{\sqrt{\text{Var}[g(\boldsymbol{Y})]}}. \tag{3}$$

若 $\boldsymbol{Y}$ 中所有随机参数都是正态分布时,可得静态一阶估计量的可靠性,

$$R = \Phi(\beta), \tag{4}$$

其中 $\Phi(\cdot)$ 为标准正态分布<sup>[9-10]</sup>.

但在实际状况中由于各种因素的影响使得零部件的强度与载荷不是固定不变的量,而都是关于时间的函数.失效状态方程可表示为

$$g(\boldsymbol{Y}, t) = r(t) - \delta(t), \tag{5}$$

$g(\boldsymbol{Y}, t)$  为状态函数,可表示车辆零件的两种状态:

$$\left. \begin{aligned} g(\boldsymbol{Y}, t) \leq 0, & \text{失效状态;} \\ g(\boldsymbol{Y}, t) > 0, & \text{安全状态.} \end{aligned} \right\} \tag{6}$$

通过式(3),式(4)可知,零部件的时变可靠性指标与时变可靠性计算式分别为

$$\beta(t) = \frac{\mu_g}{\sigma_g} = \frac{E[g(\boldsymbol{Y}, t)]}{\sqrt{\text{Var}[g(\boldsymbol{Y}, t)]}}, \tag{7}$$

$$R(t) = \Phi(\beta(t)). \tag{8}$$

时变失效率表达式为

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{1}{R(t)} \cdot \frac{dR(t)}{dt}. \tag{9}$$

根据应力-强度干涉理论,可靠性对初始参数均值 $\mu_x$ 和标准差 $\sigma_x$ 的灵敏度为

$$\frac{\partial R}{\partial X^T} = \frac{\partial R}{\partial \beta} \frac{\partial \beta}{\partial \mu_g} \frac{\partial \mu_g}{\partial X^T}, \tag{10}$$

$$\frac{\partial R}{\partial \text{Var}(\boldsymbol{X})} = \frac{\partial R}{\partial \beta} \frac{\partial \beta}{\partial \mu_g} \frac{\partial \sigma_g}{\partial \text{Var}(\boldsymbol{X})}. \tag{11}$$

式中:

$$\frac{\partial R}{\partial \beta} = \phi(\beta(t)); \tag{12}$$

$$\frac{\partial \beta}{\partial \mu_g} = \frac{1}{\sigma_g}; \tag{13}$$

$$\frac{\partial \mu_g}{\partial X^T} = \left[ \frac{\partial R}{\partial X_1} \frac{\partial R}{\partial X_2} \cdots \frac{\partial R}{\partial X_n} \right]; \tag{14}$$

$$\frac{\partial \beta}{\partial \sigma_g} = -\frac{\mu_g}{\sigma_g^2}; \tag{15}$$

$$\frac{\partial \sigma_g}{\partial \text{Var}(\boldsymbol{X})} = \frac{1}{2\sigma_g} \left[ \frac{\partial g}{\partial \boldsymbol{X}} \otimes \frac{\partial g}{\partial \boldsymbol{X}} \right]. \tag{16}$$

再代入式(10)和式(11),就计算出基础变量的可靠性灵敏度 $\partial R/\partial X^T$ 和 $\partial R/\partial \text{Var}(\boldsymbol{X})$ .

## 2 车辆零件磨损可靠性设计实例

在车辆零件可靠性设计中,零件的磨损是影响车辆可靠性的最大因素<sup>[11]</sup>.在实际使用状况中,磨损速度主要是由汽车行驶状况、零部件所处的环境温度、润滑特性、载荷等因素所决定的.磨损速度具有分散性,属于随机变量,在研究零部件磨损时通常是研究其最大磨损量.若某时刻磨损最大速度 $v_{\max}$ 已知,则经过 $t$ 时间后最大磨损量为

$$U_{\max} = v_{\max} \cdot t. \tag{17}$$

当其最大磨损量超过许用磨损量 $U_{\max}$ (mm)时零部件就可能无法完成人们预先设计的功能,即产生失效现象.因此磨损是零部件可靠性的影响因素.

人们为了实现某一特定的预期功能而设计出某一零件,但由于理论、材料、工艺等方面的因素,使得机械零件在应用中会产生各式各样的不可靠的现象.由此,必须大力进行总结开拓现代的机械可靠性设计理论与方法.现以车辆拉杆和扭杆为例,研究车辆零部件基于磨损的动态可靠性及相关变量的灵敏度问题.

### 2.1 考虑磨损失效的车辆拉杆渐变可靠性设计模型

图1是截面为管形的某车辆拉杆结构,且承受压缩载荷作用.



图 1 拉杆结构  
Fig. 1 Structure of tension rod

管形直拉杆的拉应力为

$$\sigma(t) = \frac{4Q}{\pi((D - U_{\max}(t))^2 - (d - U_{\max}(t))^2)}. \tag{18}$$

式中: $Q$  为载荷; $d$  为管形截面的内径; $D$  为管形截面的外径.

应用应力极限状态表示出车辆拉杆的状态方程为

$$g_x(t) = r - \sigma_{\max}(t). \tag{19}$$

式中: $r$  为零件强度值; $\sigma_{\max}$  为变量 $Q, D$  和 $d$  的函数.

2.2 考虑磨损失效的车辆扭杆渐变可靠性设计模型

图 2 是扭杆弹簧结构,连接于车架与车轮之间的一种弹性元件.在汽车行驶中当遇到障碍物汽车向上跳动时,车轮就会通过摆臂使扭杆发生弹性变形,并存储能力,使得车轮在脱离障碍物时能够迅速回位.按其截面可将扭杆分为:片状扭杆、圆形扭杆、管形扭杆及组合式扭杆等.其中圆形扭杆最为常见,而因管形扭杆能够节省材料降低成本与质量,应用也较为广泛.

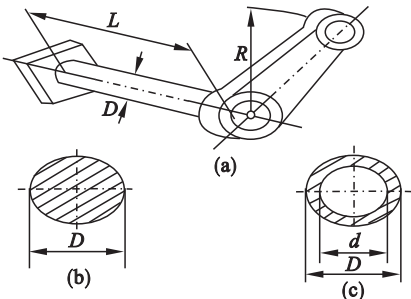


图 2 扭杆弹簧  
Fig. 2 Torsion bar spring

(a)—扭杆结构; (b)—圆形扭杆; (c)—管形扭杆.

通过图 2 对圆形和管形扭杆进行扭力分析,其扭杆所受应力为

$$\tau(t) = \frac{16(D - U_{\max}(t))T}{\pi((D - U_{\max}(t))^4 - (d - U_{\max}(t))^4)} \quad (20)$$

式中: $T$  为附加给扭杆的扭矩; $D, d$  分别为管形扭杆横截面的外径和内径(圆形扭杆内径为零).

应用应力极限状态表示出扭杆的状态方程为

$$g_x(t) = r - \tau_{\max}(t) \quad (21)$$

式中: $r$  为扭杆的材料强度; $\tau_{\max}$  为变量  $T, D$  和  $d$  的函数.

3 数值算例

3.1 拉杆

在一般实际情况中,机械零部件几何尺寸变量和所使用材料的强度变量都是服从正态分布的随机变量.某车辆拉杆的基本随机参数如表 1 所示,且变量间相互独立.同时考虑车辆拉杆的磨损速度为 0.001 156 8 mm/h.

通过运用上述动态可靠性方法得出随时间变化的拉杆可靠性和灵敏度的变化曲线,并分别通过 Monte Carlo(虚线)进行验证.

图 3 表示的是运用时变磨损可靠性模型(实

线)计算得到的车辆拉杆动态可靠性曲线与运用 Monte Carlo(虚线)仿真实验计算得到的车辆拉杆动态可靠性曲线的拟合结果.从图中可以看出两者的变化趋势相一致,吻合较好.从而说明运用时变磨损可靠性模型计算得到的可靠性结果是正确的.

图 4 和图 5 分别表示的是均值灵敏度  $\partial\mu_{x_i}$  曲线和标准差灵敏度  $\partial\sigma_{x_i}$  曲线与 Monte Carlo(虚线)仿真实验计算得到的灵敏度曲线的拟合结果.从图中可以看出两者的变化趋势相一致,吻合较好.这说明运用时变磨损可靠性模型计算得到的车辆拉杆动态灵敏度结果是正确的.

表 1 某型车辆拉杆危险截面基本随机参数均值和标准差值

Table 1 Mean and standard deviation of the basic random parameters of dangerous cross-section of a tension rod

参数	均值	标准差
$D/\text{mm}$	30	0.15
$d/\text{mm}$	25	0.125
$r/\text{MPa}$	400	11
$Q/\text{N}$	$1.7 \times 10^5$	$2.6 \times 10^3$

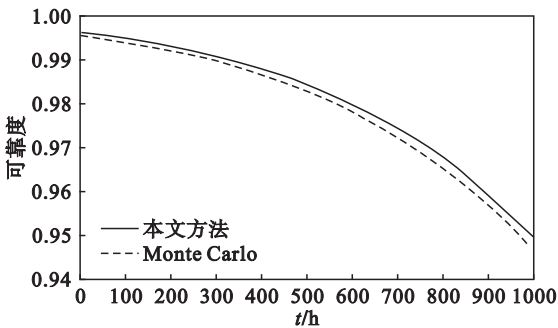


图 3 车辆拉杆可靠性变化曲线  
Fig. 3 Reliability changing curve of vehicle tension rod

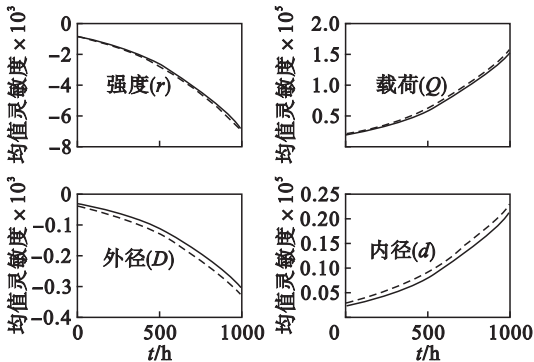


图 4 车辆拉杆均值灵敏度变化曲线  
Fig. 4 Mean sensitivity changing curve of vehicle tension rod

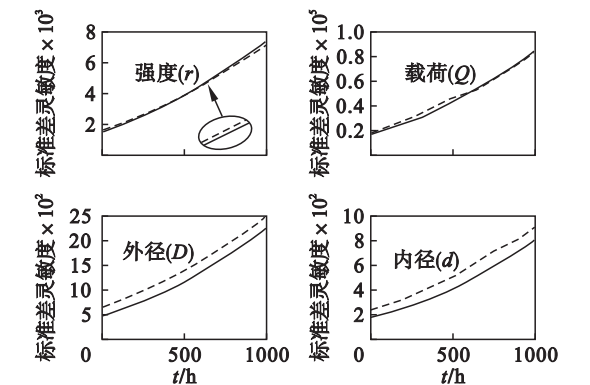


图 5 车辆拉杆标准差灵敏度变化曲线  
Fig. 5 Standard deviation sensitivity changing curve of vehicle tension rod

3.2 扭杆

以某汽车的管型扭杆为例,其基本随机参数如表 2 所示,扭杆所受的扭矩和材料的疲劳极限均为服从正态分布的随机变量.扭杆的磨损速度为 0.006 035 24 mm/h.

表 2 某型汽车的扭杆危险截面基本随机参数均值和标准差		
Table 2 Mean and standard deviation of the basic random parameters of dangerous cross-section of a torsion bar		
参数	均值	标准差
$d/\text{mm}$	25	0.125
$D/\text{mm}$	30	0.175
$T/(\text{N}\cdot\text{mm})$	$6.708\,7\times10^5$	$8.824\,9\times10^3$
$r/\text{MPa}$	680.017 3	35.8

通过运用上述动态可靠性方法得到此扭杆随时间变化的动态可靠性曲线和灵敏度曲线,并分别通过 Monte Carlo(虚线)进行验证.

图 6 中表示的是运用时变磨损可靠性模型(实线)计算得到的车辆扭杆动态可靠性曲线与运用 Monte Carlo(虚线)仿真实验计算得到的车辆扭杆动态可靠性曲线的拟合结果,两者的变化趋势相一致,吻合较好.从而说明运用时变磨损可靠性模型计算得到的汽车扭杆动态可靠性结果是正确的.

图 7 和图 8 分别表示的是运用时变磨损可靠性模型计算得到的扭杆均值灵敏度 $\partial\mu_{x_i}$ 曲线和标准差灵敏度 $\partial\sigma_{x_i}$ 曲线与 Monte Carlo(虚线)仿真实验计算得到的灵敏度曲线的拟合结果,从图中可以看出两者的变化趋势相一致,吻合较好.从而说明运用时变磨损可靠性模型计算得到的车辆扭杆动态灵敏度结果是正确的.

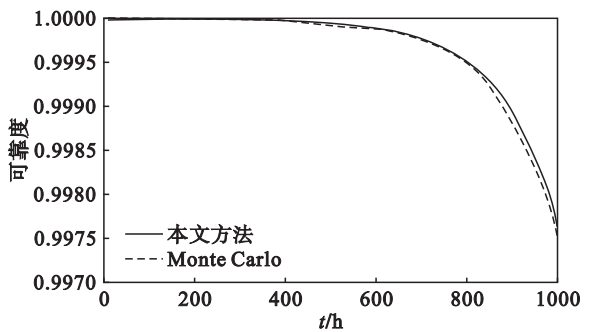


图 6 扭杆可靠性变化曲线  
Fig. 6 Reliability changing curve of vehicle torsion bar

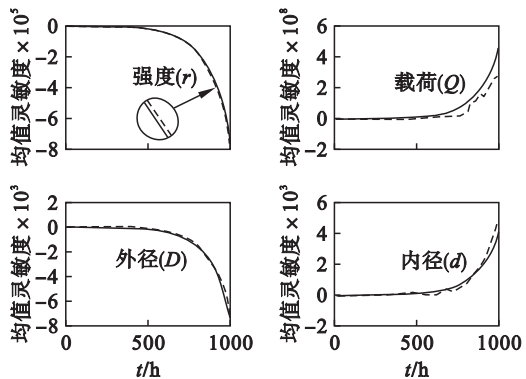


图 7 车辆扭杆均值灵敏度变化曲线  
Fig. 7 Mean sensitivity variation curve of vehicle torsion bar

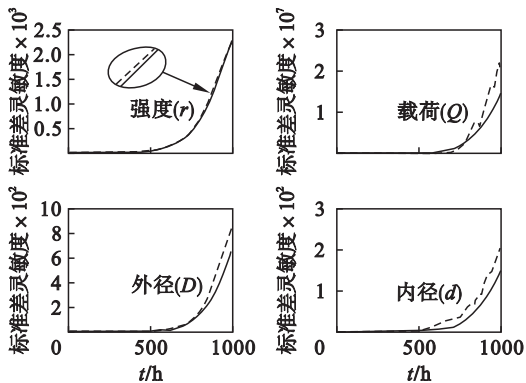


图 8 车辆扭杆标准差灵敏度变化曲线  
Fig. 8 Standard deviation sensitivity changing curve of vehicle torsion bar

4 结    论

- 1) 本文在车辆零件可靠性研究的基础上,将影响车辆零件可靠性的磨损因素考虑到渐变可靠性数学模型中,使之进一步符合实际情况.
- 2) 在考虑零件的磨损基础上建立了渐变功能数学模型,结合随机摄动法和二阶矩得出相应的动态可靠性指标和随时间变化的渐变可靠性曲线和渐变灵敏度曲线,并用 Monte Carlo 方法验证其方法的可行性.
- 3) 在磨损的条件下,几何尺寸对灵敏度的影



响最大,载荷最小. 即几何尺寸对可靠性影响最大,这与静态情况下一致.

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