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RELIABILITY ANALYSIS BY COMPUTER SIMULATION AND ITS APPLICATIONS TO SHAFTS

Summary. This paper deals with the reliability simulation of machine elements. The random numbers which have the distribution of the given parameter can be generated by Monte Carlo method. Then the reliability can be directly simulated by substituting them properly into the strength formulars. The assumptions for common analytical method are not needed. Hence the results of simulation can be more reasonable.

This paper also deals with the reliability simulation of shofts Some suggestions are proposed and formulars are derived.

Examples are given in this paper to show the applications of the simulation to the reliability analysis of shafts.

1. INTRODUCTION

The assumptions that the stresses and fatigue limits of machine elements are normally distributed are usually made in the existing analytical method for estimating reliability of machine elements [1] [2] [3]. The formulars for calculating the means and variances of the functions of random variables are given in [1].

According to the central limit theorem the sum of random variables $X_i (i=1,\ldots n)$, which can have any kinds of distributions, is approximately normally distributed when n is large enough. But if the number of the random variables n is small and the nonlinear operations such as production, division, exponentiation ... are also included in the operation of the random variables the result generally is not normally distributed.

Nonlinear operations are usually involved in the calculations of stresses and fatigue limits of machine parts and sometimes the number of random variables involved is not large. Hence the results of the stresses and fatigue limits are not normally distributet even though all initial random variables involved are normally distributed. Therefor the assumptios above causes errors and they can not be estimated. Sometimes the fatigue limits of materials are considered to have Weibull distribution. But the computed fatigue limits of the parts generally do not have Weibull distribution.

Monte Carlo simulation is adopted in this paper. It is no need to make the assumptions mentioned above. The distributions of the computed stresses and strength limite of the part considered can be simulated directly from the distributions of the given random variables. Then the reliability of the part can also be simulated. The confidence interval of the reliability then can be estimated. The results obtained in this way are more reasonable and reliable.

This paper also deals with the reliability simulation of shafts. Some suggestions are propose and formulare are derived. Several examples are given in this paper to iluetrate the procedure and application of the simulasion.

2. RELIABILITY ANALYSIS OF MACHINE PARTS BY COMPUTER SIMULATION AND THE DETERMINATION OF CONFIDENCE INTERVAL OF RELIABILITY

1) Reliability Analysis of Machine Parts by Computer Simulation

The reliability of machine parts can be determined by the following formular:

$$R = P_{\delta}(\delta \geqslant \sigma) = P(\delta - \sigma \geqslant 0) \tag{1}$$

where R — reliability; δ — strength limit of the part; σ — stress of the part; P_{δ} — probobility.

The main procedure of simulation of estimating the reliability of machine elemente is as follow:

(1) For each given independent random variable generate a set of N random numbers which has the same distribution as the one of the given variable.

(2) Randomly pick out one number from each set of random numbers generated above and then substitute them into the necessary formulars to calculate the corresponding stresses and strength limits of the part. Check if it is safe in this specific case. This step is repeated N times and the number safety NS is cumulated.

(3) Calculate the reliability of simulation R = NS/N and the confidence interval of the reliability.

Obviousely this procedure simulates the pratical situation which occurs in a set of N parts. After the simulation the distributions of $(\delta - \sigma)$, δ and σ are atomatically obtained. It is no need to make the assumptions mentioned above. Hence the results of simulation are more reasonable and reliable.

2) Generation of Random Numbers

It is important to generate random numbers which have the same distribution as the given one in reliability simulation.

(1) Generation of random numbers which have a given cumulative probobility distribution function

There are several methods which can be applied [4]. For example, the inverse transform method can be used. Its formular is:

$$X = F_x^{-1}(U) \tag{2}$$

where U – random numbers uniformly distributed over the interval (0,1); $F_x(x)$ – the given cumulative probobility distrubution function; X – the needed random numbers.

The random numbers uniformly distributed over the interval (0,1) can be obtained from the special function of most computers. And the computer algorithm for generating these random numbers can be found in some references [4]. It should noted that the uniformity of these random numbers has great influence on the accuracy of the simulation.

(2) Generation of random numbers which are normally distributed

The random numbers which are normally distributed are widely used in reliability analysis. There are several methods to generate them [4]. The algorithm used in this paper is as follow:

$$Z_1 = (-2\ln r_1)^{1/2} \cos(2\pi r_2); \quad Z_2 = (-2\ln r_1)^{1/2} \sin(2\pi r_2)$$

$$x_1 = \mu + Z_1 S_6; \quad x_2 = \mu + Z_2 S_6$$

where r_1, r_2 – two numbers of the uniformly distributed random numbers over (0,1); μ, S_6 – the mean and standard deviaton of the needed random numbers normally distributed; x_1, x_2 – two numbers of the needed random numbers.

Fig. 1 is a reduced computer printout of the distribution of a normally distributed random variable generated by the computer program used in this paper. Because line printer is used all numbers in each interval of the abscissa of the histogram are rounded to the lower bound of the interval. Tab. 1 shows the results of both theoretical and statistical analysis of this set of random numbers.

Tab. 1

	Theoretical Analysis	Statistic Analysis
Size		2000
Mean	30000	29999
Standard Deviation	2600	2594.8
$P_r(x \leqslant 2400)$	1.05%	1.05%
$P_r(x \leqslant 2690)$	11.67%	11.7%
$P_r(x < 2845)$	27.68%	27.85%
$P_r(x \leqslant 3400)$	93.8%	94.3%

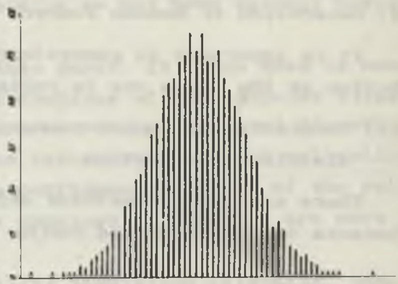

Fig. 1

It can be seen from the Fig. 1 and Tab. 1 that distribution of the generated random numbers is close to the theoretical distribution and can be used in the simulation.

The desity of the random numbers in a few intervals of fig. 1 is a little higher. This is caused by the ununiformity of the distribution of the random numbers and the unsufficiency of the size N. The curve is smoother when the size of the random numbers N is increased. The influence of the size N on the accuracy of the simulation is taken into account by the confidence interval of the reliability.

3) Estimation of the Confidence Interval

There are only two events - safety or unsafety - in the reliability analysis. So it has (0,1) distrubution. According to the statistics the approximate formulars for estimating the $100(1-\alpha)\%$ confidence interval of reliability are [5]:

$$P_1 = (-b - \sqrt{b^2 - 4ac})/2a; \quad P_2 = (-b + \sqrt{b^2 - 4ac})/2a$$

$$a = N + Z^2_{\alpha/2}; \quad b = -(2N\bar{P} + Z^2_{\alpha/2}); \quad c = N\bar{P}^2 \tag{3}$$

where P_1, P_2 - the needed lower and upper bound of the $100(1-\alpha)\%$ confidence interval of the reliability; N - size of the sample; α - significance level; $Z_{\alpha/2}$ - two-side 100α percentile point of standard normal distrubution; $\bar{P}$ - the reliability of the test.

It can be seen from formular (3) that the size N has great effect on the width of confidence interval.

EXAMPLE 1

Determine the reliability of a rod with round section subjected to an axial tensile load, the mean and standard deviation of which $\bar{F}$, S_F are 30000 (N) and 1000 (N) respectively. The mean and standard deviation of the diameter of the rod $(\bar{D}, S_\alpha^2) = (6.4, 0.3^2)$ mm and the strength limit of the material $(\bar{\delta}, S_\delta^2) = (1076, 42.2^2)$ MPa. Suppose that these variables are normally distributed and independent.

Solution:

According to the mechanics of material the stress in the section of the rod is:

$$\sigma = F/(\tfrac{1}{4}\pi D^2)$$

The flow diagram of the computer program is showed in Fig. 2.

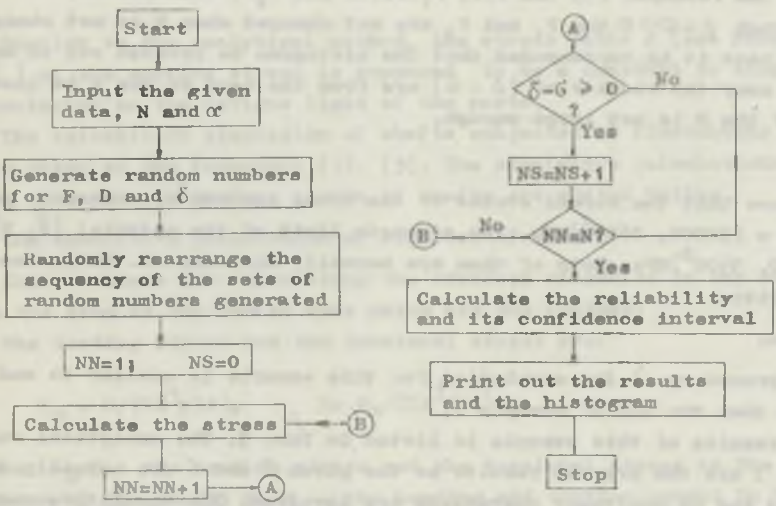

Fig. 2

Tab. 2

	Simulative Results
Number of safety	1819
Statistical reliability	90.95%
Significance level	0.5
100(1 − α)% confidence interval	89.61% 92.13%
Size of sample N	2000

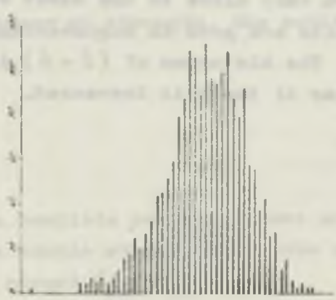

Fig. 3

The results of this example are listed in Tab. 2. Fig. 3 shows the distribution of the $(\delta - \sigma)$. It is obviously that resulted distribution is not a normal one. The assumptions mentioned above are unreasonable in these cases. The analytical result of reliability based on the assumptions above [1], [3] is R=93.07%. The error resulted by analytical method is evident.

It should be noted that the random numbers are generated from the same subprogram in this paper, the numbers in the same place of the sets generated may have some kind of relations. To make sure that the numbers sequentially picked out from each set have no any relations, which means that they are independent, a step of randomly rearranging the sequence of the numbers in each set is applied right after the random numbers are generated in Fig. 2. Then the numbers of the sets with new sequences can be sequentially substituted into the necessary formulars in the followed steps in Fig. 2.

If there are no any occurances of unsafety after the simulation, according to the formular (3) the $\bar{P}=1$, $P_1=0.998$ and $P_2=1$ when N=2000. Even though $\delta - \sigma >> 0$ the P_1 and P_2 are not changed when N is not changed. In this case it is recommended that the histogram be printed out to know how far away the results of $(\delta - \sigma)$ are from the zero or the N be increased if the N is not large enough.

EXAMPLE 2

Suppose that the normal stress of the cross section of a machine part $(\bar{\sigma}, S_{\sigma}^2) = (30000, 2600^2)$MPa. The strength limit of the material $(\bar{\delta}, S_{\delta}^2) = (40000, 3500^2)$MPa. Both of them are normally distributed. Determine its reliability.

Solution:

The procedure of the simulation for this example is similar to and simpler than the one of example 1.

The resulte of this example is listed in Tab. 3. The analytical sults in Tab. 3 are the precise results as the given δ and σ are normally distributed and no nonlinear operations are involved. The simulative results are very close to the exact solution, which means that the simulative results are good in engineering analysis.

The histogram of $(\delta - \sigma)$ is showed in Fig. 4. The curve will be smoother if the N is increased.

Tab. 3

	Simulative Results	Analysis Results
Size	2000	
Mean	10020	10000
Standard Deviation	4363.6	4301.16
Reliability	99.2%	98.9%
Significant level	0.05	
$100(1-\alpha)\%$ Confidence Interval	99.51% 98.7%	

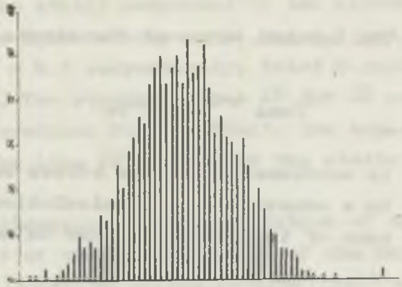

Fig. 4

3. RELIABILITY SIMULATION OF SHAFTS SUBJECTED TO FLUCTUATING LOADS

Similar to the analytical method, the stress ratio r (see formular (8)) of the working stress is supposed to be a constant to simplify the calculation of the fatigue limit of the parts.

The reliability simulation of shafts subjected to fluctuating load is also based on the formulars (1), (3). The simulative calculations of working stresses and fatigue limits of shafts are stated bellow.

1) The simulative Calculation of Stresses of Shafts

The formulars for calculating the stresses of shafts in the simulation are the same as the common ones which are the follows:

The bending stress and the torsional stress are:

$$\sigma_w = M/(\pi d^3/32); \qquad \tau = M_n/(\pi d^3/16) \tag{4}$$

where σ_w τ - the bending stress and the torsional stress in the cross section of the shaft; M, M_n - the bending and torsion moment in the section; d - the diameter of the section.

According to the energy-of-distortion theory of strength, the equivalent stress σ_f can be written as

$$\sigma_f = \sqrt{\sigma_w^2 + 3\tau^2} \tag{5}$$

In the common cases the bending stress is a complete reverse stress and the torsional stress can be considered as a static stress. Hence the dynamic and static component of the equivalent stress σ_{fa}, σ_{fm} are:

$$\sigma_{fa} = \sigma_w; \qquad \sigma_{fm} = \sqrt{3}\tau \tag{6}$$

The maximum value of the stress σ_{fmax} is:

$$\sigma_{fmax} = \sigma_{fa} + \sigma_{fm} \tag{7}$$

As mentioned above the stress ratio of working stress r is considered to be a constant in the calculation of the fatigue limit of the part. So the mean of it is used and can be written as:

$$\bar{\gamma} = \frac{\bar{\sigma}_{fmin}}{\bar{\sigma}_{fmax}} = \frac{1 - \bar{\sigma}_{fa}/\bar{\sigma}_{fm}}{1 + \bar{\sigma}_{fa}/\bar{\sigma}_{fm}} = \frac{1 - \bar{P}}{1 + \bar{P}} \tag{8}$$

where $\bar{P} = \bar{\sigma}_{fa}/\bar{\sigma}_{fm}$

$\bar{\sigma}_{fa}$, $\bar{\sigma}_{fm}$ - the means of σ_{fa} and σ_{fm} respectively.

σ_{fa} and σ_{fm} can be obtained by substituting the means of loads and geometric parameters into the formulars (4) and (6).

The prodecure of simulating the equivalent stress is similar to the one mentioned in example 1. After generating the corresponding sets of random numbers for the given parameters and randomly rearranging the sequencies of the numbers in the sets, sequentially pick up one from each set and substitute them into the necessary formulars of (4) - (7). The resulted numbers are the needed ones which shows the distribution of the equivalent stress.

2) The Simulation of Fatigue Limits of Shafts

The commonly used method for calculating the fatigue limits of shafts are also used in the simulation. The simplied curve of fatigue limit stress showed in Fig. 5 is adopted in this paper.

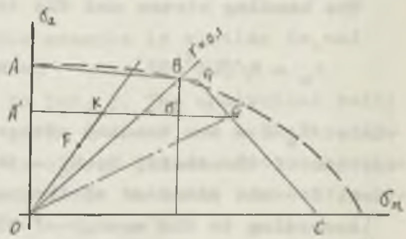

Fig. 5

Because the fatigue limit of stress ratio r = 0.1 is given in the handbook of reliability design instead of r = 0, the fatigue limit of r = 0.1 is taken as a reference point. The r = 0.1 is very close to r = 0 and the fatigue limit of r = 0.1 is close to and a little smaller than the limit of r = 0, hence the simplified diagram is close to and a little safer than the one of r = 0.

The formulars of fatigue limit which take r = 0.1 as a point of reference can be derived easily in the similar way of r = 0.

In Fig. 5 the dotted line is the theoretical fatigue limit of the material. The abscissa σ_m represents the static component of the alternating stress and the ordinate σ_a is the dynamic component. Point A and B are the fatigue limits of r = 1 and r = 0.1 respectively. Point C represents the yield limit of the material. Two straight lines $\overline{AB}$ and $\overline{CG}$ represent the simplifield curve of the theoretical fatigue limit. The angle between $\overline{CG}$ and the abscissa is 45°. The line $\overline{CG}$ represents the static yield limit of the material.

Because the stress concentration, dimension and the condition of the part only affect the dynamic component of the fatigue limit of the part, the line which represents the dynamic component of the fatigue limit of the part is decrease to $\overline{A'B'G'}$ from the line $\overline{ABG}$ which represents the dynamic component of the fatigue limit of the material.

The equation of the line $\overline{A'B'G'}$ is

$$\sigma_{-1} = K_\sigma \sigma_a' + \psi_\sigma \sigma_m'$$

where

$$\psi_\sigma = \frac{\sigma_{-1} - \sigma_{0.1a}}{\sigma_{0.1m}} \tag{9}$$

$$K_\sigma = \varepsilon B / k_\sigma \tag{10}$$

When the working stress of the part considered is at point F (Fig. 5) and if its stress ratio r is unchanged when the loads are increased, then its corresponding point of fatigue limit is point K. The value of the limiting stress $\overline{OK}$ can be written as:

$$\sigma_a' = \frac{\sigma_{-1}}{K_\sigma + \psi_\sigma / p} \qquad \sigma_m' = \frac{\sigma_a'}{p} \tag{11}$$

$$OK = \delta = \sqrt{\sigma_a'^2 + \sigma_m'^2} = \sigma_a' \sqrt{1 + 1/p^2} \tag{12}$$

where

$$p = \frac{1 - \gamma}{1 + \gamma} = \frac{\sigma_a'}{\sigma_m'}$$

As mentioned above, the r and p of the formulars (11), (12) are replaced by the means of them (formular (8)).

The equation of the straight line $\overline{G'C}$ is:

$$\sigma_a' + \sigma_m' = \sigma_s \tag{13}$$

In (9) - (13), σ_s - yield limit of the material; σ_{-1} - fatigue limit of the material when r = 1; $\sigma_{0.1a}$, $\sigma_{0.1m}$ - the dynamic and static component of fatigue limit of the material when r = 0.1 respectively; σ'_a σ'_m - the dynamic and static component of fatigue limit of the part considered respectively; $k_\sigma, \varepsilon, \beta$ - coefficients of effective stress concentration, dimension and condition of the surface in the cross section of the part respectively.

$$k_\sigma = 1 + \rho_\sigma(\alpha_\sigma - 1) \tag{14}$$

ρ - sensitive coefficient; α_σ - theoretical coefficient of stress concentration.

When the maximum stress and stress ratio of fatigue limit σ_{max}, r are given, the corresponding dynamic and static component σ_a, σ_m can be found by (8):

$$\sigma_a = \frac{1}{2}(1 - r)\sigma_{max}$$
$$\sigma_m = \frac{1}{2}(1 + r)\sigma_{max} \tag{15}$$

In reliability simulation the means and standard deviations of σ_{-1} and $\sigma_{0.1}$ can be found in handbook of reliability design [7]. There are different suggestions for k_σ, ε, β [2], [3]. In this paper the data in [2] are used.

The procedure of simulation of fatigue limits is similar to the one for fatigue stress mentioned above.

3) The Reliability Simulation

The reliability simulation of fatigue strength of shafts is based on the formular (1).

When the working stress of the shaft considered is on the left of $\overline{OG'}$ (Fig. 5), the working stress should be found by formular (5) and the corresponding fatigue limit δ should be calculated according to the formular (12). Compare them and then the reliability can be found.

When working stress of the shaft is on the right of $\overline{OG'}$, the working stress is limited by the static strength line $\overline{CG}$. Then the working stress should be calculated according to the formular (7) and the limiting stress should be the σ_s.

If the designer is not sure that which side of line $\overline{OG'}$ the working stress is in, then both comparations above should be done and the smaller reliability of them is the needed one.

After the significance level α is given, the 100(1 - α)% confidence level of reliability can be found from formular (3).

If the data of $(\delta - \sigma)$ are far away from zero which can be seen from the histogram of $(\delta - \sigma)$, the reliability is too large, a smaller diameter of the section should be considered to be chosen.

4. EXAMPLE OF RELIABILITY SIMULATION OF SHAFT SUBJECTED TO FLUCTUATING LOADS

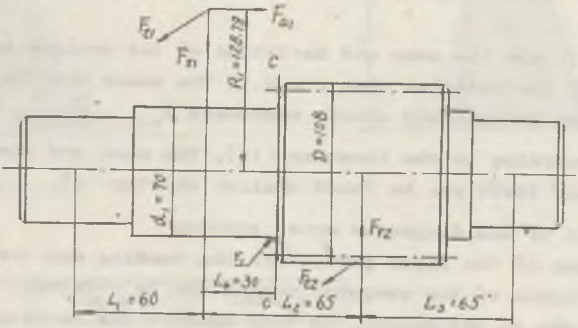

Fig. 6

Suppose that a third shaft of the gear box of a conveyer is showed in Fig. 6. The forces acting on the shaft from gears are: $F_{a1} = 1726(N)$, $F_{r1} = 4450(N)$, $F_{t1} = 12110(N)$, $F_{t2} = 32500(N)$, $F_{r2} = 11830(N)$. The torsional moment $T = 15.6 \times 10$ N-mm. The tolerance of these loads is $\pm$ 10% and they are normally distributed. The dimensions of the shaft are shown in Fig. 6. The tolerance of the lengths is $\pm$ 1% and the one of the radial dimensione is $\pm$ 0.1%. They are also normally distributed. The material of the shaft is 40CrNiMoA. The surface of the shaft is ground and its life should be longer than 10^7 cycles. Determine its reliability.

Solution:

The main steps of the simulative calculation are as follows:

1) Calculation of the standard deviations of the given parameters.

As the given parameters are normally distributed between their upper and lower bounds, this interval can be considered to be equal to $\pm$ 3 times of the standard deviation. So the standard deviations of F_{a1}, F_{r1}, ... can be written respectively as:

$$S_{Fa1} = (10\% \times F_{a1})/3; \quad S_{Fr1} = (10\% \times F_{r1})/3; \; ....$$

$$S_{L_1} = (1\% \times L_1)/3; \quad S_{L_2} = (1\% \times L_2)/3; \; ....$$

2) Determination of the stress limits of the material.

The stress limits of the material can be found in the handbook [7].

$r = -1$; $\alpha_{\sigma} = 1$; $N = 10^7$; $\bar{\sigma}_{-1} = 534$MPa; $S_{\sigma-1} = 20.0$MPa;

$r = 0.1$; $\alpha_{\sigma} = 1$; $N = 10^7$; $\bar{\sigma}_{0.1} = 1050$MPa; $S_{\sigma_{0.1}} = 33.33$MPa;

$\sigma_s = 935 - 1148$ MPa; (N - life of the shaft tested (cycle))

The $\sigma_{0.1}$, $S\sigma_{0.1}$ are the mean and deviation of the maximum stress of the fatigue limit of the material when $r = 0.1$. The means and the standard deviations of its dynamic and static component $\bar{\sigma}_{a0.1}$, $\bar{\sigma}_{m0.1}$, $S_{\sigma_{a0.1}}$, $S_{\sigma_{m0.1}}$ can be found according to the formular (15). The mean and standard deviation of the yield limit can be found similar to step 1).

3) Determination of the dangerous cross section

From the means of the given parameters the bending and tortional moment and then the diagram of the computed moment can be obtained. Then the dangerous section can be determined. In this example the section CC is the dangerous section.

4) Determination of the mean of stress ratio $\bar{r}$ of the working stress

After the means of bending and torsional stress are found, the $\bar{r}$ and can be obtained from the formulars (6), (8).

5) Determination of the coefficients affecting the stresses

k_{σ} can be found according to the handbook [6]. In this example $r_1 = 3$mm, $r_1/d_1 = 0.04$, $D/d_1 = 1.54$, so the $\alpha_{\sigma} = 2.21$. ($\bar{\rho}_{\sigma}$, S_{ρ}^2) can be found in [2]. ($\bar{\rho}_{\sigma}$, S_{ρ}^2) = (0.7341, 0.04686^2). Then the k_{σ} can be calculated according to the formular (14).

According to [2], ($\bar{\varepsilon}$, S_{ε}^2) = (0.85625, 0.08895^2) and $\beta = 1$ for this example. Then the K_{σ} can be calculated according to formular (10).

6) Generation of the random variables which have the given distributions for each parameter and random rearrangement of the sequence of the numbers in each set of random numbers.

7) Simulative calculation of δ and σ by sequentially picking out one number from each set rearranged and substituting them into the necessary formulars (4) - (15).

8) Simulation of the reliability based on the formular (1) and the calculation of $100(1 - \alpha)$% confidence interval of the reliability.

The results are listed in Tab. 4 Fig. 7 shows the distribution of the ($\delta - \sigma$). The ($\delta - \sigma$) are far from zero which means that the reliability of this shaft is too high. The comparision between this distribution and the exact normal distribution which has the same mean and standard deviation and are in the same scale of obscissa (Fig. 8) shows that the distribution of (δ-σ) is not a normal one.

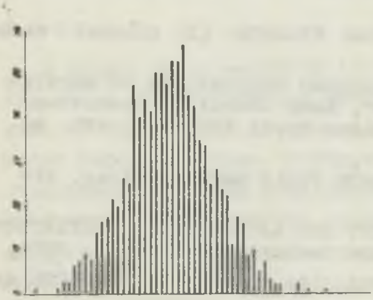

Fig. 7

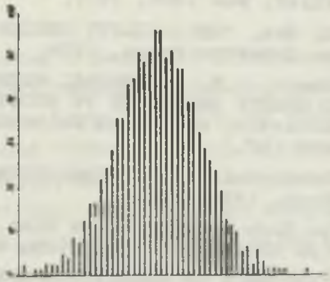

Fig. 8

Tab. 4

	Case 1	Case 2
Diameter	70	45
Size of Sample	2000	2000
Numbers of Unsafety	0	4
Reliability	100%	99.8%
Significance Level	0.05	0.05
Confidence Interval	100% 99.8%	99.9% 99.5%

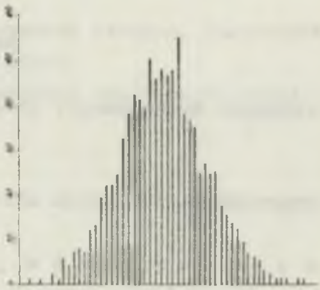

Fig. 9

When d_1 = 45 mm, r_1 = 1.5 mm are taken in this example, the results are listed in Tab. 4 and the distribution of (δ-σ) is showed in Fig. 9.

5. CONCLUSION

1) Because nonlinear operations are usually involved in the calculations of the reliability analysis of machine elements, the distributions of the equivalent stresses and fatigue limits are not the normal ones. The assumptions used in the analytical method of reliability analysis lead to some errors.

2) Simulative method mentioned in this paper is good for reliability analysis of machine elements. It can directly simulate the pratical situations and gives reasonable results.

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KOMPUTEROWA SYMULACJA ANALIZY NIEZAWODNOŚCI I JEJ ZASTOSOWANIA W SZYBACH

S t r e s z c z e n i e

Opracowanie przedstawia problemy związane z symulacją niezawodności części maszyn. Liczby losowe, które przedstawiają dystrybucję danego parametru, można generować metodą Monte Carlo. Wtedy niezawodność można symulować bezpośrednio poprzez właściwe podstawienie liczb losowych w opracowanych wyrażeniach. Nie jest konieczne stosowanie założeń prostych metod analitycznych. Rozkład obliczanych naprężeń i granic wytrzymałości rozważanej części maszyny można symulować bezpośrednio z rozkładów danych zmiennych losowych. Wtedy to można symulować niezawodność tej części, a następnie można ocenić przedział ufności niezawodności. Uzyskane w ten sposób wyniki symulacji są bardziej przekonujące i można bardziej na nich polegać.

Opracowanie zajmuje się także symulacją niezawodności szybów. Zaproponowano nowsze rozwiązania i wyprowadzono wyrażenia.

Opracowanie zawiera kilka przykładów, które ilustrują przyjętą procedurę i zastosowanie symulacji.

КОМПЬЮТЕРНАЯ АНАЛИЗА НАДЕЖНОСТИ
И ЕЁ ПРИМЕНЕНИЕ В СТВОЛАХ

Р е з ю м е

В работе представляются проблемы, связанные с имитацией надежности деталей машин. Стохастические числа, которые представляют обобщенную функцию данного параметра можно воспроизвести методом Монте Карло. Тогда надежность можно непосредственно сымитировать правильной соответственной подстановкой стохастических чисел в разработанные выражения. Не является обязательным применение данных простых аналитических методов. Распределение вычисляемых нагрузок и границ пределов выносливости для рассматриваемых деталей машин можно сымитировать непосредственно с распределения данных случайных переменных. Тогда можно будет сымитировать надежность детали, а затем оценить доверительный интервал надежности.

Полученные таким образом результаты имитации более убедительны, и на них можно полагаться.

В работе рассматривается также имитация надежности стволов. Предлагаются новые решения и вводятся математические выражения.

Работа содержит несколько примеров, иллюстрирующих принятую процедуру и применение имитации.