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RELIABILITY MODEL OF SEQUENCE MOTIONS AND ITS SOLVING IDEA

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The missions of weapon systems are becoming increasingly complex. Thus, more mechanism motions than one are required to complete one mission. Under such conditions, a sort of mission has emerged, that needs a few mechanism motions to be executed in sequence. This means that the mission is not completed until all the motions have been executed successfully in strict sequence. This sequence motion system can be considered as a traditional series system with the motions treated as subsystems. Then, the system reliability can be analyzed with the traditional series system reliability method. However, this method cannot fully reflect the characteristics of a sequence. In this work, a reliability model of sequence motions and its solving idea are proposed. In this reliability model, the influence factors of each motion are included. Particularly, the performance function of the former motion is regarded as just one of the influence factors of the next motion, which is the most significant feature for the sequence motion system. Afterward, a solving idea with characteristics of a gradually shrinking sample space is proposed based on Monte-Carlo simulation. Finally, the reliability model of sequence motions and its solving idea are illustrated with a case study on the automatic chain shell magazine sequence motions of a self-propelled artillery.

Keywords: *sequence motion reliability, motion reliability, Monte-Carlo simulation, shrinking sample space, automatic chain shell magazine.*

Misje systemów uzbrojenia stają się coraz bardziej złożone. Często, jedna misja wymaga wykonania przez układ zmechanizowany więcej niż jednego ruchu. W artykule omówiono misję, w której układ zmechanizowany wykonuje sekwencję kilku ruchów. Misja w takim układzie nie zostanie ukończona, dopóki wszystkie ruchy nie zostaną prawidłowo wykonane w ściśle określonej kolejności. Taki układ sekwencyjnych ruchów można rozważać w kategoriach tradycyjnego systemu szeregowego, traktując poszczególne ruchy jako jego podsystemy. Wówczas, niezawodność systemu można analizować za pomocą tradycyjnej metody analizy niezawodności systemów szeregowych. Jednak, metoda ta nie jest w stanie w pełni odzwierciedlić charakterystyki sekwencji. W niniejszym artykule zaproponowano model niezawodności ruchów sekwencyjnych oraz jego rozwiązanie.

Słowa kluczowe: *niezawodność ruchów sekwencyjnych, niezawodność ruchu, symulacja Monte-Carlo, malejąca przestrzeń próby, zmechanizowany układ zasilania amunicją, pocisk artyleryjski.*

1. Introduction

Mechanical structural reliability has been studied since the 1960s and gradually applied in engineering machinery, aerospace, electrical equipment, and other fields [1, 5, 8, 13, 18, 20]. However, with the development of machinery to high precision and automation, the precision of mechanism motion has gradually become the main index for reliability evaluation [9, 10]. In the 1980s, mechanism motion precision started to be analyzed comprehensively from the perspective of probability statistics. Sandler [17] analyzed the kinematic and dynamic precision of simple mechanisms with a nonlinear method. Rhyu and Kwak [16] studied the optimization design of the planar four-bar linkages based on reliability. By the 1990s, progress had been made in applications of mechanism motion reliability. Misawa [12] proposed a research method for predicting the reliability of a deployable satellite antenna based on conventional reliability analysis. Then by the turn of this century, the reliability analysis of mechanism motion became increasingly based on simulation methods with the rapid development of computer technology. Rao and Bhatti [15] systematically established a probabilistic model of a simple manipulator based on Gaussian distribution and a Markov stochastic process. Kim et al. [11] calculated the reliability of an open-loop mechanism considering machining error and hinge clearance based on AFOSM (Advanced first order second moment) method and Monte-Carlo simulation. Asri et al. [2] analyzed the fatigue reliability of a wheel steering mechanism with a Monte-Carlo simulation method. Moreover, the reliability topology optimization design was carried out by Patel et al. [14] via stochastic neural networks.

However, as mechanism motion reliability develops, the mission cannot be finished by only one mechanism motion due to the increasing requirements. Usually, a series of mechanism motions fulfills one mission in sequence. On this occasion, the motion system is usually regarded as a series system. Therefore, series system reliability analysis methods can be applied to evaluate the mission reliability. Series system reliability has been studied for a long time. Chao and Fu [6] studied the reliability of a general series system under certain regularity conditions based on a Markov chain. Chern [7] proved that some reliability redundancy optimization problems for a series system are NP-hard. Sung and Cho [19] derived a branch-and-bound algorithm for a reliability optimization problem of a series system. A new Monte Carlo simulation technique for composite system reliability evaluation has been presented [4]. Moreover, the requirements of a composite generation and transmission system reliability evaluation were described in previous research [3]. Little research has been reported for combining mechanism motion reliability and series system reliability, which is studied in this work.

Here, series system reliability analysis and mechanism motion reliability analysis are combined. Thus, each motion is regarded as an element of the series system. Moreover, a sequence motion reliability model and its solving idea are proposed according to a special feature called "unidirectional correlation." The rest of this work is organized as follows. In Section 2, the reliability model of the sequence motions is described, and the solving idea is derived. Section 3 presents a case study on the automatic chain shell magazine sequence motions of a self-propelled artillery. Section 4 concludes this study.

2. Reliability model of sequence motions and its solving idea

2.1. Reliability model of sequence motions

2.1.1. Mechanism motion reliability theory

Mechanism motion reliability refers to the ability to maintain output parameters within the allowable range, which could ensure that the mechanism achieves specified mission under the given time and conditions. An output parameter is a random function expressed as $Y(\mathbf{x})$, where $\mathbf{x}=(x_1,x_2,...,x_n)^{\mathrm{T}}$ (T is the signal of matrix transposition) is a vector including n random variables $x_1 \sim x_n$ representing influence factors. The allowable range is defined as $[Y_{\min}(\mathbf{x}),\ Y_{\max}(\mathbf{x})]$. Therefore, the motion is reliable when $Y_{\min}(\mathbf{x}) \le Y(\mathbf{x}) \le Y_{\max}(\mathbf{x})$, which is expressed as:

$$F\left(Y_{\max}(\mathbf{x})\right)-F\left(Y_{\min}(\mathbf{x})\right)=\Pr\left\{Y_{\min}(\mathbf{x}) \le Y \le Y_{\max}(\mathbf{x})\right\} \tag{1}$$

where $F(\bullet)$ is the distribution function.

First, the fundamental problem for the structural reliability theory is the computation of the reliability expressed as:

$$\Pr\left[g(\mathbf{x})>0\right]=\int_{g(\mathbf{x})>0} f(\mathbf{x})\,\mathrm{d}\mathbf{x} \tag{2}$$

where $\mathbf{x}=(x_1,x_2,...,x_n)^{\mathrm{T}}$ is a vector including n random variables $x_1 \sim x_n$ representing uncertain structural quantities, $f(\mathbf{x})$ denotes the joint probability density function of $\mathbf{x}$, and $g(\mathbf{x})$ is the performance function. Moreover, $g(\mathbf{x})>0$ means $\mathbf{x}$ belongs to the reliability set – that is, the structure is regarded as reliable when $g(\mathbf{x})>0$ [21].

Afterward, the performance function theory of structural reliability can be extended to mechanism motion reliability. $Y^*(\mathbf{x})$ and $Y(\mathbf{x})$ are used to express the ideal displacement and actual displacement, respectively, and $\mathbf{x}=(x_1,x_2,...,x_n)^T$ represents influence factors. Then, the location error can be defined as:

$$\Delta Y(\mathbf{x})=\left|Y^*(\mathbf{x})-Y(\mathbf{x})\right| \tag{3}$$

The performance function of mechanism motion reliability can be defined as:

$$g(\mathbf{x})=z-\Delta Y(\mathbf{x}) \tag{4}$$

where z is the maximum allowable location error. Thus, the reliability of mechanism motion can be expressed as:

$$\Pr\left[g(\mathbf{x})>0\right]=\Pr\left[z-\Delta Y(\mathbf{x})>0\right] \tag{5}$$

2.1.2. Reliability model of sequence motions

To fulfill a mission, it is necessary for the motion system to execute the motions according to specific rules. This is a special kind of problem in system reliability called " motion system reliability." In this section, the feature that the motions must be executed in sequence is examined.

The characteristic of sequence motions is that each motion is based on the reliable execution of its previous motion—that is, the reliability of each motion depends on the reliability of its previous motion. Thus, reliability analysis should be conducted in the same order. The reliability of the prior motion should be analyzed. If it is reliable, the reliability of the next motion would have the chance and necessity to be analyzed. The reliability model of sequence motions is shown in Fig. 1.

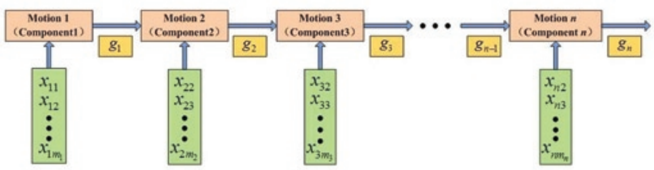


Fig. 1. Reliability model of sequence motions

Assume that the motion system involves n motions, and they must be executed in a specific sequence, which is from motion 1 to motion n. If any one of the n motions is a failure, its subsequent motions cannot be executed. It means that the failure of any motion can cause the whole motion system to fail. From the perspective of system, because each of the motion mechanisms has no " backups," the motion system can be regarded as a kind of series system. Moreover, the influence between any two consecutive motions is unidirectional—that is, the prior motion can influence the latter motion, but the latter one cannot influence the prior one. Therefore, the system is a special series system characterized by a particular correlation called "unidirectional correlation."

As is shown in Fig. 1, the motion 1 has m_1 influence factors expressed as $x_{11},x_{12},\cdots,x_{1m_1}$, and its performance function expressed as g_1 is just one influence factor of motion 2. In a similar way, the performance function of motion 2 expressed as g_2 is one influence factor of motion 3. By parity of reasoning, the performance function of motion n-1 expressed as g_{n-1} is one influence factor of motion n. The performance function of motion n expressed as g_n is also the performance function of the whole system. The specific description is as follows.

First, the successful execution of motion i (i=1,2,…,n) is denoted by event A_i ; thus, the successful completion of the whole system mission can be expressed as $\prod_{i=1}^{n}\mathrm{A}_i$. Then, based on conditional probability, it can be obtained that:

$$\begin{cases} P\left(\prod_{i=1}^{n}\mathrm{A}_i\right)=P(\mathrm{A}_1)P(\mathrm{A}_2\,|\,\mathrm{A}_1)P(\mathrm{A}_3\,|\,\mathrm{A}_1\mathrm{A}_2) \\ \qquad\cdots P(\mathrm{A}_n\,|\,\mathrm{A}_1\mathrm{A}_2\cdots\mathrm{A}_{n\text{-}1}) \\ P(A_i)=P(g_i>0) \end{cases} \tag{6}$$

$$\Downarrow$$

$$P\{g_n>0\}=P\{g_1>0\}P\{(g_2>0)\,|\,(g_1>0)\}P\{(g_3>0)\,|\,(g_1>0)\cap(g_2>0)\}$$
$$\cdots P\{(g_n>0)\,|\,(g_1>0)\cap\cdots\cap(g_{n-1}>0)\}$$

Moreover, based on Fig. 1 and the meaning of the performance function:

$$g_i(\mathbf{x}_\mathrm{m})=\begin{cases} g_i\left(x_{i1},x_{i2},\cdots,x_{ij},\cdots,x_{im_i}\right) & (i=1) \\ g_i\left(g_{i-1},x_{i2},x_{i3},\cdots,x_{ij},\cdots,x_{im_i}\right) & (i=2\sim n) \end{cases} \tag{7}$$
$$\mathbf{x}_\mathrm{m}=\left(x_{11},\cdots,x_{1m_1},x_{21},\cdots,x_{2m_2},\cdots,x_{n1},\cdots,x_{nm_n}\right)^\mathrm{T}$$

where m_i and x_{ij} are, respectively, the number of influence factors and the jth influence factor of the ith motion.

2.2. Solving idea for reliability model of motions in sequence

For the above-mentioned reliability model of motions in sequence, a solving idea characterized by a gradually shrinking sample space is proposed based on Monte-Carlo simulation. The analytical idea is shown in Fig. 2.

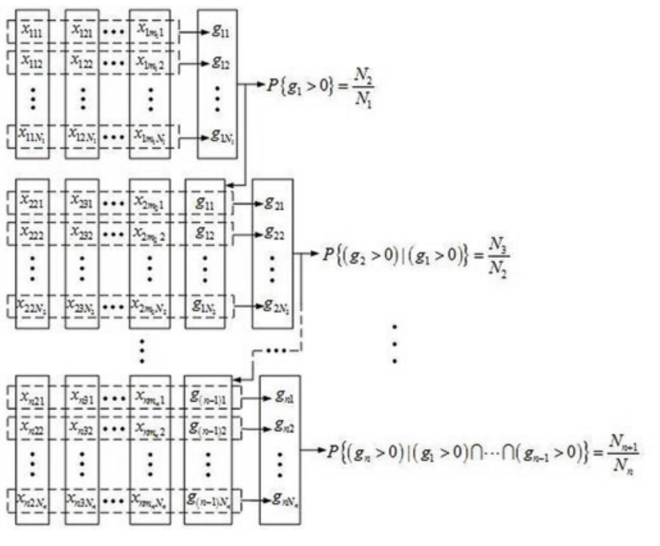


Fig. 2. Analytical idea of gradually shrinking sample space based on Monte-Carlo simulation

First, the sampling for motion 1 would be executed according to the probability density functions ($f\left(x_{1j}\right)$ $\left(j=1,2,...,m_1\right)$). The sample size and sample values are denoted, respectively, by N_1 and $x_{1j1}\sim x_{1jN_1}$. Thus, N_1 values of g_1 can be obtained, which are denoted by $g_{11}\sim g_{1N_1}$. Then, in $g_{11}\sim g_{1N_1}$, the number of items larger than 0 and their values are denoted, respectively, by N_2 and $g_{11}\sim g_{1N_2}$. Therefore, the reliability of motion 1 is $P\{g_1>0\}=\dfrac{N_2}{N_1}$.

Afterward, the sampling for motion 2 would be executed according to the conditional probability density functions ($f\left(x_{2j}\,|\,\{g_1>0\}\right)$ $\left(j=1,2,...,m_2\right)$) with the sample size N_2 . The $g_{11}\sim g_{1N_2}$ can just be regarded as the sample value for the sampling of g_1 on the condition that motion 1 is reliable; then, the N_2 sample values of g_2 are just $g_{21}\sim g_{2N_2}$. In $g_{21}\sim g_{2N_2}$, the number of items larger than 0 is denoted by N_3 . Therefore, on the condition that motion 1 is reliable, the reliability of motion 2 is $P\{(g_2>0)|(g_1>0)\}=\dfrac{N_3}{N_2}$.

Finally, it is obtained that:

$$\begin{cases} P\{g_i>0\}=\dfrac{N_{i+1}}{N_i} & (i=1) \\ P\{(g_i>0)\,|\,(g_1>0)\cap\cdots\cap(g_{i-1}>0)\}=\dfrac{N_{i+1}}{N_i} & (i=2\sim n) \end{cases} \tag{8}$$

Moreover, $N_n\le N_{n-1}\le\cdots\le N_1$, which shows that the sample space shrinks gradually.

3. Case study

The automatic chain shell magazine sequence motions of a self-propelled artillery are used for the case study. The prior motion is shell-selecting and the next is shell-pushing, which are executed in sequence to transmit the shell to the coordinator. The reliability influence factors of the two motions and the correlation between them are shown in Fig. 3. Wheel wear and sprocket setover are two main influence factors of the shell-selecting, which can lead to location error of the selected shell. Then, the mentioned location error and the section radius of the pushing rod are two considerable influence factors of the shell-pushing. The maximum contact force of the shell-cylinder is regarded as the performance function of motion 2.

As is shown in Fig. 4, the parameterized models of the two motion mechanisms were built in software called ADAMS (automatic dynamic analysis of mechanical systems). Thus, the mechanism motion reliability can be analyzed based on Monte-Carlo simulation and cycle emulation technique of ADAMS.

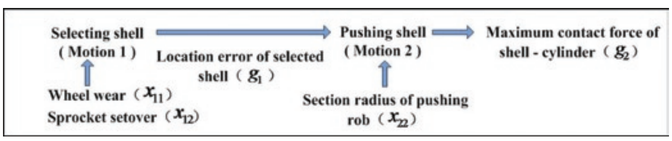


Fig. 3. Specific reliability model of the automatic chain shell magazine sequence motions

The qualitative analysis for every influence factor is described in Sections 3.1 and 3.2.

3.1. Qualitative analysis for influence factors of shell-selecting (motion 1)

First, the horizontal displacement changing processes with different wheel wear (2, 4, and 6 mm) and sprocket setover (1, 2, and 3 mm)

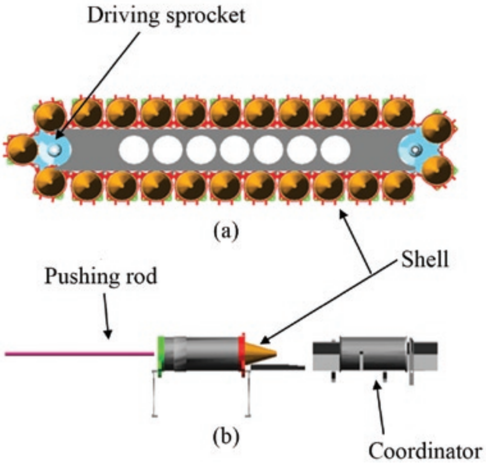
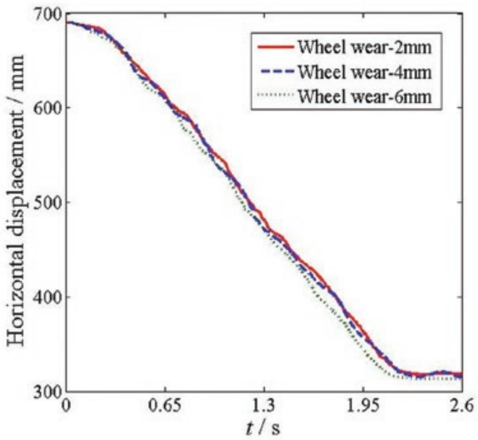
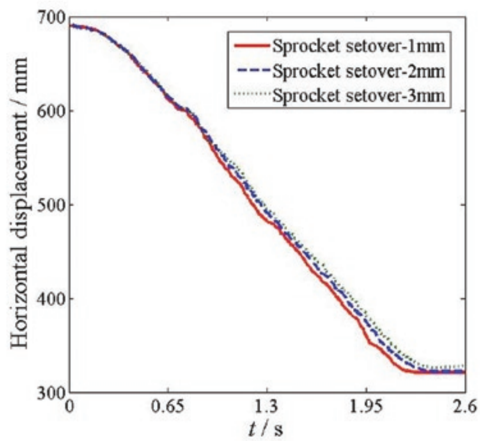


Fig. 4. Parameterized model of shell-selecting (a) and shell-pushing (b) mechanism



(a) Different wheel wear

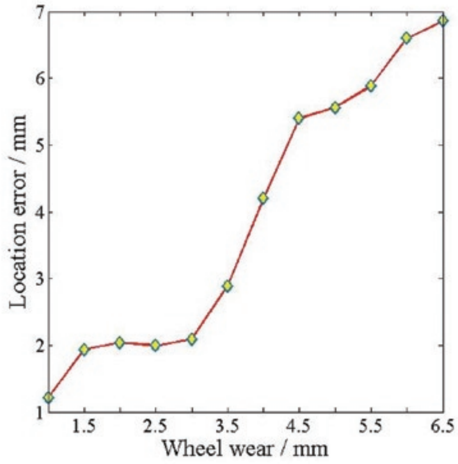


(b) Different sprocket setover

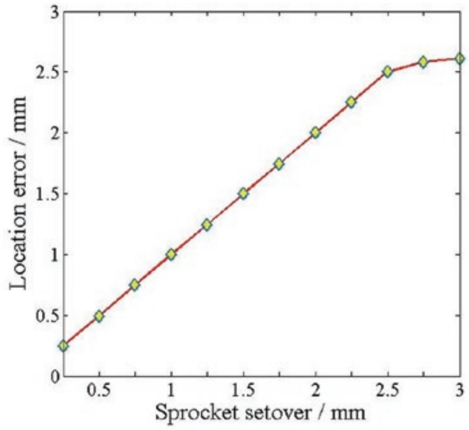
Fig. 5. Horizontal displacement changing processes with different influence factors

are shown, respectively, in Figs. 5 (a) and (b). They indicate that, with either wheel wear or sprocket setover getting larger, both the horizontal displacement oscillation and steady-state error increase.

Second, the relationship between location error and wheel wear is shown in Fig. 6 (a), and the relationship between location error and sprocket setover is shown in Fig. 6 (b). They indicate in more detail that, with the increase of wheel wear, the location error gets larger, and the increasing rate is time-varying. And then, when the sprocket



(a) Influence factor vs. wheel wear



(b) Influence factor vs. sprocket setover

Fig. 6. Relationship between influence factors and location error of shell-selecting

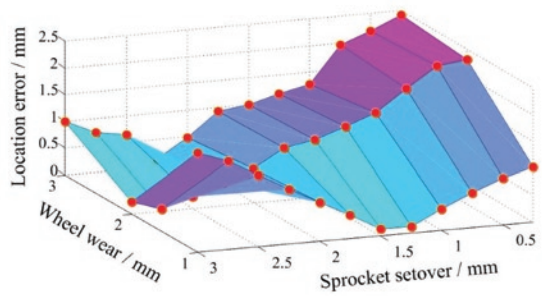


Fig. 7. Relationship for location error of selected shell and its influence factors

setover becomes larger, the location error increases, and the increasing rate changes almost linearly with time.

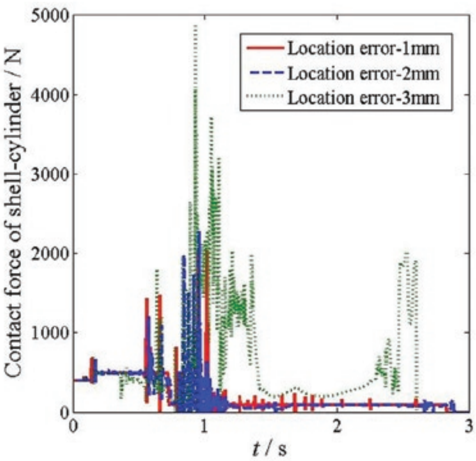
At last, as shown in Fig. 7, with the wheel wear and sprocket setover getting larger together, the location error decreases earlier and then increases. In conclusion, the location error is influenced by the two influence factors mentioned above, which indicates that the considered influence factors are reasonable for the motion reliability analysis of shell-selecting.

3.2. Qualitative analysis for influence factors of shell-pushing (motion 2)

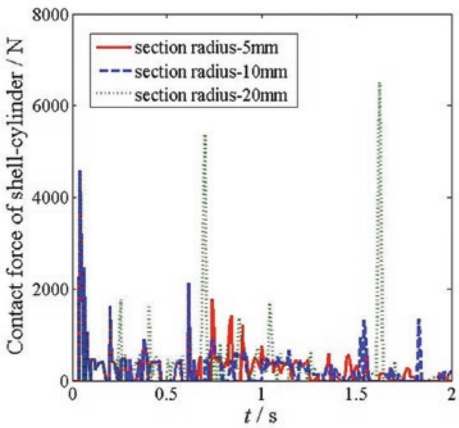
First, the shell-cylinder contact force changing processes with different location error (1, 2, and 3mm) and section radius of pushing rod (5, 10, and 20mm) are shown, respectively, in Figs. 8 (a) and (b). They indicate that, with the location error increasing or section radius decreasing, the maximum contact force of shell-cylinder increases.

Second, the relationship between maximum contact force and location error is shown in Fig. 9 (a), and the relationship between maximum contact force and section radius is shown in Fig. 9 (b). They indicate in more detail that, with the increase of location error, the maximum contact force gets larger, and the increasing rate is time-varying relatively conspicuously. And then, when the section radius becomes larger, the maximum contact force decreases, and the decreasing rate changes obviously.

At last, as shown in Fig. 10, with location error increasing and section radius decreasing, the maximum contact force gradually gets larger. In conclusion, the maximum contact force is influenced by the two influence factors mentioned above, which indicates that the considered influence factors are reasonable for the motion reliability analysis of shell-pushing.

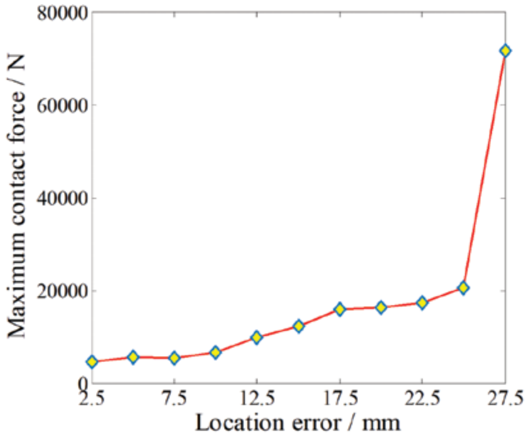


(a) Influence factor vs. location error

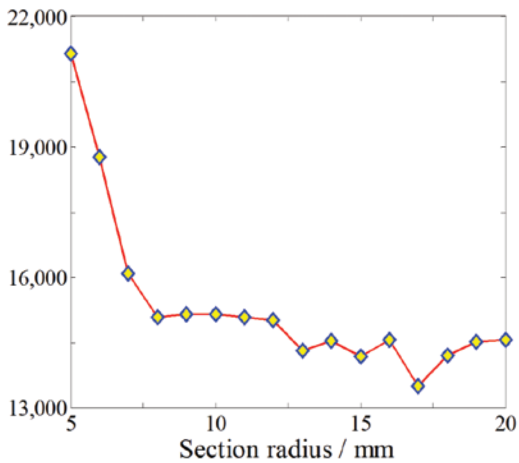


(b) Influence factor vs. section radius of pushing rod

Fig. 8. Contact force changing processes with different influence factors



(a) Influence factor vs. location error



(b) Influence factor vs. section radius of pushing rod

Fig. 9. Relationship between influence factors and maximum contact force of shell-cylinder

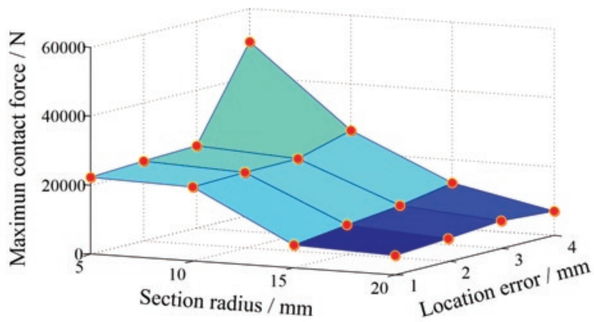


Fig. 10. Relationship for maximum contact force of shell-cylinder and its influence factors

3.3. Reliability analysis for the sequence motions (shell-selecting and shell-pushing)

The probability distribution of the influence factors is listed in Table 1. For the first motion, 50 samples were used to execute Monte-Carlo simulation, and the results of location error are listed in Table 2. Moreover, when the location error is smaller than 10mm, the motion is regarded as reliable. Thus, based on the proposed solving idea mentioned in Section 2.2, the results of maximum contact force of the shell-cylinder are listed in Table 3. Moreover, when the maximum

Table 1. Probability distribution of influence factors

Influence factor	Distribution type	Distribution parameter / mm
Wheel wear	Normal distribution	Mean value = 2 Standard deviation= 0.333
Sprocket setover	Uniform distribution	Upper limit = 3 Lower limit = 1
Section radius of pushing rod	Uniform distribution	Upper limit = 20 Lower limit = 5

Table 2. Results of location error of shell-selecting

Wheel wear/mm	Sprocket setover/ mm	Location error/ mm	Wheel wear /mm	Sprocket setover/ mm	Location error/mm
1.4748	1.3670	6.601	2.4500	1.4155	8.421
2.1692	1.7370	12.670	1.9252	1.6025	9.586
2.0939	2.2512	5.095	1.8039	1.9418	3.898
2.0111	2.5605	1.625	1.9022	1.4610	9.830
1.5559	1.1623	9.558	1.7176	2.6886	5.736
2.3755	2.8588	6.861	1.6270	1.3895	6.566
2.1166	2.5514	1.739	2.8412	1.4518	8.403
1.9004	1.9736	7.243	2.5513	1.3414	7.998
2.0076	1.8717	7.943	2.1024	1.4553	3.673
1.9128	1.8936	8.107	1.5814	1.8714	0.275
1.4172	1.6127	2.821	1.7118	1.6222	5.271
1.9049	2.0170	5.897	1.9412	2.8468	4.228
1.7232	2.0215	1.934	2.2635	1.8604	1.778
1.6739	2.6353	5.935	1.5564	1.3696	9.956
1.6149	2.5897	5.822	1.2242	2.8098	2.496
1.8223	2.2886	0.507	1.5175	2.9595	1.098
1.3331	1.7572	0.111	2.1111	1.8777	10.480
2.3211	2.6232	1.589	2.1303	1.2222	4.539
2.1732	2.0657	5.434	2.1504	1.5161	2.564
1.9933	1.7015	9.317	1.9566	1.8174	7.057
1.9884	2.8780	4.807	2.0612	2.1898	4.492
1.7342	2.7519	6.472	1.8414	1.5244	7.746
2.3392	2.1003	0.949	2.2871	2.2057	2.887
1.9556	2.2450	5.260	1.5466	2.4224	10.144
1.7621	2.1741	0.747	2.1515	1.4435	13.505

contact force is larger than 15,000N, the second motion is regarded as a failure. Then, the reliability results are calculated as follows:

$$\begin{cases} P_1 = \dfrac{N_2}{N_1} = \dfrac{46}{50} = 0.9200 \\ P_2 = \dfrac{N_3}{N_2} = \dfrac{39}{46} = 0.8478 \\ P = P_1 P_2 = 0.9200 \times 0.8478 = 0.7800 \end{cases} \tag{9}$$

4. Conclusion

Sequence motions widely exist in many complex weapon systems. However, there is limited literature focusing on this kind of system, especially the character called motions in sequence. In this work, a reliability model of sequence motion system was proposed. It takes the character-motions in sequence into account. Then, the solving idea characterized by a gradually shrinking sample space based on Monte-Carlo simulation was performed.

Moreover, the proposed reliability model and the solving idea were illustrated by the automatic chain shell magazine sequence motions of a self-propelled artillery. For the motion 1 (shell-selecting), the location error of the selected shell changed obviously with the variation of wheel wear and sprocket setover. Meanwhile, for the mo-

Table 3. Results of maximum contact force of shell-cylinder

Location error/ mm	Section radius/ mm	Maximum contact force/N	Location error/ mm	Section radius/mm	Maximum contact force/N
6.601	8.1016	30603.4861	0.747	7.2332	8529.2861
5.095	14.8078	5884.4116	8.421	18.4957	8639.9607
1.625	6.0808	4922.2563	9.586	14.6533	7876.5438
9.558	11.1034	4475.2930	3.898	11.7559	5884.4117
6.861	11.1009	4335.2860	9.830	12.4312	7349.6471
1.739	15.0040	6746.8551	5.736	8.0851	4574.7764
7.243	19.0059	31076.2078	6.566	18.4948	18059.1505
7.943	17.1643	7843.4679	8.403	16.4388	11485.6963
8.107	12.2682	4722.1065	7.998	18.2373	10611.5848
2.821	16.3512	4574.7766	3.673	9.7563	8435.3218
5.897	11.2557	7225.1924	0.275	9.2743	8665.1109
1.934	19.5768	4574.7766	5.271	15.0984	6358.5859
5.935	19.8196	10740.2859	4.228	14.9642	4574.7766
5.822	17.9622	8370.0608	1.778	13.4208	11324.0032
0.507	10.8333	44169.5195	9.956	7.4393	12017.7631
0.111	11.8211	11388.9555	2.496	14.6427	8056.4325
1.589	8.7003	9182.0909	1.098	9.2508	7800.9378
5.434	16.7663	8275.1491	4.539	12.8856	9874.3345
9.317	11.3218	4575.3470	2.564	7.9985	8450.5749
4.807	18.2426	5038.2660	7.057	6.8422	10329.3290
6.472	18.7057	13571.8120	4.492	11.1098	19864.1772
0.949	13.3743	7977.1237	7.746	9.1293	19537.9651
5.260	13.9830	5823.7299	2.887	15.7500	7056.1575

tion 2 (shell-pushing), the maximum contact force also changed obviously with the variation of location error and section radius.

Finally, the promising results suggest that the reliability model is applicable to practical systems, and the solving idea can produce a quality solution for reliability analysis.

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