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Research Article

Synchronization Reliability Evaluation Method for Mechanisms with Different Time Distribution

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Synchronization reliability problems are common in the mechanical field; motion asynchrony will affect the performance or even lead to failure. As action time of mechanisms does not share the identical distribution, the existing synchronization reliability evaluation method has great limitations. Aimed at the problem, a novel synchronization reliability evaluation method is proposed. Starting from two mechanisms, the synchronization reliability of N mechanisms can be obtained with recursive algorithm, where synchronization reliability of the mechanisms is expressed as a multiple integral, through dividing the integral domain into several independent domains, the uncertain integral limits are translated into certain integral limits, and then multiple integral can be solved. The numerical examples show that errors between the proposed methods and the MC simulation are very small, which proved that the methods are correct. Finally, synchronization reliability of folding wings is evaluated. The proposed methods make up for the limitations of the existing method and have good versatility.

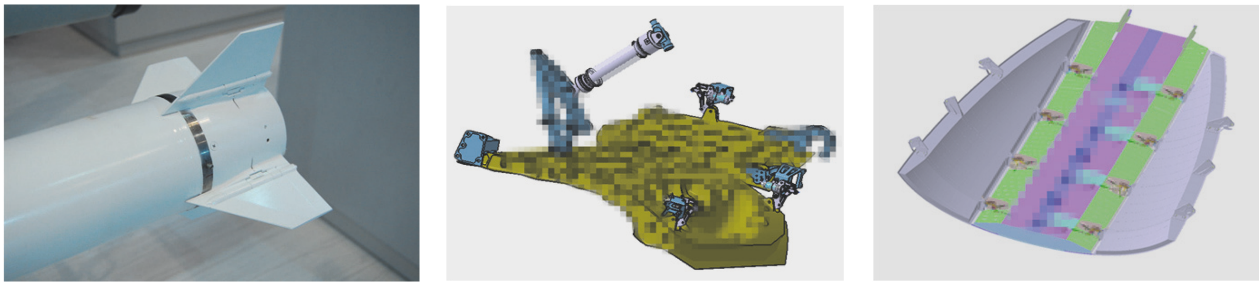
1. Introduction

In the book *Synchronization of Mechanical Systems*, Professor Alejandro Rodriguez Angeles of the University of Twente in Holland points out that "the development of today's technology and the quality requirements of production processes have led to complex integrated production systems. In this case, the use of multiple combination systems is considered the most effective solution." The composition of the combined system can be a number of identical or different units, which work together to perform tasks, and the "together" here refers to the synchronization or coordination of the work of each unit [1].

In engineering fields, especially in aerospace field, it is common that several mechanisms that have the same structure work together to accomplish a function. For example, four folding wings deployed together after missile was launched to make the missile in control (Figure 1(a)); several lock mechanisms work together to lock or unlock the landing gear doors (Figures 1(b) and 1(c)). And such examples widely exist.

Motion asynchrony will affect the performance or even lead to failure [2–8]. For example, too large time difference of the four folding wings will lead to the missile being out of control or even lead to the missile crashing. Therefore, synchronicity should be clearly put forward in the design process.

The theme of synchronization has attracted a lot of attention over the past few decades, which focuses on one of the basic issues in science, that is, how to implement the synchronization of units in multiple systems. In his doctoral thesis (1955), Blekhman of the Institute of Theoretical Engineering of the Academy of Sciences of Russian Academy of Sciences gives a clear definition of synchronization: the time consistency of two or more units, which can be expressed in certain specific relationships of the system. In addition, he expounded the synchronization problem in dynamics system in 1964 [9]. Later, Blekhman (1988) pointed out that synchronization is seen in such varied examples as weakly coupled pendulums, organ tubes, celestial bodies, electrical, electromagnetic, and quantum generators, vibrations in process equipment, turbine blades, populations of cells, swarms of fireflies, flocks of birds, schools of fish, and applauding or marching people [10]. Alejandro Rodriguez Angeles (2002) pointed out that there are several basic problems in system



(a) (b) (c)

Figure 1: Illustration of the systems that have synchronization requirement ((a) missile with four folding wings; (b) landing gear door system with three locks; (c) cabin door system with eight locks).

synchronization. First, the function of describing the desired synchronization targets must be formulated. For this reason, the type of system components and the interesting variables must be taken into account. For mechanism synchronization, the function can be defined as the norm of the difference between the variables of interest, such as the position and speed; secondly, the design of the coupling or the interconnection and feedback controllers must ensure synchronization behavior; finally, the condition that guarantees the synchronization target must be determined [1]. Further, Nagaev (2003) studied synchronization of inertial vibration exciters and dynamical objects of the general type, in which weak interaction of anisochronous and isochronous objects is considered [11].

As to the synchronization performance analysis and reliability evaluation, early studies are focused on the fire-industrial products. The minimum movement synchronization precision is obtained by kinematic simulation [4]. The reliability of synchronous function time of detonator during long term storage is obtained by the Monte Carlo method [12]. From the above references, it is clear that acting time of fire-industrial products is primarily affected by the random factors such as material of the electrodes, geometry shapes, and surface conditions. Usually, acting time of them can be regarded as identically distributed (both distribution types and distribution parameters are identical). With the identical distribution assumption, Wang ZL proposed the synchronization reliability evaluation method for two products [5].

Synchronization reliability evaluation method for three or more products has been studied by some scholars [13, 14], in which the action time of each product is also assumed to share the same normal distribution $N(u, \sigma^2)$. After sorting the variables according to the ascending order, $x_{(1)}, x_{(2)}, \ldots, x_{(n)}$, the extreme difference is expressed as $X = x_{(n)} - x_{(1)}$; according to the probability density function (PDF) of the extreme value distribute, the synchronization reliability of the n products can be expressed as $R = P\{\mathrm{x(n)} - \mathrm{x(1)} \leqslant \varepsilon\}$. But this method is very difficult to solve, and we need to calculate the extreme value distribution of variables.

Synchronization reliability problems for mechanical system are similar to these of fire-industrial products. Ideally, several mechanisms with the same structure should have the same performance, but the presence of many random factors makes the acting time different from each other. The random factors are the driving force, geometric parameters, physical parameters (e.g., coefficients of friction and damping), and the working load. Under normal circumstances, the driving force, geometrical parameters, and physical parameters of each mechanism can be regarded as sharing the same distribution, but the installation position and the attitude are usually different, which will lead to different working load distribution types or different parameters; as shown in Figure 1(a), difference of the flight attitude makes aerodynamic load of the four wings different; as shown in Figures 1(b) and 1(c), installation position of the lock mechanism results in significant differences in their working load. Accordingly, the assumption that acting time distribution types or distribution parameters are identical no longer holds in sync reliability analysis of mechanisms, which means distribution type or parameters are often different, and their extreme value distribution cannot be obtained.

Therefore, the existing synchronization reliability evaluation method cannot solve the synchronization reliability problems of mechanisms in engineering area. In order to solve the above engineering problems, this paper is going to research novel synchronization reliability evaluation method and the synchronization reliability of the folding wings will be evaluated using the proposed method.

2. Novel Methods for Synchronization Reliability Evaluation

For a system with n components, action time of each component is a random variable; it can be expressed by x_i, $i = 1, \ldots, n$. As each component shares the same structure style and working principle, the distribution type of the action time of the components should be identical. However, the distribution parameters of each action time are often different because of the random factors such as manufacturing errors and the external load. Therefore, in the following text, probability density function of action time of ith component is expressed as $f_i(x_i)$, $i = 1, \ldots, n$, where action time of all the components sharing the same distribution type and parameters is a particular case.

Synchronization requires that the difference of the action time should be less than ε, namely, $|x_i - x_j| < \varepsilon$. Therefore, synchronization reliability can be expressed as $R = P\{|x_i - x_j| < \varepsilon\}$.

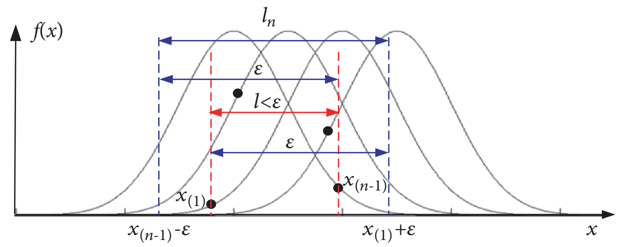


FIGURE 2: Reliable domain analysis for x_n.

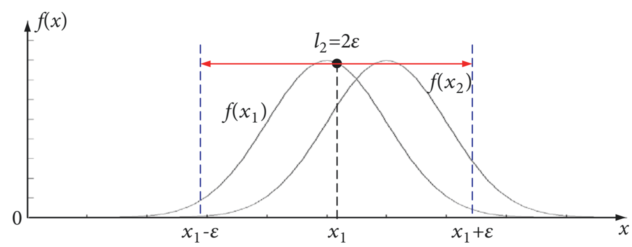


FIGURE 3: Reliable domain analysis for x_2.

Synchronization of n-1 components is the premise of synchronization of n components. When the action time of the first component is determined, in order to satisfy the requirement of the synchronization, the action time of the second component should be among $[x_1\text{-}\varepsilon, x_1\text{+}\varepsilon]$.

In the same way, while action times of the n-1 components are determined and they meet the requirement of the synchronization, sort the action time from small to large, as shown in Figure 2; the minimum action time is $x_{(1)}$ and the maximum action time is $x_{(n-1)}$, where, $x_{(n-1)} - x_{(1)} < \varepsilon$.

Then, it is obvious that when action time of x_n is among $[x_{(n-1)} - \varepsilon, x_{(1)} + \varepsilon]$, the n components will satisfy the synchronization requirement. Therefore, synchronization reliability of n components can be expressed as

$$R_{\text{syn}} = \int_0^\infty f_1(x_1)\left[\int_{x_1-\varepsilon}^{x_1+\varepsilon} f_2(x_2)\left[\int_{\max(x_1,x_2)-\varepsilon}^{\min(x_1,x_2)+\varepsilon} f_3(x_3)\cdots\int_{\max(x_1,x_2,\ldots,x_{n-1})-\varepsilon}^{\min(x_1,x_2,\ldots,x_{n-1})+\varepsilon} f_n(x_n)\,\mathrm{d}x_n\ldots\mathrm{d}x_3\right]\mathrm{d}x_2\right]\mathrm{d}x_1 \qquad (1)$$

Equation (1) shows that synchronization reliability of n components can be expressed as a N-ple integral; it can be seen that the limitation of the most outer integral is 0 to ∞, because the action time should be positive number. And the limitation of the inner integral is determined by the order of the outside variables; the lower limitation is the maximum value minus ε and the upper limitation is the minimum value plus ε.

However, (1) cannot be solved when the order of the outside variables is uncertain. Therefore, the integral space is divided into several independent domains to make the integral limitation determinately. Thus, the uncertain problem is transferred to certain problem. The dividing process is as follows.

(1) Integral Domain Dividing for Two Components. As to the synchronization reliability problem of two components, it is easy to see that when x_1 is determined, integral upper limit and lower limit of x_2 are $[x_1 - \varepsilon, x_1 + \varepsilon]$, as shown in Figure 3.

Therefore, synchronization reliability of two components can be expressed as

$$R_{\text{syn}} = \int_0^\infty f_1(x_1)\left[\int_{x_1-\varepsilon}^{x_1+\varepsilon} f_2(x_2)\,\mathrm{d}x_2\right]\mathrm{d}x_1 \qquad (2)$$

(2) Integral Domain Dividing for Three Components. As to the synchronization reliability analysis for three components, since x_1 and x_2 are not determined, the integral domain of x_3 cannot be determined and (1) cannot be solved. Therefore, the integral interval is divided into two sections: $x_1 > x_2$ and $x_1 < x_2$. When $x_1 > x_2$, x_3 should be among $[x_1 - \varepsilon, x_2 + \varepsilon]$, while $x_1 < x_2$, x_3 should be among $[x_2 - \varepsilon, x_1 + \varepsilon]$. The sketch map is shown in Figure 4 and the independent domains are listed in Table 1.

Therefore, synchronization reliability of the three components can be expressed as

$$\begin{aligned} R_{\text{syn}} &= \int_0^\infty f_1(x_1) \\ &\quad\cdot\left[\int_{x_1-\varepsilon}^{x_1} f_2(x_2)\left[\int_{x_1-\varepsilon}^{x_2+\varepsilon} f_3(x_3)\,\mathrm{d}x_3\right]\mathrm{d}x_2\right]\mathrm{d}x_1 \\ &\quad+\int_0^\infty f_1(x_1) \\ &\quad\cdot\left[\int_{x_1}^{x_1+\varepsilon} f_2(x_2)\left[\int_{x_2-\varepsilon}^{x_1+\varepsilon} f_3(x_3)\,\mathrm{d}x_3\right]\mathrm{d}x_2\right]\mathrm{d}x_1 \end{aligned} \qquad (3)$$

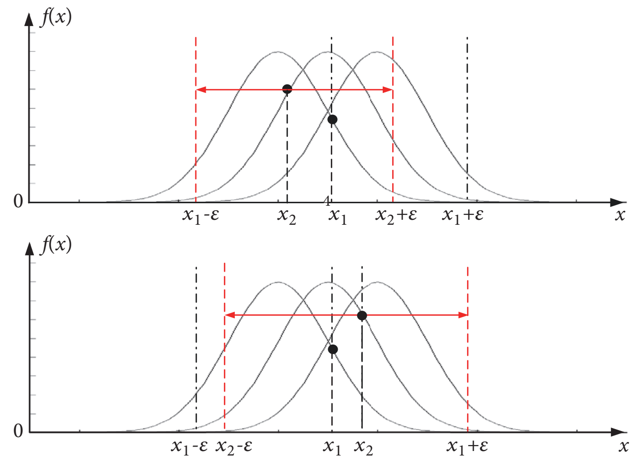


FIGURE 4: Reliable domain analysis for x_3.

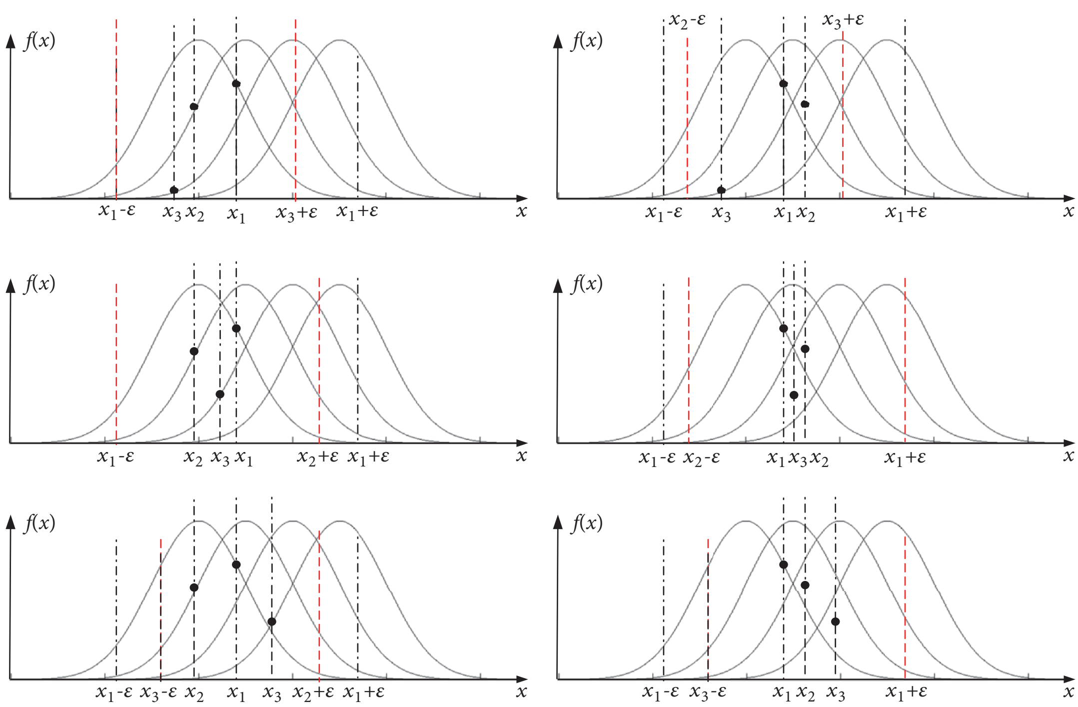


FIGURE 5: Reliable domain analysis for x_4.

TABLE 1: Independent domains for three-component synchronization analysis.

Domain of $\boldsymbol{x_2}$	Domain of $\boldsymbol{x_3}$
$x_1\text{-}\varepsilon < x_2 < x_1$	$x_1\text{-}\varepsilon < x_3 < x_2\text{+}\varepsilon$
$x_1 < x_2 < x_1\text{+}\varepsilon$	$x_2\text{-}\varepsilon < x_3 < x_1\text{+}\varepsilon$

(3) Integral Domain Dividing for Four Components. As to the synchronization reliability analysis for four components, since x_1, x_2, and x_3 are not determined, the integral domain of x_4 cannot be determined and (1) cannot be solved. Therefore, the integral interval is divided into six sections as shown in Figure 5 and the independent domains are listed in Table 2.

It can be seen that the integral domain can be divided into six independent intervals when analyzing synchronization reliability for four components. So the synchronization reliability is the sum of the reliability of each independent domain as follows:

$$R_{\text{syn}} = \int_0^{\infty} f_1(x_1)\left[\int_{x_1-\varepsilon}^{x_1} f_2(x_2)\right.$$

$$\cdot\left[\int_{x_1-\varepsilon}^{x_2} f_3(x_3)\left[\int_{x_1-\varepsilon}^{x_3+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1$$

$$+\int_0^{\infty} f_1(x_1)\left[\int_{x_1-\varepsilon}^{x_1} f_2(x_2)\right.$$

Table 2: Independent domains for four-component synchronization analysis.

Independent Domains			Independent Domains		
x_2	x_3	x_4	x_2	x_3	x_4
x_1-$\varepsilon < x_2 < x_1$	x_1-$\varepsilon < x_3 < x_2$	x_1-$\varepsilon < x_4 < x_3$+ε	$x_1 < x_2 < x_1$+ε	x_2-$\varepsilon < x_3 < x_1$	x_2-$\varepsilon < x_4 < x_3$+ε
	$x_2 < x_3 < x_1$	x_1-$\varepsilon < x_4 < x_2$+ε		$x_1 < x_3 < x_2$	x_2-$\varepsilon < x_4 < x_1$+ε
	$x_1 < x_3 < x_2$+ε	x_3-$\varepsilon < x_4 < x_2$+ε		$x_2 < x_3 < x_1$+ε	x_3-$\varepsilon < x_4 < x_1$+ε

Table 3: Relationship between number of the components and that of the independent integral domains.

Total number of the components	2	3	4	5	…	n
Number of the independent domains	1	2	6	24	…	(n-1)!

$$\begin{aligned}
&\cdot\left[\int_{x_2}^{x_1} f_3(x_3)\left[\int_{x_1-\varepsilon}^{x_2+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1 \\
&+\int_0^\infty f_1(x_1)\left[\int_{x_1-\varepsilon}^{x_1} f_2(x_2)\right. \\
&\cdot\left[\int_{x_1}^{x_2+\varepsilon} f_3(x_3)\left[\int_{x_3-\varepsilon}^{x_2+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1 \\
&+\int_0^\infty f_1(x_1)\left[\int_{x_1}^{x_1+\varepsilon} f_2(x_2)\right. \\
&\cdot\left[\int_{x_2-\varepsilon}^{x_1} f_3(x_3)\left[\int_{x_2-\varepsilon}^{x_3+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1 \\
&+\int_0^\infty f_1(x_1)\left[\int_{x_1}^{x_1+\varepsilon} f_2(x_2)\right. \\
&\cdot\left[\int_{x_1}^{x_2} f_3(x_3)\left[\int_{x_2-\varepsilon}^{x_1+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1 \\
&+\int_0^\infty f_1(x_1)\left[\int_{x_1}^{x_1+\varepsilon} f_2(x_2)\right. \\
&\cdot\left[\int_{x_2}^{x_1+\varepsilon} f_3(x_3)\left[\int_{x_3-\varepsilon}^{x_1+\varepsilon} f_4(x_4)\,\mathrm{d}x_4\right]\mathrm{d}x_3\right]\mathrm{d}x_2\Bigg]\,\mathrm{d}x_1
\end{aligned} \tag{4}$$

(4) Number Analysis of the Independent Integral Domains. According to the discussion of the integral domain, the number of independent domains for two components, three components, and four components is one, two, and six, respectively.

As to n components, since integral limit of nth variable is determined by the order of the n-1 components, the independent integral domain for n components is N=(n-1)!, and the relationship between number of the components and that of the independent integral domain is listed in Table 3.

Since the (n-1)! integral domains are independent, the synchronization reliability of n components is the sum of reliability in (n-1)! domains, and the reliability in each domain is a n-ple integral, namely,

$$R_{\mathrm{syn}} = \sum_{i=1}^{(n-1)!} R_{n,i} \tag{5}$$

For most of the distribution types, although the probability density functions are elementary functions, the integral cannot be expressed by elementary function. Therefore, numerical algorithms are often used to solve $R_{n,i}$, such as numerical integral method and Monte Carlo simulation method [15–17].

(5) Flowchart of the Method. The synchronization reliability of N mechanisms can be obtained by recursive algorithm. That means beginning from n=2 to obtain the synchronization reliability, and then adding a mechanism, until n=N; the detailed steps are as follows.

Step 1. Define the number of the mechanisms N (N>2) and obtain the probability density function (PDF) $f_i(x_i)$ of action time of each mechanism.

Step 2. Present the synchronization reliability of two mechanisms by (2).

Step 3. Keep the integral limits of x_1 to x_{n-1} unchanged, divide the integral domain of x_n into n independent domains, and obtain the corresponding reliable domain of x_{n+1}, as shown below:

$$\begin{aligned}
D_{n,1} &: \left[x_{(1)}-\varepsilon, x_{(1)}\right] \quad &\text{and } D_{n+1,1} &: \left[x_{(1)}-\varepsilon, x_{(n)}+\varepsilon\right] \\
D_{n,2} &: \left[x_{(1)}, x_{(2)}\right] & D_{n+1,2} &: \left[x_{(n)}-\varepsilon, x_{(1)}+\varepsilon\right]; \\
&\cdots & &\cdots \\
D_{n,n} &: \left[x_{(n-1)}-\varepsilon, x_{(n-1)}+\varepsilon\right] & D_{n+1,n} &: \left[x_{(n)}-\varepsilon, x_{(1)}+\varepsilon\right]
\end{aligned} \tag{6}$$

Step 4. According to the independent domains in Step 3, replace $\int_{D_{n-1,i}} f_n(x_n)$ in (2) by $\sum_{i=1}^{n} \int_{D_{n,i}} f_n(x_n) \int_{D_{n+1,i}} f_{n+1}(x_{n+1}) dx_{n+1} dx_n$; synchronization reliability of n mechanisms is expressed.

Step 5. Add a mechanism to the present n, namely, n=n+1. If n<N, execute Steps 3 and 4, or solve the expression in Step 4, which is the synchronization reliability of N mechanisms $R_{\mathrm{syn,N}}$∘

3. Validation of the Proposed Method

To validate the proposed methods, the following numerical examples are used. As shown in Table 4, there are four components, whose action times are x_1, x_2, x_3, and x_4,

Table 4: Distribution type and parameters of the action time of four components.

No. of the wing	Deploy time(ms)	Distribution type	Mean value	Standard deviation
i=1	x_1	Normal	10	1
i=2	x_2	Normal	11	0.9
i=3	x_3	Normal	12	1.2
i=4	x_4	Normal	13	0.95

Table 5: Results comparison of the reliability.

Number of components	Time difference	Synchronization reliability R_{syn}		
		Proposed method	MC method	Error/%
N=2 (i=1,2)	ε=2	0.7585	0.7587	-0.02636
	ε=3	0.9300	0.930025	-0.00269
	ε=4	0.9870	0.987063	-0.00638
N=3 (i=1,2,3)	ε=2	0.3829	0.38269	0.054875
	ε=3	0.6831	0.683033	0.009809
	ε=4	0.8831	0.883581	-0.05444
N=4 (i=1,2,3,4)	ε=2	0.1122603	0.112018	0.216305
	ε=3	0.3710127	0.374236	-0.8613
	ε=4	0.6897235	0.690952	-0.1778

respectively, and the distribution types and parameters are given in Table 4.

According to the performance index, the difference in action time should be less than ε. In order to demonstrate the applicability of the proposed method, synchronization reliability of two, three, and four components is estimated using the proposed methods and the verification method, and the comparison results are listed in Table 5.

According to the examples, it can be seen that the error between the reliability obtained from MC method and that of the proposed method is very small, so the proposed methods are proved available.

4. Synchronization Reliability Evaluation for Folding Wings

4.1. Failure Mechanism Analysis. As shown in Figure 1(a), a missile contains four folding wings, which are powered by four actuating cylinders, respectively. By screw pair, rectilinear motion is transferred into rotatory motion to achieve the wings movement.

Considering four folding wings have the same structure, the movement out of sync is mainly caused by three aspects: (1) inherent factors: motion friction coefficient is different because of manufacture errors; (2) power factor: maximum pressure and maximum flow are different due to the dosage of the dynamite and the error of damping cavity; (3) external load factors: both of the magnitude and the direction of the aerodynamic load acting on each wing are quite different. Influence factors analysis for synchronization failure is shown in Figure 6.

Performance index of the folding wing requires that the time difference should be less than 80 ms. Therefore, the synchronization reliability can be expressed as

$$R = P\left\{\left|t_i - t_j\right| < 80ms\right\} \quad i, j = 1, 2, 3, 4 \tag{7}$$

4.2. Dynamic Model and Agent Model. The dynamic model of the folding wing is built using LMS Virtual Lab, and the driving model is built using AMESim; then the cosimulation model is built combined with the dynamic model and the driving model.

As the model contains a lot of contact collision units, the calculation speed is slow, and simulating large number of samples is time-consuming; therefore, agent model is needed to replace the simulation model.

According to the failure influence factors analysis, six random factors affect the action time of the deploy wing. As a result, treat the six parameters as design variables, 50 samples are generated using the optimal Latin Hypercube Sampling (LHS) [18], and then RSM model [19], Kriging model [20], and RBF model [21] are used to establish the agent model of the four wings, respectively.

In order to validate the three models, 13 new samples are generated and simulated, and the predicted values are compared with the simulated values. The agent model verification of the 1st wing is shown in Figure 7, as those of the other three wings are similar to the 1st wing, which are not given in the paper.

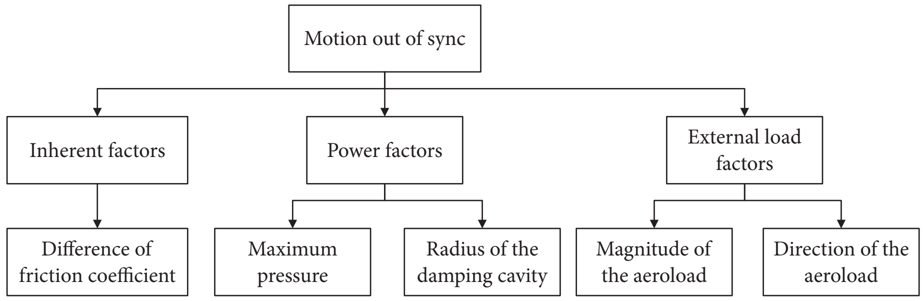
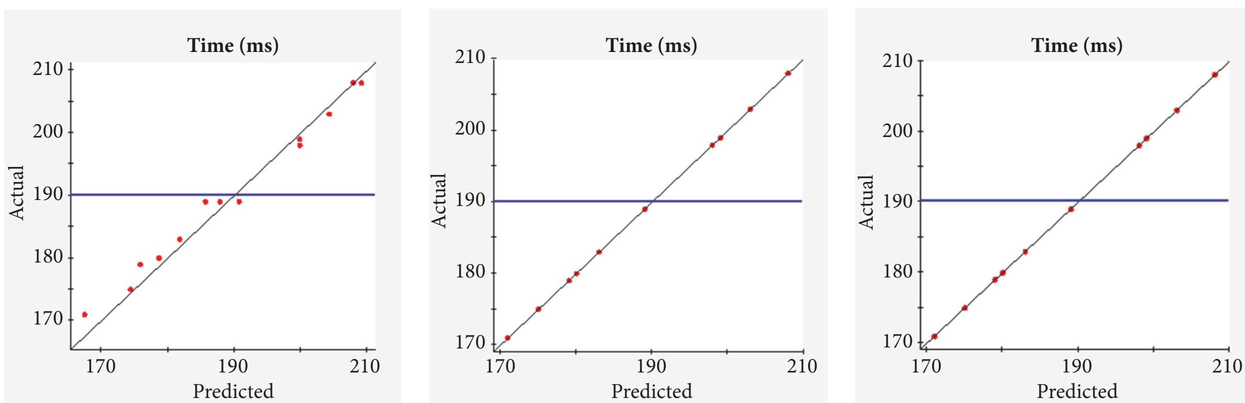


FIGURE 6: Influence factors analysis for synchronization failure.



(a) RSM Model (b) Kriging Model (c) RBF Model

FIGURE 7: Comparison between predicted values and actual values of different agent models.

From the comparison between predicted values and actual values of different agent models, it can be seen that RBF model is more accurate than the RSM model and Kriging model. Therefore, for subsequent analysis, RBF model is used instead of the simulation model.

4.3. Synchronization Reliability Evaluation for the Folding Wings. Flowchart of synchronization reliability evaluation for mechanism system is shown in Figure 8, First, the dynamic simulation model of the folding wing mechanism is set up. Secondly, the agent model of the action time of the folding wing is constructed, and the model is accurate enough by iteration. Again, after obtaining the distribution type and distribution parameters of the action time of each wing, the proposed method is used to evaluate the synchronous reliability.

According to the failure mechanism analysis, action time of the folding wings is influenced by six factors. The distribution types and parameters of each factor are shown in Table 6.

According to distribution types and parameters, 10000 random samples are generated, and then, with the four RBF models, action times of wings are obtained, through hypothesis testing [22]; all of the action times of four wings obey the normal distribution; the histogram is shown in Figure 9 and the distribution parameters are shown in Table 7.

Applying the proposed method, the synchronization reliability R_{syn} is 0.9348.

5. Conclusions

In summary, in view of the synchronous reliability characteristics of the mechanism, we presented a synchronization reliability evaluation method for mechanisms whose action times are differently distributed. In the method, the synchronization reliability of mechanisms is obtained with recursive algorithm, and the proposed method is validated by a numerical example. In addition, synchronization reliability of the folding wings is analyzed by the proposed method, and the engineering practicability of this method is verified. However, the proposed method is not exhaustive and universal enough to cover the synchronization of electric generators, vibration exciters, and some other objects, in which the dynamic connections exist. In addition, load-sharing characteristic of multiple mechanisms leads to the correlation between action times, of which synchronization reliability will be considered in our future work.

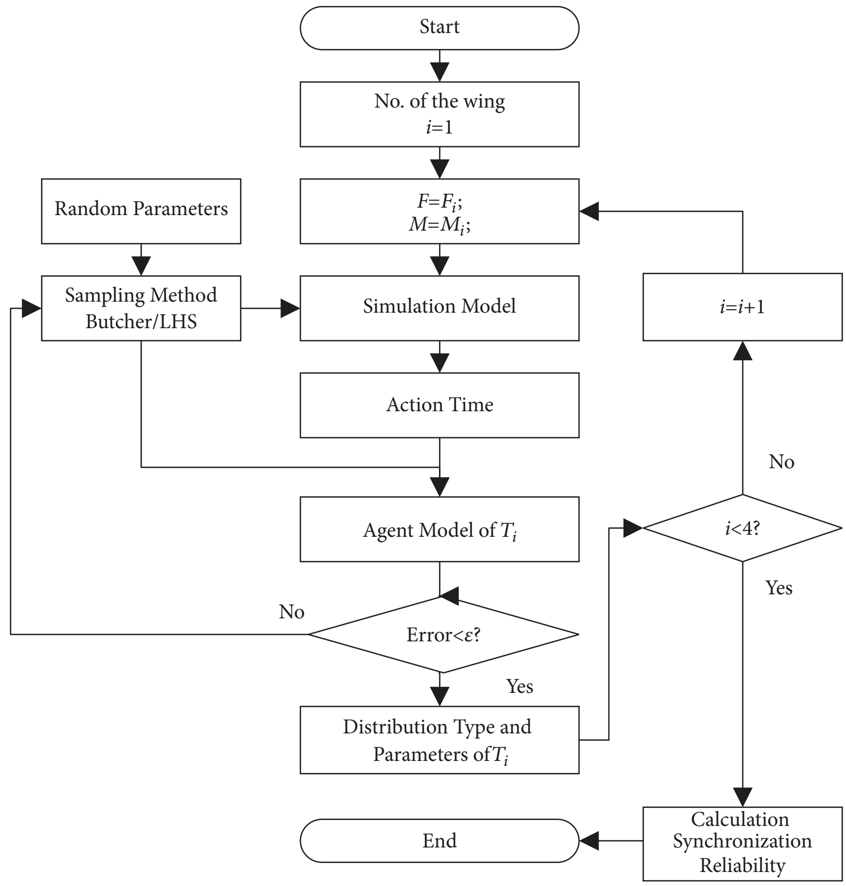


Figure 8: Flowchart of synchronization reliability evaluation for mechanism system.

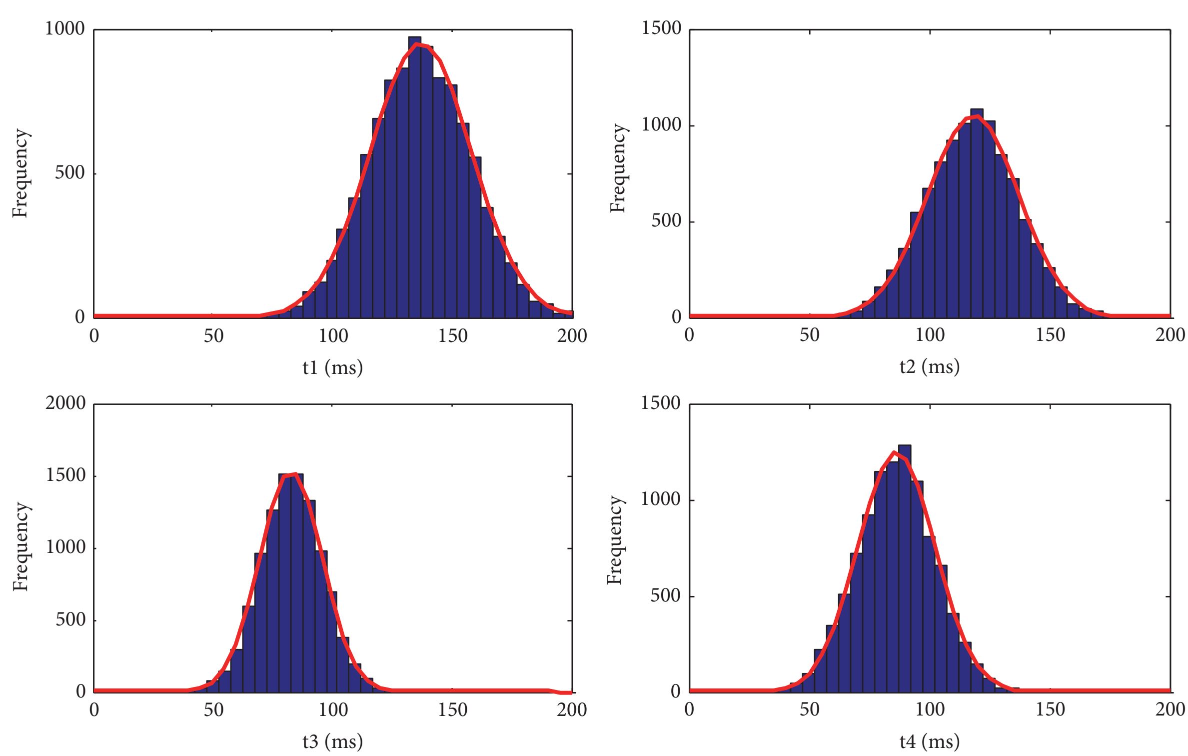


Figure 9: Histogram of the action time of the four wings.

Table 6: Distribution types and parameters of the influence factors.

No.	Variables	Meaning	Distribute type	Mean value	Standard deviation
1	P	Max Pressure /MPa	Normal	27	1
2	D	Orificing radius /mm	Normal	0.6	0.00667
3	f_1	Friction coefficient	Normal	0.4	0.01
4	f_4	Friction coefficient	Normal	0.15	0.01667
5	k_F	Force coefficient	Normal	1	0.05
6	k_M	Moment coefficient	Normal	1	0.1

Table 7: Distribution types and parameters of the action time the four wings.

No. of the wing	Action time(ms)	Distribution type	Mean value	Standard deviation
1	t_1	normal	137	21
2	t_2	normal	118	19
3	t_3	normal	83	13
4	t_4	normal	86	16

Nomenclature

u: Mean value of the random variables
σ: Standard deviation of the random variables
x_i: Action time of ith component
n: Total number of the components
$x_{(1)}$: Minimum value of the x_i
$x_{(n)}$: Maximum value of the x_i
$f(x)$: Probability density function of action time
ε: Index of time difference
R_{syn}: Synchronization reliability
a: The lower limit of the action time
b: The upper limit of the action time
R_i: Reliability of each component
R_{bound}: Reliability of all the action times among a and b
$R_{\min}$: The lower bound of the reliability
$R_{\max}$: The upper bound of the reliability
N_f: Number of the failure samples
P: Maximum pressure of the actuating cylinders
D: Radius of the damping orificing
f_1: Friction coefficient between titanium alloy and steel
f_2: Friction coefficient of the screw pair
k_{F}: Force coefficient
k_{M}: Moment coefficient.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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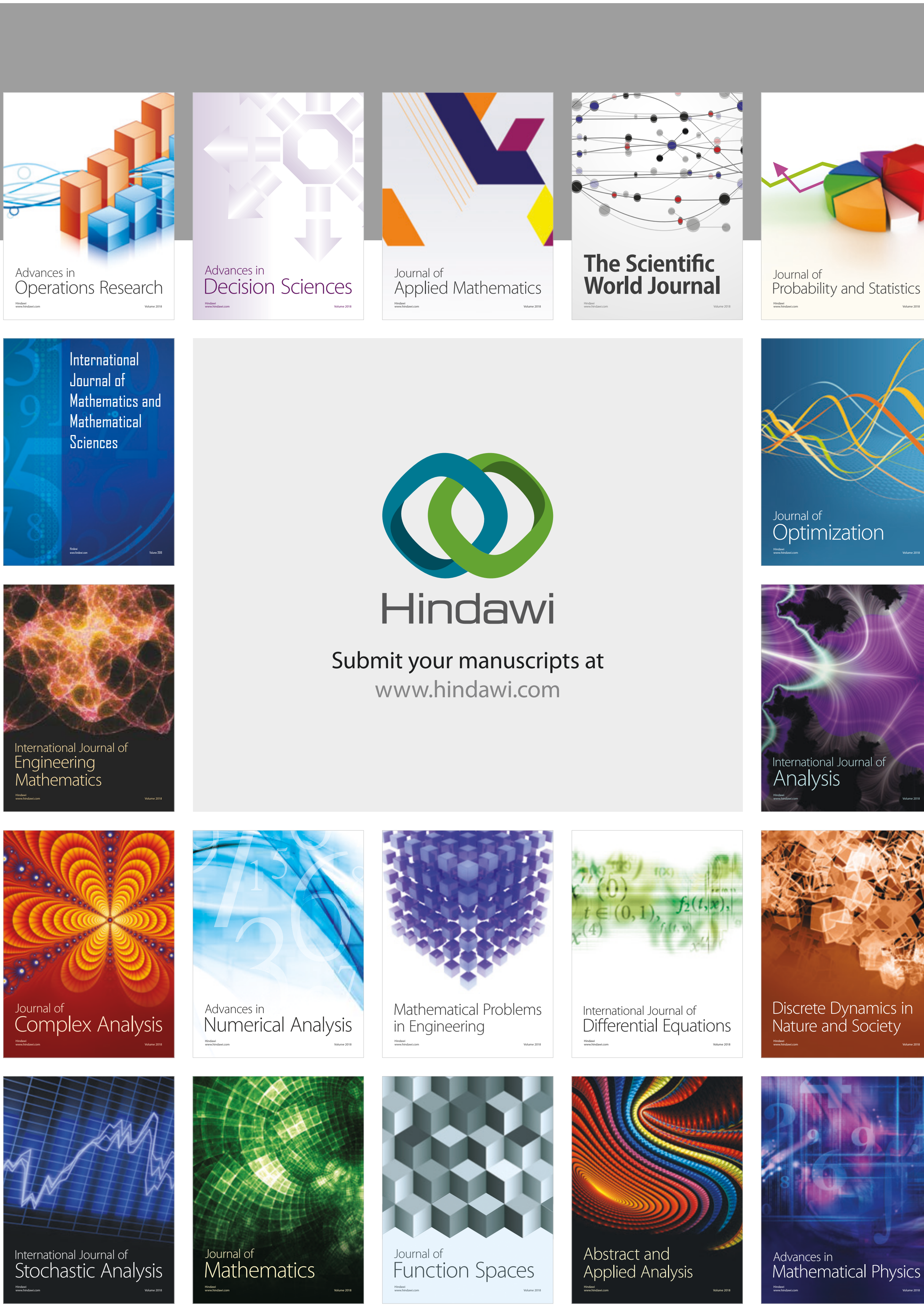
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