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Flight Safety System Evaluation and Optimal Linear Prediction

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Abstract: The complexity of flight safety system is usually affected by a variety of uncertainties. The uncertainty of overall security situation of flight safety system are hardly determined. In this work, flight safety assessment index system is firstly established based on software hardware environment liveware management (SHELM) model. And flight safety assessment is also carried out with matter-element theory algorithm to obtain safety state. According to correlation degree values of each evaluation index, key indexes affected flight safety are obtained. Under the assumption that the flight safety system is a linear dynamic system and combining the above evaluation analysis, Kalman filter algorithm is used to carry out prediction analysis on security situation. A simulation analysis is carried out based on an actual flight safety situation of an airline. The results show that the security state of airline flight safety system in a short period of time can be obtained, and main factors affecting flight safety are found out. This provides a viable way for airlines to further strengthen flight safety management.

Key words: flight safety; flight safety assessment and prediction; software hardware environment liveware management (SHELM) model; matter-element theory; Kalman filter theory

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0 Introduction

For guaranteeing the airlines security, it is the primary requirement to ensure flight safety. Therefore, it is necessary to carry out the assessment and forecast study on flight safety in advance to find out weak links in flight safety system and take effective measures to strengthen flight safety management. The security situation of flight safety system is required to predict in advance as far as possible so as to prevent flight accidents and flight accident symptoms.

A lot of studies on how to improve the level of flight safety management have been done by many scholars. Catalyurek and Brissaud et al.[1-2] analyzed flight safety reliability by using dynamic event tree methods. Janic[3] carried out safety evaluation for the whole civil aviation system based on causal and probability theory. Considering the cost and benefit of the airlines, Ahmadi et al.[4] used event tree analysis method to evaluate flight safety of airlines. Zhang et al.[5] have improved the analytic hierarchy process (AHP) and applied it to flight safety evaluation. Xu et al.[6] studied the risk control of hard landing phenomenon by using the machine learning method of support vector machine (SVM) with the hard landing phenomenon of aircraft. Shen et al.[7] adopted analytic hierarchy process to evaluate flight safety with taking the flight's ultra-limits events during takeoff and landing as an evaluation index. From the perspective of flight environment impacting flight safety, Richardson et al.[8] extended the safety margin by studying the effects of wind shear on flight envelope and developed a comprehensive set of metrics to quantify flight safety by combining various statistical information describing the stochastic

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process. Taking into account the generation of the wake of forerunner aircraft and weather conditions, Bobylev et al.[9] proposed a mathematical model to evaluate the safe separation of aircraft wake. The model was validated by experimental results, and the wake characteristics of aircraft tail while landing with various turbulent atmospheric states and the calculation of safe distance was given. Gan et al.[10] established the evaluation index system from four aspects: Human, equipment, environment and management. On this basis, the model was established by using the related vector machine under Bayesian framework to evaluate flight safety. Liu et al.[11] combed the existing typical flight safety assessment methods from the perspective of evaluation methods, and proposed that a variety of evaluation methods can be combined to evaluate flight safety in subsequent studies. With QAR data as support, Gao et al.[12] combined the set of analysis theory with Markov theory to carry out the evaluation and prediction research of flight safety situation. Xue et al.[13] applied the BP neural network, time series and support vector machine to the flight accident probability prediction model. Through the analysis of the prediction error, the basic trust allocation function of each forecasting method is calculated. Finally, the result of flight accident prediction is obtained through fusing three prediction models by the fusion rule of D-S theory.

Some scholars heavily rely on mathematical statistics for flight safety. However, sample data are reduced due to the lower incidence of accidents, which limit the use of these methods. Scholars in China concentrated on the choice of methods, and the current main problems of these evaluation methods are that neither the uncertainty between the various factors nor the complexity of the fusion of multiple methods could be better solved.

Therefore, according to the above analysis, software hardware environment liveware management (SHELM) model centering on human factors will be employed as a foundation in this paper to analyze the relationship between the factors affecting flight safety and establish a flight safety evaluation index system. Since the flight safety assessment is characterized by matter-element extension thought and the characteristics of Kalman filter optimization regression data processing, the research on flight safety assessment and prediction is carried out. Finally, the validity and rationality of the method are verified by an example.

1 Evaluation Index System

In terms of the trend of world aviation history development, the proportion of flight accidents caused by human factors continues to increase[14].

The SHELM model is formed on the basis of the SHELL model centered on human factors (L), which increases the security management (M). The factors that may affect flight safety are extracted from the flight accident database by summarizing the accident description attributes in flight accident database, which is provided by the ASN (China Civil Aviation Safety Information System)[15]. The flight safety assessment index system based on SHELM model is established (Fig.1).

2 Matter-Element Theory

The research objects of matter-element theory are mainly the complex and incompatible problems of multi-level and multi-objective, which is to establish matter-element model by the matter-elements transformation as compatible problems[16]. The matter-element theory is to calculate by establishing dependent function, which can be used to indicate the degree of certain properties of things from both qualitative and quantitative aspects. The evaluation modeling processes are described as follows.

2.1 Concept of matter-element

The name of study subject is N, which is feature U of N in terms of X. So, $\boldsymbol{R}=(N, U, X)$, ordered triples as the elements that describe things N, is referred to the material element. If the features of things N are embodied in many aspects, namely U_1, U_2, U_3, $\cdots$, U_m, m of measured values X_1, X_2, X_3, $\cdots$, X_m to describe the properties of things N, $\boldsymbol{R}$ is a m-dimensional matter, which is represented as

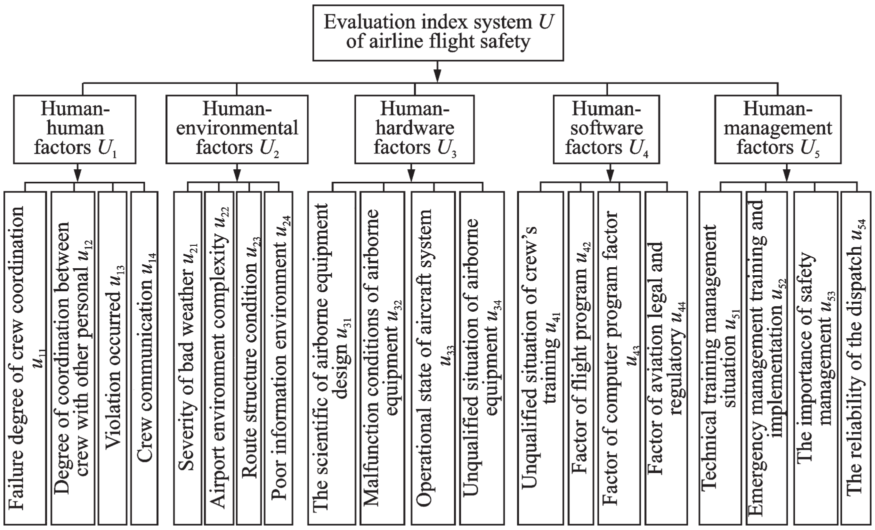

Fig.1 Flight safety assessment index system

$$\boldsymbol{R}=\begin{bmatrix} N & U_1 & X_1 \\ 0 & U_2 & X_2 \\ \vdots & \vdots & \vdots \\ 0 & U_m & X_m \end{bmatrix} \tag{1}$$

2.2 Single index evaluation

In the flight safety assessment index system, $U=\{U_i\}$ is the set of evaluation indexes, where U_i ($i=1, 2, \cdots, m$) is the influencing factor layer; $U_i=\{u_{ij}\}$, in which u_{ij} ($i=1, 2, \cdots, m$; $j=1, 2, \cdots, n$) is index layer.

2.2.1 Classical domain and joint domain

The classical domain is a value range of evaluation indexes on each evaluation level, and the matrix is represented as

$$\boldsymbol{R}_{if}=\begin{bmatrix} U_{if} & u_{i1} & X_{if1} \\ 0 & u_{i2} & X_{if2} \\ \vdots & \vdots & \vdots \\ 0 & u_{in} & X_{ifn} \end{bmatrix}=\begin{bmatrix} U_{if} & u_{i1} & [a_{if1}, b_{if1}] \\ 0 & u_{i2} & [a_{if2}, b_{if2}] \\ \vdots & \vdots & \vdots \\ 0 & u_{in} & [a_{ifn}, b_{ifn}] \end{bmatrix} \tag{2}$$

where U_{if} means that when the evaluation level of primary influencing factor is f, $f=(1, 2, \cdots, p)$, the classical domain of secondary index u_{in} is $[a_{ifn}, b_{ifn}]$.

Joint domain refers to the range of values specified by the whole evaluation levels for evaluation index, which can be expressed as

$$\boldsymbol{R}_{ip}=\begin{bmatrix} U_{ip} & u_{i1} & X_{ip1} \\ 0 & u_{i2} & X_{ip2} \\ \vdots & \vdots & \vdots \\ 0 & u_{in} & X_{ipn} \end{bmatrix}=\begin{bmatrix} U_{ip} & u_{i1} & [a_{ip1}, b_{ip1}] \\ 0 & u_{i2} & [a_{ip2}, b_{ip2}] \\ \vdots & \vdots & \vdots \\ 0 & u_{in} & [a_{ipn}, b_{ipn}] \end{bmatrix} \tag{3}$$

where U_{ip} means the whole evaluation levels of primary influencing factors, the reference range specified by u_{in} on all evaluation levels is $[a_{ipn}, b_{ipn}]$.

2.2.2 Matter-element values

The specific data obtained by the matter-element analysis of evaluation index is expressed as

$$\boldsymbol{R}_i=\begin{bmatrix} U_i & u_{i1} & Y_{i1} \\ 0 & u_{i2} & Y_{i2} \\ \vdots & \vdots & \vdots \\ 0 & u_{in} & Y_{in} \end{bmatrix} \tag{4}$$

where U_i is the corresponding primary influencing factor in evaluation index system, and Y_{in} the specific matter value of secondary index u_{in} under influence factor U_i.

2.2.3 Correlation degrees

Correlation degrees indicate the degree to which the evaluation indexes attach to a certain evaluation level.

Single-index correlation degrees: When the safety of the second index u_{ij} in level f, the correlation degree is

$$K_f(Y_{ij})=\begin{cases} \dfrac{\rho(Y_{ij}\,X_{ifj})}{\rho(Y_{ij}\,X_{ipj})-\rho(Y_{ij}\,X_{ifj})} & Y_{ij}\notin X_{ifj} \\ \dfrac{-\rho(Y_{ij}\,X_{ifj})}{|X_{ifj}|} & Y_{ij}\in X_{ifj} \end{cases} \tag{5}$$

where

$$\rho(Y_{ij}\,X_{ifj})=\left|Y_{ij}-\frac{1}{2}(a_{ifj}+b_{ifj})\right|-\frac{1}{2}(b_{ifj}-a_{ifj}) \tag{6}$$

$$\rho(Y_{ij}\,X_{ipj})=\left|Y_{ij}-\frac{1}{2}(a_{ipj}+b_{ipj})\right|-\frac{1}{2}(b_{ipj}-a_{ipj}) \tag{7}$$

2.3 Evaluation results

(1) Correlation degree of primary impact factors for each safety level

When the safety level of primary impact factors U_i is graded by f, the correlation degree is defined as

$$K_f(U_i)=\sum_{j=1}^{n}\omega_j^i K_f(Y_{ij})\quad i=1,2,\cdots,m \tag{8}$$

where ω_j^i means the weights of evaluation index.

(2) Comprehensive correlation

When flight safety level is f, the correlation degree of airline flight (N) to be evaluated is calculated as

$$K_f(N)=\sum_{i=1}^{m}W_i K_f(U_i) \tag{9}$$

(3) Safety grade

According to the principle of maximum membership, the safety level of airline flight safety is determined by the results of Eq.(9)

$$K_0=\max K_f(N) \tag{10}$$

3 Flight Safety Prediction Based on Kalman Filter Theory

3.1 Description of Kalman filtering theory

Kalman filter theory is an optimal autoregressive data processing algorithm, which uses a state space mode to describe a system, and a recursive form algorithm to optimize state variables after eliminating the noise of Kalman filter, so that the data storage capacity becomes smaller. Due to this, Kalman filter theory is widely used in the fields of inertial navigation, target tracking, communication and signal processing[17].

3.2 Kalman filtering algorithm for flight safety prediction

A flight safety system is defined as a linear dynamic system which is affected by many factors. By increasing a state space model in Kalman filter algorithm, namely dynamic time domain model with implied time as the independent variable, the security situation prediction analysis of flight safety system is carried out, combing with the linear autoregressive analysis of Kalman filter algorithm. It is assumed that the linear state space model of flight safety system is an observable time series and unobservable state vector time linear function, while the motion of state vector follows the first order vector autoregressive process. Therefore, the linear state space model of flight safety system can be expressed as

$$\begin{aligned} x_t&=\boldsymbol{F}_t x_{t-1}+w_t && \text{Equation of state}\\ y_t&=\boldsymbol{H}_t x_t+v_t && \text{Observe equation}\end{aligned} \tag{11}$$

while w_t and v_t are noise disturbances, and obey the Gaussian distribution of variance $\boldsymbol{Q}$ and $\boldsymbol{R}$, that is

$$\begin{aligned} w_t&\sim N(0,\boldsymbol{Q})\\ v_t&\sim N(0,\boldsymbol{R})\end{aligned} \tag{12}$$

where $t=1,2,\cdots,T$. The equation of state describes the change of state vector over time.

The observation equation describes generation of observed vector. $\boldsymbol{F}_t$ and $\boldsymbol{H}_t$ represent the state transition matrix and observation matrix, respectively.

Therefore, the detailed analysis steps for security situation of flight safety system using Kalman filtering algorithm are as follows.

(1) Prediction model parameters

On the basis of the evaluation and analysis results of flight safety system above, the prediction and analysis of system security situation are carried out. Assuming the order of linear prediction model, MATLAB is used to fit the system parameters under each prediction model.

(2) Prediction

The system parameters of various orders prediction model obtained in the previous step are taken into the formula of Kalman filter algorithm as the initial state parameters to be analyzed and calculated. The formula of Kalman filter algorithm is as follows.

Prediction

$$\begin{aligned} x_{t|t-1}&=\boldsymbol{F}_t x_{t-1|t-1}+w_t\\ \boldsymbol{P}_{t|t-1}&=\boldsymbol{F}_t\boldsymbol{P}_{t-1|t-1}\boldsymbol{F}_t^{\mathrm{T}}+\boldsymbol{Q}\end{aligned} \tag{13}$$

Correction

$$\begin{aligned} k_t&=\boldsymbol{P}_{t|t-1}\boldsymbol{H}_t^{\mathrm{T}}(\boldsymbol{H}_t\boldsymbol{P}_{t|t-1}\boldsymbol{H}_t^{\mathrm{T}}+\boldsymbol{R})^{-1}\\ m_t&=y_t-\boldsymbol{H}_t x_{t|t-1}\\ x_{t|t}&=x_{t-1|t-1}+k_t m_t\\ \boldsymbol{P}_{t|t}&=(\boldsymbol{I}-k_t\boldsymbol{H}_t)\boldsymbol{P}_{t|t-1}\end{aligned} \tag{14}$$

where $\boldsymbol{P}_t$ is the covariance matrix of state vector, m_t the residual value, and k_t the Kalman gain.

(3) The order of prediction model

By comparing the residual values of prediction models, the final order of prediction model is determined by the minimum residual value.

(4) Analysis of flight safety prediction results

Through substituting the last phase of system parameters updated by Kalman filter algorithm into the prediction model determined by the previous step, the predicted value of flight safety system security situation can be obtained.

4 Application and Analysis

This paper takes the safety situation of a domestic airline flight safety system as an example. First, the safety rating of evaluation index is divided into four levels, namely absolute safe, safe, relative safe, and unsafe. The classical domain for each evaluation index is determined by experts according to professional knowledge and experiences. Second, fifteen experts in civil aviation fields give the matter-element values of each secondary index, and take average of all matter values as the final matter value of this secondary index. The evaluation indexes of human-human factors were taken as an example to make a concrete analysis.

4.1 Matter-element theory modeling

(1) Classic domain (Table 1)

Table 1 Classic domain

Domain	Human factor			
	f_1	f_2	f_3	f_4
Failure degree of crew coordination	85—100	75—85	60—75	0—60
Degree of coordination between crew with other personal	85—100	75—85	60—75	0—60
Violation occurred	90—100	75—90	60—75	0—60
Crew communication skill	90—100	75—90	60—75	0—60

(2) Joint domain

$$\boldsymbol{R}_{1p}=\begin{bmatrix} U_1 & u_{11} & 0—100 \\ 0 & u_{12} & 0—100 \\ 0 & u_{13} & 0—100 \\ 0 & u_{14} & 0—100 \end{bmatrix}$$

(3) The matter-element values

$$\boldsymbol{R}_1=\begin{bmatrix} U_1 & u_{11} & 83 \\ 0 & u_{12} & 72 \\ 0 & u_{13} & 88 \\ 0 & u_{14} & 75 \end{bmatrix}$$

(4) Correlation degrees

Eqs.(5—7) are used to determine the correlation degrees of secondary evaluation indexes to four safety levels, as shown in Table 2.

Table 2 Correlation degrees of human-human factor indexes for each safety level

Evaluation index	f_1	f_2	f_3	f_4
Failure degree of crew coordination	−0.105 3	0.2	−0.32	−0.575
Degree of coordination between crew with other personal	−0.317 1	−0.096 8	0.12	−0.3
Violation occurred	−0.142 9	0.133 3	−0.52	−0.7
Crew communication skill	−0.361 1	0.133 3	−0.08	−0.425

By using the same method, the correlation degrees between other assessment indexes and four safety levels are shown in Table 3.

(5) Weights of evaluation indexes

In this paper, analytic hierarchy process (AHP) is used to determine the weights of evaluation indexes as shown below. The specific solution process is not introduced in detail.

$\boldsymbol{W}=(0.327, 0.116, 0.253, 0.184, 0.12)$

$\boldsymbol{\omega}^1=(0.225, 0.24, 0.308, 0.227)$

$\boldsymbol{\omega}^2=(0.209, 0.215, 0.212, 0.358)$

$\boldsymbol{\omega}^3=(0.275, 0.219, 0.341, 0.165)$

$\boldsymbol{\omega}^4=(0.30, 0.246, 0.220, 0.189)$

$\boldsymbol{\omega}^5=(0.297, 0.224, 0.258, 0.221)$

4.2 Evaluation results analysis

(1) Correlation degrees of primary influential factors for each safety level

The correlation degree values of secondary evaluation index for each safety level as well as indexes weights are substituted into Eq.(9), and correlation degree values of the five primary influence factors for four safety levels are obtained, as shown in Table 4.

Table 3 Correlation degrees of secondary indexes to each safety level

Evaluation index		Correlation degree			
		f_1	f_2	f_3	f_4
U_2	u_{21}	−0.058 8	0.1	−0.36	−0.60
	u_{22}	−0.105 3	0.2	−0.32	−0.575
	u_{23}	−0.272 7	0.1	−0.04	−0.40
	u_{24}	−0.333 3	0.333 3	−0.2	−0.5
U_3	u_{31}	−0.258 1	0.2	−0.08	−0.425
	u_{32}	−0.173 9	0.4	−0.24	−0.525
	u_{33}	−0.297 3	−0.037 0	0.066 7	−0.35
	u_{34}	−0.307 7	0.466 7	−0.28	−0.55
U_4	u_{41}	−0.343 8	0.266 7	−0.16	−0.475
	u_{42}	−0.307 7	−0.069 0	0.133 3	−0.325
	u_{43}	−0.317 1	−0.096 8	0.2	−0.3
	u_{44}	−0.333 3	−0.142 9	0.333 3	−0.25
U_5	u_{51}	−0.272 7	0.1	−0.04	−0.4
	u_{52}	−0.241 4	0.3	−0.12	−0.45
	u_{53}	−0.222 2	0.266 7	−0.44	−0.65
	u_{54}	−0.2	0.5	−0.2	−0.5

Table 4 Correlation degrees of primary influence factors to each safety level

Primary influence factor	Correlation degree				Class f
	f_1	f_2	f_3	f_4	
Human-human	−0.225 8	0.0931	−0.221 5	−0.513 5	2
Human-environmental	−0.212 1	0.2044	−0.224 1	−0.512 8	2
Human-hardware	−0.261 2	0.2070	−0.098 0	−0.441 9	2
Human-software	−0.311 6	0.0147	0.091 8	−0.335 7	3
Human-management	−0.236 6	0.2762	−0.196 5	−0.497 8	2

(2) Comprehensive correlation degrees

For the data in Table 4, the correlation degrees of flight safety to four safety levels are shown in Table 5.

Table 5 Airline flight safety comprehensive assessment results

Evaluation object	Correlation degree				Class f
	f_1	f_2	f_3	f_4	
Airline flight safety	−1.247 2	0.795 5	−0.648 3	−2.301 7	2

In summary, according to the principle of maximum membership, the safety level of airline flight safety is safe. As can be seen from Table 4, the safety level of human-software factor (U_4) is safer, with the correlation degree of 0.091 8 being the smallest dependent degrees compared with other factors.

4.3 Flight safety prediction based on Kalman filter theory

The sensitivity analysis is carried out by the above assessment results. The different matter-element values of secondary index in human-software factors are selected for simulation analysis. Matter-element values of the selected evaluation indexes gradually increases, which are on the basis of original matter-element values according to certain proportion (5%) within the scope of joint domain. Other indexes values and weights remain same. After repeated simulation analysis, the function curves which airline flight safety to f_1 is obtained, as shown in Figs.2,3.

Assuming that the flight safety system is a dynamic linear complex system, the initial parameters of flight safety system prediction model are obtained by fitting the curve in Figs.2,3, which assumed the order number of flight safety system linear prediction model, as shown in Table 6.

The initial parameters obtained in Table 6 are substituted into the Kalman filter Eqs.(13), (14) to get the prediction models residuals, as shown in Figs.4—6.

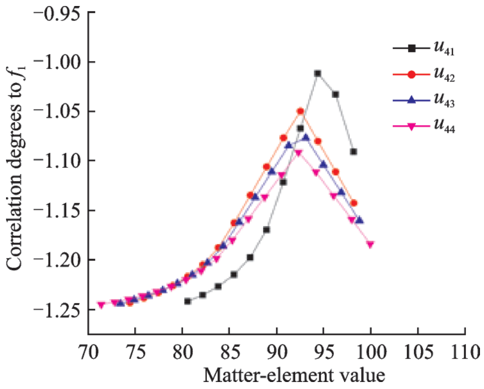

Fig.2 Correlation degrees of flight safety to f_1

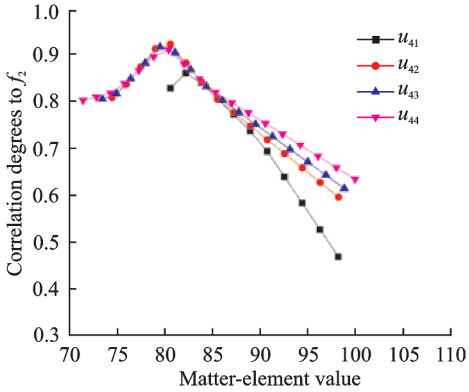

Fig.3 Correlation degrees of flight safety to f_2

Table 6 Initial model parameters

Model order	$a^{(1)}$	$a^{(2)}$	$a^{(3)}$	$a^{(4)}$
Linear	0.557 3	−0.003 3		
Quadratic	0.586 16	−0.011 0	0.000 2	
Cubic	0.567 2	−0.013 0	−0.000 4	−0.018 6

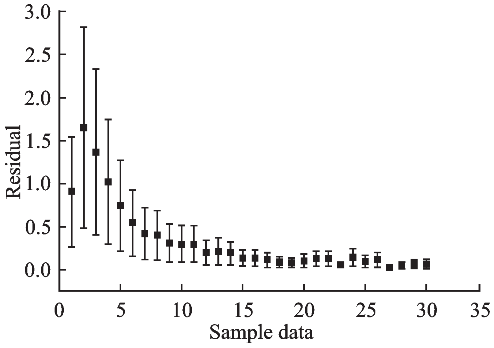

Fig.4 Residuals of linear prediction model

By comparing the residual values of prediction models, it is found that the residual got by the cubic prediction model is the smallest, about 0.039 194 26 (the residual mean of the last 15 samples). Therefore, the prediction model of flight safety system security situation is defined as

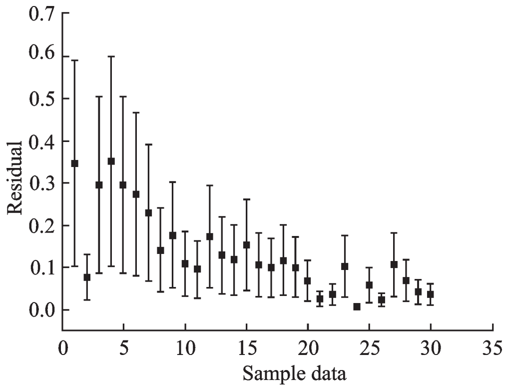

Fig.5 Residuals of quadratic prediction model

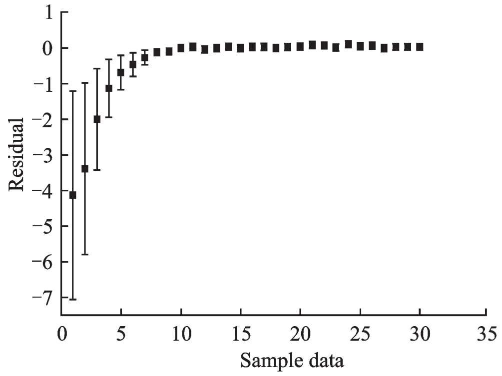

Fig.6 Residuals of cubic prediction model

$$y = a_t^{(4)} x^3 + a_t^{(3)} x^2 + a_t^{(2)} x + a_t^{(1)} + \delta \tag{15}$$

where t is the time, δ the residual value, and $\delta = 0.039\ 194\ 26$.

The parameters of each time period are simulated by Kalman filter algorithm, as shown in Table 7. The system parameters in corresponding period are found to make short-term prediction.

Table 7 Cubic prediction model system parameters

t	$a^{(1)}$	$a^{(2)}$	$a^{(3)}$	$a^{(4)}$
1	0.567 2	−0.013 0	−0.000 4	−0.018 6
2	0.603 4	−0.012 8	0.001 730	−0.014 4
3	0.635 0	−0.013 3	−0.025 4	−0.011
4	0.655 1	−0.012 7	0.026 454	−0.008 7
5	0.672 4	−0.012 9	−0.024 34	−0.006 8
6	0.694 0	−0.013 1	0.018 129	−0.004 8
7	0.720 4	−0.013 6	−0.015 49	−0.002 6
8	0.735 0	−0.013 3	0.011 041	−0.001 4
9	0.751 74	−0.013 4	−0.008 44	−1.1788E−04
10	0.761 72	−0.013 20	−0.004 67	5.845 6E−04

This paper selects the time period of August 2015 to January 2016 to predict the security state of flight safety system in February 2016, as shown in

Fig.7

Fig.7 shows that the security status of airline's flight safety system subordinate to class f_2 correlation degree is 0.801 494. Therefore, the airline still needs to strengthen the security management, in particular, human-software influence factors.

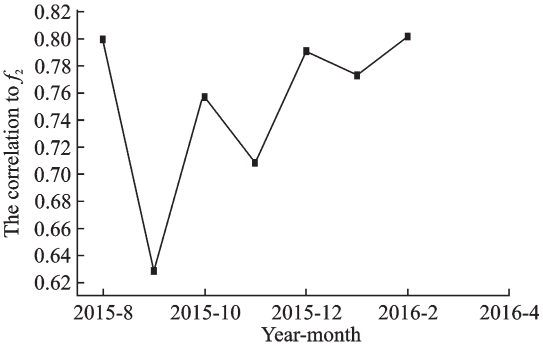

Fig.7 Security state forecast of flight safety system

5 Conclusions

The safety of flight is affected by many uncertain factors such as environmental factors, human factors and equipment factors among which the influence of human factors are most prominent. Therefore, this paper establishes flight safety evaluation index system based on SHELM model, which analyzes the relationship between various uncertain factors and human factors. Flight safety assessment model is established by matter-element theory. It solves the ambiguity of "partial determination, partial uncertainty" among decision-making factors, and correctly reflects the internal relations and changes of matter and quantity. This paper obtains the correlation degrees of four safety levels through analysis and calculation, and the main indexes affected flight safety are judged according to the principle of maximum membership. Under the hypothesis that predictive model order, Kalman filter algorithm is adopted to analyze the optimal short-term prediction of flight security situation, combining the results of assessment. With the results obtained by this method, the security situation of flight safety system could be controlled, and meanwhile the main influence factors of evaluation results are targeted to take protective measures to ensure the flight safety.

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