Study on civil aviation pilots fatigue comprehensive quantitative evaluation system

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Abstract—Purpose **Establish evaluation index system and weight determination of fatigue risk factors of civil aviation pilots. Methods Questionnaires of flight pilots fatigue were issued to 291 pilots of an airline company in China and the influencing factors of pilot fatigue were analyzed by single linear regression method. By means of theoretical analysis, expert survey and issuing questionnaires to civil aviation pilots of all ages, various factors affecting the fatigue risk of civilian pilots were summarized. According to the comprehensive analysis of fatigue influential factors, taking 5 factors as the criterions, a pilot fatigue risk comprehensive valuating index system was established. Then order relation analysis method (G1 method) was used to calculate the weights of indexes. Results According to the established comprehensive evaluation index system, influence factors of pilot fatigue from heavy to light are respectively work factors, sleep factors, environmental factors, psychological factors and physiological factors. Conclusion Comprehensive quantitative evaluation system completes the qualitative and quantitative analysis of flight fatigue, which can be used as the basis for further quantification of fatigue risk.**

Keywords—civil aviation pilots, fatigue, risk evaluation system, comprehensive evaluation, order relation analysis method

I. INTRODUCTION

For ordinary person fatigue may simply be a subjective discomfort of the human body. But for transport airline pilots fatigue is a potential trigger for accidents. Fatigue will weaken the physiological and psychological ability of pilots to a certain extent which leads to decreased alertness, slow reaction, wrong decision and other unsafe behaviors. So fatigue affects the safe operation of flights. According to a British study, about a fifth of pilots experience fatigue in the cockpit[1]. A US survey[2] has found that about 10 per cent of pilots struggle to get regular sleep and rest which puts them at risk of reduced alertness. They may even be drowsy during flight. According to the statistical data of 79 flight accidents of international transport aircraft, some researchers[3] analyzed and concluded that "lack of rest and fatigue" became the second major cause of flight accidents caused by flight personnel factors which accounts for 17.3%. The indirect effects of flight fatigue, such as "distraction, mental state and wrong judgment" should not be underestimated which accounts for 14.8% of the total causes.

Fatigue not only reduces the physical and mental strength of flight personnel, but also affects their ability to concentrate, process information and make decisions. To some extent pilots also experience impaired memory, long reaction times, depression and other bodily functions. Fatigue has a negative impact on teamwork, communication and other aspects, thus affecting flight safety. It is necessary to study the influence factors of flight fatigue. It is of great practical significance to national reputation and social and economic development to prevent and control fatigue risk as much as possible, to find effective measures to alleviate pilot fatigue, to avoid flight accidents caused by fatigue of flight personnel, to reduce the loss of people's lives and property.

At present the methods of identifying and evaluating fatigue at home and abroad include subjective sensory inquiry table[4], physiological parameter testing method[5], biochemistry test, job performance measurement fatigue, etc. Physiological parameter measurement method is often limited by the application of measuring equipment and the measurement method is relatively complex. It is difficult to determine the biochemical test index and measurement may cause certain trauma to the body of the subject. The evaluation method of subjective sensation inquiry is relatively subjective. But combined with relevant principles or methods of statistics it can well reflect the fatigue of the subjects.

Most civil aviation managers do not have medical and public health background. How to evaluate the fatigue risk of civil aviation pilots in a quick, convenient and effective way, how to establish a scientific evaluation index system and put forward a set of practical and simple evaluation methods are the key problems in the evaluation of fatigue risk of civil aviation pilots.

II. OBJECTS AND METHODS

A. Objects

By adopting cluster sampling civil aviation pilots of a domestic airline company were randomly selected as survey objects and self-test questionnaires were issued. The methods of self-report and investigator inquiry were adopted to conduct questionnaire survey on the research objects. In the introduction to the questionnaire the purpose and significance of the survey are explained in detail and the nature of the survey is voluntary participation. A total of 308 questionnaires were collected, among which 17 questionnaires were seriously missing, so 291 valid questionnaires were obtained for analysis.

B. Methods

- Pilot fatigue questionnaire and regression analysis

If there is a linear correlation between the dependent variable Y and the independent variable X, that is to say, for a certain value of the independent variable X, the value of the dependent variable Y is not unique. There are many possible values which are distributed above and below a line. Because Y is also affected by other factors besides the independent variable. The magnitude and direction of the influence of these factors are uncertain and are usually expressed by a random variable, also known as the random disturbance term. Therefore, the dependence between Y and X can be expressed as

$$y_i=\alpha+\beta x_i+\mathcal{E}_i \tag{1}$$

$$\hat{y}=a+bx_i \tag{2}$$

$$\begin{cases} b=\dfrac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sum(x_i-\bar{x})^2}=\dfrac{n\sum x_i y_i-\sum x_i\sum y_i}{n\sum x_i^2-\left(\sum x_i\right)^2} \\ a=\dfrac{\sum y_i}{n}-b\times\dfrac{\sum x_i}{n}=\bar{y}-b\bar{x} \end{cases} \tag{3}$$

- Order relation analysis

26 occupational disease prevention and control experts, safety managers, human factors researchers and senior civil aviation pilots were invited to conduct questionnaire survey. Solicit and refine the opinions of expert groups. Screen and verify the factors that may induce the fatigue risk of civil aviation pilots. Order relation analysis (G1) was used to determine the weight of each evaluation index. In order to facilitate calculation, the second layer of sub-factors of civil aviation pilots fatigue risk index was graded and quantified. According to the established risk assessment system model of civil aviation pilots' fatigue, the index score of civil aviation pilots' fatigue risk can be calculated according to the index system by developing self-assessment questionnaire and using the weight value of the calculated indexes. Determine the value range of fatigue risk of civil aviation pilots by statistical analysis. Finally, we finished the comprehensive quantitative evaluation which can provide data support for the realization of civil aviation pilot fatigue risk management.

- Rationale for risk assessment

There are many factors that affect fatigue. It is fuzzy and difficult to quantify these factors. So we used order relation analysis method (G1 method) to assign weights to the indexes and then applied fuzzy relation synthesis principle to make multi-level fuzzy evaluation on the membership degree of fatigue risk. Order relation analysis method G1 is an improved method of AHP method proposed by professor Yajun Guo of Northeastern University[8] . It overcomes the defect of AHP method. Each step of the method fully reflects the expert's wishes. The method is simple and practical with clear and definite process. There is no need to judge the matrix and no need to conduct consistency test.

- Definite order relation

If the importance of evaluation index x_i relative to an evaluation criterion is greater than x_j, then it can be denoted as:

$$x_i>x_j \tag{4}$$

From the evaluation index set { x_1, x_2, …, x_m }, experts select one of the most important indicators and mark it as:

$$x_1>x_2>x_3>x_4\ldots>x_m \tag{5}$$

TABLE I. R_K ASSIGNMENT TABLE

r_k	Degree of importance
1.0	x_{k-1} is just as important as x_k
1.2	x_{k-1} is slightly more important than x_k
1.4	x_{k-1} is more important than the x_k
1.6	x_{k-1} is significantly more important than x_k
1.8	x_{k-1} is extremely important than x_k

- Relative importance

For some problems it is not enough to give order relations. We also need to determine the weight coefficient of the evaluation index to a certain evaluation criterion and judge the relative importance of x_{k-1} to x_k.

The ratio of importance is adopted to represent the experts' comparative judgment on the relative importance between adjacent indexes x_{k-1} and x_k:

$$r_k=\omega_{k-1}\ \omega_k^{-1}(k=m, m\text{-}1, m\text{-}2, \ldots 3, 2) \tag{6}$$

- Weight coefficient

If the r_k rational assignment given by experts (or decision makers) meets the requirements in table I, then ω_k is:

$$\omega_m=\left[1+\sum_{k=2}^{m}\prod_{i=k}^{m}r_i\right]^{-1} \tag{7}$$

$$\omega_{k-1}=r_k\omega_k \tag{8}$$

III. RESULTS

A. Regression analysis of pilot questionnaire fatigue influencing factors

There are many factors affecting pilot fatigue and the interaction mechanism is complex. In order to summarize the factors affecting pilot fatigue from the perspective of the system, by referring to domestic and foreign literatures, we compiled and issued questionnaires to pilots to summarize the factors that may lead to pilot fatigue, as shown in table II. SPSS statistical software was used to analyze the correlation between flight fatigue influencing data and explore the linear regression coefficient between important variables.

There was a positive correlation between physical fatigue, mental fatigue and sleep quality and no correlation with age. Sleep quality is slightly more correlated with physical fatigue than with mental fatigue. There were no significant differences in fatigue and sleep quality between the captain and co-pilot. The total flight time was not significantly correlated with physical fatigue, mental fatigue and sleep quality. There was no significant correlation between fatigue

and sleep quality on European routes. North American routes, Oceania routes and southeast Asian routes show a small negative correlation with physical fatigue which may be related to scheduling and flight management. There was no significant correlation between domestic flight and physical fatigue and sleep quality.

TABLE II. STATISTICAL TABLE OF THE SURVEY RESULTS OF PILOT FATIGUE INFLUENCING FACTORS (PERCENTAGE)

Fatigue influencing factor	No	Mild	Moderate	Severe	Very serious
(1)High frequency take-off and landing times	23.21%	42.04%	25.78%	8.35%	0.62%
(2)The flight duty period is long and the flight hours are long	5.92%	27.23%	37.88%	21.35%	7.62%
(3)Irregular schedules	3.94%	14.21%	30.59%	26.38%	24.88%
(4)High attendance rate	9.74%	26.25%	31.35%	20.88%	11.78%
(5)Short rest time	4.12%	22.35%	29.68%	28.46%	15.39%
(6)Influence of flight environment	8.32%	33.33%	34.54%	13.36%	10.45%
(7)Family environment and friendship	25.32%	50.92%	18.38%	4.09%	1.29%
(8)The influence of bad weather	13.82%	44.42%	30.55%	9.24%	1.97%
(9) The impact of flight delays	8.43%	37.12%	31.62%	15.28%	7.55%
(10) Physiological trough work	21.55%	46.21%	22.83%	4.87%	4.54%
(11)Arrange other work during rest period	9.67%	33.82%	30.59%	15.26%	10.66%
(12)Plateau route	62.32%	23.39%	10.54%	3.58%	0.17%
(13)Take off and land too early or too late	4.88%	20.31%	27.49%	27.21%	20.11%
(14) Poor sleep environment on long flight	28.36%	26.88%	24.53%	11.28%	8.95%
(15)Many overnight days	11.53%	32.28%	30.15%	13.26%	12.78%
(16)Poor sleeping environment overnight	12.42%	36.63%	33.82%	10.18%	6.95%

B. Pilot fatigue risk evaluation index system

Above questionnaire has its limitations, such as the choice of the public and the strong subjectivity of individuals which will affect the results of the questionnaire. On the basis of the questionnaire we searched for relevant information, compiled the expert questionnaire according to the theoretical knowledge of fatigue and the actual working characteristics of pilots.

26 occupational disease prevention and control experts, safety management personnel, human factors researchers and senior pilots were invited to conduct questionnaire survey. We solicit and extract expert group opinions. Then screen and verify the factors that may induce pilot fatigue. The pilot fatigue risk evaluation index system was established considering work factors, physiological factors, sleep factors, psychological factors and environmental factors.

C. Determine the index weight of pilot fatigue evaluation index system

According to the above-mentioned evaluation index system of fatigue risk of civil aviation pilots, expert consultation questionnaire was developed. Experts were invited to sort each layer of indicators first and then gave the importance evaluation between two indicators. We consulted a total of 26 experts, 25 of whom answered the questionnaires effectively. According to the ranking and importance comparison of indicators of each layer by experts, G1 method was adopted to determine the weights of indicators of each layer. Table III shows the calculation results of the weights of secondary and tertiary factors.

TABLE III. INDEX WEIGHT TABLE OF OCCUPATIONAL STRESS RISK ASSESSMENT OF CIVIL AVIATION PILOTS

Second indicators	Third indicators	Index weight
Work factor 0.3382	x1 Continuous working hours	0.2083
	x2 Attendance rate	0.1889
	x3 Number of landing	0.1519
	x4 Degree of work and rest regularity	0.1246
	x5 Work at a physiological trough	0.0922
	x6 Takeoff and landing time	0.0753
	x7 Flight route	0.0622
	x8 Station	0.0515
	x9 Sleepover days	0.0451
Physiological factors 0.1150	x1 Age	0.3731
	x2 BMI	0.2649
	x3 Chronic disease	0.2017
	x4 Exercising habit	0.1603
Sleep factors 0.2368	x1 Actual hours of sleep per night	0.3852
	x2 Coughing or snoring loudly	0.1352
	x3 Difficulty falling asleep	0.1523
	x4 Easy to wake up at night or early	0.3273
Psychological factors 0.1333	x1 Interpersonal relationship	0.3177
	x2 Work stress	0.2688
	x3 Emotional control ability	0.2168
	x4 Personal responsibility	0.1967
Environmental factors 0.1767	x1 Adverse weather	0.2686
	x2 Flight delay	0.1971
	x3 flight environment	0.1686
	x4 Overseas hotel environment	0.3657

D. Evaluation index model of fatigue risk of civil aviation pilots

In order to facilitate calculation, the indexes of the second layer of factors were graded and quantified and were divided into four grades (0 to 3). Each fatigue index corresponded to different levels of fatigue and the grading results were shown in table IV.

According to the risk evaluation index system of fatigue of civil aviation pilots established above, the self-test questionnaire of fatigue of civil aviation pilots was developed. Then we issued self-test questionnaire to civil aviation pilots of an airline company of CAAC. A total of levels of fatigue were stratified according to the results of the Fatigue Scale-14 questionnaire. There are 12 persons without fatigue(4.12%), 54 persons with mild fatigue (18.56%), 124 persons with moderate fatigue (42.61%) and 101 persons with high fatigue (34.71%). The fatigue classification intervals can be divided by sorting the 291 calculated pilots' fatigue index and combining with the proportion of the number of people whose fatigue degree has been calculated.

The results are shown in table V.

TABLE IV. CORRESPONDING TABLE OF FATIGUE DEGREE OF CIVIL AVIATION PILOTS

Risk indicator	Degree of stress
3	High fatigue
2	Moderate fatigue
1	Mild fatigue
0	Without fatigue

TABLE V. RESULTS OF PILOT FATIGUE INTERVAL DIVISION

Degree of fatigue	High fatigue	Moderate fatigue	Mild fatigue	Without fatigue
Fatigue indicator	[2.6571,3)	[1.3692,2.6571)	[0.2538,1.3692)	[0,0.2538)

IV. CONCLUSION

The international civil aviation organization (ICAO) defines flight fatigue[9] as "A physiological state in which the ability to perform mental or physical activities is reduced by lack of sleep, prolonged wakefulness, disturbance of circadian rhythms or excessive work load (mental and/or physical activity). This state impairs the alertness of the crew and their ability to safely operate the aircraft or perform safety-related duties." In this study, the fatigue risk evaluation index system of civil aviation pilots was established from five aspects: work factor, physiological factor, sleep factor, psychological factor and environmental factor. According to the G1 method, we determined the weight of each index and establishment of an effective fatigue risk assessment model for civil aviation pilots by issuing questionnaires.

The results of this study showed that among the five secondary factors, the influence factors of pilot fatigue from heavy to light was respectively the work factor, sleep factor, environmental factor, psychological factor and physiological factor.

Workload is the most important factor leading to pilot fatigue. This study shows that the most important factors affecting pilot fatigue are continuous working time, monthly attendance rate, take-off and landing frequency, work and rest regularity and physiological trough work. Fatigue caused by long periods on duty is widely accepted. NASA found that fatigue is related to the physiological rhythm of human body[10]. During a long flight the internal clock is out of sync with the outside world because pilots often fly across time zones. The body clock doesn't have enough time to adjust to its destination time zone. In addition, the long working hours combined with 1-2 days of stopovers create a different work/rest cycle from the usual one, resulting in pilot fatigue. The largest part of the flight task is focused on take-off and landing. During this stage, the program to complete the action is more and physical strength is a big load to the pilot. The pilot pressure is bigger during these periods. Thus the number of ups and downs is related to pilot fatigue degree directly.

Sleep is the second leading cause of pilot fatigue. Sleep is a basic physiological need of human. People normally need about eight hours of sleep every day and night. Studies[11] have shown that fatigue caused by 17 hours of non-sleep is equivalent to a blood alcohol level of 0.05%. In other words sleeping less than four hours a night decreases muscle speed and alertness. If stay awake for more than 20 hours the tendency to sleep becomes almost irresistible. Flight crew members have to cope with rapid time zone changes when flying across time zones. They can't sleep at night and want to sleep during the day. Pilots who fly at night have to break their sleep habits. This will lead to the disruption of biological rhythms and sleep loss. Sleep apnea syndrome and poor sleep quality due to poor sleep environment are also important causes of pilot fatigue.

The third major factor affecting pilot fatigue is environmental factors. Some environmental factors cause fatigue by increasing mental load while others cause fatigue by affecting pilots' sleep and psychology. Flying is a "weather - depending" job. Whether the weather is good or bad directly affects the normal or not of flight and how much energy the pilot pays. Flight delay is a common phenomenon in the current high saturation operating environment which directly increases the pilot's duty time and workload. The environment of a foreign hotel directly affects the sleep quality of pilots. After large transport aircraft move into "autonomous flight" mode for long distances there are "repetitive low sensory stimulation", "narrow vision", "limited physical activity", "little interaction" and "moderate cockpit temperature and low brightness lights" and other factors in the cockpit. After long hours in such a "monotonous" environment the pilots' heart rates slowly dropped by about 30 percent according to the Electrocardiography. Pilots have undetectable fatigue and decreased vigilance. They are easy to fall asleep.

Positive emotions can increase endurance and reduce fatigue. People's emotions are influenced by their work environment and workload as well as their ability to regulate themselves. The overly serious cockpit atmosphere, anxious mood of flight delay, complicated air route weather and the heavy workload in the take-off and landing stage all increase the fatigue of the flight staff which affect the flight operation. But the harmonious interpersonal relationship, the harmonious team atmosphere, the good self-control ability, the strong individual responsibility, the positive work mentality are helpful to reduce the fatigue.

The results show that the fatigue risk level of pilots can be quantitatively determined by this model. This model can quickly and effectively realize the self-evaluation of pilot fatigue comprehensive condition, thus providing reliable reference and basis for relevant units to make reasonable work plans, reduce work load and improve convalescence and health care system.

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