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Probability Distribution of China Aviation Network Average Degree of Edge Vertices and Its Evolutionary Trace Based on Complex Network

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Abstract: In order to reveal the complex network characteristics and evolution principle of China aviation network, the probability distribution and evolution trace of average degree of edge vertices of China aviation network were studied based on the statistics data of China civil aviation network in 1988, 1994, 2001, 2008 and 2015. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. Based on the statistical data, the average degrees of edge vertices in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method and regression analysis approach, it was found that the average degree of edge vertices had the probability distribution of normal function and the position parameters and scale parameters of the probability distribution had linear evolution trace.

Key words: Complex network, China aviation network, average degree of edge vertices, normal distribution, linear evolution trace.

1. Introduction

Aviation network is typical complex network with small world characters [1, 2]. The nodes of the network have multiple parameters such as degree, clustering coefficient, and average path length, which can be used as the basis for studying the characteristics of nodes, but the number of edges of the network is not only far greater than the number of nodes, but also the study of edge characteristics is more difficult to start for the network without edge weights. Here, the average degree of the edge vertices was used to describe the features of the edge, and the degree of the two vertices of the edge was used as the mean obtained by the arithmetic average as the relevant parameters to describe the edge, which was used as the basis for studying the properties of the edge. The node degree of China aviation network has the probability distribution characteristics of power function [3], but the probability distribution of the average degree of edge vertices needs to be obtained after calculation and analysis. This paper faces to the aviation network of China through analyzing the passenger data [4] of civil aviation airlines in year 1988, 1994, 2001, 2008 and 2015 to reveal the complex network feature. According to complex network theory, network system of airports and airlines of China was constructed with airports regarded as nodes and airline regarded as edges to study the probability distribution of average degree of edge vertices and its evolution trace of aviation network of China. Based on the statistical data, the average degrees of edge vertices in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method and regression analysis approach, it was found that the average degree of edge vertices had the probability distribution of normal function and the

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position parameters and scale parameters of the probability distribution had linear evolution trace.

2. Probability Distribution of Average Degree of Edge Vertices of China Aviation Network

For network $G=(V,E)$, where $v_i \in V$ is the node of G. V is the set of nodes. E is the set of edges [5], $(v_i,v_j)\in E$. Matrix $A=(a_{i,j})_{n\times n}$ was constructed, where:

$$a_{i,j}=\begin{cases}1,(v_i,v_j)\in E\\ 0, otherwise\end{cases} \tag{1}$$

Matrix A was called adjacent matrix of network G. The degree of node v_i was defined as the number of edges connected to v_i. The average degree of edge vertices is defined as following:

$$D_{i,j}^{EVA}=\frac{1}{2}(k_i+k_j) \tag{2}$$

In Eq. (2): k_i is the degree of node v_i; k_j is the degree of other nodes v_j; $(v_i,v_j)\in E$.

2.1 Probability Distribution of Average Degree of Edge Vertices in China Aviation Network in 1988

The adjacent matrix A_{1988} was gotten from statistic data [4]. The average degrees of edge vertices D_n^{EVA} ($n=1,2,3,\ldots\ldots,265$) of 265 edges in 1988 were gotten from A_{1988} and Eq. (2). The data in Table 1 were done statistics by these data according to the interval in Table 1. The scattered points in Fig. 1 were drawn by the data in Table 1. It was similar to normal distribution function by observation. Let the quantity of edges be N, the quantity of interval be m, the spacing of interval i be δ, the times of appearance in interval i be k_i, the frequency of appearance in interval i be q_i, the probability of appearance at median point in interval i be p_i. Here $N_{1988}^{E}=265$, $m_{1988}=5$, δ_{1988}=8. It could be known from the probability density function of normal distribution [6] in Table 1 and Fig. 1:

$$q_i=\frac{k_i}{N_{1988}^{E}},\sum_{i=1}^{m_{1988}}q_i=1 \tag{3}$$

$$q_i=p_i\delta_{1988}\Rightarrow p_i=\frac{q_i}{\delta_{1988}},\sum_{i=1}^{m_{1988}}p_i=\frac{1}{\delta_{1988}} \tag{4}$$

Table 1 Probability distribution of China aviation network average degree of edge vertices in 1988.

Interval	[2, 10]	(10, 18]	(18, 26]	(26,34]	(34, 42]
Median	6	14	22	30	38
Times	62	80	92	27	4
Frequency	0.234	0.3019	0.3471	0.1019	0.0151
Probability	0.0292	0.0377	0.0434	0.0127	0.019

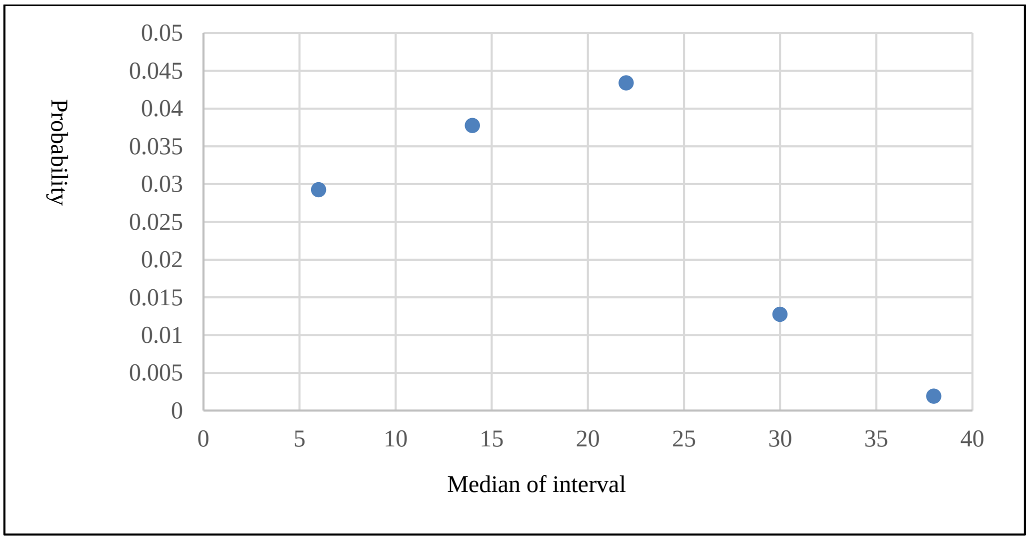

Fig. 1 Probability distribution diagram of China aviation network average degree of edge vertices in 1988.

The normal distribution function is $N(\mu,\sigma)$, μ is the location parameter, σ is the scale parameter, its probability density function is $f(x)$.

$$f(x)=\frac{1}{\sqrt{2\pi}\sigma}e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{5}$$

It could be gotten from the statistical properties of normal distribution [6]:

$$\hat{\mu}_{1988}=\frac{1}{N_{1988}^{E}}\sum_{i=1}^{N_{1988}^{E}}x_i=17.2 \tag{6}$$

$$\hat{\sigma}_{1988}=\sqrt{\frac{1}{N_{1988}^{E}-1}\sum_{i=1}^{N_{1988}^{E}}(x_i-\overline{x})^2}=7.95 \tag{7}$$

Let $\hat{\mu}_{1988}$ and $\hat{\sigma}_{1988}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{1988}=0.05e^{-0.0079(x-17.2)^2} \tag{8}$$

The fitting curve (Eq. (8)) and sample points $p_{i,1988}$ were drawn in Fig. 2 with good fitting effect.

To take $\varepsilon_{i,1988}$ (i = 1, 2, 3, 4, 5) as residual to investigate the degree of approximation of fitting through the residual distribution [6]:

$$\varepsilon_{i,1988}=p_{i,1988}-\hat{y}_{i,1988} \tag{9}$$

The residual $\varepsilon_{i,1988}$ was drawn in Fig. 3. All points in Fig. 3 were random fluctuation around $\varepsilon=0$ and the range of fluctuation was very small. $|\varepsilon_{i,1988}|<0.011<\hat{\sigma}_{1988}=7.95$. This illustrated that the fitting effect was very good.

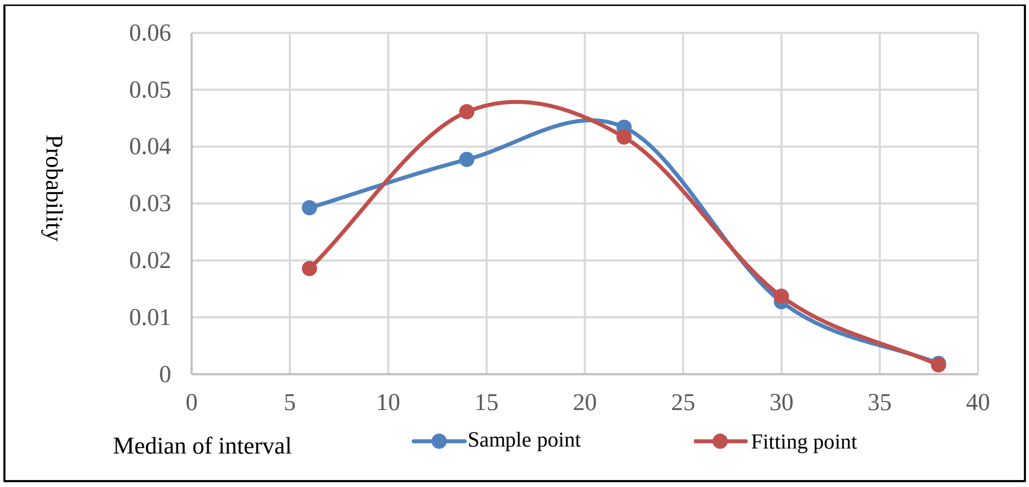

Fig. 2 Fitting effect diagram of probability distribution of average degree of edge vertices in 1988.

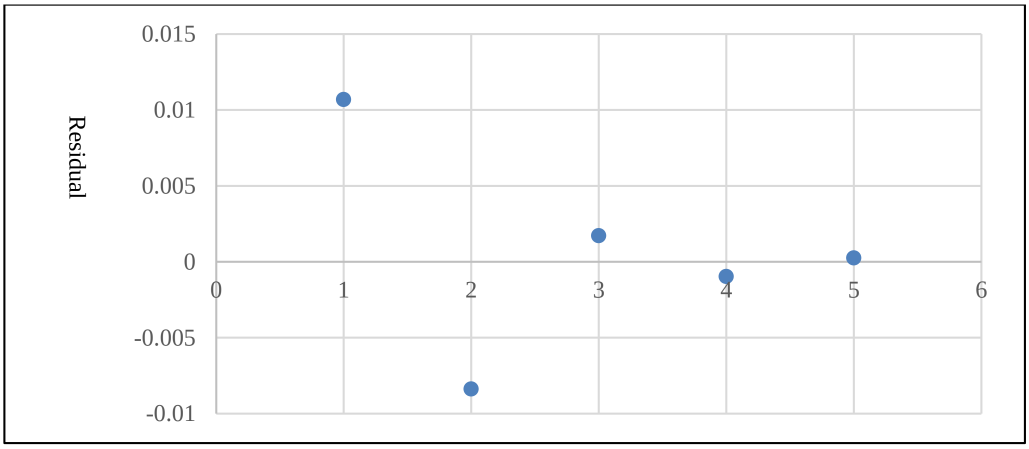

Fig. 3 Residual diagram of fitting curve of probability distribution of average degree of edge vertices in 1988.

2.2 Probability Distribution of Average Degree of Edge Vertices of China Aviation Network in 1994

The adjacent matrix A_{1994} was gotten from statistic data. The average degrees of edge vertices D_n^{EVA} ($n=1,2,3,......,589$) of 589 edges in 1994 were gotten from A_{1994} and Eq. (2). The data in Table 2 were done statistics by these data according to the interval in Table 2. The scattered points Fig. 4 were drawn by the data in Table 2. It was similar to normal distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Section (2.1). Here, $N_{1994}^E=589$, $m_{1994}=5$, $\delta_{1994}=12.7$. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{1994}=\frac{1}{N_{1994}^E}\sum_{i=1}^{N_{1994}^E}x_i=27.64 \tag{10}$$

$$\hat{\sigma}_{1994}=\sqrt{\frac{1}{N_{1994}^E-1}\sum_{i=1}^{N_{1994}^E}(x_i-\bar{x})^2}=10.8 \tag{11}$$

Let $\hat{\mu}_{1994}$ and $\hat{\sigma}_{1994}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{1994}=0.037e^{-0.0043(x-27.64)^2} \tag{12}$$

The fitting curve (Eq. (12)) and sample points $p_{i,1994}$ were drawn in Fig. 5 with good fitting effect.

To take $\varepsilon_{i,1994}$ (i = 1, 2, 3, 4, 5) as residual to investigate the degree of approximation of fitting through the residual distribution [7]:

$$\varepsilon_{i,1994}=p_{i,1994}-\hat{y}_{i,1994} \tag{13}$$

The residual $\varepsilon_{i,1994}$ was drawn in Fig. 6. All points in Fig. 6 were random fluctuation around $\varepsilon=0$ and the range of fluctuation was very small. $|\varepsilon_{i,1994}|<0.001<\hat{\sigma}_{1994}=10.8$. This illustrated that the fitting effect was very good.

2.3 Probability Distribution of Average Degree of Edge Vertices of China Aviation Network in 2001

The adjacent matrix A_{2001} was gotten from statistic data. The average degrees of edge vertices D_n^{EVA} ($n=1,2,3,......,730$) of 730 edges in 2001 were gotten from A_{2001} and Eq. (2). The data in Table 3 were done statistics by these data according to the interval in Table 3. The scattered points in Fig. 7 were drawn by the data in Table 3. It was similar to normal

Table 2 Probability distribution of China aviation network average degree of edge vertices in 1994.

Interval	[1.5, 14.2]	(14.2, 26.9]	(26.9, 39.6]	(39.6, 52.3]	(52.3, 65]
Median	7.85	20.55	33.25	45.95	58.65
Times	55	225	237	61	11
Frequency	0.093	0.382	0.402	0.104	0.019
Probability	0.0074	0.0301	0.0317	0.0082	0.0015

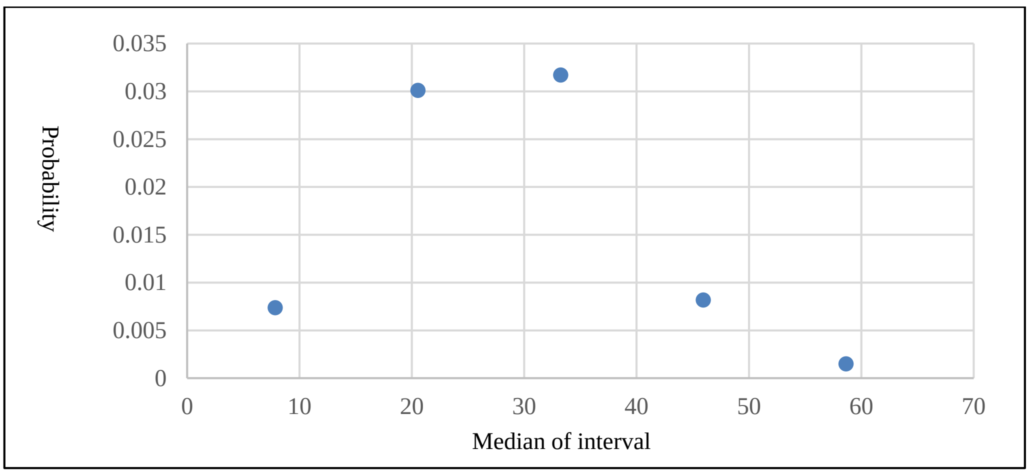

Fig. 4 Probability distribution diagram of China aviation network average degree of edge vertices in 1994.

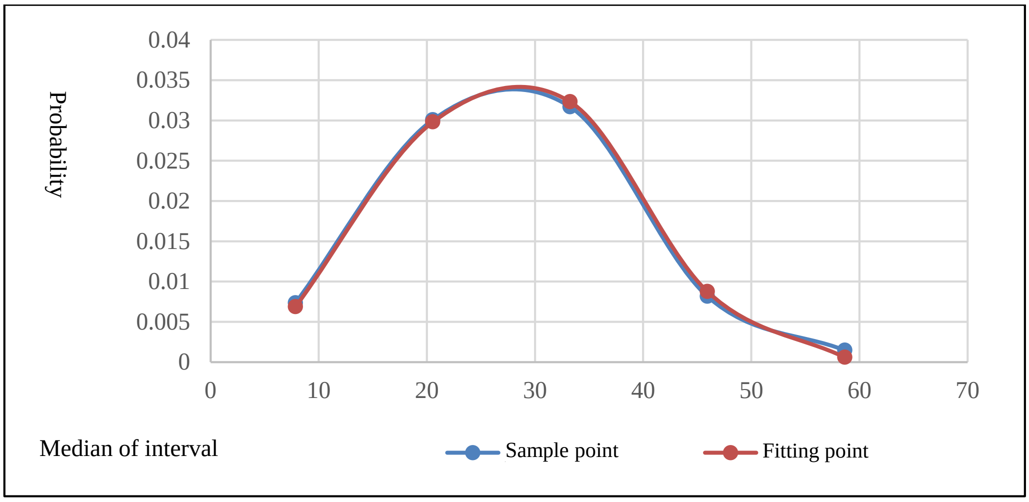

Fig. 5 **Fitting effect diagram of probability distribution of average degree of edge vertices in 1994.**

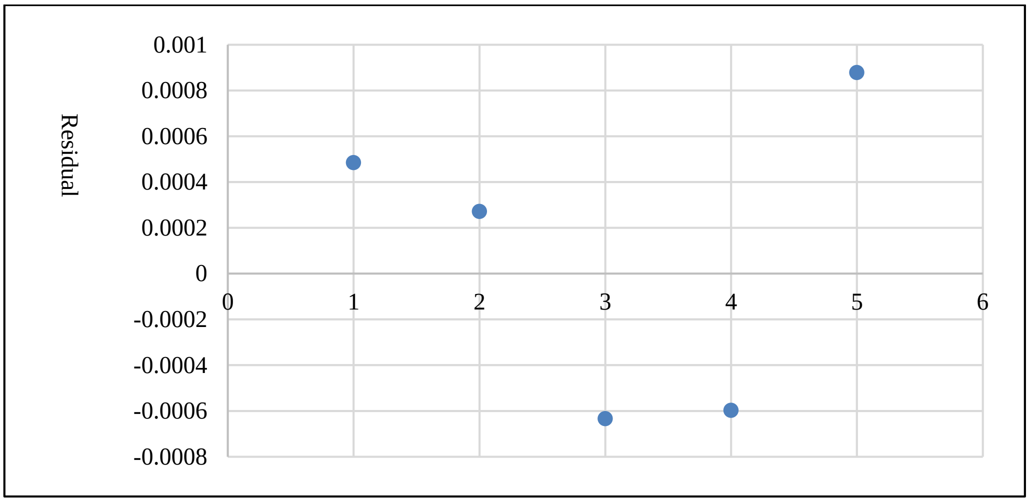

Fig. 6 **Residual diagram of fitting curve of probability distribution of average degree of edge vertices in 1994.**

distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Section 2.1. Here, $N_{2001}^{E}=730$, $m_{2001}=5$, δ_{2001}=14.8 . It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2001}=\frac{1}{N_{2001}^{E}}\sum_{i=1}^{N_{2001}^{E}}x_i=30.66 \tag{14}$$

$$\hat{\sigma}_{2001}=\sqrt{\frac{1}{N_{2001}^{E}-1}\sum_{i=1}^{N_{2001}^{E}}(x_i-\overline{x})^2}=13.8 \tag{15}$$

Table 3 **Probability distribution of China aviation network average degree of edge vertices in 2001.**

Interval	[1.5, 16.3]	(16.3, 31.1]	(31.1, 45.9]	(45.9, 60.7]	(60.7, 75.5]
Median	8.9	23.7	38.5	53.3	68.1
Times	80	321	255	63	11
Frequency	0.1096	0.4397	0.3493	0.0863	0.0151
Probability	0.0074	0.0297	0.0236	0.0058	0.001

Let $\hat{\mu}_{2001}$ and $\hat{\sigma}_{2001}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2001}=0.029e^{-0.0026(x-30.66)^2} \tag{16}$$

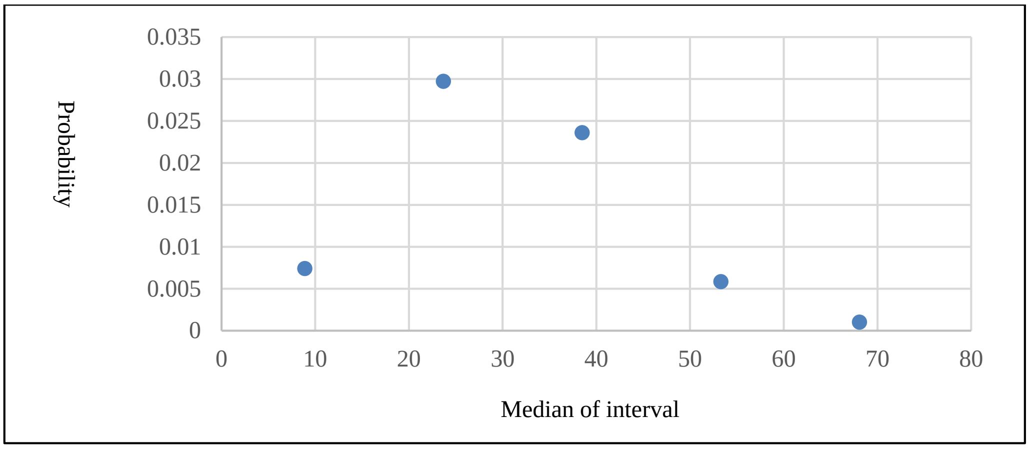

Fig. 7 Probability distribution diagram of China aviation network average degree of edge vertices in 2001.

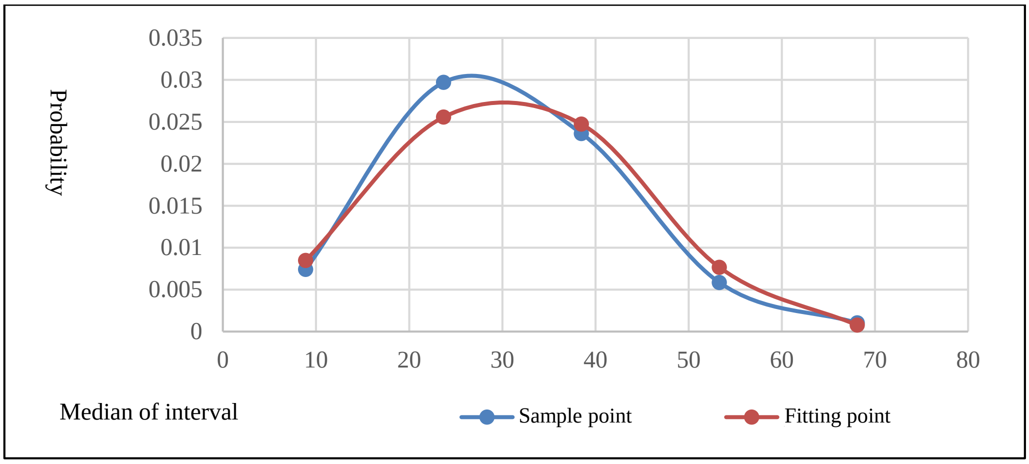

Fig. 8 Fitting effect diagram of probability distribution of average degree of edge vertices in 2001.

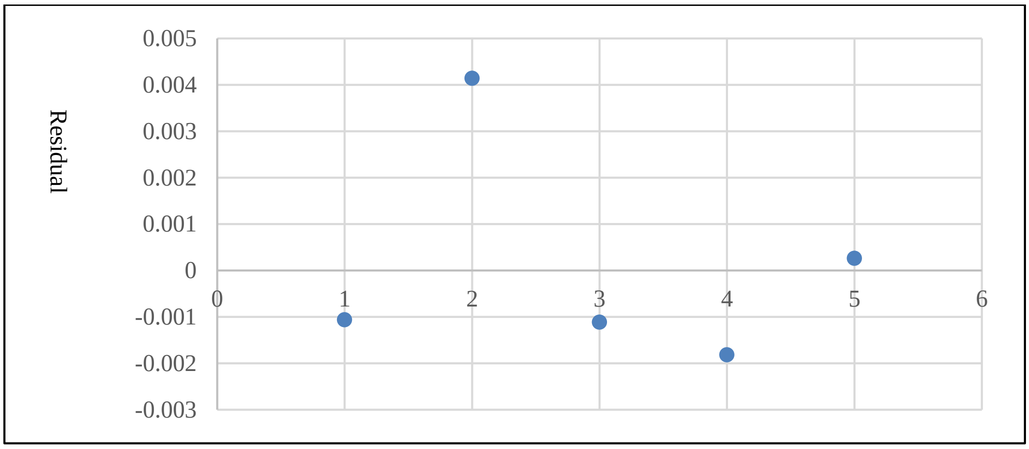

Fig. 9 Residual diagram of fitting curve of probability distribution of average degree of edge vertices in 2001.

The fitting curve (Eq. (16)) and sample points $p_{i,2001}$ were drawn in Fig. 8 with good fitting effect.

To take $\varepsilon_{i,2001}$ (i = 1, 2, 3, 4, 5) as residual to investigate the degree of approximation of fitting through the residual distribution:

$$\varepsilon_{i,2001} = p_{i,2001} - \hat{y}_{i,2001} \tag{17}$$

The residual $\varepsilon_{i,2001}$ was drawn in Fig. 9. All points in Fig. 9 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small.

$|\varepsilon_{i,2001}| < 0.005 < \hat{\sigma}_{2001} = 13.8$. This illustrated that the fitting effect was very good.

2.4 Probability Distribution of Average Degree of Edge Vertices of China Aviation Network in 2008

The adjacent matrix A_{2008} was gotten from statistic data. The average degrees of edge vertices D_n^{EVA} ($n = 1, 2, 3, ..., 940$) of 940 edges in 2008 were gotten from A_{2008} and Eq. (2). The data in Table 4 were done statistics by these data according to the interval in Table 4. The scattered points in Fig. 10 were drawn by the data in Table 4. It was similar to normal distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Section (2.1). Here, $N_{2008}^E = 940$, $m_{2008} = 5$, $\delta_{2008} = 16.8$. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2008} = \frac{1}{N_{2008}^E} \sum_{i=1}^{N_{2008}^E} x_i = 35.9 \qquad (18)$$

$$\hat{\sigma}_{2008} = \sqrt{\frac{1}{N_{2008}^E - 1} \sum_{i=1}^{N_{2008}^E} (x_i - \bar{x})^2} = 13 \qquad (19)$$

Let $\hat{\mu}_{2008}$ and $\hat{\sigma}_{2008}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2008} = 0.031 e^{-0.003(x-35.9)^2} \qquad (20)$$

The fitting curve (Eq. (20)) and sample points $p_{i,2008}$ were drawn in Fig. 11 with good fitting effect.

To take $\varepsilon_{i,2008}$ (i = 1, 2, 3, 4, 5) as residual to investigate the degree of approximation of fitting through the residual distribution:

$$\varepsilon_{i,2008} = p_{i,2008} - \hat{y}_{i,2008} \qquad (21)$$

The residual $\varepsilon_{i,2008}$ was drawn in Fig. 12. All points in Fig. 12 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small. $|\varepsilon_{i,2008}| < 0.0035 < \hat{\sigma}_{2008} = 13$. This illustrated that the fitting effect was very good.

Table 4 Probability distribution of China aviation network average degree of edge vertices in 2008.

Interval	[1.5, 18.3]	(18.3, 35.1]	(35.1, 51.9]	(51.9, 68.7]	(68.7, 85.5]
Median	9.9	26.7	43.5	60.3	77.1
Times	74	404	361	90	11
Frequency	0.0787	0.4299	0.384	0.0957	0.0117
Probability	0.0047	0.0256	0.0229	0.0057	0.0007

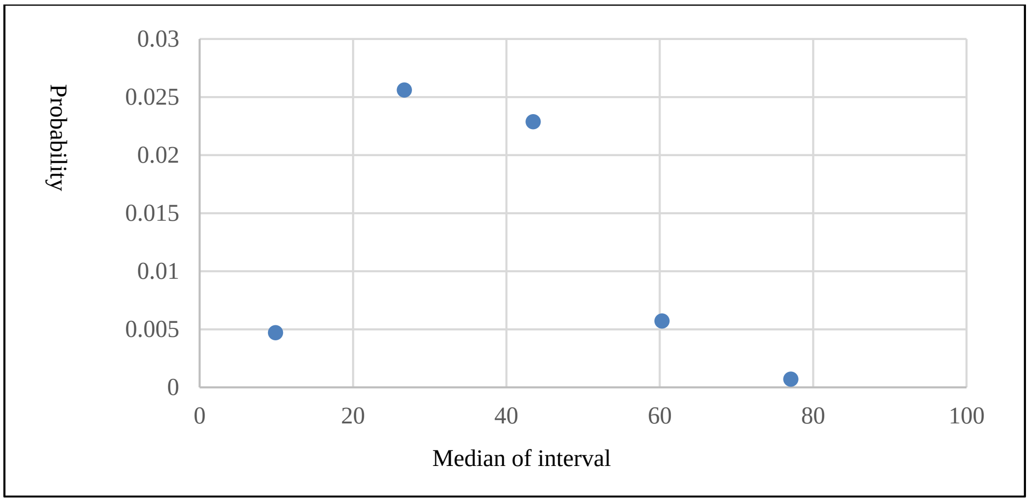

Fig. 10 Probability distribution diagram of China aviation network average degree of edge vertices in 2008.

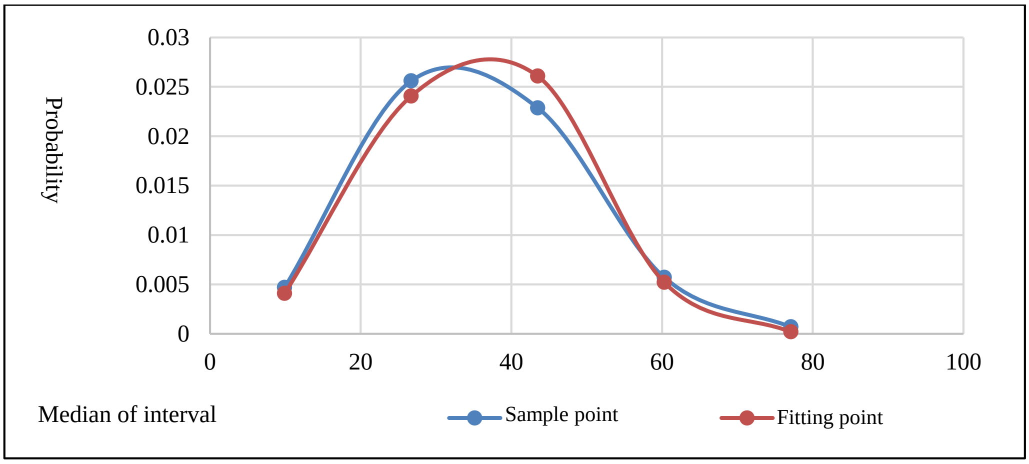

Fig. 11 **Fitting effect diagram of probability distribution of average degree of edge vertices in 2008.**

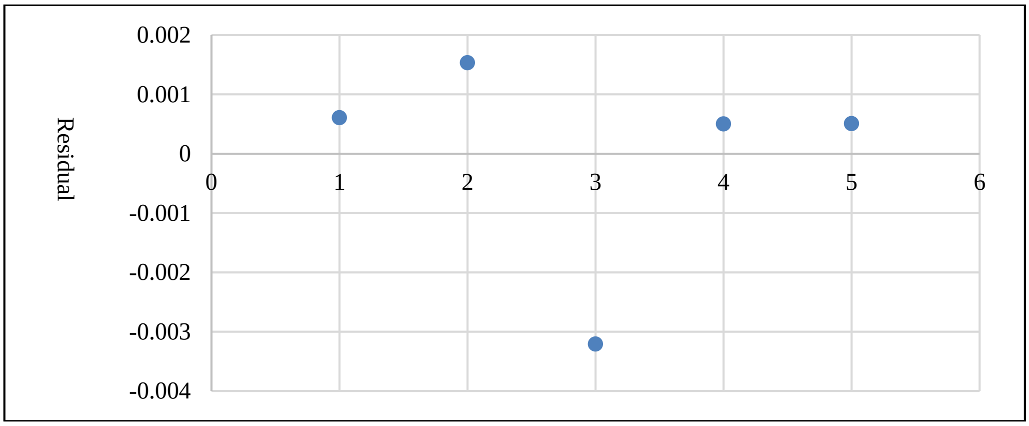

Fig. 12 **Residual diagram of fitting curve of probability distribution of average degree of edge vertices in 2008.**

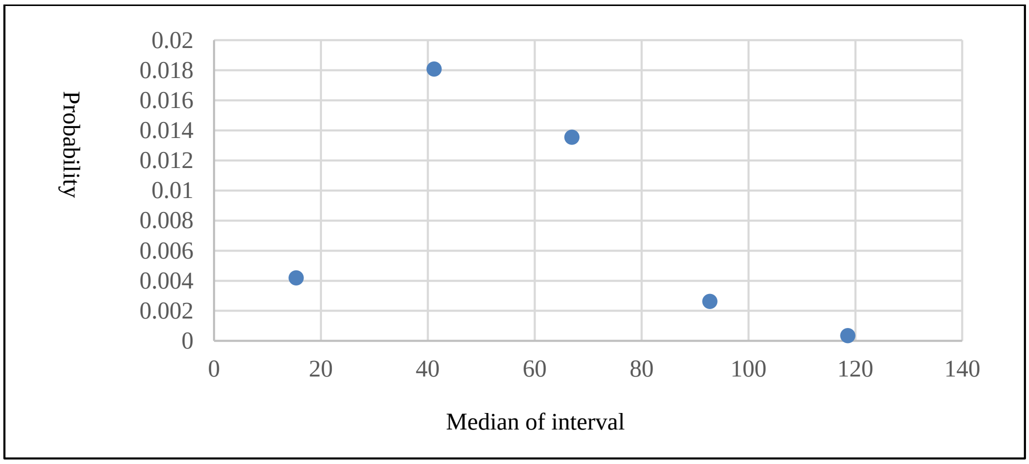

Fig. 13 **Probability distribution diagram of China aviation network average degree of edge vertices in 2015.**

2.5 Probability Distribution of Average Degree of Edge Vertices of China Aviation Network in 2015

The adjacent matrix A_{2015} was gotten from statistic data. The average degrees of edge vertices ($n=1,2,3,\ldots\ldots,1924$) of 1,924 edges in 2015 were gotten from A_{2015} and Eq. (2). The data in Table 5 were done statistics by these data according to the interval in Table 5. The scattered points in Fig. 13 were drawn by the data in Table 5. It was similar to normal distribution function by observation. The definition of

Table 5 Probability distribution of China aviation network average degree of edge vertices in 2015.

Interval	[2.5, 28.3]	(28.3, 54.1]	(54.1, 79.9]	(79.9, 105.7]	(105.7, 131.5]
Median	15.4	41.2	67	92.8	118.6
Times	208	897	672	130	17
Frequency	0.1081	0.4662	0.3493	0.0676	0.0088
Probability	0.0042	0.0181	0.0135	0.0026	0.0003

parameters and relationship of parameters were similar with Eqs. (3) and (4) in Section 2.1. Here, $N^E_{2015}=1924$, $m_{2015}=5$, δ_{2015}=25.8. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2015}=\frac{1}{N^E_{2015}}\sum_{i=1}^{N^E_{2015}}x_i=51.74 \quad (22)$$

$$\hat{\sigma}_{2015}=\sqrt{\frac{1}{N^E_{2015}-1}\sum_{i=1}^{N^E_{2015}}(x_i-\bar{x})^2}=19.7 \quad (23)$$

Let $\hat{\mu}_{2015}$ and $\hat{\sigma}_{2015}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2015}=0.02e^{-0.0013(x-51.74)^2} \quad (24)$$

The fitting curve (Eq. (24)) and sample points $p_{i,2015}$ were drawn in Fig. 14 with good fitting effect. To take $\varepsilon_{i,2015}$ (i = 1, 2, 3, 4, 5) as residual to investigate the degree of approximation of fitting through the residual distribution:

$$\varepsilon_{i,2015}=p_{i,2015}-\hat{y}_{i,2015} \quad (25)$$

The residual $\varepsilon_{i,2015}$ was drawn in Fig. 15. All points in Fig. 15 were random fluctuation around $\varepsilon=0$ and the range of fluctuation was very small. $|\varepsilon_{i,2015}|<0.0015<\hat{\sigma}_{2015}=19.7$ This illustrated that the fitting effect was very good.

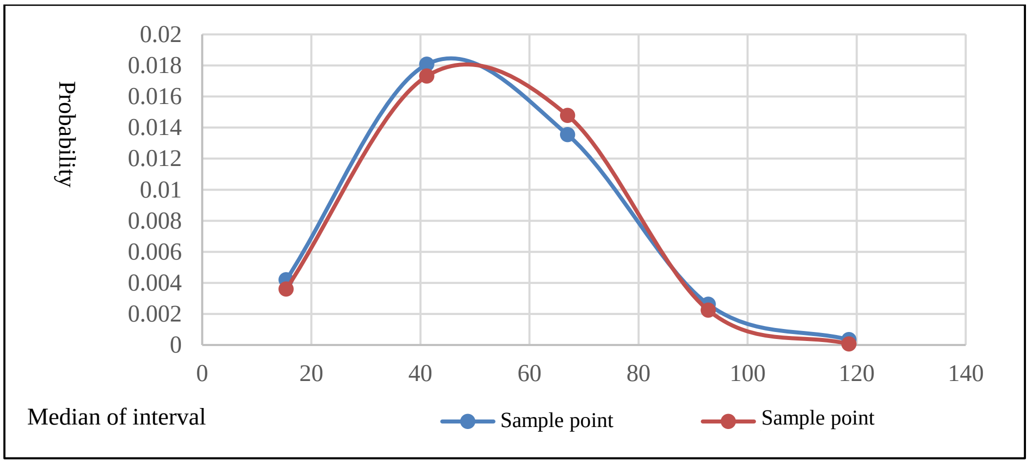

Fig. 14 Fitting effect diagram of probability distribution of average degree of edge vertices in 2015.

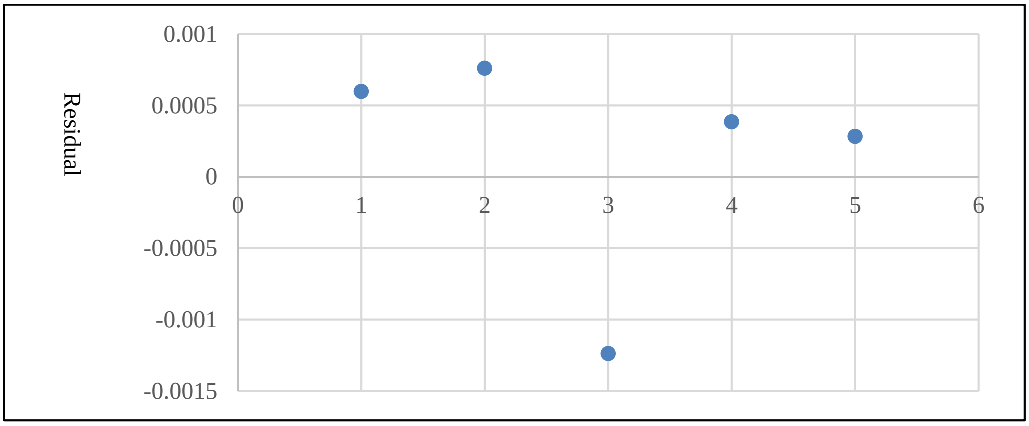

Fig. 15 Residual diagram of fitting curve of probability distribution of average degree of edge vertices in 2015.

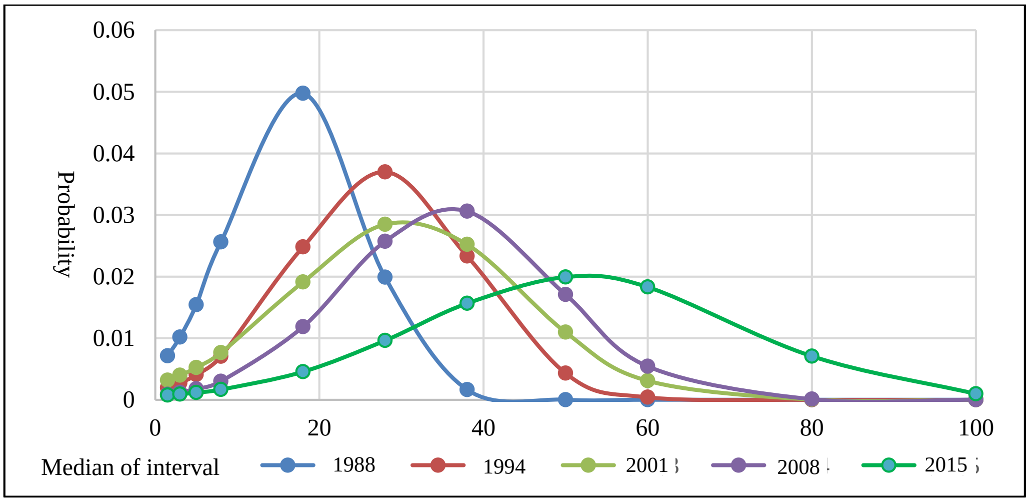

Fig. 16 **The evolution diagram of probability distribution curve of average degree of edge vertices of China aviation network.**

Table 6 **The evolution of probability distribution parameter of average degree of edge vertices of China aviation network.**

Year	1988	1994	2001	2008	2015
Location parameter	17.2	27.64	30.66	35.9	51.74
Scale parameter	7.95	10.8	13.8	13.0	19.7

2.6 Evolution of the Probability Distribution of Average Degree of Edge Vertices of China Aviation Network

The probability distribution parameters of the average degree of edge vertices in China aviation network were listed in Table 6. In order to more intuitively observe the evolution trend of the probability distribution of the average degree of edge vertices, the probability distribution function curves of these five years were plotted in Fig. 16. It could be found that in Fig. 16, the five normal distribution curves from left to right were the probability distributions of 1988, 1994, 2001, 2008 and 2015 respectively. The width of the curve changed from narrow to wide and the peak value of the curve changed from high to low. The change of the position parameter reflected the same situation, that was, the median point of the curve moved to the right and became larger year by year. The change of scale parameters was also the same, that was, the scale parameters increase year by year, and the curve gradually wider. Because the area under the curve was unchanged and all were 1, the peak value became lower.

3. The Evolution Trace of Probability Distribution Parameter of Average Degree of Edge Vertices of China Aviation Network

The evolution trace of probability distribution parameters of average degree of edge vertices in China aviation network was discussed here. Let the location parameter of normal distribution be x. Let the scale parameter of normal distribution be y, to take x as abscissa and y as ordinate. The location parameters and scale parameters in Table 6 were drawn in Fig. 17 as scattered points. The correlation coefficient r of scattered points in Fig. 17 was calculated.

$$r = \frac{L_{xy}}{\sqrt{L_{xx}L_{yy}}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (26)$$

Here, $n = 5$. Using the data in Table 6, the value of correlation coefficient r was calculated, $r = 0.975$. The critical value of $r_{\big|\substack{\alpha=1\% \\ f=3}}$ was 0.959 found in critical value table [7] at degree of freedom $f = n - 2 = 3$ and level of significant α of 1%. Since $|r| = 0.975 > 0.959 = r_{\big|\substack{\alpha=0.01 \\ f=3}}$, the scattered points in Fig. 17 had significant linear correlation. Least square method [7] was used as an approach in Eq. (27) to fit the line with points in Fig. 17.

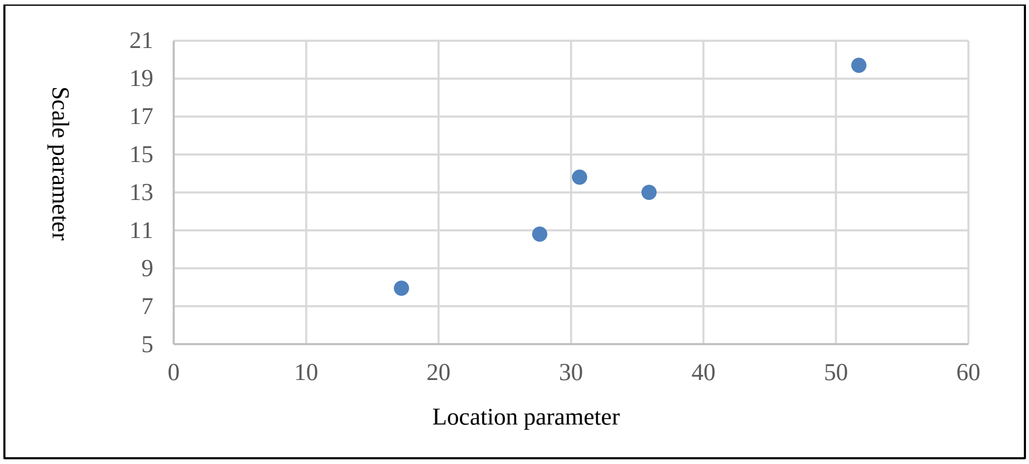

Fig. 17 The scattered points diagram of parameter relationship of probability distribution of average degree of edge vertices.

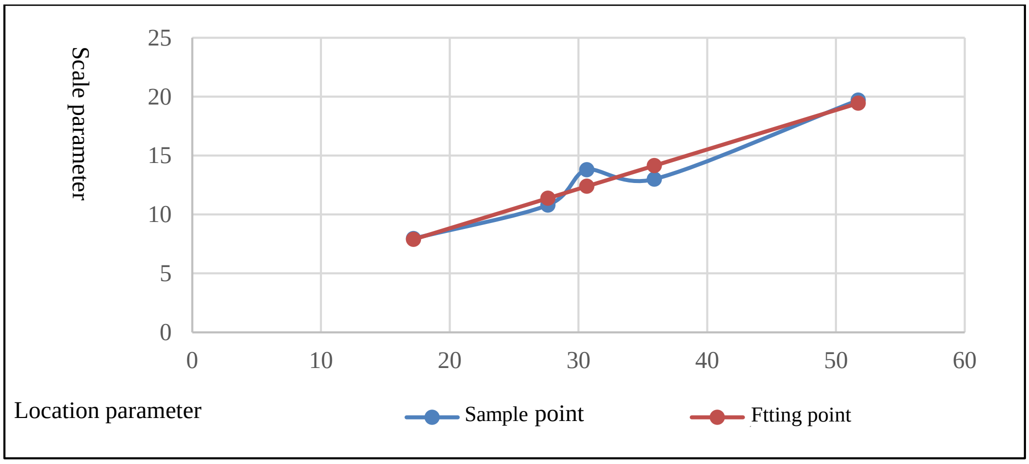

Fig. 18 The fitting effect diagram of linear relationship of probability distribution of nearest neighbor average degree.

$$\begin{cases} \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} = 2.12 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = 0.335 \end{cases} \quad (27)$$

The linear equation:

$$\hat{y} = 2.12 + 0.335x \quad (28)$$

The fitting line (Eq. (28)) was drawn with the sample points in one diagram of Fig. 18 with good fitting effect.

To take t test [7] of Eq. (28), test hypothesis is: $H_0 : \beta_1 = 0$.

When the hypothesis was true, there is:

$$\hat{\beta}_1 \sim N(0, \frac{\sigma^2}{L_{xx}}) \quad (29)$$

Here, $\hat{\beta}_1$ fluctuates near zero, statistic t is build.

$$t = \frac{\hat{\beta}_1}{\sqrt{\dfrac{\hat{\sigma}^2}{L_{xx}}}} = \frac{\hat{\beta}_1 \sqrt{L_{xx}}}{\hat{\sigma}} \quad (30)$$

where:

$$\hat{\sigma}^2 = \frac{1}{n-2} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (31)$$

Statistic t was calculated by data in Table 6 and Eq. (29)-(31): $t = 7.66$.

To check the t distribution table [7], at significant level α of 0.01 and degree of freedom $f = n - 2 = 3$ the value of $t_{|\alpha=0.01, f=3}$ in table is 4.541. So, $|t| = 7.66 > 4.541 = t_{|\alpha=0.01, f=3}$, null hypotheses H_0 is refused. The linear correlation of Eq. (28) is significant. The linear relationship between location parameter and scale parameter in Fig. 18 illustrated that the evolution of probability distribution of average degree of edge vertices of China aviation network had linear trace.

4. Conclusion

Based on the statistics of China civil aviation of in 1988, 1994, 2001, 2008 and 2015, the probability distribution and evolution trace of the average degree of edge vertices in China aviation network were studied. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. The average degree of edge vertices of each edge was calculated, and it was found that it had the probability distribution of normal function, and the position parameters and scale parameters of the probability distribution had linear evolution trace.

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