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Time Series ARIMA Model for Failure Prediction of Landing Gear Retraction/Extension System

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Abstract—**Airplane equipment failures will bring hidden dangers to flight safety. Timely detection and maintenance of problems can not only better ensure flight safety, but also enable airlines to avoid huge losses caused by accidents. Therefore, it is necessary to scientifically predict system failures and provide data support for maintenance. This paper calculates the historical data of the main landing gear retraction and extension cycle time of the A320 fleet, and establishes a seasonal ARIMA model to predict the possibility of failure of the landing gear retraction/extension system. Finally, it is found that the retraction time of the left main landing gear of an aircraft has a tendency to slow down recently, and will exceed the time range required by the AIRBUS manual after half a year, which may bring the risk of unretractable after takeoff. Through inspection, it is caused by the fatigue wear of the actuator, and the normal working level is restored after timely replacement. The research results show that the SARIMA model is feasible and effective for predicting the failure of landing gear retraction/extension system.**

Keywords—landing gear, system failure, seasonal ARIMA model, retraction/extension system

I. INTRODUCTION

With the vigorous development of the civil aviation market and the emergence of a new generation of high-performance commercial aircraft, the competition among airlines has become increasingly fierce. The safety, reliability and maintainability of aircraft have become the main problems facing the development of aviation technology. From the perspective of operators, the reduction of aircraft maintenance costs plays a very important role in the profitability. A study conducted by the International Air Transport Association (IATA) Maintenance Cost Task Force in 2018 showed that the maintenance costs of commercial aircraft totaled $76 billion in 2017, which is estimated to reach $118 billion by 2027 [1]. According to the statistical results of the Federal Aviation Administration (FAA) and National Transportation Safety Board (NTSB) on flight accidents in the past decade, failures of subsystems and components contribute 24% on-board fatalities, 26% are due to loss of control in-flight and a large part of which is also caused by hardware failures [2]. The NTSB also decomposed the causes of hardware failure events and found that engine and landing gear failures occurred with the highest frequency, each accounting for 19% [2].

Landing gear is one of the major components on an aircraft, and the working performance of its retraction/extension system directly affects the flight safety. With the annual growth in air transportation demand, the cycle life of landing gear is shortened, and the probability of failure of its retraction/extension system is also higher under large dynamic loading conditions and complex operating environment [3]. Transportation Safety Board of Canada (TSB) sorted out 1,166 aircraft accidents during the landing phase from 2007 to 2016 [4], the results showed that 21% of the accidents were caused by landing gear collapsed or retracted. There are several accidents involving landing gear failure in recent years: a Saudia A330 made an emergency landing with its nose landing gear retracted due to hydraulic system failure on May 21, 2018, and resulting in passengers injury during forced landing [5]; a LOT B767 experienced a hydraulic leak, resulting in the failure of the landing gears and proceed belly landing on Nov. 1,2011 [6]; On September 25, 2010, a Delta Air Lines CRJ900 landed with its right main landing gear retracted because of the interference between the main landing gear door and the main landing gear fairing seal [7]. Fortunately, these accidents did not lead to passenger fatality, but they will bring expensive maintenance costs to airlines.

Generally speaking, the key components of an aircraft are periodic checked after a certain amount of time or usage to ensure the continuing airworthiness, so as to avoid losses caused by unplanned shutdown. However, it may also lead to additional maintenance costs and resource consumption, and the aircraft maintenance checks cannot completely solve and predict sudden failures.

II. LANDING GEAR RETRACTION/EXTENSION SYSTEM

The main function of the landing gear retraction and extension system is to realize the retraction and extension of the landing gear and landing gear doors during takeoff and landing phases. The mechanism of this system is complicated, it requires that specific operating procedures be adhered, i.e the correct matching and coordination of the retraction and extension of the landing gear and landing gear doors, unlocking and locking of the up lock and down lock, etc. Otherwise, unsafe events will be caused. And according to the statistics of American Aviation Safety Reporting System (ASRS), most landing gear accidents are caused by the failure of the retraction/extension system [8], so it is very important to pay attention to it.

A. System Composition

The landing gear retraction/extension system mainly consists of selector valve, actuator, up lock actuator, down lock actuator and hydraulic accessories, etc. The structure of A320 main landing gear is shown in Fig. 1.

The whole system is hydraulically operated and electrically controlled. In which the selector valve provides the retraction or extending pressure, the lock actuator is used to lock or unlock the landing gear, and the landing gear actuator retracts or extends the landing gear based on the hydraulic pressure. The role of shock absorber is to absorb and dissipate velocity, acceleration and energy upon impact, such that the forces imposed on the aircraft and the passengers are tolerable.

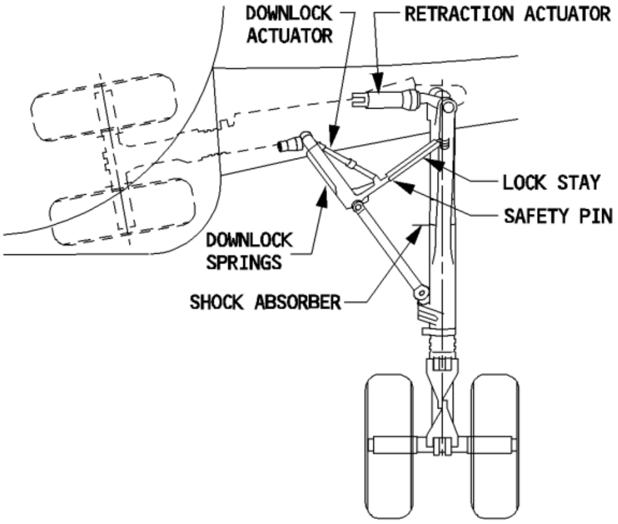

Fig. 1. Main landing gear structure of A320 [9]

B. System Control Principle

Hydraulic operation is controlled by a two position landing gear handle which located on the center main instrument panel. It also has a gravity extension system controlled by two selectors in case of the normal extension system failed. But we do not discuss more about it in this paper.

The retraction and extension of the landing gear and the operation of the landing gear doors are electrically-controlled by two landing gear interface units (LGCIU). The two LGCIUs alternately control the retraction and extension sequence. Only one controls the landing gear movement, while the other will continuously send signals. When each unit completes a complete gear cycle or one of them fails, the other will automatically switches over.

The A320 landing gear and doors are actuated by green hydraulic system. The safety valve is controlled by two signals: the position of the handle and the speed of the aircraft. If the aircraft speed is greater than 260 knots, the valve will be closed, and the system will be cut off hydraulic supply to prevent the landing gear from being mistakenly extended in the air until the handle is put to DOWN position and the speed decreases below 260 knots. The principle of the operating system for normally retract and extend landing gear is shown in Fig. 2.

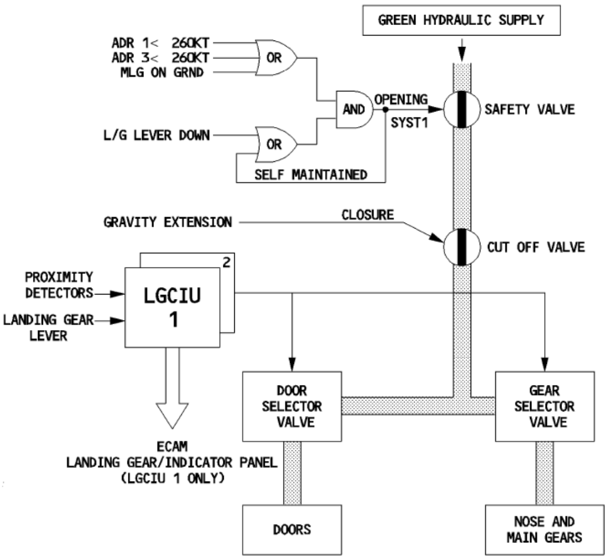

Fig. 2. Schematic of A320 landing gear normal retraction and extension operation system [9]

C. System Failure Analysis

Aircraft landing gear retraction/extension system is a complex nonlinear system. Its reliability is mainly affected by two aspects: one is mechanical failure, including corrosion, wear and tear, cracks, etc. The other is hydraulic system failure, including oil leakage of actuator, air mixed in hydraulic oil, etc. [10]. The occurrence of these faults is related to the service time and scheduled inspection and maintenance, and is a gradually evolving process.

The failure process of the landing gear retraction and extension system is shown in Fig. 3. After normal operation for a period of time, it will appear some potential and detectable failure risks due to the damage accumulation. If the operation continues without timely maintenance and corrected, then the system will degrade until failure. Before point P, the abnormal behavior may be too small to detected, so P is the point where we can find out that it is failing. F is the point where the system has functional failure. The time period between P and F is called P—F interval, it means that our inspection interval should be smaller than this so that we can catch the failure after it is detectable.

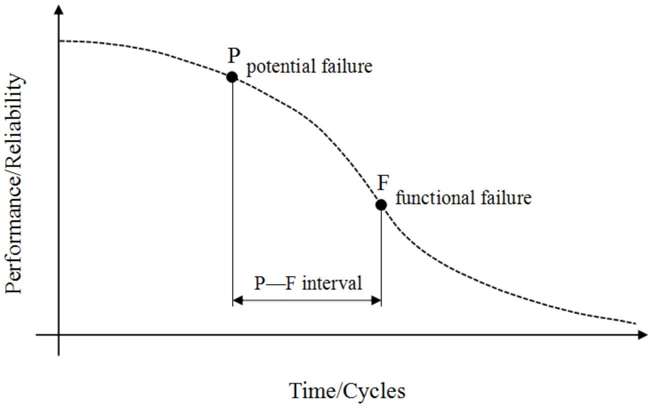

Fig. 3. Evolutionary process of landing gear retraction/extension system

Experts have developed failure prognosis and health management systems for landing gear retraction and extension system to prevent risks. G. Petrone et al. [11] collected data from sensor networks and using specific algorithms to process signals and estimate the health status of landing gear, this method can achieve lower maintenance costs to ensure the flight safety. YANG YANG[12] of Cranfield University designed a failure diagnosis system based on expert system by studying the landing gear retraction/extension system, and proposed a system component failure prediction method based on feature analysis. Jie Chen et al. [13] from Northwestern Polytechnical University proposed an effective prognosis tool based on stochastic filtering to predict the failure time of the landing gear retraction/extension system, and predicted the failure according to the operational principle and failure feature analysis of the landing gear system. However, the development of the above-mentioned systems are relatively complicated and faces many challenges such as new technologies and commercial problems. So far, they have not been widely and maturely applied in airlines. Therefore, the reliability of these systems is also lack of verification [14].

III. MAIN LANDING GEAR RETRACTION/EXTENSION TIME

QAR data of landing gear, landing gear doors and the handle during takeoff phase are shown in Fig. 4. The pilot retracts the landing gear by operating the handle to UP position, then the landing gear door starts to open. When the door reaches the fully opened state, the landing gear starts to retract. After that, the door starts to close when the landing gear are fully retracted. The extension process is in a similar manner.

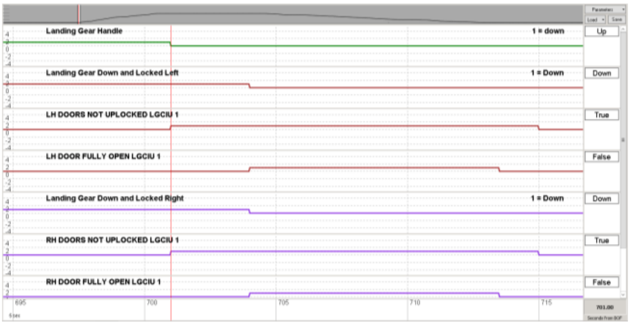

Fig. 4. QAR data for retracting landing gear

According to the functional test of normal retraction and extension of landing gear of AIRBUS manual, the entire retraction cycle of A320 landing gear(from the first door-uplock open to the last door-uplock closed) takes 10-15 seconds, while the time range for extension cycle is between 15 and 21 seconds. According to reference [15], the main failure symptom of landing gear retraction and extension system is the time cycle tends to enlargement. So in this paper, we extract the QAR data of an airline's A320 fleet from July 2010 to June 2019. After data cleaning and calculation, about 1.2 million valid samples are obtained. The retraction and extension time distribution of the left and right main landing gear are shown from Fig. 5 to Fig. 8. It can be seen that the retraction time are mainly distributed between 13s and 15s, and the extension time are mainly between 15s and 19s. Most of the actuation time of the flights can meet the requirements of the manual, but there are still some data that exceed or even far above the normal level.

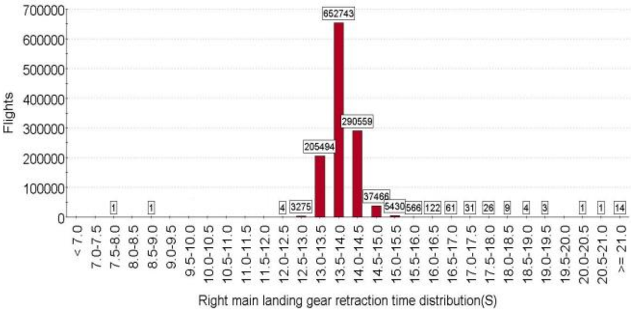

Fig. 5. Right main landing gear retraction time distribution of A320 fleet

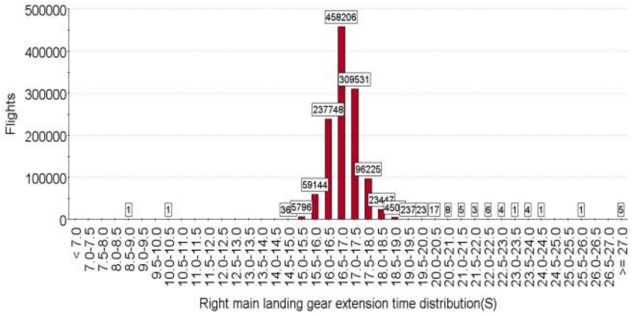

Fig. 6. Right main landing gear extension time distribution of A320 fleet

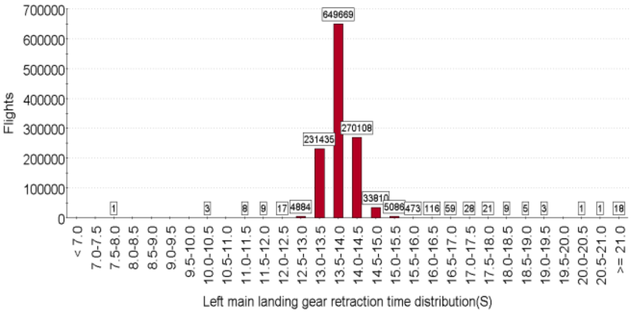

Fig. 7. Left main landing gear retraction time distribution of A320 fleet

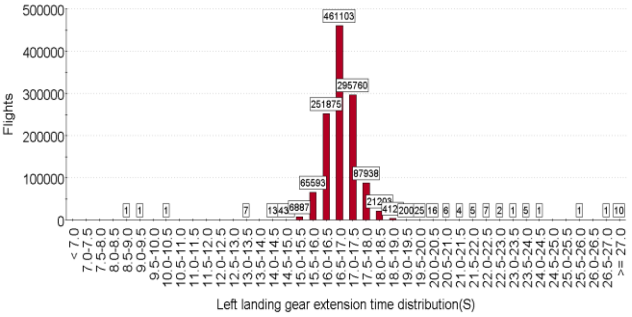

Fig. 8. Left main landing gear extension time distribution of A320 fleet

First of all, the abnormal values of the right main landing gear retraction time are analyzed. It is found that they are mainly from a certain aircraft, and its tail number is marked as B-XXX1 here. Its distribution of monthly average historical records is shown in Fig. 9. We can observe that the outliers occurred during June and August 2013, and then returned to normal level. Besides, the standard deviations are also very high, which indicates that there exist individual maximum values. But this does not well reflected the obvious overall degrade of the landing gear retraction performance. We obtain the same results as above through the analysis of the extension time.

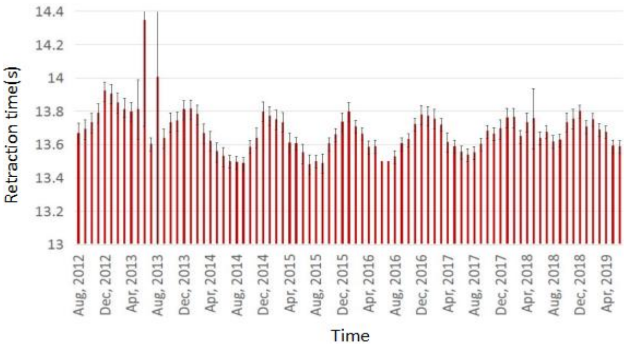

Fig. 9. Monthly average retraction time of B-XXX1

By analyzing the abnormal values of the retraction and extension time of the left main landing gear, we are aware that there may be a potential failure on an aircraft. And it is still not detected by the maintenance department. Its tail number is marked as B-XXX2 here. From the statistical results of the historical data, as shown in Fig. 10, there is a clear expanding trend of the retraction time since 2017. And the standard deviations explain that the data are very concentrated, which well reflected the reliability level of the system is descending rapidly.

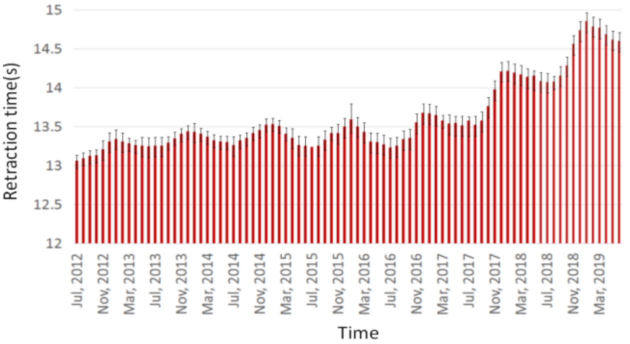

Fig. 10. Monthly average retraction time of B-XXX2

This airlines has set up monitoring items of the retraction and extension time, but according to the current technology, it is unable to effectively reduce and predict the occurrence of landing gear failure in flight. Therefore, by developing a seasonal Auto-regressive Integrated Moving Average (SARIMA) model, this paper predicts the failure time of the left main landing gear of the B-XXX2 aircraft.

IV. TIME SERIES FORECASTING METHOD

A series of predictive models have been developed and applied in different fields based on the application of mathematical statistics and artificial intelligence technology. Through scientific prediction methods, the risk of failure can be reduced and the future situation can be predicted. ARIMA model is a prediction technology and widely used in studying time series. It refers to in the process of transforming a non-stationary time series into a stationary one, then establish a model by regression of dependent variable on its lagged values, the present value and lagged value of random error term. And it is more robust and effective in short-term prediction [16].

ARIMA model has been used in civil aviation and achieved a series of prediction achievements. Song Juan [17] proposed to analyze the passenger reservation rules through the change of the passenger occupancy rate during the reservation period, and to establish a prediction model for the final passenger occupancy rate using ARIMA model. Zhao Yuting [18] predicted the remaining life of the engine through ARIMA model, and verified it with the actual engine performance data from the airlines. In general, aircraft failures exhibit seasonal characteristics. Seasonal time series model (SARIMA) can be used to solve such problems. For example, Yanming Yang etc. [19] scientifically predicted aircraft fault rate through SARIMA model and made scientific decisions in aviation maintenance to improve maintenance support capability.

A. Non-Seasonal ARIMA Model

The ARIMA(p,d,q) model includes auto-regressive model AR, moving average model MA and the combination of AR and MA. This model has three variables to account for: where p is the order of the AR part, its value determines which previous periods of the time series that we use when calculating the auto-regressive part; d is the order for differencing a time series into a stationary one(mean and variance are constant); q is the order of MA, this variable denotes the lag of the error term. The d order difference of the observed value X_t can be expressed as:

$$\nabla^d X_t = (1-B)^d x_t \quad (1)$$

where the difference order d is usually equals to 1 or 2, B is the backshift operator.

In this paper, the ARIMA(p,d,q) model is briefly expressed as:

$$\phi_p(B)\nabla^d X_t = \theta_q(B)\varepsilon_t \quad (2)$$

where $\Phi_p(B)$ is the auto-regressive operator of p, $\theta_q(B)$ is the moving average operator of q. ε_t is the random error, it assumed to be identically and independently distributed with a mean of zero and a constant variance of σ^2.

B. Seasonal ARIMA Model

SARIMA(p,d,q)(P,D,Q)$_S$ is similar to ARIMA model, just add in a few parameters to account for season. P, D and Q represents the p, d and q for the seasonal part of the time series. S refers to the number of periods in each season. Here, the seasonal differencing should be taken into account to compare the current value with it's value in the previous month. Given a dependent time series, the mathematical expression of SARIMA can be written as:

$$\phi_p(B)\Phi_P(B^S)\nabla^d\nabla_S^D X_t = \theta_q(B)\Theta_Q(B^S)\varepsilon_t \quad (3)$$

where $\Phi_P(B^S)$ is seasonal auto-regressive operator of P, $\Theta_Q(B^S)$ is the seasonal moving average operator of Q.

C. Modeling Process

In this paper, the modeling process of SARIMA is completed in RStudio. The main steps are as follows:

1) If the data is non-stationary, differencing processing is required until the autocorrelation function(ACF) and partial autocorrelation function(PACF) of the processed data are not significantly different from 0.

2) Model identification can be performed by calculating the ACF and PACF after differencing. The estimation of the *possible values of p, P, q and Q can be done by observing the correlation graph.*

3) The comparison and parameterization of the SARIMA model are using Root Mean Squared Error (RMSE) and Akaike information criterion (AIC).

4) Least square method is used here to estimate the parameters in this model after determining the order.

5) We use the ACF and PACF residuals to test the residual white noise and validity of the model.

V. SARIMA MODELING PROCESS

The retraction time of the B-XXX2 is very close to the upper limit of the time range. Taking into account the seasonal affects on the landing gear retraction/extension system, we use the SARIMA model to predict the possible failure time in next twelve months.

A. Check Stationarity

Stationary time series data are prerequisite for modeling a SARIMA model [20]. As can be seen from Fig. 10, the retraction time of the landing gear has a strong seasonal cycle, each year to reach a significant peak at winter and in summer is trough. In addition, the whole time series has a non-stationary trend with increasing averages. Therefore, we make the first order difference and first order seasonal difference of the original data to achieve stationary. Fig. 11 shows the stationary time series data after the difference is applied. The data are clearly fluctuate around 0, thus they can be considered stationarized.

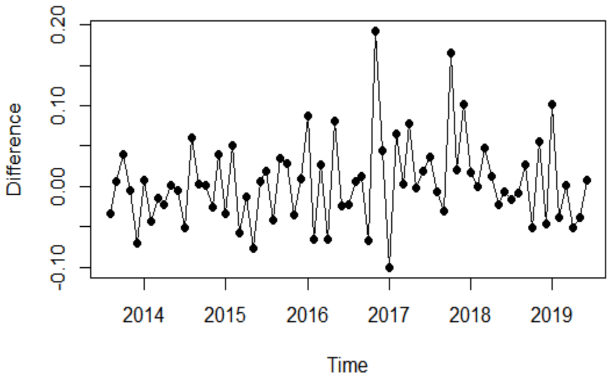

Fig. 11. First difference of the monthly average retraction time

B. Model Identification

For the SARIMA(p,d,q)(P,D,Q)$_S$ model identification, the chosen of parameters of d and D have been completed through the difference and they both equal to 1. The determination of the others can be initially done by the results of ACF and PACF tests for the stationary data. And the plots of them are shown in Fig. 12 and Fig. 13. Significant autocorrelations are present at lag 12 and lag 24, ACF has a truncation at lag 1. While PACF has a trailing at lag 1 and lag 13.

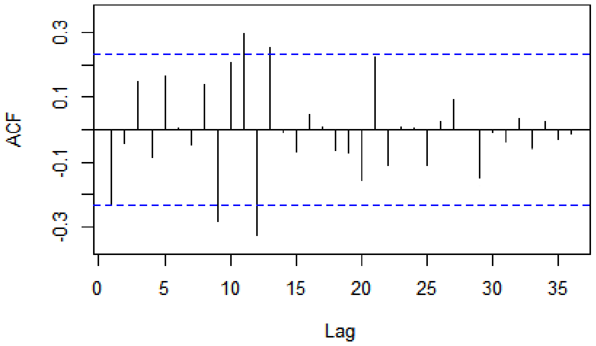

Fig. 12. ACF of the first difference of monthly average retraction time

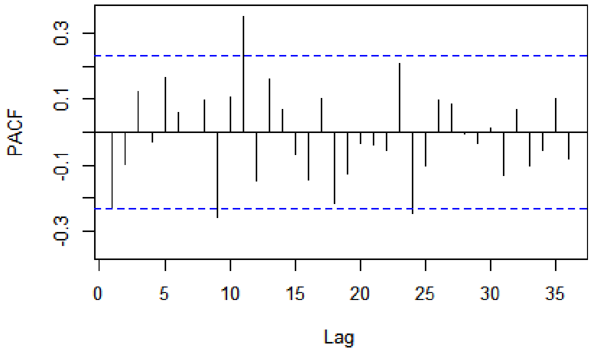

Fig. 13. PACF of the first difference of monthly average retraction time

But it is still difficult to recognize the orders which are optimal for our model. In this paper, we attempt all possible combinations to determine the ideal model with the smallest AIC and RMSE. According to TABLE I, the final model is SARIMA(0,1,1)(0,1,1)$_{12}$.

TABLE I. STATISTICAL RESULTS OF DIFFERENT SARIMA PARAMETERS FOR RETRACTION TIME

SARIMA	*AIC*	*RMSE*
(1,1,0)(1,1,0)[12]	-207.989	4.914E-02
(0,1,1)(0,1,1)[12]	**-212.7407**	**4.859E-02**
(0,1,1)(1,1,1)[12]	-206.7597	4.867E-02
(0,1,1)(0,1,0)[12]	-205.4344	5.114E-02
(0,1,1)(0,1,2)[12]	-206.7553	4.867E-02
(1,1,1)(0,1,1)[12]	-206.7613	4.869E-02
(0,1,0)(0,1,1)[12]	-210.6945	4.863E-02
(0,1,0)(1,1,1)[12]	-208.7034	4.862E-02
(0,1,0)(0,1,2)[12]	-208.7016	4.862E-02
(1,1,0)(0,1,1)[12]	-208.7469	4.869E-02
(0,1,0)(0,1,0)[12]	-203.5827	5.255E-02

C. Residual Analysis

The residuals between the actual and the fitted values of the monthly average retraction time is calculated to test the goodness of our model. Fig. 14 shows the comparison between the real and fitted values of the retraction time, and most of the residuals are between 0.2 second. Besides, The residuals can be considered as normally distributed from Fig. 15 and Fig. 16 because of the points in the plot are generally form a straight line. Thus, it reveals the goodness of our SARIMA model.

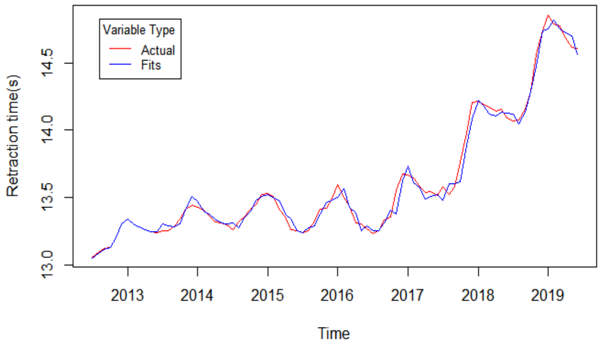

Fig. 14. Comparison between the predicted and actual values

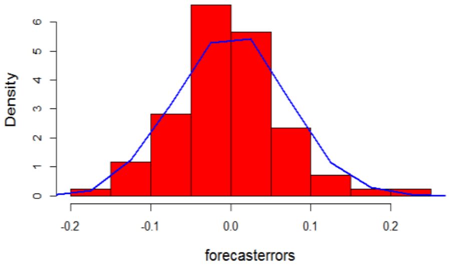

Fig. 15. Residual plot of the monthly average retraction time

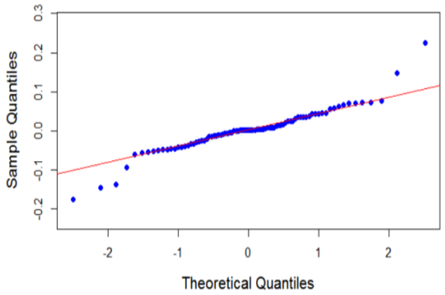

Fig. 16. Residual Q-Q plot of the monthly average retraction time

The ACF and PACF for residuals are investigated to verify the white noise feature of the predicted data. From Fig. 17 and 18, almost all of the presented spikes are falling into the confidence limits. So the residuals can be considered as uncorrelated which shows the goodness of our forecasting model and owns a better forecast effect. Few of the ACF and PACF residuals are beyond the limitation, but the number is really small and still within the 95% confidence interval.

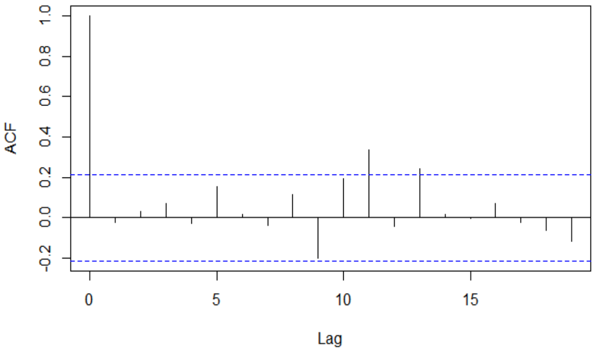

Fig. 17. ACF of the residuals of the monthly retraction time

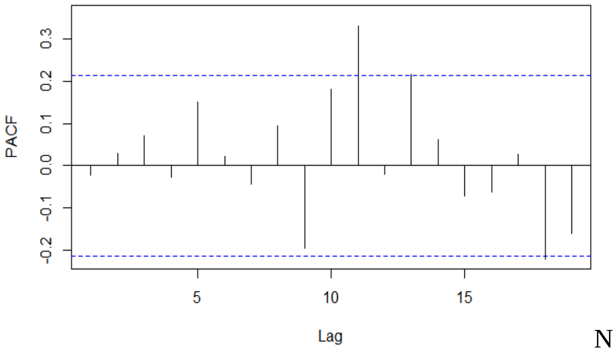

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Fig. 18. PACF of the residuals of the monthly retraction time

D. Forecasting Results

Short term forecasting for the next 12 months are applied based on the best model with the historical data of the retraction time. Fig 19 shows the expected monthly average retraction time of the B-XXX2 left main landing gear in one year, which are also displayed in detail in TABLE II. The general fluctuation trend is maintained here due to the temperature changes. As shown in Fig. 19, the general trend of the retraction time keep increasing with the time which may expected since the reliability of the system degrades. And will overtake 15s in Nov. 2019 approximately.

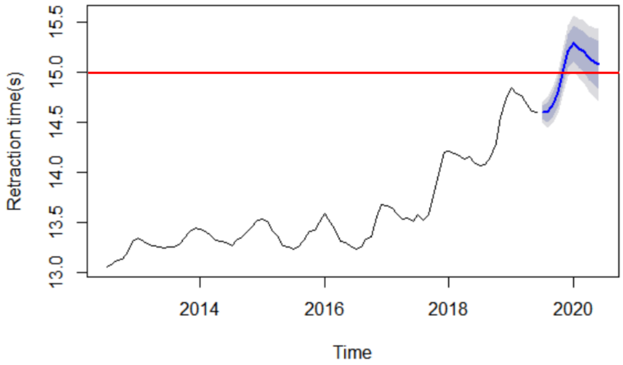

Fig. 19. Forecast values of the monthly average retraction time

TABLE II. FORECAST VALUES FOR LEFT MAIN LANDING GEAR MONTHLY AVERAGE RETRACTION TIME IN NEXT 12 MONTHS

Time	***Predicted Values(s)***	***95% Confidence Interval***	
		Lower(s)	***Upper(s)***
July, 2019	14.589	14.492	14.687
Aug., 2019	14.601	14.464	14.739
Sept., 2019	14.670	14.502	14.839
Oct., 2019	14.818	14.623	15.012
Nov., 2019	15.075	14.858	15.292
Dec., 2019	15.269	15.031	15.507
Jan., 2020	15.347	15.089	15.604
Feb., 2020	15.296	15.021	15.571
Mar., 2020	15.277	14.986	15.569
Apr., 2020	15.210	14.903	15.517
May, 2020	15.153	14.831	15.476
June, 2020	15.139	14.803	15.476

The results of the coefficient estimation are shown in TABLE III and the final model can be expressed as:

$$\nabla\nabla_{12}X_t = \varepsilon_t + 0.372\,\varepsilon_{t-12} + 0.031(\varepsilon_{t-1} + 0.372\,\varepsilon_{t-13}) \quad (4)$$

TABLE III. PARAMETER ESTIMATION RESULTS

Type	***Coefficient***	***Standard Error***	***T Statistic***	***P***
MA	-0.031	0.141	2.149	0.000
SMA	-0.372	0.154	4.222	0.000

VI. CONCLUSIONS

Safety operation is crucial for airlines. Monitoring and predicting the operating conditions of key components of an aircraft can not only save maintenance costs, but also better ensure flight safety. In this paper, SARIMA model is established based on the historical data of retraction time of an aircraft and the possible failure time of the landing gear system is carried out. Due to the actuator has the possibility of unable to work within its life span, which will affect the reliability of the whole system. After replacement, the retraction time has gone back to normal working level and with a monthly average retraction time of 14.437s in July 2019. This article also explains the SARIMA model can effectively make a forecast because of its low data input requirement and simple calculation process. In order to check the reliability and validation of the prediction values, the goodness of the model is tested by the RMSE and AIC criterion. The analysis of the residuals further demonstrating the effectiveness of the model. At last, the method used in this paper provides a new angle for future reliability research on the landing gear retraction/extension system and also applicable to other aircraft types.

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