Study on the Clustering Method of Flights and Life Prediction for Individual Aircraft Tracking (IAT)

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Introduction & Backgrounds

"Aircraft Fleet Life" Management

Control the usage according to the predetermined DSG;

To be overhauled or retired when reached the given period ;

"Regular maintenance", with limitations.

Individual Aircraft Tracking

"Individual Aircraft Life" Management

Monitor life expenditure and adjust maintenance plan;

Accumulate service data and evaluate life extension ;

Change "regular maintenance" to "Condition Based Maintenance(CBM)"

Large Difference between Aircraft Usage Damage and Design Status

- Annual difference
- Task difference
- Individual aircraft difference

Introduction & Backgrounds

Fatigue cumulative damage theory

◆ Miner's linear damage cumulative theory:

$$\lambda \sum \frac{n_i}{N_i} = Q$$

Theoretically, Q = 1.0 is destroyed, but in fact Q is very dispersed.

◆ Relative Miner's linear damage cumulative theory：

The fatigue life of other untested parts is estimated by using the fatigue life of the known parts under the spectral load.

$$N_A = N_B \left(\sum n_i/N_i\right)_B \Big/ \left(\sum n_i/N_i\right)_A$$

$(\sum n_i/N_i)_A$、$(\sum n_i/N_i)_B$ are cumulative damage of spectra A and B, respectively；

N_A，N_B are estimated life under spectrum A and test life of similar spectrum B

◆ Damage analogy method to obtain aircraft life:

$$\lambda' = \frac{\sum_{i=1}^{k} n_i \Delta g_i^{\,m}}{\sum_{i=1}^{j} n_i' \Delta g_i'^{\,m}} \lambda$$

λ is the life of known aircraft, n_i is the repeated times of load increment Δg_i for the known aircraft.

The load history (load spectrum) and fatigue life of one aircraft can be estimated when the load history of another aircraft is known.

Flights Cluster Analysis based on PCA

Equivalent damage for baseline usage

Equivalent Damage：A damage parameter that measures the degree of damage to a structure under the action of a load history (load spectrum).

$$D = \sum_{i=1}^{n} \left(G_{max,0i}\right)^{m}$$

Oding's Transform

$$G_{max,0i} = \frac{(\Delta G)_i}{\sqrt{1 - R_i}}$$

Goodman's Transform

$$G_{max,0i} = \frac{(\Delta G)_i}{1 - R_i \frac{(\Delta G)_i}{G_{jx}(1 - R_i)}}$$

Baseline usage

Damage model

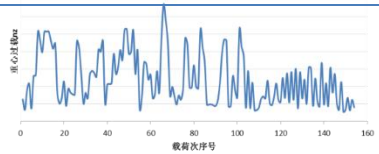
Equivalent damage for baseline usage

Reference equivalent damage per flight hour (Standard Equivalent Damage Rate)

$$D_{R,0} = \frac{D_{jz}}{400} = 361.6$$

Reference spectrum Spectrum from L/ESS of a certain aircraft, the corresponding 335 flights is 400 hours.

No.	Flight No.	Occurrence	No.	Flight No.	Occurrence
1	A-01	1	21	D-08	14
2	A-02	3	22	D-09	8
3	A-03	1	23	D-12	9
4	A-04	1	24	D-13	6
5	A-05	7	25	E-04	29
6	A-06	1	26	E-05	24
7	A-07	2	27	E-06	52
8	A-08	4	28	F-01	25
9	B-01	1	29	F-06	57
10	B-03	1	30	F-09	12
11	B-04	1	31	F-12	11
12	B-05	1	32	G-01	2
13	B-06	2	33	G-02	1
14	B-07	3	34	G-03	1
15	B-08	5	35	G-04	1
16	B-10	1	36	G-05	2
17	C-01	10	37	G-06	3
18	D-01	15	38	H-01	1
19	D-02	8	39	H-04	1
20	D-03	5	40	H-05	3

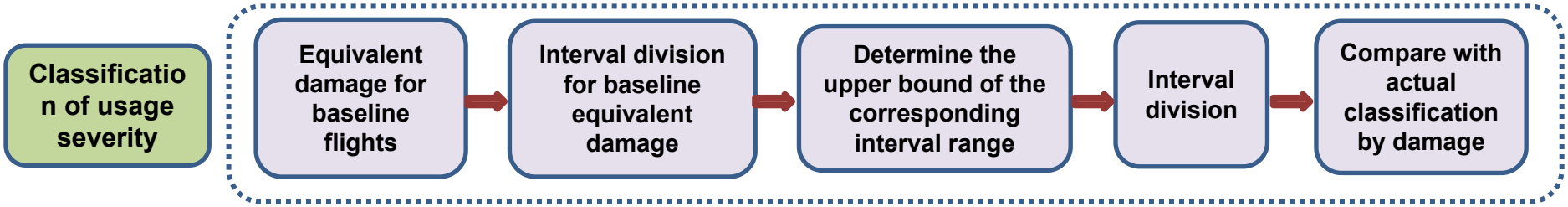


Curve of nz history for typical flight

Flights Cluster Analysis based on PCA

Classification and prediction of flights usage severity

- **Mild severity**. Indicates that the damage of the structure caused by the flight is small.
- **Moderate severity**. Represents that the structure damage caused by the flight is in the middle.
- **Heavy severity**. Indicates that the structure damage caused by the take-off and landing is heavy.



$$D = \sum_{k=1}^{m} \sum_{j=1}^{i_k} D_{k,j}$$

$$n_1 + n_2 + n_3 = mi_k$$

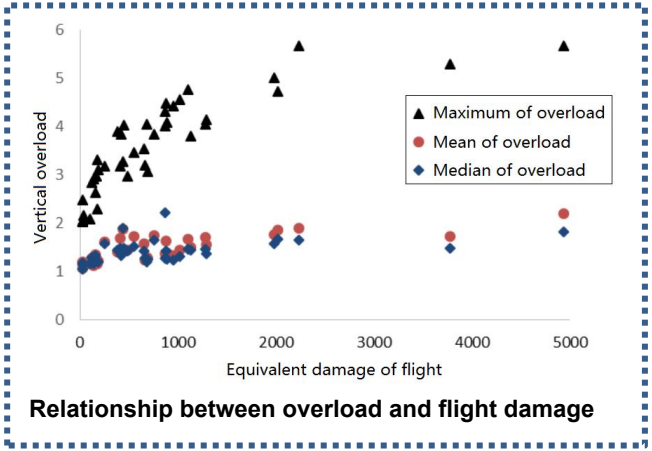
$$B_3 = max\{[f(x_1, x_2, \cdots, x_n)]_i\}$$

$$B_3 = \frac{1}{mi_k} \sum_{i=1}^{m*i_k} [f(x_1, x_2, \cdots, x_n)]_i$$

$$B_3 = median\{[f(x_1, x_2, \cdots, x_n)]_i\}$$

Flights Cluster Analysis based on PCA

Classification and prediction of flights usage severity



Relationship between overload and flight damage

Usage severity interval

↓

Index of classification

↓

Adjust the range of B1 and B2

↓

Classification of severity

The classification indexes are the maximum of vertical overload, the average of vertical overload and the median of vertical overload, respectively, and the upper limit B3 of the corresponding interval range is determined.

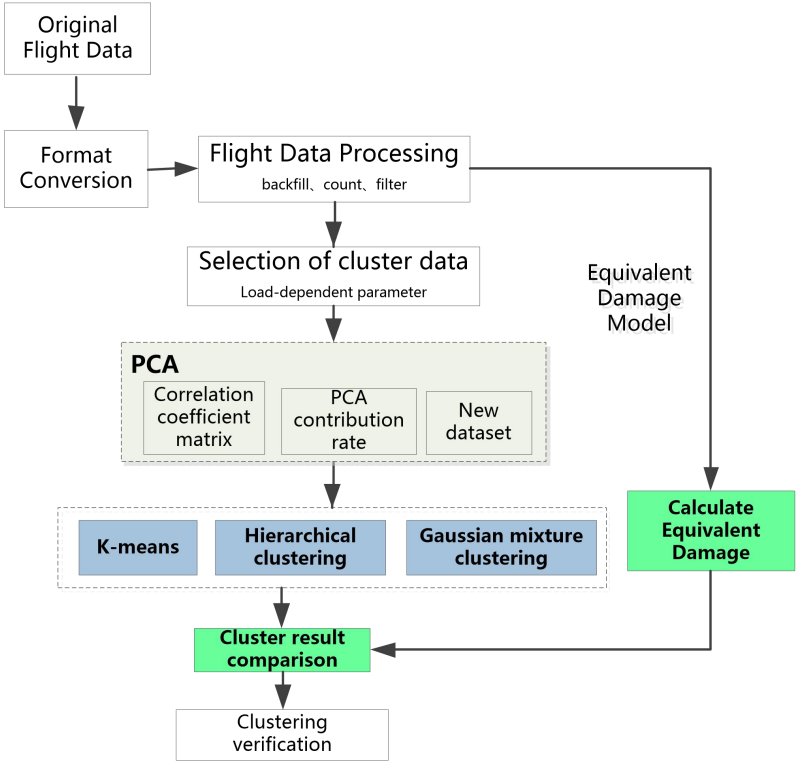
So that the number of flights in[0, B1], [B1, B2],[B2, B3] is approximately equal

NO	Flight num-ber	Classification by damage		Classification by maximum Nz		Classification by Nz mean		Classification by Nz median	
		Damage value	Result	Nz_max	Result	Nz_ mean	Result	Nz_ median	Result
1	A-01	155	Mild	2.923	Mild	1.122	Mild	1.158	Mild
2	A-02	839.8	Heavy	4.573	Heavy	1.443	Moderate	1.324	Moderate
3	A-03	170.8	Mild	3.108	Mild	1.228	Mild	1.202	Mild
4	A-04	155.8	Mild	2.971	Mild	1.265	Mild	1.236	Mild
5	A-05	1808.2	Heavy	5.02	Heavy	1.77	Heavy	1.579	Heavy
…	…	…	…	…	…	…	…	…	…
40	H-05	551.7	Moderate	4.322	Heavy	2.115	Heavy	2.221	Heavy

Index of vertical overload	Mild、Moderate	No. different from damage	Accuracy%	Modera te、Heavy	No. differen t from damage	Accuracy%
Maximum	26	2	92.3%	27	3	88.9%
Mean	26	6	76.9%	27	1	96.3%
Median	26	5	80.8%	28	4	85.7%

Flights Cluster Analysis based on PCA

Flights clustering based on Principal Component Analysis(PCA)



Flight cluster flowchart based on PCA

- Flights data are pre-processed to obtain the processed takeoff and landing data.
- Select the load-related types of data, such as overload, height, speed, weight, angular velocity, angular acceleration, rudder angle, etc., from the take-off and landing data.
- The data of each flight is transformed by PCA.
- Different clustering algorithms such as k-means, hierarchical clustering, and Gaussian mixed clustering are selected to conduct cluster analysis and compare the clustering effect.
- Calculate the equivalent damage of each flight according to damage theory.
- Compare the clustering effect of flights with the flight parameters and damage value.
- The clustering method with the smallest error will be determined as the clustering method based on PCA.

Flights Cluster Analysis based on PCA

Flights clustering based on Principal Component Analysis(PCA)

Parameter selection: **eight flight parameters** including longitudinal overload n_x, lateral overload n_y, normal overload n_z, pressure altitude H_p, flight speed v, roll angle velocity P, pitch angle speed Q and yaw angle velocity R were selected for cluster analysis.

Principal components	eigen values	Principal component contribution rate	Cumulative contribution rate
1	0.0487	50.9%	50.9%
2	0.0188	19.6%	70.5%
3	0.0087	9.1%	79.6%
4	0.0056	5.9%	85.5%
5	0.0046	4.8%	90.3%
6	0.0034	3.6%	93.8%
7	0.0025	2.6%	96.4%
8	0.0021	2.2%	98.6%
9	0.0013	1.4%	100.0%

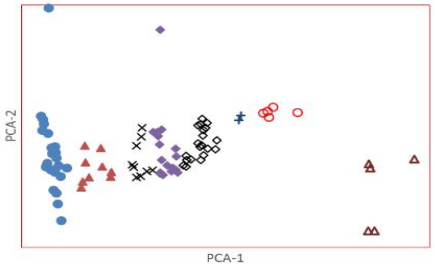
No.	Vector 1	Vector 2	Vector 3	Vector 4	Vector 5	Vector 6	Vector 7	Vector 8	Vector 9
1	-0.199	-0.408	-0.405	-0.084	-0.139	-0.408	-0.337	-0.414	-0.390
2	-0.257	0.091	0.028	-0.669	-0.654	0.075	0.184	0.066	0.078
3	0.906	-0.029	-0.053	-0.156	-0.193	-0.080	0.205	-0.205	-0.151
4	0.185	-0.122	0.376	-0.304	0.057	0.324	-0.761	0.121	-0.123
5	0.134	0.398	-0.485	-0.185	0.110	-0.201	-0.377	-0.041	0.599
6	0.057	0.203	-0.537	0.306	-0.326	0.396	-0.141	0.405	-0.356
7	0.061	-0.636	-0.361	-0.315	0.333	0.201	0.204	0.369	0.179
8	0.113	-0.212	0.191	0.212	-0.313	-0.603	-0.138	0.599	0.146
9	0.029	-0.401	0.027	0.395	-0.430	0.340	-0.095	-0.326	0.515

The first three principal components covering nearly 80% of the contribution rate in the data. Therefore, the **first, second and third principal components** were selected as the basis for classification to represent the original 8 flight parameters and the characteristics of flight equivalent damage.

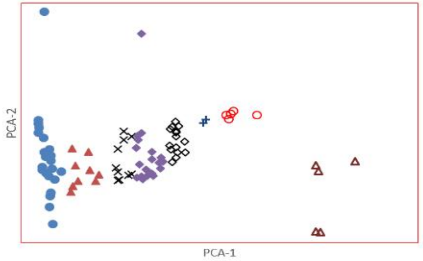
Flights Cluster Analysis based on PCA

Flights clustering based on Principal Component Analysis(PCA)

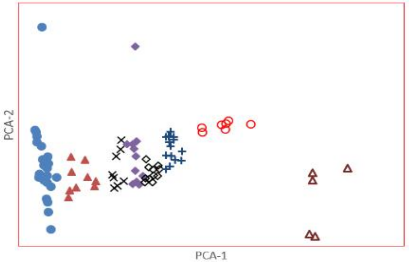
k-means cluster



Hierarchical cluster



Gaussian mixture cluster



Cluster Analysis

- The 10 most damaged flights
  - All three methods are divided into three categories
  - k-means and GMM clustering results are consistent
  - Hierarchical clustering:1 flight not consistent with k-means and GMM, the other 9 are consistent

No.	Flight No.	Equivalent Damage	K-means	Hierarchical cluster	GMM cluster
1	16	3849.9	1	0	0
2	15	2978.3	1	0	0
3	14	1891.5	1	0	5
4	5	1808.2	3	4	6
5	62	1576.4	3	4	6
6	76	1200.0	5	1	4
7	9	1099.1	1	0	0
8	12	1069.0	1	0	5
9	78	1050.7	1	0	0
10	8	1021.4	1	0	5

- Minimum damage of 5 flights
  - Results of the three methods are consistent

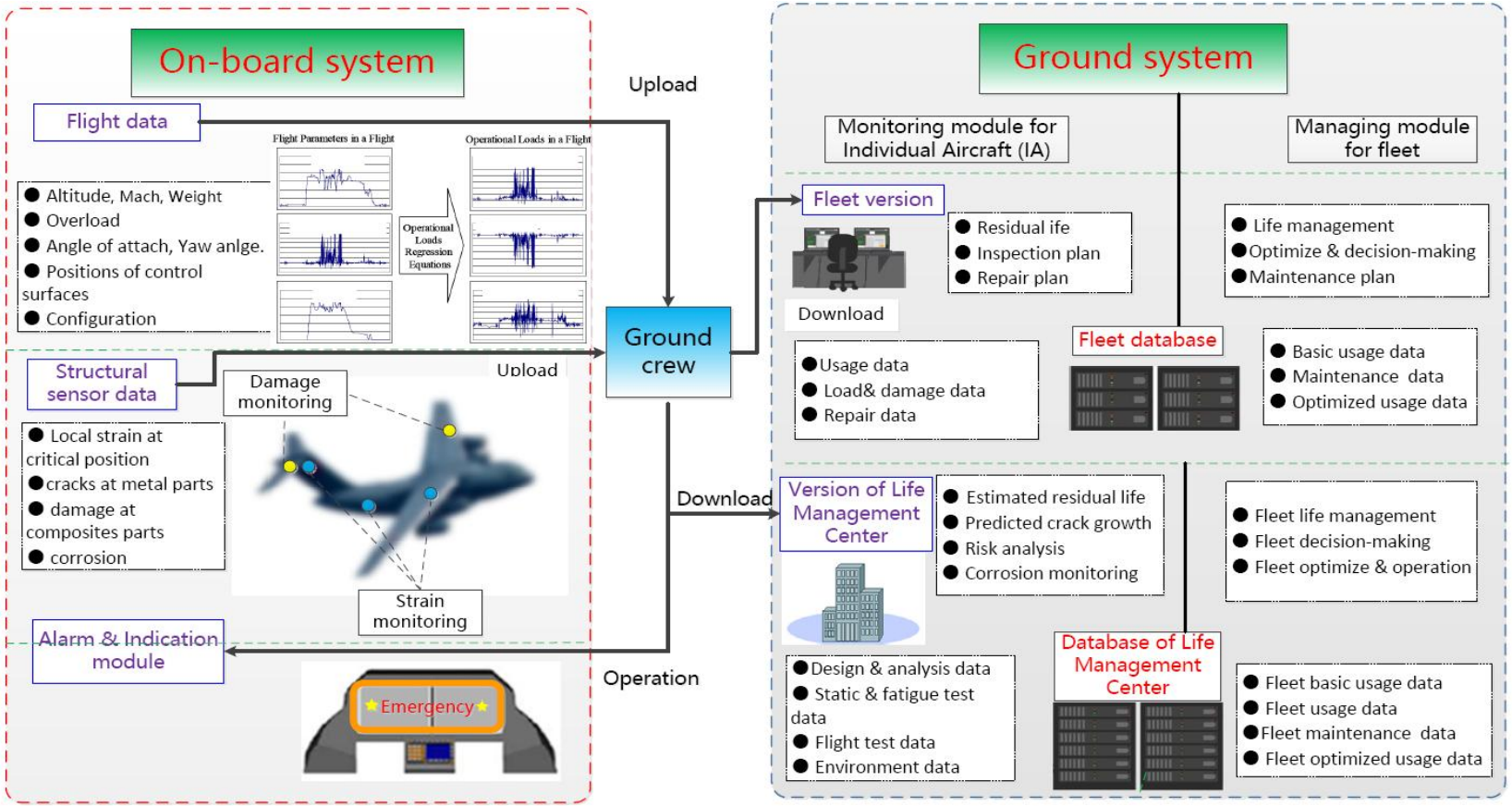
No.	Flight No.	Equivalent Damage	K-means	Hierarchical cluster	GMM cluster
1	94	7	0	5	1
2	89	10.3	0	5	1
3	95	13.2	0	5	1
4	92	15.8	0	5	1
5	93	16.2	0	5	1

By contrasting with the flight damage: :

- The classification of GMM has good classification recognition degree, and has good correlation with the flight damage.
- Gaussian mixture clustering can better identify flight with medium damage.

Damage & life prediction of IAT

Schematic diagram of structural health monitoring system



Damage & life prediction of IAT

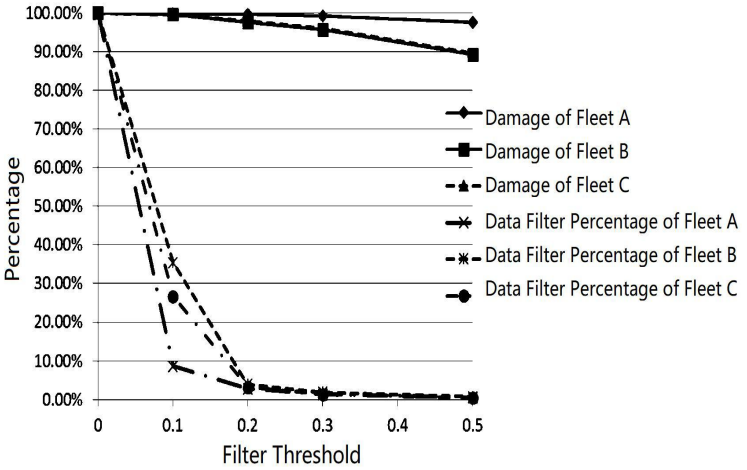
Determination of filter threshold of individual aircraft tracking

Filter Threshold:

- The flight data of fleet A, fleet B and fleet C in a certain year were selected respectively for equivalent damage calculation.
- The equivalent damage values under different filtering thresholds (0, 0.1g, 0.2g,0.3g, 0.5g) were calculated respectively according to the equivalent damage model, and the filtered data compression was combined for comparative analysis.

Results Comparison:

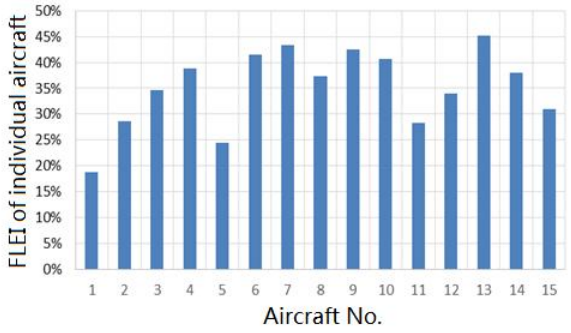
- Data compression was very effective by increasing the filter threshold.
- Data compression lelel varies from different fleets under the same filter threshold.
- Under the threshold of 0.3g, the data size was compressed to less than 2% of the original data with the damage error less than 5%.
- Under the threshold of 0.1g, the data size was compressed to less than 1/3 of the original data with the damage error less than 0.5%.



Damage & life prediction of IAT

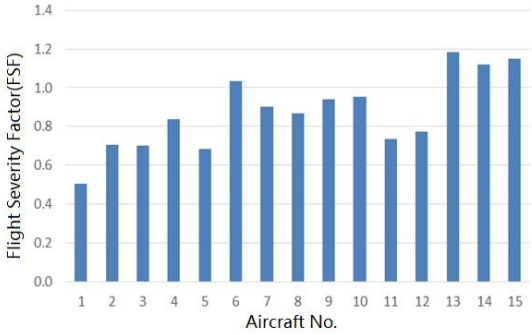
Damage & life predicition of Individual Aircraft Tracking

GUI of ground analysis software for individual aircraft tracking System)



Fatigue Life Expenditure Index (FLEI)

- For aircraft with large FLEI, it is necessary to carry out ladder control according to fleet usage plan to ensure the attendance of aircraft.
- For aircraft with large Flight Severity Factor (FSF), it is necessary to increase the flight subjects with small mission load and small maneuvering overload.
- For aircraft with small FSF, flight subjects with large load, large maneuvering can be arranged to control the uniform increase of FLEI of individual aircraft in the fleet.



Flight Severity Factor (FSF)

Summary

The clustering method of flights and fatigue life consumption prediction of individual aircraft tracking are analyzed and studied, and the conclusions are as follows:

- Established the flight clustering method based on Principal Component Analysis(PCA), studied and compared the effectiveness of K-means, hierarchical clustering and GMM clustering methods after dimension reduction based on PCA.
- Proposed feasible theoretical methods and practical cases for carrying out individual aircraft tracking and evaluating aircraft usage severity: mild, moderate and heavy severity.
- According to the IAT of a certain aircraft, a filter threshold value determination method suitable for fleet tracking was proposed, and individual aircraft damage analysis was carried out.

QUESTIONS / SUGGESTIONS?