Research on Compression Method of Aero Turbofan Engine Starting Real-time Data

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Abstract. The aero turbofan engine starting controller is responsible for starting aero turbofan engine, and records the real-time data of the whole starting process while ensuring the aero turbofan engine working reliably, which is great significant for evaluating the aero turbofan engine working condition and fault detection. Firstly, evaluate the aero turbofan engine starting probability based on AHP to solve the problem of lacking long-time aero turbofan engine starting data and evaluate aero turbofan engine working properly for multiple experts based on GCA. Secondly, rearrange the signal position and order based on sample data for EFDR and compresses the coded date of EFDR based on LZW again to increase compression ratio. Finally, test the performance under abnormal room, high and low temperature and the result proves aero turbofan engine starting controller working reliably.

1. Introduction

The aero turbofan engine starting controller is responsible for starting aero turbofan engine, and records the real-time data of the whole starting process while ensuring the aero turbofan engine working reliably, which is great significant for evaluating the aero turbofan engine working condition and fault detection[1-3]. The key point of this paper is how to store the information of aero turbofan engine starting process in limited space and harsh environment without affecting the control precision of starting time.

The process of removing redundant parts of data is called compression, which can be divided into lossy compression and lossless compression [4, 5]. Lossy compression is an irreversible compression, and the redundant parts should be deleted as much as possible to obtain a higher compression ratio when preserving data features, such as dead-zone limit algorithm and swinging door trending algorithm [6]. Lossless compression is a reversible compression, and the redundant data are deleted without abandoning any valid information in the source data, such as Huffman algorithm, arithmetic coding and run-length encoding [7-9] based statistics compression algorithms, and LZ77 (Lempel-Ziv 1977), Lempel - Ziv 1978 and LZW (Lempel-Ziv-Welch) based dictionary compression algorithms [10-12].

The starting mode of the aero turbofan engine is fixed, and the signal changes regularly during the starting process. In order to obtain the maximum data compression ratio, the original data should be analysed and processed. Since long-term sample data can’t be obtained, the probability of each aero turbofan engine starting mode would be determined by expert evaluation, and the subjective and objective weighting methods include AHP (analytic hierarchy process)[13, 14], entropy weight method [15, 16].
Firstly, the probability of different aero turbofan engine starting mode evaluated by AHP, and the probability of multi-expert evaluation determined by GCA (grey correlation analysis). Secondly, the storage data position of the aero turbofan engine starting controller rearranged according to EFDR (extended frequency-directed run-length) to improve the compression ratio. Finally, the improved LZW used to compress the data after EFDR again, which further reducing the redundancy of data.

2. Storage Algorithm for Aero Turbofan Engine Starting Real-time Data

2.1. Data Compression Algorithm

EFDR is a double run-length encoding algorithm, which improves the utilization ratio of run-length effectively by encoding both 0 and 1 data at the same time, and the compression effect is better than single run-length encoding. EFDR run encoding for data 0 firstly, run encoding for data 1 secondly, and then run encoding finished until all data encoded.

Supposing the length of data is \( l \), the group can be built as follow.

\[
g = \left\lfloor \log_2(l+3) - 1 \right\rfloor \tag{1}
\]

Supposing the run-length of 0 is \( l_1 \) and the run-length of 1 is \( l_2 \) which belong to \( l \), then the total length encoded by EFDR can be calculated as follow.

\[
L = 2(g_1 + g_2) = 2(\log_2(l_1 + 3) - 1 + \log_2(l_2 + 3) - 1) = 2(\log_2(l_1 + 3)(l_2 + 3) - 2) = 2(\log_2(l_1l_2 + 3(l_1 + l_2) + 9) - 2) \tag{2}
\]

The data length \( l \) is the shortest and the compression efficiency is the highest when the difference between \( l_1 \) and \( l_2 \) is the largest. Since the aero turbofan engine starting mode is fixed and the signals are regular, how to arrange the position of the recorded signals of aero turbofan engine starting controller becomes the key to compression efficiency, and the algorithm would be described in Section 2.2.

The core of LZW is "dictionary", and the essence of LZW is the collective expansion of 8-bit ASCII characters, ASCII mapping between the compressed string and the definition in the dictionary is realized. The expanded characters are used to represent the continuous string which appearing in the compressed data. Traditional LZW expansion is to extend 8-bit ASCII to 9-12 bits, when the amount of data is small or the degree of data redundancy is low, this kind of expansion with constant length has little effect on data compression. In order to improve the adaptability and flexibility of LZW to aero turbofan engine starting fault mutation, the concepts of adaptive and variable code length are introduced [17].

Mode 1: \( k \) supposed be a new string, then the output by LZW would be less than \( k \) and will take up \( \log_2 k \) space, through LZW decoding can also obtain the source \( k \).

Mode 2: when the probability of occurrence of some characters in the compressed data is much higher than that of other characters, the character judged whether belongs to a certain 128 characters, if the character meets the requirements, it can be represented by a shorter encoding of the string to further improve the compression ratio of data.

A bit would be added to the coding front to distinguish between mode 1 and mode 2. Since the aero turbofan engine starting data are recorded for a long time and the probability of string repetition is relatively high, the compression ratio of the aero turbofan engine starting controller will not be affected.

2.2. Sample Data Acquisition of Aero Turbofan Engine Starting

Since the aero turbofan engine starting controller only records the data of aero turbofan engine in the recent limited time, the probability of each starting mode cannot be obtained from the historical data. Therefore, experts of aircraft power propulsion system and aero turbofan engine control are invited to make probability evaluation based on experience to obtain the probability of each starting mode.
According to the actual work condition of aero turbofan engine, the starting mode hierarchy can be constructed, as shown in Figure 1.

![Figure 1. The hierarchy of aero turbofan engine starting mode](image)

(1) Construct judgment matrix

The aero turbofan engine starting mode probability is defined by scale, as shown in Table 1. According to the scale and definition, the initial matrix can be constructed, as shown in Table 2.

| Scale $c_{ij}$ | Definition |
|----------------|------------|
| 1              | $c_i$ has the same probability as $c_j$ |
| 3              | The probability of $c_i$ is slightly more likely than $c_j$ |
| 5              | The probability of $c_i$ is more likely than $c_j$ |
| 7              | The probability of $c_i$ is much more likely than $c_j$ |
| 9              | The probability of $c_i$ is definitely higher than $c_j$ |
| 2, 4, 6, 8     | A scale between these probabilistic judgments above |

| Table 2. The initial matrix |
|-----------------------------|
| $A_1$ $A_{i1}$ $A_{i2}$ ... $A_{in}$ |
| $A_{i1}$ 1 $A_{i2}/A_{i1}$ ... $A_{in}/A_{i1}$ |
| $A_{i2}$ $A_{i1}/A_{i2}$ 1 ... $A_{in}/A_{i2}$ |
| ... ... ... ... ... ... ... |
| $A_{in}$ $A_{i1}/A_{in}$ $A_{i2}/A_{in}$ ... 1 |

(2) Matrix consistency judgment

$$C.I. = \frac{\lambda_{\text{max}} - n}{n - 1}$$  \hspace{1cm} (3)

In the formula, $\lambda_{\text{max}}$ is the maximum characteristic root of matrix $A$, and $n$ is the order of the matrix.

(3) Calculate the probability of each starting mode

$$\bar{w}_j = \sqrt[n]{\prod_{i=1}^{n} a_{ij}} \quad (i=1,2,3,...,n; \ j=1,2,3,...,n)$$  \hspace{1cm} (4)

(4) Normalize the calculated data
\[ W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad W = (w_i)_{ext} \] (5)

(5) Determine the evaluation matrix of different experts
Suppose m experts participate in the probability judgment, the expert comprehensive evaluation matrix \( X \) can be formed.

\[ X = \begin{bmatrix}
    x_{11} & x_{12} & \cdots & x_{1n} \\
    x_{21} & x_{22} & \cdots & x_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    x_{m1} & x_{m2} & \cdots & x_{mn}
\end{bmatrix} \]

(6) Determine the reference sequence
As experts are affected by subjective preferences in the evaluation process, the evaluation results are different to some extent. In order to ensure the objectivity of the probability distribution, GCA is adopted to make a comprehensive probability judgment on expert [18]. In order to reflect the dispersion degree and consistency of each expert evaluation, the average value of all expert comprehensive evaluation indexes is taken as the reference sequence.

\[ X_0 = (x_{01}, x_{02}, \ldots, x_{0n}) \quad x_{0i} = \frac{1}{m} \sum_{k=1}^{m} x_{ki} \] (6)

In order to reflect the size evaluated by different experts more intuitively, the expert comprehensive evaluation matrix is normalized to form the matrix \( Y \) and \( y_{ki} \) is shown as follow.

\[ y_{ki} = x_{ki} / \sum_{k=1}^{m} x_{ki} \] (7)

(7) Calculate by GCA
According to the calculation formula of GCA, the correlation coefficient of each expert's starting evaluation probability relative to the reference sequence can be shown as follow.

\[ \xi = \frac{\min_{1 \leq k \leq m, 1 \leq i \leq n} |y_{0i} - y_{ki}| + \rho \max_{1 \leq k \leq m, 1 \leq i \leq n} |y_{0i} - y_{ki}|}{|y_{0i} - y_{ki}| + \rho \max_{1 \leq k \leq m, 1 \leq i \leq n} |y_{0i} - y_{ki}|} \] (8)

In the formula, \( \rho \in [0, 1] \), and \( \rho \) supposed to be 0.5 here.

According to formula 8, the GCA matrix can be calculated as follow.

\[ \xi = (\xi_{ki})_{m \times n} = \begin{bmatrix}
    \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\
    \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    \xi_{m1} & \xi_{m2} & \cdots & \xi_{mn}
\end{bmatrix} \]

The probability correlation degree of all experts for the same starting mode can be calculated by GCA.

\[ r_{ok} = \frac{1}{n} \sum_{i=1}^{n} x_{ki} \] (9)

The grey correlation degree indicates the correlation degree between the probability value of a certain starting mode evaluated by different experts and the reference sequence. The larger the value is,
the closer it is to the reference sequence; on the contrary, the greater the dispersion degree of the evaluated probability is. This can be expressed as the correct degree for expert evaluation.

$$\delta_k = r_{0k} / \sum_{k=1}^{m} r_{0k} \quad D = (\delta_k)_{m \times m} = [\delta_1, \delta_2, \ldots, \delta_m]$$

(10)

(8) Determine the expert comprehensive probability evaluation

$$W = D \times X = (w_1, w_2, \ldots, w_n)$$

(11)

3. Data Analysis

3.1. Calculation the Probability of Different Aero Turbofan Engine Starting Mode

Two aircraft power propulsion system experts ($A_1$, $A_2$) and two aero turbofan engine control experts ($A_3$, $A_4$) are invited to evaluate the probabilities of different starting mode. Due to the limited paper space, only the probability evaluation process of starting mode $A$ is listed and the following matrix can be formed according to AHP as follow.

$$A_1 = \begin{pmatrix}
1 & 3 & 5 & 7 & 9 & 8 & 9 \\
0.3333 & 1 & 3 & 4 & 8 & 8 & 9 \\
0.2000 & 0.3333 & 1 & 3 & 5 & 4 & 5 \\
0.1429 & 0.2500 & 0.3333 & 1 & 3 & 4 & 4 \\
0.1111 & 0.1111 & 0.2000 & 0.3333 & 1 & 1 & 2 \\
0.1111 & 0.1111 & 0.1429 & 0.1429 & 0.3333 & 1 & 3 \\
0.1111 & 0.1667 & 0.2000 & 0.3333 & 1 & 1 & 1
\end{pmatrix}$$

$$A_2 = \begin{pmatrix}
1 & 4 & 3 & 9 & 9 & 8 & 9 \\
0.2500 & 1 & 3 & 3 & 7 & 7 & 9 \\
0.3333 & 0.3333 & 1 & 3 & 7 & 7 & 7 \\
0.1111 & 0.3333 & 0.3333 & 1 & 3 & 3 & 5 \\
0.1111 & 0.1429 & 0.1429 & 0.3333 & 1 & 2 & 3 \\
0.1111 & 0.1111 & 0.1429 & 0.1429 & 0.3333 & 0.5000 & 1 \\
0.1111 & 0.1111 & 0.1111 & 0.1429 & 0.1429 & 0.3333 & 1
\end{pmatrix}$$

$$A_3 = \begin{pmatrix}
1 & 3 & 5 & 9 & 9 & 8 & 9 \\
0.3333 & 1 & 1 & 5 & 7 & 7 & 6 \\
0.2000 & 1 & 1 & 3 & 5 & 5 & 5 \\
0.1111 & 0.2000 & 0.3333 & 1 & 3 & 4 & 3 \\
0.1111 & 0.1429 & 0.2000 & 0.3333 & 1 & 3 & 1 \\
0.1250 & 0.1429 & 0.2000 & 0.2500 & 0.3333 & 1 & 3 \\
0.1111 & 0.1667 & 0.2000 & 0.3333 & 1 & 1 & 1
\end{pmatrix}$$

$$A_4 = \begin{pmatrix}
1 & 3 & 5 & 9 & 9 & 8 & 9 \\
0.3333 & 1 & 2 & 5 & 7 & 7 & 5 \\
0.2000 & 0.5000 & 1 & 4 & 5 & 7 & 5 \\
0.1111 & 0.2000 & 0.2500 & 1 & 5 & 3 & 2 \\
0.1111 & 0.1429 & 0.2000 & 0.3333 & 1 & 3 & 2 \\
0.1250 & 0.1429 & 0.1429 & 0.3333 & 0.3333 & 1 & 2 \\
0.1429 & 0.2000 & 0.2000 & 0.5000 & 0.5000 & 0.5000 & 1
\end{pmatrix}$$

The starting mode evaluation probabilities of the four experts are shown as follow.

$$W_1=(0.4265, 0.2630, 0.1335, 0.0803, 0.0354, 0.0378, 0.0235)$$
$$W_2=(0.4222, 0.2365, 0.1692, 0.0784, 0.0392, 0.0317, 0.0228)$$
$$W_3=(0.4488, 0.2140, 0.1637, 0.0731, 0.0388, 0.0277, 0.0339)$$
$$W_4=(0.4351, 0.2299, 0.1651, 0.0680, 0.0395, 0.0304, 0.0320)$$

A new matrix is formed and normalized according to $W_1$, $W_2$, $W_3$ and $W_4$ as follow.

$$Y = \begin{pmatrix}
0.2462 & 0.2788 & 0.2114 & 0.2678 & 0.2315 & 0.2960 & 0.2087 \\
0.2437 & 0.2507 & 0.2679 & 0.2615 & 0.2564 & 0.2482 & 0.2034 \\
0.2590 & 0.2268 & 0.2592 & 0.2438 & 0.2538 & 0.2169 & 0.3024 \\
0.2511 & 0.2437 & 0.2614 & 0.2268 & 0.2583 & 0.2388 & 0.2855
\end{pmatrix}$$

The reference sequence of GCA is set as follow, and 0.25 represents all of the four experts are equal.

$$X_0=[0.25, 0.25, 0.25, 0.25]$$
According to GCA, the matrix can be calculated as follow.

\[ X = \begin{pmatrix}
0.8952 & 0.4891 & 0.4150 & 0.6105 & 0.6019 & 0.3724 & 0.3986 \\
0.8269 & 1 & 0.6093 & 0.7131 & 0.8254 & 0.9616 & 0.3693 \\
0.7632 & 0.5448 & 0.7591 & 0.8307 & 0.8975 & 0.4536 & 0.3421 \\
0.9840 & 0.8272 & 0.7144 & 0.5445 & 0.7785 & 0.7198 & 0.4361
\end{pmatrix} \]

The average correlation coefficient of each expert is calculated: \( r_1 = 0.5404, r_2 = 0.7580, r_3 = 0.6558 \) and \( r_4 = 0.7149 \). The grey relational weight of each expert is obtained as follow.

\[ D = [0.2026, 0.2840, 0.2457, 0.2679] \]

The comprehensive aero turbofan engine starting modes probability is obtained as follow:

\[ W = [0.4331, 0.2346, 0.1595, 0.0747, 0.0384, 0.0316, 0.0281] \]

The evaluation probability of different experts is integrated based on GCA, which is more according with the actual probability of aero turbofan engine starting mode, as shown in Figure 2.

**Figure 2.** The starting probability comparison among different experts

### 3.2. Aero Turbofan Engine Starting Data Compression

The sample data of each starting mode is collected from the aero turbofan engine in airplane, and real state sample data can be formed according to the probabilities of different aero turbofan engine starting modes calculated in Section 3.1. For the CPU, the external discrete signal such as 28V/suspended or grounded/suspended are processed by the hardware, the data collected by the CPU through the I/O port is 0/1.Where, 0 means the signal is invalid and 1 means the signal is valid. The probability of each signal changing to 1 can be obtained by statistical analysis of the sample data. There are 72 input and output signals of the aero turbofan engine starting controller. According to the probability of changing of each signal, the storage location is rearranged. The arrangement principle is as follows: the greater probability of signal changing to 1, it is ranked at the end of the data; the greater probability of signal changing to 0, it is ranked at the front of the data. Take a period of sample of one aero turbofan engine starting mode, and use black to represent 0 bit of data, and white to represent 1 bit of data, as shown in Figure 3 and Figure 4. It is obvious that the long run-length of the rearranged positions data increases and the short run-length decreases, which is beneficial to data compression.
In the process of aero turbofan engine starting, the value of signal is relatively unchanged within a certain period of time such as 4s or 10s, and the value of I/O collected by CPU remains 1 or 0. Therefore, the data after EFDR still has high redundancy, and the improved LZW algorithm can be used to carry out the secondary compression.

4. Example
To verify the reliability of the proposed algorithm, an automatic test equipment for the aero turbofan engine starting controller was designed to simulate the signal changes on the aero turbofan engine, as shown in Figure 5. Power load equipment is used for load simulation of different input/output signals, which providing maximum voltage 60V, maximum current 30A, and maximum power 150W; DC power equipment simulates 28V DC power on aero turbofan engine, with adjustable voltage of 9–32V, meeting the DC power requirements of GJB 181B-2012; AC power equipment adopts programmable AC power, with maximum voltage 150V, maximum current 6A and maximum frequency 1000Hz, which can meet the AC power requirements of GJB 181B-2012. The fault injection/test interface can realize the injection of different faults during the starting process, and the abnormal accidents on the aero turbofan engine can occur. Upper computer control interface is used to control test mode of aero turbofan engine starting controller, which can be fully automatic, semi-automatic and manual test; the data reading interface can read out the data recorded by the aero turbofan engine starting controller and restore the starting process. Six starting modes are selected randomly by the automatic test equipment, and the starting is carried out at random for 2h according to the probability calculated in Section 3.1, a total of six sample data are formed. Here, EFDR, LZW, LZ77, Huffman and EFDR-LZW are respectively used to compress 6 sample data, and the results are shown in Figure 6 and Figure 7.

**Figure 5.** The automatic test equipment for the aero turbofan engine starting controller
Figure 6 and Figure 7 show EFDR-LZW achieves the maximum compression ratio, but its compression time is also the largest. In order to meet the requirements of aero turbofan engine starting control timing sequence, the data stored for a long time is not compressed, but compressed once when the data meets the fixed threshold until the aero turbofan engine starting controller work is completed. To test whether the aero turbofan engine starting controller meets the time sequence control requirements after the addition of compression algorithm, the signals that need to be timed for 1s, 3s, 8s, 10s, 20s, 27s, 29s, 30s, 32s, 60s and 70s were tested separately, repeatedly and for a long time. The results are shown in Figure 8. The average error of the un-added algorithm is 0.1863% (this error includes aero turbofan engine starting controller and automatic test equipment), and the average error of the added EFDR-LZW algorithm is 0.3245%, meeting the requirement that the signal timing control precision is not more than ±5%. The aero turbofan engine starting controller is used to record 2h data by segmental compression, and the compression ratio calculated after decompression is within the range of the above test EFDR-LZW compression ratio, which proves that the compression ratio of segmental compression is approximately the same as that of the whole compression.

In order to prove the effect of improved LZW, the EFDR-LZW and the improved EFDR-LZW are used to compress the above 6 sample data respectively. The results are shown in Figure 9 and Figure 10. The average compression ratio increased by 3.42%, while the compression time remained basically unchanged.
sequence (un-rearranged), and the compression ratio of EFDR and EFDR-LZW are calculated respectively, as shown in Figure 11 and Figure 12, those shows that the average compression ratio of EFDR and EFDR-LZW decreased by 12.63% and 7.23% by sample data rearranged, while the compression time remained basically unchanged, which proves that the rearrangement of signal recording position is effective for compression ratio.

All the above data are based on the normal data collected from the aero turbofan engine in airplane. In case of any abnormal situation of the aero turbofan engine, the signals collected by the aero turbofan engine starting controller are inconsistent with the above ones. For example, some unrelated signals to the starting mode changed during a certain starting. To verify the reliability of the proposed algorithm, four unrelated signals to each starting mode would be selected and changed. Six starting modes are selected randomly by the automatic test equipment, and the starting is carried out at random for 2h according to the probability calculated in Section 3.1, a total of six sample data are formed. The six sample data are compressed segmentally by improved EFDR-LZW and the result can be shown in Figure 13, the average compression ratio increased by 1.57%, but it also better than other compression algorithms by compared with Figure 6.

In order to verify the reliability of the aero turbofan engine starting controller at high and low temperatures, tests are carried out in accordance with the high-temperature working requirements of GJB 150.3A-2009 and low-temperature working requirements of GJB 150.4A-2009. The test results are shown in Figure 14 with the above normal starting sample data and abnormal starting sample data.

Figure 14 show compression ratio of the aero turbofan engine starting controller is basically unchanged when working at room temperature, high temperature and low temperature, which proves the stability of the electron component used in the aero turbofan engine starting controller and the compression algorithm.

5. Conclusions
(1) A starting probability evaluation method based on AHP is presented to solve the problem of not being able to obtain a long time sample data. GCA is used to judge the multi-expert evaluation comprehensively, which ensures the objectivity of the data.
(2) The positions of recorded data were rearranged according to the characteristics of EFDR, and the average compression ratio of EFDR decreased by 12.63% and that of EFDR-LZW decreased by 7.23%, effectively increasing the compression ratio.

(3) The ratio compression of improved EFDR-LZW is better than other compression algorithms. To solve the time-consuming problem of the new algorithm, a segmental compression strategy is presented, and the compression ratio is unchanged basically. The influence on signal control timing sequence is verified, the average error without EFDR-LZW is 0.1863%, and the average error after adding EFDR-LZW is 0.3245%, which meets the control requirements of aero turbofan engine starting time precision. At the same time, the compression ratio of the improved EFDR-LZW is 3.42% higher than EFDR-LZW.

(4) A fault test is added for the possible abnormal situation of aero turbofan engine, the ratio compression of abnormal starting is 1.57% higher than that of normal starting, but it is still superior to other compression methods. The ratio compression of the aero turbofan engine starting controller is basically the same as that of normal temperature under high and low temperature conditions, which prove the stability of controller and the compression algorithm.

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