Static Source Error Correction Model Based on MATLAB and Simulink

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Abstract—**During the flight, the aircraft acquires the airspeed and altitude from the data collected by the pitot tube. Therefore, the static pressure source error of the pitot tube has a very large influence on the accuracy of the collected data. In order to correct the static source error, the static source error correction model was established based on Matlab & Simulink. Neural network and interpolation are used to build the error correction model. Firstly, the modified model collects the interface data of the atmospheric data computer (ADC), then it uses the neural network to make a preliminary forecast of the data, and displays the forecast results. Finally, the forecast results are modified by the cubic spline interpolation method, and the final modified results are output. This paper validates the model from both theory and practice, and proves that it can be used to correct the static source error.**

Keywords- Pitot Static Probe; Static Source Error; MATLAB&Simulink; Modified model

I. INTRODUCTION

The static source error is an inevitable problem when the pitot tube collects atmospheric parameters. In response to this problem, the national military standard GJB1623-93 [1] and the Standard for airworthiness of transport aircraft CCAR25 [2] proposed clear compensation requirements for these errors. There are two main sources of static source error —instrument error and measurement error. The instrument error is generally determined when the equipment is shipped from the factory. It can be directly compensated, and the compensation accuracy is high [3]. The measurement error is closely related to the airspeed, angle of attack and flight altitude of the aircraft. For the measurement error, the compensation methods mainly include pneumatic compensation and computer software correction [4]. Pneumatic compensation is to analyze the flow field of an airspeed tube at the beginning of its design, and select the point that is least affected by the flow field to set up a static pressure measuring port [5]. The computer compensation is the post-compensation processing of the collected data through the relevant software. This method has strong versatility, but the accuracy is greatly affected by the compensation method. Therefore, how to find a high-precision compensation method has become a subject studied by many scholars. In this paper, the progressive error correction is carried out by forecast and interpolation, and the error correction model based on Simulink is established. After the actual measurement result is input, the corrected value can be directly output.

II. STATIC SOURCE ERROR OF AIRSPEED TUBE

A. Introduction to the Working Principle of Airspeed Tube

Taking Boeing series aircraft as an example, the aircraft's pitot-static system generally includes four associated pitot tubes, two standby hydrostatic holes, and connecting pipes [6].

There are four pitot tubes on the left and right sides of the nose, two standby pitots on the lower side. The captain's pitot on the upper-left side, and the first officer's pitot on the upper-right side. The collected signals are transmitted to the atmospheric data computer (ADC). Pitot tube position and signal transmission path are shown in Fig. 1.

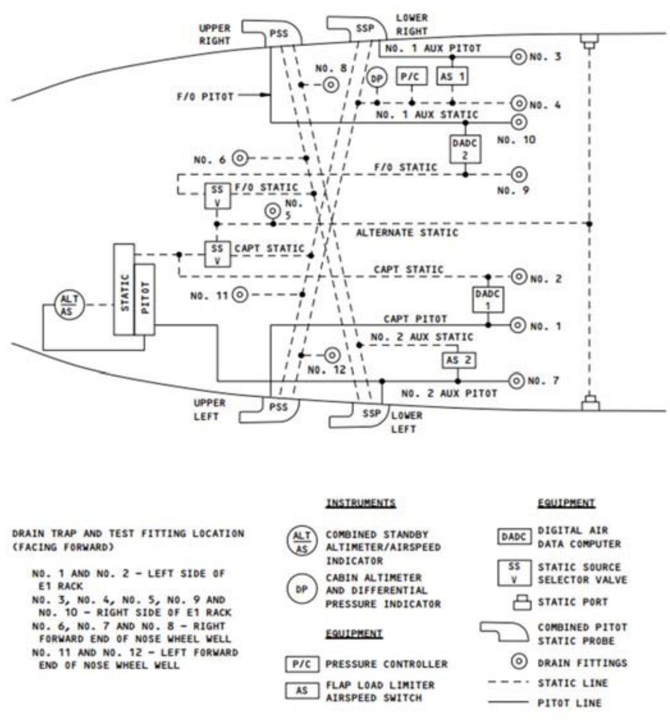

Figure 1. Pitot static system schematic

The two static pressure holes of the captain's pitot tube are respectively connected to the static pressure holes of the right backup pitot tube to prevent measurement errors caused by a single pitot tube plug. In addition to the static pressure signals collected by the aircraft pitot tube, there are two static pressure

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holes on both sides of the aircraft. The collected static pressure signals are mainly transmitted to the alternate combined altitude/airspeed indicator to determine the flight altitude and airspeed of the aircraft.

B. Static Source Error Generation Principle

There are two main signals collected by the Boeing 737-300 airspeed tube: Pitot pressure p* and static pressure p_s. According to the Bernoulli equation [7], the relationship between pitot pressure and static pressure and airspeed is as in

$$p^* = p_s + \frac{\rho c^2}{2}. \quad (1)$$

In the formula, ρ is the atmospheric density at the position where the airspeed tube is located, and c is the corresponding airspeed.

In the flight, the airspeed tube transmits the measured pitot pressure and static pressure to the ADC or related instruments, and then the corresponding airspeed can be obtained according to formula (1). However, there is a problem in the above calculation process, that is, the static pressure measured by the airspeed tube is the static pressure in the flight field of the aircraft, which is different from the static pressure at the same altitude where the airflow is not disturbed by the aircraft. If the static pressure measured by the airspeed tube is defined as p_i and the static pressure of the remote undisturbed airflow is defined as p_∞, then the static pressure source error can be expressed as in

$$\Delta p_s = p_i - p_\infty. \quad (2)$$

The relative error of the static pressure source is expressed as in

$$\frac{\Delta p_s}{p_\infty} = \frac{p_i - p_\infty}{p_\infty}. \quad (3)$$

III. ERROR CORRECTION THEORY

A. Data Preprocessing

ADC or Airspeed Meter converts the total and static pressure signals collected by the airspeed tube into corresponding airspeed with the follow formula [8].

$$p^* - p_s = 101.325[(1 + 0.13327 \times 10^{-6} c^2)^{3.5} - 1] \quad (4)$$

In the formula, p*is the total pressure, p_s is the static pressure. When the value of p_s is the static pressure (p_i) which is measured by the airspeed tube, the calculated airspeed c is the indicated airspeed. When the value of p_s is the static pressure (p_∞) of the remote undisturbed airflow, the calculated airspeed c is the true airspeed. Therefore, the main source of airspeed error is p_s, which is consistent with the error of p*- p_s. In this paper, the value of p*- p_s is taken as a whole, p*- p_i is taken as the input sample, and p*- p_∞ is taken as the expected output sample to train BP neural network.

Fig. 2 shows the comparison between the measured value and the true value of p*- p_s for a certain type of aircraft at a flight altitude of 26,000ft. It is not difficult to see from the diagram that with the increase of the indicated airspeed, the error between the measured value and the true value increases gradually, but the relationship is not obvious.

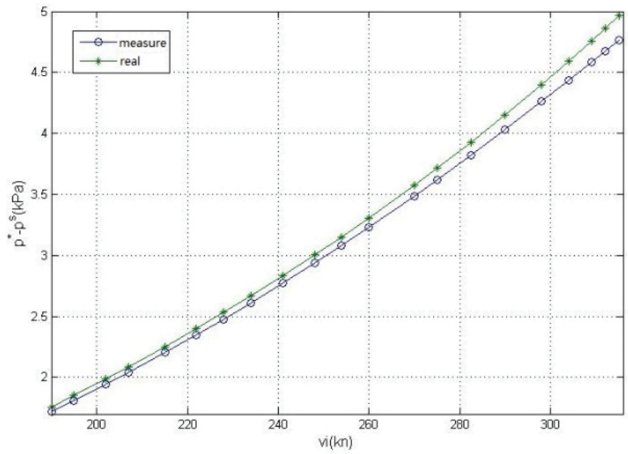

Figure 2. Comparison of real and measured values at different airspeeds

B. Basic Calculation of BP Neural Network

BP (Back Propagation) neural network is a multilayer feedforward neural network trained according to the error back propagation algorithm. The BP neural network contains an input layer and an output layer, and at least one hidden layer, so the BP neural network contains at least three layers of network structure. A neuron of any layer on the BP neural network is connected to all nodes/neurons in its previous layer, and simultaneously transmits function signals and error signals. The BP neural network structure is shown in Fig. 3.

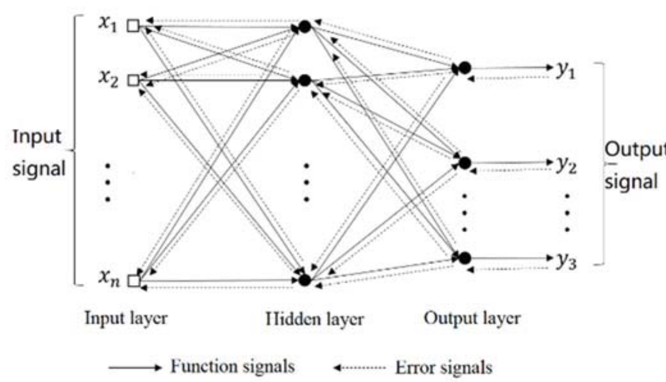

Figure 3. BP Neural network structure

BP neural network takes the mean square error as the cost function. For each sample input, the actual output is compared with the expected output, and the network parameters are constantly adjusted to minimize the mean square error.

When the neuron j is iterated in step n, the output error signal is defined as in

$$e_j(\mathrm{n}) = d_j(n) - y_j(n) \ . \quad (5)$$

In the equation, d_j(n)is expected output value, y_j(n)is actual output value.

The cost function of network training as in

$$\varepsilon(\mathrm{n}) = \frac{1}{2}\sum_{j=1}^{m_L} e_j^2\,(n) \ . \quad (6)$$

Adjust the weights according to the error correction learning rule.

$$w_{ji}(\mathrm{n}+1) = w_{ji}(n) + \Delta w_{ji}(n) \tag{7}$$

$$\Delta w_{ji}(\mathrm{n}) = -\eta \frac{\partial \varepsilon(n)}{\partial w_{ji}(n)} \tag{8}$$

In the equation (8), η is learning rate parameter.

The induced local domain of neuron j as in

$$v_j(\mathrm{n}) = \sum_{i=0}^{m_{L-1}} w_{ji}(n) y_i(n) \ . \tag{9}$$

According to the above equations, the actual output can be finally obtained.

$$y_j(\mathrm{n}) = \varphi_j(v_j(n)) \tag{10}$$

In the formula, $\varphi_j(x)$ is the nonlinear activation function of neuron j. There are step function, breaking linear function and sigmoid function, which can be selected according to actual needs [9].

The training process of BP neural network is computationally intensive and needs to be implemented by means of a computer. MATLAB provides more support for the calculation of BP neural network. It is not necessary to input complicated training formulas manually. Complex formulas can be invoked by simple MATLAB language.

The BP neural network is created by Neural Net Fitting in the MATLAB toolbox, and the input and output (expected output) data are imported. The number of layers of the hidden layer is selected according to the training situation. The training algorithm selects the conventional Levenberg-Marquardt algorithm.

Train the neural network using the data in Section Ⅲ-A. The training effect is shown in Fig. 4.

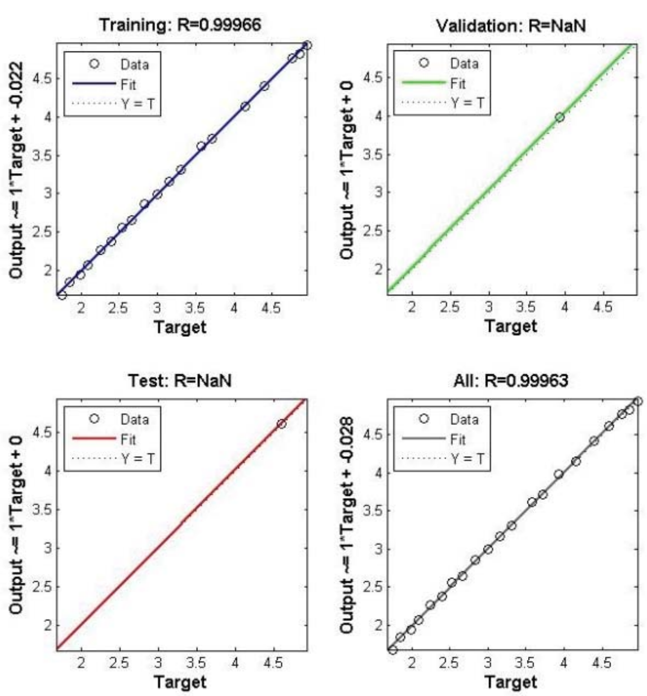

Figure 4. Neural network training R value

As shown in Fig. 4, the training parameter R (Regression) value is close to 1, which shows that the training result is very satisfactory. Then the trained neural network is used to forecast another data set in advance. The forecast data was collected by the same flight at 34,000 ft. The forecast value, the real value and the measured value are compared after training, and the result is shown in Fig. 5.

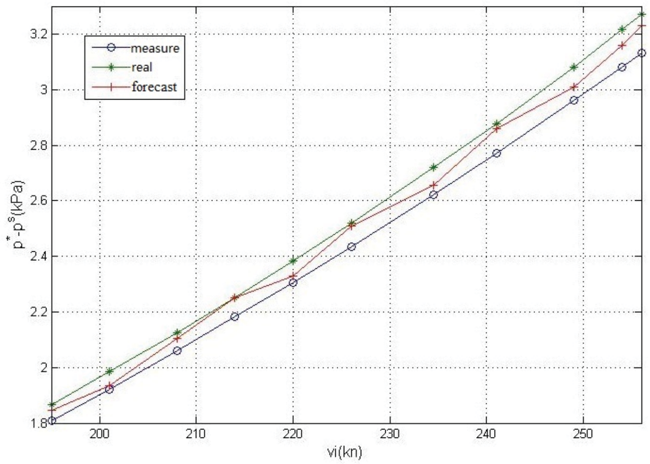

Figure 5. Comparison of forecast results

According to the comparison results in Fig. 5, it can be seen that each forecast value is closer to the true value than the original measurement value, but some forecast value deviation is larger, and some forecast value deviation is smaller. Moreover, the results predicted by the BP neural network are not exactly the same every time, which also brings uncertainty to the actual use. Therefore, further correction of the data is needed.

C. Interpolation Error Correction

Interpolation is widely used in many fields, and it is the most widely used in the field of image processing [10]. In addition, some scholars have studied how to improve the interpolation algorithm [11]. The interpolation algorithms used in the aviation field are mainly Lagrange interpolation, stepwise linear interpolation and Newton interpolation. The advantages and disadvantages of each method can be found in literature [12].

Through experiments and theoretical analysis, Cubic Spline Interpolation is introduced to further correct the forecast results.

In order to construct cubic spline function, six BP neural networks are trained with the same data, and the forecast is performed simultaneously. Then, according to formula (10), the output is $y_j(n)$, where n is the input measurement number, j= (0, 1, 2, 3, 4, 5). Numbering the 6 forecast results is x_j=(a=0,1,2,3,4,5=b). This calculation process is very complicated and can be implemented with MATLAB, which have been introduced in section Ⅲ-B. The forecast results of the 6 BP neural networks are shown in Table Ⅰ.

TABLE I. NEURAL NETWORK FORECAST RESULTS

NUMBER / INPUT	FORECAST					
	0	1	2	3	4	5
1.8086	1.8384	1.8462	1.8471	1.8499	1.8525	1.8762
1.9223	1.9329	1.9398	1.9475	1.965	1.9664	1.983

2.0595	2.0995	2.1051	2.1083	2.1104	2.1112	2.12
2.181	2.232	2.2394	2.2411	2.2462	2.247	2.2506
2.306	2.3163	2.3206	2.3259	2.3288	2.348	2.349
2.4346	2.4898	2.4901	2.4962	2.4994	2.5093	2.528
2.6229	2.6453	2.6466	2.6565	2.6636	2.6728	2.6844
2.7717	2.8316	2.8333	2.8547	2.8605	2.8621	2.8653
2.9607	3.0079	3.0178	3.0192	3.0195	3.0214	3.0414
3.0821	3.1505	3.1508	3.1512	3.1595	3.1682	3.2428
3.1314	3.2115	3.2187	3.22	3.2309	3.2424	3.3234

According to the definition of the cubic spline function [13], the constructed cubic spline function needs to satisfy the following three items.

1) The second derivative of s(x) is continuous.

$$s(x) \in C^2[a,b] \tag{11}$$

2) s(x) is a cubic polynomial in each cell [x_j, x_(j+1)] (j = 0, 1, ..., 5).

3)

$$s(x_j) = f(x_j) = y_j (j=0, 1,\ldots,5). \tag{12}$$

According to the definition, it is necessary to add two conditions to obtain the cubic spline function s(x), so it needs to be supplemented by the boundary condition. Three types of boundary conditions are given in reference [14]. In this paper, second boundary conditions are chosen.

$$\begin{cases} s''(0) = f_0'' \\ s''(x_5) = f_5'' \end{cases} \tag{13}$$

At this point, the cubic spline function s(x) can be obtained.

According to the 11 sets of data in Table Ⅰ, 11 spline functions can be determined, x_j corresponding to each spline function is numbered, and y_j is one of the forecast values. The spline function curves drawn from the first four sets of data are as shown in Fig. 6, arranged in order from left to right and top to bottom.

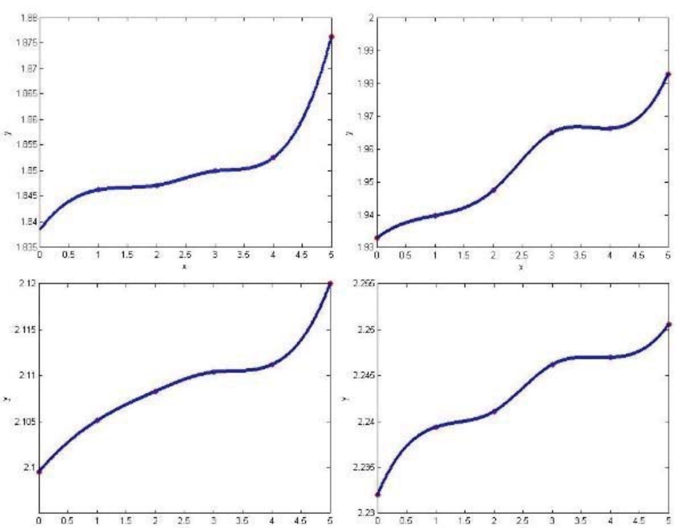

Figure 6. Spline function curve

To get the final correction value through the spline function s(x), we also need to know the insertion point. The insertion point of this paper is obtained through experiments, that is, different insertion points are selected for experiment, and the point with better output is selected as the insertion point.

According to the experimental test, the insertion point is finally selected at x=4.5, and according to the spline function curve, the corresponding corrected y value can be obtained. Spline all the data in Table 1 to determine the final output of the 11 sets of data, and define the result as the final correction value. The measured values, forecast values, corrected values and real values are compared, and the comparison results are shown in Fig. 7.

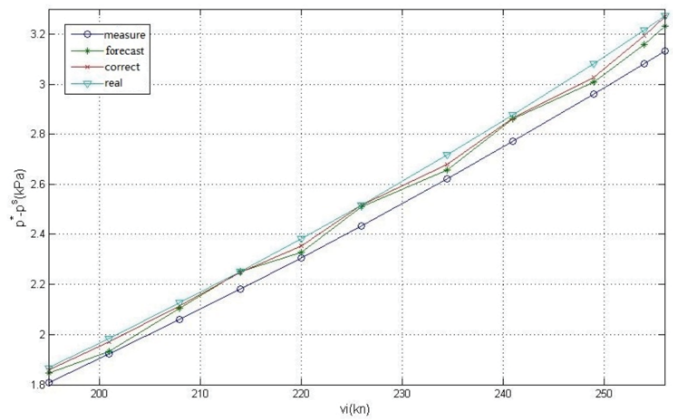

Figure 7. Comparison of correction results

It can be seen from Fig. 7 that after the spline interpolation is used for correction, all the forecast values are positively corrected, that is, the correction value is closer to the true value, so the method can be used for the correction of the static pressure source error.

IV. MATLAB & SIMULINK MODEL BUILDING

Simulink is a visual simulation tool provided by MATLAB for users to realize system simulation and modeling. According to the above analysis, the model includes 5 modules, as shown in Fig. 8.

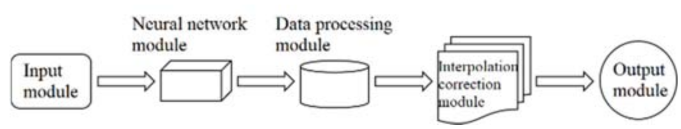

Figure 8. Module distribution diagram of Simulink model

The input module is the actual data collected by the airspeed tube and can be read directly from the interface in the ADC.

The detailed network diagram of the BP neural network module is shown in Fig. 9.

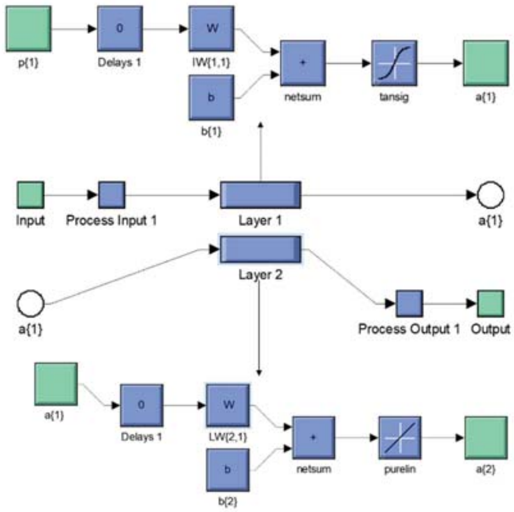

Figure 9. BP neural network model diagram

The main function of the data processing module is to collect the data predicted by the neural network and process the data into a matrix arranged in order from small to large. In data processing, the matrix is created using Matrix Concatenate tool of simulink, and the sorting is implemented by function customization module of MATLAB.

The interpolation correction module performs interpolation correction on the data collected in the previous step. For the specific correction process, refer to Section □-C of this paper. Since there is no corresponding tool in Simulink, this function is also implemented by using MATLAB function custom module programming.

The final Simulink static source error correction model is shown in Fig. 10.

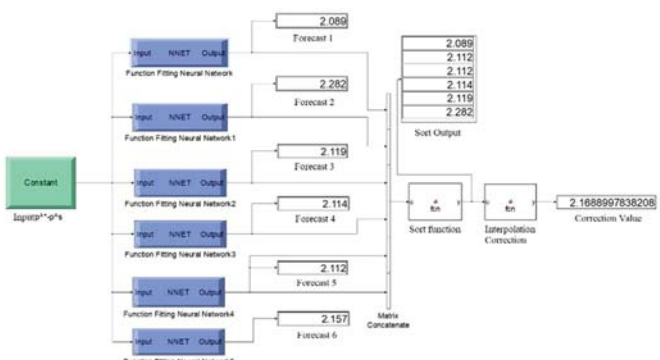

Figure 10. Error correction model of static source

In the model established in this paper, the results of neural network forecast can be displayed, the results of data processing and the final correction value can be displayed. Through these values, the changes of the entire process data can be seen more intuitively. The model running in Fig. 10, the input data is 2.0595, and the corrected output data is about 2.1689. The real value is 2.1762, you can get it from Fig. 7. So that, the output is closer to the true value.

V. Conclusion and Prospect

In this paper, the neural network forecast and interpolation correction are combined to correct the static pressure source error, and the Matlab & simulink model is established to simulate the method. Through calculation analysis and experimental tests, it is proved that this method can effectively correct the static source error. Since the model is based on the MATLAB & simulink platform, it can be directly embedded in the aircraft's ADC to correct the static pressure source error. Compared with the design improvement of the airspeed pipe, the method is less costly and more versatile. It should be noted that due to the difference in the measured values of the airspeed tubes of different aircraft, the parameters of the model should be adjusted according to the actual situation. In addition, the model can also be used for data processing of airspeed measuring equipment. By introducing the calculation of airspeed, the actual measured airspeed can be directly output.

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