RESULT VALIDATION OF A RUDDER SIMULATION MODEL

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ABSTRACT
Air vehicle simulation has been extensively used with the advantages of economic and security. As an important part in guidance control system of air vehicle, the rudder plays a key role in vehicle simulation. Thus evaluating the credibility of the rudder model is of considerable significance. This paper presents an approach to the result validation of the rudder model, which uses the consistency of the rudder model outputs and the real rudder system outputs to obtain credibility of the rudder model. The procedure includes: 1) building an rudder credibility evaluation index system; 2) providing validation methods including feature consistency quantification, proximity of position quantification, similarity of shape quantification and spectral analysis; 3) achieving the validation result based on index system and validation methods.

Keywords: result validation, rudder model, data consistency, feature consistency

1. INTRODUCTION
Air vehicle simulation has been extensively used with the advantages of economic and security. As an important part in air vehicle, the rudder is not only an actuator but also a major component in the guidance and control system. Modeling and simulation of the rudder is an important aspect of air vehicle simulation, which affects the credibility of the air vehicle especially the guidance control simulation system (Sargent 2013). The credibility of the simulation system directly determines the success or failure of the simulation application. Model validation is the primary means to research the credibility of model, and result validation is one way to achieve the validation process (Balci 2003). Result validation is the process of measurement of the similarity between the simulation data and experimental data with the same inputs.

As early as 1967, Naylor (1967) pointed out that face validation can be carried out according to the intuition, and that the similarity between the simulation model and the real object can be carried out according to the typical events, assumptions and other internal features of the two. Mckenny (1967) also considered that the validation process should be done on condition that the simulation and reference system should be with the same inputs. Simulation outputs can be divided as static outputs and time series outputs. Under this hypothesis, static validation metric can be separated into two categories: 1) parameter estimation, model parameter updating, or system identification (Oberkampf and Barone 2006); 2) hypothesis testing or significance testing (Yu 2011). Time series can be validated with Theil inequality coefficient (TIC) (Kheir and Holmes 1978), grey relational analysis (Wu J., Wu X.Y. and Chen Y.X. 2010), etc.

In this paper, we first analyze the character of the rudder system and build the index system of the validation mission; then select the validation method based on the feature of index; finally calculate the validation result based on the simulation and experimental data.

2. INDEX SYSTEM OF THE RUDDER MODEL REAULT VALIDATION

The air vehicle rudder is a complicated electro-mechanization system. There are numerous factors which influence the credibility of the rudder model. Thus, it is important to validate the simulation model in different input condition. The output of the rudder model we most concern is the angle of rudder reflection with diverse input condition during the result validation procedure. The typical working condition of the rudder is following the tracks of the constant value input instructions and periodic signal input. Therefore, the input conditions of the rudder are a step signal with different amplitude and a sinusoidal signal with different frequency. Thus, the index system of the rudder model result validation is established as below (see Figure 1).

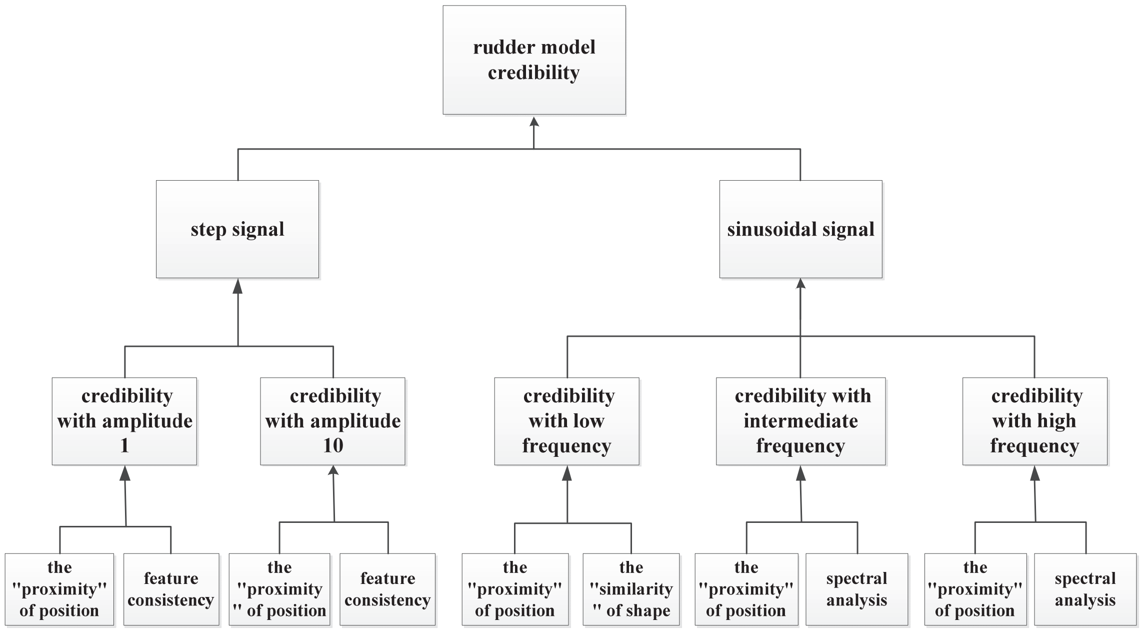

Figure 1: the Index System of the Rudder Model Result Validation

Figure 1 shows the index system. According to the characteristics of the step signal, the response characteristics (e.g. overshoot, steady state error, rise time, etc.) and the position proximity of the simulation output and the reference output under step input are concerned. According to the characteristics of the sinusoidal signal, the simulation output under sinusoidal input is divided into three frequency domain: low frequency, medium frequency, high frequency, and different indexes are used to assess consistency. Proximity of position and similarity of sharp are concerned for low frequency. For middle and high frequency, in addition to the proximity of position in time domain analysis, the consistency of frequency domain characteristics should also be concerned, so spectral analysis is used to assess consistency. The reason for that we analyze middle and high frequency separately is that the rudder works mainly in middle frequency. Therefore, the weight of middle frequency is higher than that of high frequency when we determine the index weight. The weights of index system are determined by domain experts using the AHP method.

3. RESULT VALIDATION METHODS OF THE RUDDER MODEL

According to the index system in Section 2, we carry out result validation of the rudder model by using methods of feature consistency, and data consistency. The data consistency methods including: proximity of position, similarity of shape, spectral analysis, etc. These methods are introduced below respectively.

3.1 Feature consistency

c_r is a feature extracted from a reference output Y_r. And c_s is a feature extracted from a simulation output Y_s. Relative error is used to represent their difference and is given by Eq. (1). Then we obtain the degree of consistency of c_r and c_s by mapping their difference into an interval (0,1] according to Eq. (2).

$$\eta_c = \begin{cases} \dfrac{|c_s - c_r|}{|c_r|}, & c_r \neq 0 \\ |c_s - c_r|, & c_r = 0 \end{cases} \tag{1}$$

$$V(c_s, c_r) = e^{-\lambda_c \eta_c} \tag{2}$$

Where, $\lambda_c > 0$ is a model parameter of feature consistency quantification, which is given based on the specific application domain.

3.2 Proximity of Position

$y_r = <y_r(1), y_r(2), \cdots y_r(p)>$ and $y_s = <y_s(1),\ y_s(2),\ \cdots,\ y_s(p)>$ represent the time series of reference output and simulation output respectively.

TIC coefficient (Ming Yang, Wei Li, etc. 2014) is often used to describe the position difference between two time series. The TIC algorithm is shown in Eq. (3).

$$T(y_r, y_s) = \frac{\sqrt{\dfrac{1}{p}\sum_{i=1}^{p}(y_r(i) - y_s(i))^2}}{\sqrt{\dfrac{1}{p}\sum_{i=1}^{p} y_r(i)^2} + \sqrt{\dfrac{1}{p}\sum_{i=1}^{p} y_s(i)^2}} = \frac{\sqrt{\sum_{i=1}^{p}(y_r(i) - y_s(i))^2}}{\sqrt{\sum_{i=1}^{p} y_r(i)^2} + \sqrt{\sum_{i=1}^{p} y_s(i)^2}} \tag{3}$$

Where, $T(y_r, y_s)$ is the TIC coefficient.

According to Eq. (3), $T(y_r, y_s) \in [0,1]$. It describes a relative error, which facilitates its use and comprehension. However, if we use it in simulation model validation directly, there exist some problems as below.

In Figure 2(a), $y_r(t) \equiv c_r$, $y_s(t) \equiv c_s$, $t = 1, 2, \cdots, p$. c_r and c_s are constants and $c_r \leq 0$, $c_s > 0$. Based on Eq. (3), $T(y_r, y_s) \equiv 1$. This indicates that the proximity of position of y_r and y_s is the worst, which is unreasonable obviously. In Figure 2(b), $y_r(t) = f(t)$, $y_{s1}(t) = f(t) + c$, $y_{s2}(t) = f(t) - c$, $t = 1, 2, \cdots, p$. c is a constant and $c > 0$. We can judge intuitively that $T(y_r, y_{s1}) = T(y_r, y_{s2})$, but $T(y_r, y_{s1}) > T(y_r, y_{s2})$ according to Eq. (3).

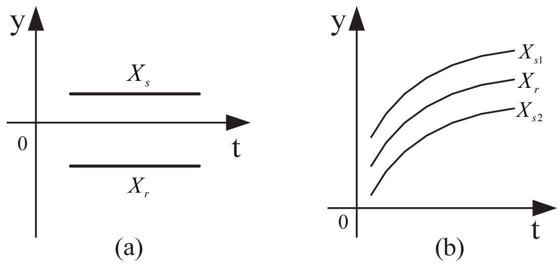

Figure 2: Reference Outputs and Simulation Outputs in Two Special Cases

The reason why the results above are not consistency is that the relative error of y_r and y_s is calculated by the benchmark of

$$\sqrt{\sum_{i=1}^{p} y_r(i)^2} + \sqrt{\sum_{i=1}^{p} y_s(i)^2} \tag{4}$$

It is not calculated by the benchmark of reference outputs. Based on the TIC coefficient, this paper proposes an improved algorithm for the proximity of position, which is shown in Eq. (5) ~ (6).

$$T(y_r, y_s) = \begin{cases} \dfrac{\sqrt{\sum_{i=1}^{p}(y_r(i) - y_s(i))^2}}{\sqrt{\sum_{i=1}^{p} y_r(i)^2}}, & \sqrt{\sum_{i=1}^{p} y_r(i)^2} \neq 0 \\ \sqrt{\sum_{i=1}^{p}(y_r(i) - y_s(i))^2}, & \sqrt{\sum_{i=1}^{p} y_r(i)^2} = 0 \end{cases} \tag{5}$$

$$d(y_r, y_s) = e^{-\lambda_d T(y_r, y_s)} \tag{6}$$

Where, $\lambda_d > 0$ is a model parameter for proximity of position quantification, which is given based on the specific application domain.

3.3 Similarity of Sharp

Grey incidence degree is adopted in this paper to describe the similarity of shape. The calculation formulas are listed in Eq. (7) ~ (8).

$$r(t) = \frac{\min_t \Delta(t) + \lambda_s \max_t \Delta(t)}{\Delta(t) + \lambda_s \max_t \Delta(t)}, \quad t = 1, 2, \cdots, p \qquad (7)$$

$$s(y_r, y_s) = \frac{1}{p}\sum_{t=1}^{p} r(t) \qquad (8)$$

Where, $\Delta(t) = |y_r(t) - y_s(t)|$; $\lambda_s \in [0,1]$ is a resolution coefficient and generally $0 \le \lambda_s \le 0.5$.

3.4 Spectral Analysis

The principle of spectral analysis is to compare the compatibility of two time series samples with same model in frequency domain. Each frequency point $\omega_i(i=0,1,\cdots,m)$ is tested respectively for consistency. If the power spectrum estimation $\hat{S}_x(\omega)$ and $\hat{S}_y(\omega)$ of each frequency point are the same, then the two time series samples are compatible. Set the spectral density estimation of two time series $\{x_t\}$ and $\{y_t\}$ are $\hat{S}_x(\omega)$ and $\hat{S}_y(\omega)$, where $\omega \in [-\pi, \pi]$.

We obtain respective spectral density through window spectrum analysis, then we describe the differences between X_{rf} and X_{sf} based on the spectral density differences. Kheir and Holmes (1978) introduced the specific principle. The spectral density difference is defined as

$$F_H(X_S, X_R) = 1 - m/M \qquad (9)$$

Where, $F_H(X_S, X_R)$ is the spectral density difference between X_{rf} and X_{sf}; M is the number of points that X_{rf} and X_{sf} are converted to frequency domain; m is the number of points that passed the compatibility test.

4. RESULT VALIDATION OF THE RUDDER SIMULATION MODEL

This section is to validate outputs of the rudder model based on the validation index system of the rudder model proposed in Section 2 and the validation methods proposed in Section 3. According to output styles of the rudder, the validation can be divided into step response with amplitude 1, step response with amplitude 10 and sinusoidal response of low frequency, medium frequency and high frequency.

4.1 Result Validation under Step Input

The step input signal here has two types: step input with amplitude 1 and step input with amplitude 10. According to the step input signal characteristics, the validation under the step input can be divided into two parts: the feature consistency and the proximity of position. Figure 3 is a schematic diagram of simulation output feature extraction on condition that step with amplitude 1 is the input signal. And Figure 4 is a schematic diagram of reference output feature extraction on condition that step with amplitude 1 is the input signal. Table 1 shows the validation result when the input signal is step with amplitude 1.

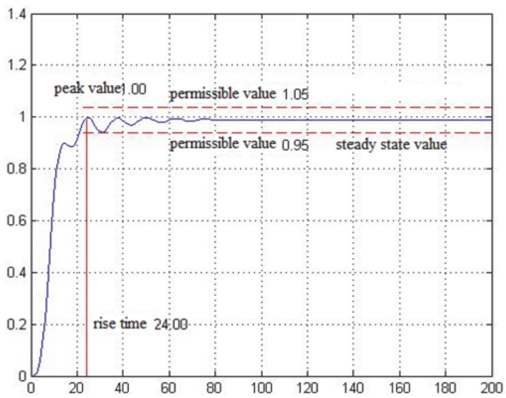

Figure 3: Experimental Output after Feature Extract under Step Single with Amplitude 1

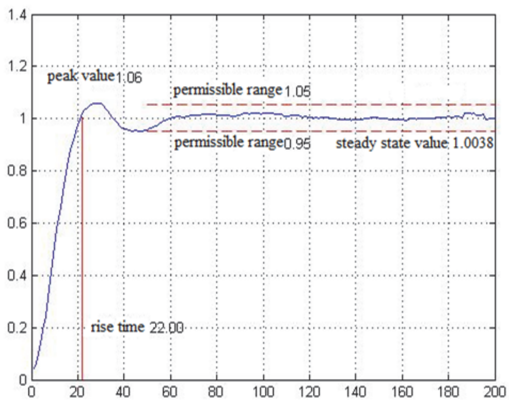

Figure 4: Simulation Output after Feature Extract under Step Single with Amplitude 1

Table 1: Date Feature and Validation Result under Step Single with Amplitude 1

Feature name	Simulation output	Experimental output	Validation result
Rise time/s	0.024	0.022	0.913
Peak value/°	1.000	1.060	0.942
Steady state value/°	0.989	1.004	0.985

4.2 Result Validation under Sinusoidal Input

Sinusoidal input is continuously variable signal from 1Hz to 50Hz. According to the characteristics of the sinusoidal signal, we divide it into three parts: low frequency, medium frequency and high frequency. Sinusoidal signal with frequency 1Hz is chosen as low frequency signal, focusing on the similarity of its position and shape. Sinusoidal signal with frequency 18Hz-22Hz is chosen as medium frequency signal, focusing on the similarity of its position and frequency spectrum. Sinusoidal signal with frequency 48Hz-52Hz is chosen as high frequency signal, focusing on the similarity of its position and frequency spectrum too.

Figure 5 is the simulation and experimental output under sinusoidal single with frequency 1 Hz. Table 2 shows the validation result under sinusoidal single with frequency 1 Hz.

Figure 6 shows the simulation and experimental output under sinusoidal single with frequency 20 Hz. The validation results under sinusoidal single with middle and high frequency are listed in Table 3.

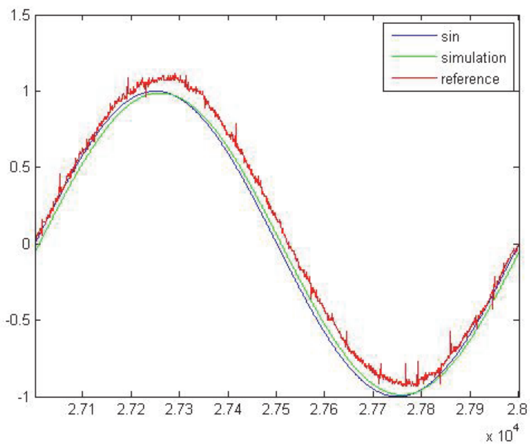

Figure 5: Simulation and Experimental Output under Sinusoidal Single with Frequency 1 Hz

Table 2: Validation Result under Sinusoidal Single With Frequency 1 Hz

Single frequency	Proximity of position	Similarity of sharp
1Hz	0.9792	0.873

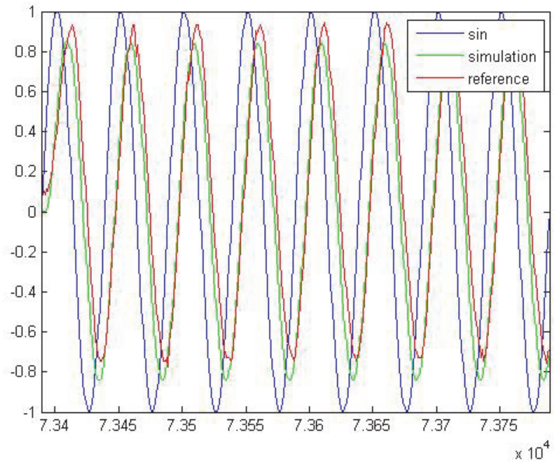

Figure 6: Simulation and Experimental Output under Sinusoidal Single with Frequency 20 Hz

Table 3: Validation Result under Sinusoidal Single With Middle and High Frequency

Single frequency	Spectral analysis	Proximity of position
18~22Hz	1.000	0.9148
48~52Hz	0.801	0.5874

4.3 Comprehensive Validation Result

The results of the rudder model validation are shown in Table 4. According to the index system given in Figure 1, comprehensive validation result is calculated using weighted average method.

According to the existing validation result, the credibility of the rudder model is 90.6 (full score of 100). Thus the rudder model is creditable. Although the entirety credibility of the rudder model is well, the credibility under high frequency sinusoidal single is poor. Therefore, the model needs some future improvements.

Table 4: Index Similarity and Model Validation Result

<table>
<tr><th>Output</th><th colspan="2">Index</th><th>Index result</th><th>Index weight</th><th>Validation result(%)</th></tr>
<tr><td rowspan="4">Step single with amplitude 1</td><td colspan="2">Proximity of position</td><td>0.987</td><td>0.8</td><td>98.7</td></tr>
<tr><td rowspan="3">Feature consistency</td><td>Rise time</td><td>0.913</td><td rowspan="3">0.2</td><td rowspan="3">94.7</td></tr>
<tr><td>Peak value</td><td>0.942</td></tr>
<tr><td>Steady-state value</td><td>0.985</td></tr>
<tr><td rowspan="4">Step single with amplitude 10</td><td colspan="2">Proximity of position</td><td>0.974</td><td>0.8</td><td>97.4</td></tr>
<tr><td rowspan="3">Feature consistency</td><td>Rise time</td><td>0.595</td><td rowspan="3">0.2</td><td rowspan="3">86.3</td></tr>
<tr><td>Peak value</td><td>0.996</td></tr>
<tr><td>Steady-state value</td><td>0.997</td></tr>
<tr><td rowspan="2">Sinusoidal single with frequency 1 Hz</td><td colspan="2">Proximity of position</td><td>0.979</td><td>0.7</td><td>97.9</td></tr>
<tr><td colspan="2">Similarity of sharp</td><td>0.873</td><td>0.3</td><td>87.3</td></tr>
<tr><td rowspan="2">Sinusoidal single with frequency 18~22 Hz</td><td colspan="2">Proximity of position</td><td>0.915</td><td>0.5</td><td>91.5</td></tr>
<tr><td colspan="2">Spectral analysis</td><td>1.000</td><td>0.5</td><td>100</td></tr>
<tr><td rowspan="2">Sinusoidal single with frequency 48~52 Hz</td><td colspan="2">Proximity of position</td><td>0.587</td><td>0.5</td><td>58.7</td></tr>
<tr><td colspan="2">Spectral analysis</td><td>0.801</td><td>0.5</td><td>80.1</td></tr>
</table>

5. CONCLUSIONS

As an important part in air vehicle, the rudder is not only an actuating mechanism of its guidance system, but also an important part of the guidance loop. The rudder model can influence the air vehicle system especially the credibility of the guidance control system, thus the rudder model is a major part of the air vehicle modeling and simulation. To ensure the credibility of a rudder model, this paper presents a result validation method of the rudder model, which used the consistency of simulation outputs and reference outputs to evaluate the credibility of the rudder model.

The main work of this paper includes: 1) Build the index system of the rudder model result validation; 2) Extract the rise time, peak value and the steady-state value under the step input as the validation feature; 3) TIC and feature analysis method are chosen for the result validation under the step input; 4) TIC, grey relational analysis and spectral analysis are chosen for the result validation under sinusoidal input; 5) Determine the comprehensive evaluation method of the index system and obtain the credibility of the rudder model.

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