# A framework of credibility assessment for CFD software

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**Abstract.** This article presents a framework of credibility assessment for Computational Fluid Dynamics (CFD) software. In order to quantify the credibility of the computational results of CFD software, this work carried out the theoretical research on credibility assessment methodology, and built a framework which consists of two parts: indicator system and algorithm for quantitative assessment. The framework specified the general elements and processes of CFD software credibility assessment, proposed the principles for the design of assessment indicator system, and developed effective quantitative algorithm, which solved the key problems such as what to assessment and how to quantify the agreement between computational results and referenced data.

**Keywords:** Computational Fluid Dynamics, Software Computing, Aerodynamics.

## 1. Introduction

CFD numerical simulation technology has been widely used in the design of fluid products. However, due to the inherent error and uncertainty of CFD algorithm, it's difficult to answer the credibility of the CFD calculation results, which restricted CFD to play a more important role. Systematic and quantitative assessment method of the credibility assessment for CFD software is a scientific problem which needs to be solved urgently.

Verification and validation (V&V) are the primary means to assess accuracy and credibility in CFD simulations. In 1998, AIAA published the first guide for CFD V&V [1], which proposed and established basic terms and methods for CFD verification and Validation. In the definition of the guide, verification is the process of determining that the conceptual (continuum mathematics) model is solved correctly by the discrete mathematics embodied in the computer code, and validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

The AIAA Guidelines have greatly promoted the concepts of validation and validation in the field of CFD and gained sustained research. These research can be roughly divided into two categories: 1)research on theoretical methods to verify software code bug and numerical error [2, 3, 4, 5, 6]; 2)validate certain problems related to fluid dynamic using several models, assess and compare the agreement between the computational results and experiment data qualitatively, such as AIAA Drag Prediction Workshop and High Lift Prediction Workshop [7, 8].But there is little research on the issue that how to assess and quantity the credibility of CFD software. With the support of the National Numerical Windtunnel (NNW) and NSAF [9, 10], this article developed methodology for credibility assessment and built a universal framework.

## 2. Elements and processes of credibility assessment

The basic strategy of CFD software reliability evaluation is to verify and quantify the reliability of software by gathering enough evidence. Usually, the evidence is the agreement between the CFD results and referenced data. Referenced data can be analytic solution, highly reliable experimental data and high-precision computational result. The assessment framework and methodology mainly focuses on what evidence to collect and how to quantify the evidence. In the field of social science, it has been formed a mature theory around assessment purpose and process, construction of assessment indicator system, determination of indicator weight, and assessment data processing [11].

Taking it as a reference and considering the characteristics of CFD software, this article build an assessment framework with two basic elements: indicator system and algorithm for quantitative assessment.

The indicator system aims to specify the assessment content and standard models for different assessment targets. The indicator system can be described with hierarchical dendrogram as shown in Fig.1.The target can be decomposed into different levels by "building-block", which ensures the scientificalness and systematicness of the assessment. Quantitative evaluation methods include validation metric method and weighting method, which study how to quantify the agreement between CFD results and referenced data and how to describe the importance of different indicators or models mathematically.

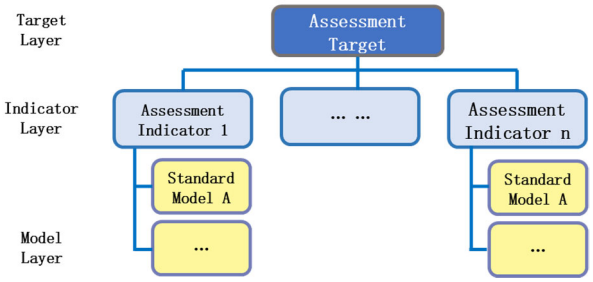


**Figure 1.** Assessment indicators architecture schematic diagram.

Based on the elements mentioned above, the process of CFD software credibility assessment can be summarized as fellow:

1) Establish assessment indicator system.

2) Simulate and quantify the agreement. Numerical simulate all standard models with the CFD software, and then quantify the agreement between CFD results and referenced data of standard models.

3) Calculate the weight of indicators at all levels.

4) Calculate score for each upper-level indicators or target to obtain overall quantitative assessment result.

## 3. Indicator system—what to assess

The assessment indicator system is composed of assessment target, assessment indicators, assessment models and hierarchical structure relationship among them. It is the basis of CFD software reliability evaluation. As shown in Fig.1, the assessment indicator system can be divided into target layer, indicator layers, and model layer. The target layer can be formulated according to the different needs of software developers, users or evaluators. The indicator layer is the specific description and decomposition of the assessment target. Several sub-indicator layers can be added according to the complexity of target. The model layer provides the standard models to evaluate corresponding indicators.

Scientificalness is the core principle for the design of assessment indicator system, which directly affects the assessment result. This article holds that six basic principles should be followed to ensure scientificalness, including

1) Purposefulness. The assessment indicator system should have a clear assessment purpose. The hierarchical structure, classification method and granularity of the indicators should be designed around the purpose.

2) Systematicness. The assessment indicators are comprehensive and specific decomposition and description of the assessment target, which needs to cover the basic content to achieve the assessment purpose.

3) Typicality. Assessment indicators should be as simple and accurate as possible to reflect typical problems concerned for assessment purpose.

4) Operability. The assessment indicators need to be operable and practical. For CFD reliability assessment, the availability of standard model data and acquisition cost should be considered.

5) Quantifiability. The indicators are quantifiable.

6) Expandability. With the development of software and assessment requirements, indicators can be dynamically corrected, supplemented and eliminated.

## 4. Algorithm for quantitative assessment

Quantitative assessment algorithm includes two parts: validation metric algorithm and indicator weighting algorithm.

### 4.1 Validation metric algorithm

Validation metric algorithm is used to quantify the agreement between CFD results and referenced results. The rating interval can be set to a range of (0, 1], with a full score of 1 when the CFD results are exactly the same as the referenced data. Different scholars put forward their own understanding of the ideal characteristics of CFD Validation metric [12, 13, 14]. This article holds the most basic and the most common feature, which includes

1) Quantitative. The metric should be a quantitative assessment of agreement between CFD results and referenced results;

2) Objective. For the given CFD results and referenced results, the metric obtained by different analysts should be determined and identical.

By investigating and practicing several algorithms, it is recommended to use the algorithm proposed by Oberkampf [13] for assessment of CFD software. The formula is

$$V = 1 - \frac{1}{n}\sum_{i=1}^{n} \tanh\left|\frac{y_{i,c} - y_{i,e}}{y_{i,e}}\right| \tag{1}$$

Where V is the validation metric, $y_{i,e}$ and $y_{i,c}$ represent the referenced results and computational results respectively. This type of metric is based on comparison of relative error for each of the individual measurements and the computations, which has the following advantages. It normalizes the difference between the computational results and the experimental data. When the difference between the computational results and the experimental data is zero at all measurement locations, then the validation metric is unity. When the summation of the relative error becomes large, the validation metric approaches zero.

### 4.2 Indicator weighting algorithm

Since the importance of different indicators is varied, it's necessary to set weight for different indicators to make the assessment more scientific. Indicator weighting algorithm is used to determine the weight of indicators scientifically.

Weighting methods can be divided into subjective methods and objective methods. Subjective methods have been studied earlier, and theoretical methods are relatively mature. The weight reflects the importance of indicators and is used to strengthen the impact of key indicators on assessment result. Objective methods become a hot topic in recent years, whose weight reflect and highlight data difference between participants. When new participants are added, weights need to be updated. Both kind of methods are widely used for different assessment purposes. For CFD software reliability assessment, subjective methods which can reflect the importance of indicators is more applicable and commendatory. There are many subjective weighting algorithms. One useful and easy algorithm is the sequential relationship analysis [15]. It is based on the simplification of classical analytic hierarchy process (AHP) [16], and has similar principles but less calculation. The basic steps of are as follows.

1) Rank indicators by importance. Rank indicators in descending order of importance to determine the ranking relationship.

2) Qualitatively compare and describe the relative importance of indicators. Compare the relative importance of adjacent indicators as the ranking order, and describe the relationship of importance using qualitative linguistic values such as "equally important", "slightly important", "significantly important".

3) Quantify the importance relationship. According to the scale law shown in Table 1, quantify the importance relationship. The quantified value represents the weight ratio between two indicators. Set the weight of the k-th indicator as

$$r_k = w_{k-1} / w_k, k = m, m-1, m-2 ... 3, 2 \tag{2}$$

**Table 1.** Preface relationship law.

| Importance relationship | $r_k$ |
|---|---|
| I is the same important as J | 1 |
| I is slightly more important than J | 1.2 |
| I is obviously more important than J | 1.4 |
| I is intensely more important than J | 1.6 |
| I is extremely more important than J | 1.8 |

4) Calculate the weight. Since the sum of weights of all indicators is 1, the weight calculation formula can be deduced as

$$\begin{cases} w_m = \left(1 + \sum_{k=1}^{m-1} \prod_{i=k}^{m-1} r_i\right)^{-1} \\ w_k = \prod_{i=k}^{m-1} r_i \cdot w_m, k = 1,2,3...,m-1 \end{cases} \tag{3}$$

When using the subjective methods, in order to minimize the impact of the randomness and subjectivity of single decision maker as much as possible, multiple experts need to be invited to make group decisions to ensure the scientificity.

## 5. Example

This chapter gives a simple example of software assessment.

1) Establish indicator system. For simplicity, this chapter is not demonstrated according to a complete assessment indicator system, while a simpler indicator system is chose, as shown in Fig.2. The assessment target is "Credibility of high lift configuration" and divided into three indicators, including the simulation credibility of lift(Cl), drag(Cd) and pitch moment(Cm). The DLR-F11 is selected as the standard model, which is widely used to investigate the prediction ability of CFD software for high lift configuration in High Lift Prediction Workshop.

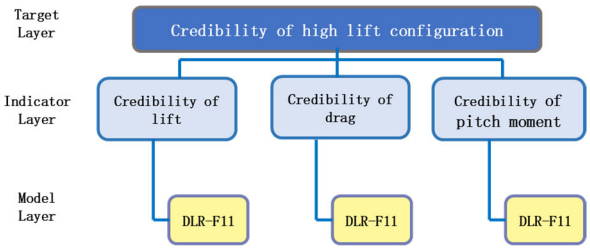


**Figure 2.** Indicator system.

2) Simulate and quantify the agreement. The configuration of DLR-F11 is numerically simulated with self-developed software A and commercial software B to obtain the aerodynamic characteristics. The agreement between computational results and experiment data is shown in Fig.3, and is quantified with the validation metric algorithm. The result is shown in Table 2. From the point of

view of score, it can be intuitively found that self-developed software and commercial software have comparatively accuracy, and the self-developed software has slightly higher accuracy in lift and pitch moment than commercial software.

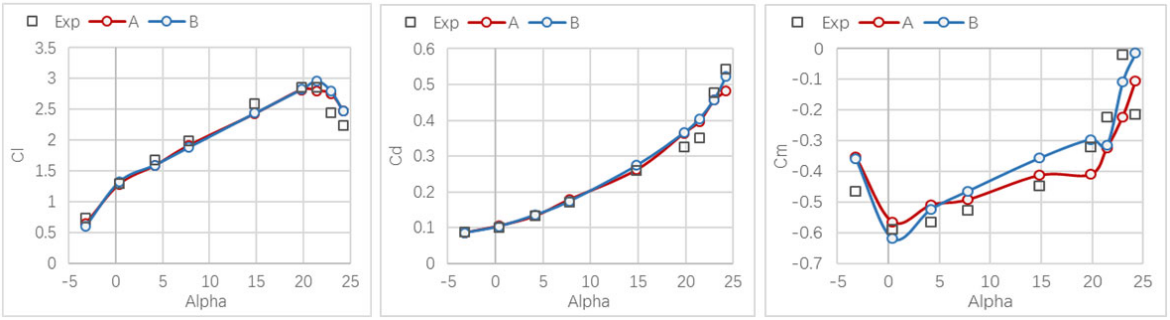


**Figure 3.** Comparison of aerodynamic force characteristics.

**Table 2.** Indicator quantification result.

| Indicator | Software A | Software B |
|---|---|---|
| Lift | 0.9654 | 0.9619 |
| Drag | 0.9526 | 0.9615 |
| Pitch moment | 0.8777 | 0.8794 |

3) Calculate the weight of indicators. Assume that the "lift" indicator is obviously more important than the "pitch moment" indicator, and the "pitch moment" indicator is slightly more important than the "drag" indicator, then calculate the weight of lift, drag and pitch moment indicators with the sequential relationship analysis. The weights are shown in Table 3.

**Table 3.** Indicator weighting result.

| Indicator | Weight |
|---|---|
| Lift | 0.4330 |
| Drag | 0.2577 |
| Pitch moment | 0.3093 |

4) Calculate score for each upper-level indicators or target. Based on the scores and weights of lift, drag and pitch moment indicators, the overall assessment scores for aerodynamic characteristics simulation capability of high lift configuration can be calculated. The result is shown in Table 4.

**Table 4.** Overall assessment results.

| Software | Overall Score |
|---|---|
| Software A | 0.9363 |
| Software B | 0.9350 |

## 6. Conclusion

This paper studied the theoretical methodology of CFD software credibility assessment from two aspects of "assessment indicator system" and "quantitative algorithm", established the design principles of indicator system, developed effective indicator quantification algorithm and indicator weighting algorithm, and proposed the general process of CFD software credibility assessment, which formed a universal framework of credibility assessment for CFD software.

## Acknowledgments

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