Stiffness-similar models for wind tunnel tests based on 3D printing

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Abstract. Wind tunnel testing is a reliable means for R&D aerial vehicles of aerospace, e.g. aircraft, missiles, rockets etc. The wind tunnel models are the objects used in the tests, and stiffness-similar models are important for the structural and aerodynamic design of aerospace vehicles. The accuracy and economy of the model design and fabrication have a significant impact on the quality and cycle of vehicle R&D. The review will first give an overview introduction of the wind tunnel models with stiffness-similarity, and then detail design procedure and fabrication processing, which are developed by the author’s group based on 3D printing. The review can provide new methods to design and fabricate stiffness-similar models for wind tunnel tests for designers and researchers concerning the structural and aerodynamic studies in the aerospace industry.

1. Introduction
Despite the significant development of numerical computing and flight testing, the current aerospace industry heavily relies on experimental data from wind tunnel tests [1-3]. As depicted in figure 1, wind tunnel tests show particular importance for the concept design, which determines the full-life-cycle performance and economy of vehicles [4]. The increase of the flight speed and the structural complexity of air vehicles, coupled with the need to avoid risky and costly problem identification during flight testing, have actually driven continued increases in wind tunnel tests [5].
Figure 1. Wind tunnel tests in the R&D aerial vehicles [4].

Wind tunnel models are reduced-scale alternatives to the prototypes of aerial vehicles used in wind tunnels. The design and fabrication of wind tunnel models is of an important aspect to the quality and cost of data-acquisition. The fabrication of wind tunnel models has traditionally been a highly skilled and time-consuming process [6], and remarkable efforts have been made to improve the models [7, 8]. As shown in figure 2, the introduction of 3D printing (or additive manufacturing, rapid prototyping) into model fabrication has received much attention [9,10]. A number of studies[11-14] have demonstrated the advantages of 3D printing for building wind-tunnel models in speed and cost relative to traditional techniques.

Figure 2. Comparison of model design and fabrication based on traditional and 3D printing technologies.

Among all the models used in the wind tunnel tests, models possess stiffness similarity with the real vehicle are especially important to study the dynamic, aerodynamic and aeroelastic properties of the aerial vehicles [1, 15]. To quantitatively represent the real vehicle (the prototype) operated the atmosphere, the stiffness-similar models test in the tunnels should maintain a similar aerodynamic shape (geometry similarity) and similar structural parameters (stiffness similarity) with the real vehicle [3]. Traditionally, the design and fabrication of stiffness-similar models are difficult and time-consuming. 3D printing can directly fabricate 3D parts through accumulating raw materials of different type, e.g. plastics with low modulus and density built by Stereolithography (SL), Selective Laser Sintering (SLS), and Fused Deposition Modelling (FDM). A remarkable aspect of 3D printing is the ability to produce internal forms, that would be difficult to fabricate by traditional techniques. The introduction of 3D printing in the fabrication of stiffness-similar models with complex internal structure, can greatly improve the model fabrication, such as reducing the number of parts, and have the potential to change current strategy of the model design.
The paper will give an overview introduction of the design requirements of stiffness-similar models, and detail technologies concerning the design and fabrication of two types of these models developed by the authors’ group based on 3D printing [16-20]. The first one is a kind of static aeroelastic models meeting the geometry and stiffness similarities [7, 16]. Integral shell made by 3D printing with stiffness-contribution to the whole model was emphasized. The second model is of dynamic that meets stiffness and mass similarities [18]. Thanks to the good fabrication capacity of 3D printing, structure similarity was also obtained and it has not been reported by other groups adopt traditional techniques.

2. Overview of stiffness-similar models

2.1. Requirements

According to test purposes, the model should meet similarity requirements, measuring requirements, strength requirements, etc. Among them, similarity requirements are the of most critical. Wind tunnel models are designed according to the similarity requirements [21] that determine the factors scaling-down from aerial vehicles(prototypes). The geometric similarity (External contour) means that the external contour of the model is consistent with the vehicle (after scaling, the same below) to ensure the similarity of the flow, which is the basic criterion to be met by all models. The stiffness similarity and mass similarity determine internal structure of model that has the same stiffness and mass distribution as the vehicle, according to which static elastic models and free-flight models are designed. For dynamic models, e.g. flutter models, the dynamic similarity should be meet. For models discussed in the paper, the stiffness similarity is of importance that determines internal structure of model.

2.2. Model design and fabrication based on 3D printing

Based on 3D printing, the design and fabrication procedure of the model is shown in figure 3, including demand analysis, model designing, printing (fabrication), calibration and wind tunnel tests. In designing step, the corresponding parameters of the model are obtained from the geometry and structure parameters of the vehicle prototype according to the similarity requirements. After data processing of the design result (e.g. CAD), the database is generated and the physical model is fabricated by the 3D printers. To ensure the accuracy and safety of tests, the model must pass the strength calibration, stiffness calibration, vibration calibration etc. And then the model can be installed and test in the wind tunnels to obtain aerodynamic data.

![Figure 3. Procedure of models based on 3D printing technologies.](image)

3. Static aeroelastic models with integral shells [16]

The aeroelastic models are used to study the aeroelasticity of aerial vehicles, which is one of most aspects concerning the safety and performance for high-speed vehicles, e.g. fighters, missiles, etc. The static aeroelastic model was mostly in a beam-shell structure with the beam(s) to provide all the stiffness and the segmented shells to keep the aerodynamic contour, as shown on the left side of figure 4. Based on 3D printing, a new structure of static aeroelastic models with an integral shell was developed, as shown on the right side of figure 4. The structure can solve the influence of the deformation of the segmented shells on the aerodynamic shape of the model, and thus ensured the
accuracy of the wind tunnel test [16, 20].

![Figure 4. Structures of static aeroelastic models with a segmented shell [22] and an integrated shell [16].](image)

### 3.1. Model design

#### 3.1.1. Design of segment structures.

As mentioned above, the model wing consists of a single steel spar and a single plastic shell made by SL. For convenience of design and fabrication, the rectangular section was adopted for the metal spar. For the integral shell, its dimensions of its internal cavity were designed according to the stiffness similarity. To more accurately simulate the torsional deformation of the vehicle prototype and ensure the stiffness similarity, a vertical web was designed at the rear edge of the model that divided the cavity into two independent chambers. Fixing holder and mounting surface were designed to ensure reliable bonding of the spar and shell.

#### 3.1.2. Optimization of stiffness distribution.

The optimal design method was adopted to determine the structural dimensions of the selected sections. The objectives of the optimized design included the position of the cross-section twist center and the dimensions of the beam and the shell. Constrained gradient-based optimization algorithm is adopted in the work. The implementation of the stiffness design is provided by the ANSYS software package. The algorithm is named as the First-order method in the package, which makes use of derivative information that is formed for the objective function and leads to a search direction in design space. The optimization results shown that errors of the bending stiffness are less than 5%, errors of the torsional stiffness and the shear center position are less than 2%, which are acceptable for industrial purposes.

### 3.2. Model fabrication and test

#### 3.2.1. Model fabrication.

As shown in figure 5, the model CAD obtained from the similarity design was processed during the data preparation where the whole model was sectioned into parts according to the printing envelope of the printer and support structures were added to ensure the model stability during fabrication. With the data, model parts were printed by the SPS450B printer, a home-made SL machine. Supports were removed and the residual raw materials were clean to obtain the green parts of the model. In order to improve material properties and surface roughness, the model parts were post-cured and sand blasted.

![Figure 5. Fabrication procedure of the model [20]](image)
3.2.2. **Stiffness calibration.** The model deformations under loads were measured by a non-contact optical system. As shown in figure 6(a), the resin shell was assembled on the metal spar and fixed on the workbench by the clamp. Figure 6(b), shows the typical distribution of the wing deformation along the spar, including both the measured (experiment) and calculated (simulation) values. The calculated values were obtained using the same fixing and loading condition. In general, the simulated and measured values were generally very consistent, as the maximum deviation was less than 5%.

(a) Configuration of the stiffness calibration test, (b) comparison of the deformation results from the measurement and the simulation

**Figure 6.** Setup for the calibration test and typical results.

3.2.3. **Wind tunnel testing.** The wind tunnel test was conducted in the FL-24 transonic wind tunnel (Aerodynamics Research and Development Center, P. R. China) using a test section with a size of 1.2 m × 1.2 m. The model installed in the wind tunnel is shown in figure 7 (a). It can be inferred that the model's torsional divergence Mach number was in the range of 0.6 to 0.65, which is consistent with the prototype's torsional divergence condition (Ma=0.63). This verified the feasibility of the static aeroelastic model structure.

(a) Assembled model installed in the wind tunnel, and (b) lift coefficient according to AOA

**Figure 7.** Setup and typical results of the wind tunnel test [16].

4. **Dynamic models with similar internal structures [18]**

Dynamic models are used in wind tunnel tests to investigate flutter and other aeroelastic characteristics of aerial vehicles, e.g. high speed aircraft, missiles, etc. [23]. To map the data of the tests to the actual flights, the dynamic model should meet most of similarity requirements, e.g. geometric similarity, stiffness similarity and mass similarity. The design and fabrication of this kind of model are traditionally complex and time/cost-consuming. Based on 3D printing, this work developed a new design and fabrication method for low-speed wind tunnel flutter models[18]. Benefiting from the low elastic modulus of SL resins and the fabrication capacity to build complex structures of SL process, structural similarity between models and prototypes could be ensured.

As shown in figure 8, structural similarity between the aluminum vehicle prototype and the SL model was obtained due to the consistency of both external and internal structures of the wing-box. On the contrary, as several simplifications must be made, e.g. the scaled dimensions are too small to be machined if the same structure is maintained, current metal-based models were usually some simplified versions of prototypes. Therefore, compared with traditional methods, the SL-based method could be expected to design and fabricate aeroelastic models with higher similarity accuracy in the
sense of load-path matching.

![Figure 8. Structural similarity of metal and plastic models to the vehicle prototype.](image)

4.1. Design of the model

4.1.1. General procedure. The procedure of the work includes design, fabrication and test of the model. To obtain the SL model, a three-step design procedure was conducted, including dimensional scale-down, optimization design of stiffness and optimization design of mass. To assess the feasibility of this method, the dynamic behaviours of the fabricated model were tested.

4.1.2. Optimization design of stiffness. MEIC (Matrices of Elastic Influence Coefficients, [24]) method was adapted to obtain the structural dimensions of model according to the stiffness distribution scaled-down from the vehicle prototype. The similar stiffness is defined as similar displacements under similar loads in specific directions which were determined by the desired modes from the modal analysis of the model. The procedure of stiffness design was formulated as an optimization problem, and was implemented with ANSYS software. Through sequential calculations of Single Run, DV Sweep and First-Order, the stiffness similarity was obtained with an average error of less than 5%.

4.2. Fabrication and test of the model

4.2.1. Fabrication. With the CAD data from design procedure, the wing-box was fabricated with SPS450B SL printer through data processing, printing and post-treating, as shown in figure 9.

![Figure 9. Fabricating procedure of the model based on SL [25].](image)
4.2.2. Stiffness calibration test. A non-contact optical testing system was adopted to measure the deformation of the model. The Cartesian coordinates of the model on selected points were measured and the deformation was calculated by comparing the values before and after loading. The configurations for physical testing and simulating computing (FEM) are depicted in figure 10 (a) and (b). The same loading condition was brought to both the physical and simulating models. As shown in figure 10 (c) and (d), the deformations of the physical and simulating models were very consistent. The maximum error of 3.4% means the property fluctuation of material stiffness is very small and acceptable for the model design.

![Stiffness calibration test setup and results](image)

(a) Deformation test; (b) Simulating computation
(c) Deformation of the test; (d) Results of Simulating computation

**Figure 10.** Stiffness calibration test setup and results [17].

4.2.3. Dynamic calibration Test. A laser-vibration-measuring apparatus PSV-400 from Polytec Corp. was employed to test the dynamic behaviors of the model. figure 11 (a) and (b) demonstrates the test setup. As shown in the figure 11(c), the actual results matched the desired data fairly, and it can be concluded that the SL model can represent the aluminium vehicle prototype in the prediction of dynamic behaviours.

![Setup and results of the modal calibration test](image)

(a)Configuration of the test; (b) Excitation of the model; (c) 1st bending modal of the model

**Figure 11.** Setup and results of the modal calibration test.

5. Conclusion and future studies
The paper reviewed the authors’ work to develop two kind of with stiffness similarity, e.g. static aeroelastic models with stiffness-contributing integral shells and dynamic models with similar internal load-transiting structures. The models were designed according to the requirements of stiffness-similarity and implemented with the optimization method. They were fabricated with photocurable plastics by Stereolithography, one of the 3D printing processes. The stiffness calibration tests reveals good consistency of the actual stiffness distribution with the desired one. 3D printing can greatly
improve both the design procedure and fabrication economy of wind tunnel models. Thanks to the good fabrication capacity for complex internal structures and compatibility of many easy-tailoring-performance materials, e.g. soft non-metal materials, new kinds of models can be designed and fabricated, which can help to improve the acquisition quality and economy of aerodynamic data from wind tunnel tests for aerial vehicles designers.

However, due to the property inferiority of the pure plastics and the limited fabrication envelope of the 3D printer, these models can only be used for preliminary studies in low speed tests. Recently, significant advances have been made in the printing of light-weight composites with high-performances [26], several printers with large envelope are commercially available [27]. The technique has promising potential to efficiently build stiffness-similar wind tunnel models with high-performance materials, which could extend the utility of 3D print models in the high-speed test for aerial vehicles R&D.

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