Wind tunnel testing of additive manufactured aircraft components

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Abstract

Purpose – This paper reports upon the physical distortions associated with the use of additive manufactured components for wind tunnel testing and procedures adopted to correct for them.

Design/methodology/approach – Wings of a joined-wing test aircraft configuration were fabricated with additive manufacturing and tested in a subsonic closed-loop wind tunnel. Wing deflections were observed during testing and quantified using image-processing procedures. These quantified deflections were then incorporated into numerical simulations and results were found to agree well with wind tunnel measurement results.

Findings – Additive manufacturing provides cost-effective wing components for wind tunnel test components with fast turn-around time. They can be used with confidence if the wing deflections could be accounted for systematically and accurately, especially at the region of aerodynamic stall.

Research limitations/implications – Significant wing flutter and unsteady deflections were encountered at higher test velocities and pitch angles. This reduced the accuracy in which the wing deflections could be corrected. Additionally, wing twists could not be quantified as effectively due to camera perspectives.

Originality/value – This paper shows that additive manufacturing can be used to fabricate aircraft test components with satisfactory strength and quantifiable deflections for wind tunnel testing, especially when the designs are significantly complex and thin.

Keywords – Additive manufacturing, Wind tunnel testing, Joined-wing aircraft, Aerodynamics

Paper type – Research paper

1. Introduction

One of most intriguing aircraft types currently undergoing significant research is the unconventional joined-wing configuration, whereby two sets of wings are attached to the fuselage and joined at their tips to form “diamond-shaped” wings. The main motivation driving the present interest in such configurations lies in the sharp growth in air traffic volume in recent years. In addition to the increase in air travel, there is also increased pressure on airline operators to exercise their corporate social responsibilities by minimizing aircraft emissions. To address these issues, alternative aircraft designs are being pursued and joined-wing configuration shows promise of improved aerodynamic efficiency. The joined-wing was first proposed by Wolkovitch (1986), and has the horizontal stabilizer sweeping forward to connect with the conventional main wing to form a diamond shape in both the frontal and planform views. Another similar concept is the PrandtlPlane, aptly named by Frediani (2005) as it arises from Prandtl's work on biplanes and multiplanes (Prandtl, 1924). It derived from Prandtl's search for the configuration with the least induced drag and the result is the PrandtlPlane, where another wing connects the wing tips of the upper and lower wings. Kroo (2001) and Demasi et al. (2015) and many others have investigated on the aerodynamic efficiency of non-planar wing systems and reduction of induced drag.

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However, it is still not obvious if any penalties incurred by implementing this configuration would be more significant than the benefits in the reduction of the induced drag. Therein lies the need for further testing in wind tunnel testing to further evaluate the pros and cons of such a configuration.

When a joined-wing configuration is to be scaled down to fit typical wind tunnel test sections for any aerodynamic testing, it will soon be clear that the wings will have to be relatively thin and conventional manufacturing methods such as CNC machining will be inadequate. Note that it is always preferred for joined-wings to be fabricated as a complete piece rather than individual machined parts welded together, for the sake of material and strength consistencies. Additive manufacturing is able to circumvent the above-mentioned concerns associated with conventional manufacturing, on top of a much shorter production time. . Although Chuk and Thomson (1998) previously reported that rapid prototyping then would not be able to totally replace conventional machining for load wind tunnel parts due to their structural integrity, current state-of-the-art is now able to resolve this issue. Improvements in printing techniques and material selection made it possible to fabricate satisfactory wind tunnel models, as shown by the various studies conducted over the years [Hildebrand et al. (2003), Heyes and Smith (2004), Tyler et al. (2005), Zhou et al. (2008), Yang et al. (2011), Zhu et al. (2011), Yang et al. (2013), Wang et al. (2015)]. In particular, Hildebrand et al. (2003), Heyes and Smith (2004) and Tyler et al. (2005) took advantage of additive manufacturing to include intricate internal structures within the models for placing multiple pressure taps. To improve the structural strength of the models, Zhou et al. (2008) coated the model with an electrodeposition layer of nickel, while Yang et al. (2011, 2013) and Wang et al. (2015) used an internal metal frame to support the outer layer, manufactured with

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3 a photopolymer resin through additive manufacturing, which formed the geometry of interest.
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6 Zhu et al. (2011) also demonstrated that it is possible to design wind tunnel models with similar
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8 external geometry, internal structure and stiffness in comparison to the actual model, to better
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10 study the aero-elastic effects.
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15 However, it is expected that potential aero-elasticity effects such as wing deflections will be
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17 observed during the experiments, due to the choice of the material used for the additive
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19 manufacturing. Generally speaking, it would be challenging to analytically evaluate the
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21 deflections due to the complex designs of the joined-wing component, even when a known load
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23 is applied. Take for instance, finite element analysis conducted by Patil (2003) showed good
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25 correlations with experimental results captured at smaller wing loads, but failed to accurately
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27 capture the wing tip deflections as the loads were increased.
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34 Unlike a conventional wing, which can be modelled as a cantilever beam after taking into
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36 account the relatively straight-forward wing geometry, the entire joined-wing component has to
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38 be evaluated as an integral structure as the wings are all connected. In addition, the flow
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40 behaviour and aerodynamics of the two sets of wings for each joined-wing configuration
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42 mutually influences each other and there is no intuitive way to determine the spanwise wing
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44 loading distribution under such circumstances, especially at aerodynamic stall. The purpose was
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46 to verify the hypothesis proposed by Teo et al. (2016) that wing deflections might have caused a
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48 discrepancy in the stall angle predicted by CFD as compared to experimental results, as the wing
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50 deflections were not accounted for in the CFD analysis. In view of these challenges, an
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experimental and numerical study was conducted to look into the feasibility of correcting wing deflections associated with additive manufactured joined-wing components empirically.

2. Experimental Setup and Procedures

2.1 Wind tunnel

A subsonic closed-looped wind tunnel with a test section size measuring 0.72m (H) × 0.78m (W) × 2m (L) was used for this study. The maximum operating free-stream velocity is 80m/s and it has a streamwise turbulence intensity level of 0.1%. A sting balance measures the aerodynamic forces and moments acting on the mounted test models, with 0.11% full-scale (i.e. 500N) accuracy for the drag component and up to 0.14% full-scale (i.e. 600N) accuracy for the lift component. The angle-of-attack (AOA) can be varied from -10° to 25° through computer control and all data acquisition were performed by a National Instruments data-acquisition platform using LabView™ software. During the experiments, the data was acquired at a sampling rate of 47Hz for 30 seconds for each AOA.

2.2 Wind tunnel models

6061 aluminium alloy was used to manufacture the aircraft test model fuselage, where it has a maximum surface roughness of Ra 40 microns. In contrast, polyamide (PA) 2200 or nylon, was used to manufacture the joined-wings. Due to physical scale of the test aircraft, it was difficult to manufacture the joined-wings, especially at the joints, unless additive manufacturing was used. Nylon was chosen after material characteristic strength, surface finishing, cost and time were taken into account. It should be noted that the strength of the material used is crucial, since the joined-wings had to withstand the full extent of the aerodynamic forces throughout the entire

study. In this case, the nylon material used has a reported flexural modulus of 1500MPa and flexural strength of 58MPa, which were deemed to be sufficiently robust for the wind tunnel experiments to be conducted. Surface finishing is important as well, as it may affect the location and extent of flow transitions, which in turn impact upon the resulting aerodynamic behaviour, forces and moments. For a satisfactorily smooth surface finishing, the additive manufactured wings were carefully sanded down using 2000 grit sandpaper.

All geometric information of the test models were contained in the Common Parametric Aircraft Configuration Schema (CPACS) file format. CPACS is a text based file based on Extensible Markup Language (XML) and was introduced by Nagel et al. (2012) to tackle the problem of managing the vast amount of data generated when doing a multi-disciplinary optimization (MDO) of an aircraft design. In addition to the geometry, results from aerodynamic analysis can also be stored in CPACS. TiGL Geometry Library (TiGL) can then be used to visualise the geometric information stored in CPACS, and also export it into neutral Computer-Aided Design (CAD) formats such as Stereo Lithography (STL), which can be used directly for additive manufacturing purposes. This simplifies the design process as all the required information is stored within a single file.

2.3 Joined-wing aircraft test models

The joined-wing test configuration studied in the present investigation was based on an earlier study carried out by Bottoni and Scanu (2004). The PP250 model used in that study was scaled down to fit the wind tunnel test section and minimize wind tunnel wall effects. To better highlight the performance of the joined-wings, the fuselage was modelled as a simple sharp-

Figure 1. PP250 joined-wing test model mounted on the sting balance in the wind tunnel test section

ogive cylinder with a diameter of 0.06m, length of 0.528m and fineness ratio of 2.5. While a higher fineness ratio could have led to improved lift-to-drag performances (Mayo, 1965), the physical geometry was constrained by the size of the test section. The span of the joined-wing measures 0.372m and the front wing root and tip chords are 0.049m and 0.01m respectively. For the rear wing, the root and tip chords measure 0.034m and 0.025m respectively. More importantly, note that the thickest cross-section of the joined-wing structure measures only 0.002m at the front wing tip, which further justified the use of additive manufacturing here. Figure 1 shows a photo of the complete test model installed within the wind tunnel test section. The model was tested based on a free-stream velocity of 30m/s, which resulted in a test Reynolds number of $Re=62,000$ based on the mean aerodynamic chord and experimental conditions.

2.4 Wing deflections and correction procedures

To quantify any wing deflections, a digital single-lens reflex (DSLR) Canon EOS 550D camera equipped with a 50mm, $f1.4$ lens was used to capture images of the test model from two orientations during the experiments. Side-view images of the test model were taken outside of the test-section to quantify deflections in the vertical axis, while spanwise curvatures of the wings were captured by positioning the camera inside the wind tunnel test section. For the second orientation, the camera was mounted onto a plate with pivot joints such that the camera

Figure 2. Camera setup located (a) by the side and (b) inside of the wind tunnel test section circled in red

height and angle could be easily adjusted. During the experiments, the plate was adjusted to match the AOA of the test model so that the camera faced the model normally. Figures 2(a) and 2(b) show the camera setup by the side of as well as inside the wind tunnel test section respectively.

As the aim of the present study is to look into whether variations in the lift performance caused by wing deflections at the stall point can be systematically corrected for, two AOAs of 8° and 10° were chosen to illustrate the deflection correction procedures here. In this present study, only wing deflections were accounted for within the present study, while wing twists were not. The primary reason was that overall wing distortions due to wing deflections were significantly more severe than due to wing twists. Hence, aerodynamic corrections for wing deflections were deemed to be more critical than those for wing twists. Additionally, significant additional equipment not available to the present study would have been required if both wing twists and deflections were to be tracked and corrected simultaneously. To calculate the wing deflections, images of both the stationary and deformed wings were first read into MATLAB. Excess area was then cropped out to reduce the computational time, after which the coloured images were

Figure 3. Deflections (in red colour) for $AOA=8^\circ$ at $Re=62,000$, as captured from the (a) side- and (b) rear-views

then converted into binary images to pick out the outline of wings. With the location data of the boundary of the wings picked out, the deflections could then be calculated.

For the $8^\circ AOA$, the white nylon wings provided good contrast against the black wind tunnel background and a MATLABTM script was able to correctly identify the wing deflections. For $10^\circ AOA$ however, the increase in the pitch angle rendered part of the background to include the lightly coloured wind tunnel wall. This resulted in poor colour contrast and the deflection could not be identified with the same script. In this case, a digitizer was used instead to visually pick out the deflections where 10 equidistant points were marked along the joined-wing trailing-edges to create smooth splines to model the curved wings. Figures 3(a) and 3(b) show the deflections captured for $8^\circ AOA$ from the side- and rear-views of the joined-wing test model respectively. The images with the deflections were then superimposed on the stationary images for comparison.

Based on the images and procedures described earlier, the maximum deflection results at the wing tips are presented in Table 1. The accuracy of the methods was based on the pixel count

Table 1 Maximum wing tip deflection magnitudes.

Wing/AOA	y [m]
Upper wing/8° AOA	0.0067
Lower wing/8° AOA	0.0068
Upper wing/10° AOA	0.0064
Lower wing/10° AOA	0.0086

and pixel-size to real-world dimension calibration information, and was determined to be $\pm 0.00012\text{m}$. The semi-span of the wing was used as the reference length for the calibration. The deflections were most significant in the y-axis or the vertical direction, as shown in Figure 3(b).

3. Numerical Simulations

Teo et al. (2016) reported a slight discrepancy between the numerical simulation and wind tunnel experimental results around the stall angle region, where it could have resulted from the omission of modelling the wing deflections in the simulations. To address this, wing deflection data and curvatures extracted from the images captured in the present study were included into the joined-wing geometry through modifying the CAD model and the simulations repeated at the two selected AOAs after regenerating the grids. It is worth mentioning that there were a few assumptions taken for the present numerical simulation and analysis. Firstly, wing curvatures captured experimentally were only incorporated into the upper and lower wings. This was because contribution to both the lift and drag forces from the middle wing was insignificant compared to those by the upper and lower wings. Hence the deflection of the middle wing was neglected although all the three wing sections (i.e. upper wing, lower wing, as well as the middle wing connecting the upper and lower wings) were deflected. Secondly, the lower wing root was

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assumed to originate from the same location as before. Thirdly, the vertical tail remained non-deflected and was at the same location as before.

For a fair comparison, the new mesh created for the modified geometry was very similar to that of the original geometry through the use of edge sizing and surface sizing. Edge-sizing controlled the number of points along a given edge, while the surface-sizing controlled the sizes of the grids on a given surface. Combining these two measures helped to minimize any discrepancy between the two grids. Although utilizing grid deformation methods would ensure that the grid topology remains the same, such an approach may severely deteriorate the mesh quality through skewness of the cells when deformations are significant. Moreover, Martin-Burgos (2017) notes that there are still deficiencies of mesh deformation methods when used in areas with moving intersections. In this case, the tips where the wings meet and join form such an intersection and hence, regenerating the mesh was deemed as a more appropriate approach.

For the numerical simulations, a commercial finite volume-based solver was used to solve the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, where second-order upwind schemes were used. The Spalart-Allmaras (SA) one-equation turbulence model was used to model the transport equation (Spalart and Allmaras, 1992). Due to the low speeds of the test condition, the air density and viscosity were assumed to remain constant under incompressible flow conditions. The free-stream conditions were introduced by a velocity inlet and pressure outlet. To reduce computational time, a symmetry boundary condition was also imposed. Non-slip wall conditions were imposed upon the surfaces of the test-model to be modelled in the simulations. The grid created for the updated geometry had 6.7 million elements.

Table 2 Comparison of C_L values and % difference with respect to the wind tunnel results.

	Wind tunnel	Original CFD	Deflected CFD
8° AOA	0.548	0.625 (+14.1%)	0.505 (-7.86%)
10° AOA	0.611	0.700 (+14.5%)	0.648 (+5.94%)

Table 3 Comparison of C_D values and % difference with respect to the wind tunnel results.

	Wind tunnel	Original CFD	Deflected CFD
8° AOA	0.102	0.117 (+15.4%)	0.110 (+7.56%)
10° AOA	0.151	0.143 (-5.38%)	0.128 (-15.2%)

It was made up of an unstructured tetrahedral mesh, with prism inflation layers to capture the boundary layer effects. The maximum y^+ was found to be less than 1.

4. Results and Discussions

The latest numerical simulation results show that the agreement between the numerical simulations and experiments was significantly improved over that in Teo et al. (2016) when the wing deflections were incorporated into the simulation geometry. For instance, Tables 2, 3 and Figure 4 show the discrepancy between the experimental and simulation lift coefficient (C_L) has decreased from 14% for both AOAs when the deflections were not taken into account, to 8% and 6% for 8° and 10° AOAs respectively when they were. On the other hand, the maximum discrepancy between the experimental and simulation drag coefficient (C_D) remains at 15%, regardless of whether deflections were taken into consideration. The outstanding discrepancies could be attributed to numerical errors typically encountered during numerical simulations, as well as the middle wing which was not modelled here. It was observed that before incorporating

Figure 4. Comparison of (a) C_L and (b) C_D obtained from wind tunnel experiments and numerical simulations with and without the deflections taken into account

the wing deflections, the CFD consistently under-predicts the C_L values. One of the possible causes to the lower C_L from the CFD is due to the turbulence model used. Nordanger et al. (2015) reported lower C_L values, when also using the Spalart-Allmaras turbulence model in the numerical simulations, as compared to experimental wind tunnel results for a 2D airfoil. Although Nordanger et al. (2015) did not run the simulations for the whole range of AOAs, it still highlights the possible deficiency of the Spalart-Allmaras turbulence model.

At a Reynolds number of $Re=62,000$ and 8° AOA, the wing tip deflection was 0.0068m for the front wing and 0.0067m for the rear wing. On the other hand, at 10° AOA, the wing tip deflections were 0.0064m and 0.0086m for the front and rear wings respectively. The different deflection magnitudes in the front and rear wings implied that the angle at which the middle wing joins the front and rear wings had changed. This also suggests that, as the AOA increased from 8° to 10° , less of the total lift force was generated by the front wing as compared to the rear wing. From the numerical simulation results, the ratio of C_L generated by the front wing to that of the rear wing decreased from 0.813 to 0.759.

Figure 5. C_p plots obtained through numerical simulation for upper wing surfaces at $Re=62,000$, (a) $AOA=8^\circ$ (no deflections), (b) $AOA=8^\circ$ (with deflections), (c) $AOA=10^\circ$ (no deflections), and (d) $AOA=10^\circ$ (no deflections)

To better understand the effects of including the wing deflections into the numerical simulations, the coefficient of pressure (C_p) along the upper surface of the wing, as determined from the numerical simulations, are plotted at three different spanwise positions: 1/4, 1/2 and 3/4 of the semi-span (s). They are plotted against locations along the surface in the streamwise direction normalized by the sectional chords for 8° and 10° AOAs with and without wing deflections taken into account. When comparing the C_p distribution on the top surfaces of the front and rear wings in Figure 5, they can be observed to be generally similar. In that case, a closer look into how the deflections affect the detailed aerodynamic behaviour would be warranted. When comparing the C_p plots at different spanwise locations along the wing in Figure 6, it can be seen that the magnitudes of the peak C_p are generally higher when the wing deflections were not included. On

Figure 6. Comparison of C_p from CFD analysis along the upper surface for the (a) front wing and (b) rear wing at $AOA=8^\circ$, and the (c) front wing and (d) rear wing at $AOA=10^\circ$, at $Re=62000$

the other hand, exceptions occur at 8° AOA at $1/4s$ location and 10° AOA at $3/4s$ location of the front wing. Typically, a forward-swept wing would experience a positive section twist and an aft-swept wing would experience a negative section twist with upwards bending. However, this might not be the case in the joined wing configuration, as the aft-swept front wing and forward-swept rear wing are connected by a middle wing, hence forming a constraint on each other. This produces higher overall C_L magnitudes and leads to instances where numerical simulation C_L magnitudes were higher than those obtained experimentally.

The preceding results and discussions demonstrate that deflections of additive manufactured wings need to be taken into consideration when they are subjected to wind tunnel testing for force measurements. This is particularly the case if the nature of the flow scenario is more complex than usual, such as the joined-wing test model used in the present study. The positive outcome arising from the present study is that it is possible to compensate for the use of highly flexible additive manufactured wings in a systematic manner during the initial design stages, and that their flexibility need not deter further implementations such as a wholly additive manufactured test model. Having said that, it should be noted that a coupled CFD-CSD (Computational Structural Dynamics) analysis remains the most appropriate approach during the final design stages, and the present methodology could complement it in the initial design stages.

With the systematic estimation of the wing deflections accounted for, future work involving the use of scalar visualizations [Lim et al. (2006), Shi and New (2013)] and particle-image velocimetry technique [New et al. (2015), Wei et al. (2015)] employed by the authors previously will be employed to look more closely into the detailed vortex dynamics governing fore- and aft-wing flow interactions at different AOAs.

5. Conclusions

Wind tunnel testing of joined-wing aircraft test models constructed partially through additive manufacturing was conducted in the present study. The material chosen, nylon, had sufficient strength and flexibility to withstand the aerodynamic forces without failure. The surface finishing of the additive manufactured wings was adequate and could be complemented by using fine grit sandpaper to further smoothen the finishing. Although wing deflections were observed, they can be accounted for systematically. As such, minimal discrepancies between the

experimental and numerical results in terms of the aerodynamic forces can be achieved. This reinforces the notion that additive manufacturing is a viable and cost-effective means for fabricating aerodynamic test models, as long as the major deflections are systematically taken into account. However, at higher AOAs and test velocities, larger wing flutter effects associated with additive manufactured components will require further efforts to compensate for the additional flexibility.

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Figure 1. PP250 joined-wing test model mounted on the sting balance in the wind tunnel test section

Figure 2. Camera setup located (a) by the side and (b) inside of the wind tunnel test section circled in red

932x381mm (72 x 72 DPI)

Figure 3. Deflections (in red colour) for AOA=8° at Re=62,000, as captured from the (a) side- and (b) rear-views

1375x421mm (72 x 72 DPI)

Figure 4. Comparison of (a) C_L and (b) C_D obtained from wind tunnel experiments and numerical simulations with and without the deflections taken into account

155x65mm (300 x 300 DPI)

Figure 5. CP plots obtained through numerical simulation for upper wing surfaces at $Re=62,000$, (a) $AOA=8^\circ$ (no deflections), (b) $AOA=8^\circ$ (with deflections), (c) $AOA=10^\circ$ (no deflections), and (d) $AOA=10^\circ$ (no deflections)

1375x863mm (72 x 72 DPI)

Figure 6. Comparison of C_p from CFD analysis along the upper surface for the (a) front wing and (b) rear wing at AOA=8°, and the (c) front wing and (d) rear wing at AOA=10°, at Re=62000

1397x1126mm (72 x 72 DPI)