Research Note

In-Flight Measurement of Wing Deformation*

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Nomenclature

- c : lens focal length
 X, Y, Z : position of an object in the world coordinate system
 X_0, Y_0, Z_0 : viewpoint in the world coordinate system
 x, y : point on image in the image coordinate system
 x_0, y_0 : displacement of principal point
 X_b : aircraft body axis system (X_b, Y_b, Z_b)
 X_t : coordinate system of a total station
 ω, φ, κ : orientation of view
 ϕ, θ, ψ : aircraft attitude angles

1. Introduction

Aircraft design tools such as optical measurements in wind tunnel testing, computational fluid dynamics and fluid-structure coupling techniques are developing rapidly.^{1–5)} In-flight measurement technique is necessary in order to further improve the aircraft design tool by giving the aircraft design tool the feedback on flight test data.

An aircraft's wings are deformed by aerodynamic loads during flight. Changes of wing bending and twist due to deformation are important considerations in aircraft design because they greatly influence the aircraft's aerodynamic characteristics.^{1–6)} During the aircraft design phase, the amount of wing bending and twist are predicted via numerical simulations and ground-based structural and fluid experiments, however, these methods have limitations. If wing deformation is measured qualitatively in flight test, it would be useful to validate and improve design tools such as fluid-structure coupling techniques and to improve ground test techniques and simulations.

For the measurement of wing deformation, exposed sensors or cables on the wing outer surface should be avoided because they affect the airflow, so non-intrusive measurement methods are highly desired. Moreover, measurement methods should avoid major structural modifications of an aircraft due to high cost.

The objective of this study is to develop a technique to quantitatively measure the wing deformation in flight.

Burner studied wing deformation measurement using one

camera system in a special modified aircraft.⁶⁾ On the other hand in this study, a stereo camera measurement system with two cameras is developed for flexibility of measurement system. This paper also discusses a camera calibration method for a large object like an aircraft, and methods to improve the accuracy of the measurement in the limited environment of flight test. Moreover it investigates whether it is possible to measure the deformation of the wing with various load factors in flight.

2. Experimental Setup

2.1. Aircraft

Flight tests to measure the wing deformation were conducted using a JAXA's research aircraft, Beechcraft Type 65 Queen Air, in Fig. 1. The aircraft is a low-wing type, and the upper surface of the wing is visible from the cabin windows. The cabin is unpressurized. The aircraft's dimensions are as follows. Length: 10.16 m, width: 13.98 m, height: 4.32 m.

2.2. Flight tests

The flight tests were conducted over the Pacific Ocean around the Bay of Sagami near Tokyo. The aircraft was operated from JAXA's Chofu Aerospace Center Aerodrome Branch, which is located next to Chofu airport.

Flight tests were conducted at less than 3,000 ft altitude, and flight speeds were varied between Indicated Air Speed $IAS = 120$ mph (miles per hour) and 160 mph. Flight patterns were straight and level flight to investigate wing deformation at a load factor of 1 g, and counter-clockwise circling flight at bank angles of 45 and 60 degrees to investigate wing deformation under load factors of 1.4 g and 2 g respectively.

2.3. Measurement system

Figure 2 shows the outline of the stereo camera measurement system. The measurement system does not require large modifications for an aircraft. Moreover it measures many points simultaneously, and it has an advantage that gives fewer disturbances to the airflow.

The measurement system consists of two high-resolution CCD cameras which output image data in Internet Protocol (IP) network packets, a synchronizer to synchronize the shutters of the cameras, a laptop computer for image capture and

Fig. 1. JAXA's research aircraft.

Fig. 2. Measurement system.

processing, and an Ethernet network hub to connect the cameras to the laptop computer. It is important to synchronize the cameras because the stereo camera measurement requires images that are acquired from both cameras simultaneously. The synchronizer sends an electrical trigger signal to the cameras when commanded by the laptop computer. The cameras release their shutters upon receiving the trigger signal, and the image data are then sent immediately to the laptop computer.

The cameras were arranged to observe the upper surface of port (left) wing of the aircraft through the cabin windows. Figure 3 shows the measurement system with cameras and the synchronizer. The cameras are monochrome CCD cameras with a 4872×3248 pixel sensor resolution and 12-bit A/D converters. A 24-mm focal length lens is affixed to each camera with the aperture set at $f/11$. The cameras were fixed to an optical bench at the top of a measurement equipment rack installed in the aircraft's cabin. The optical bench and the measurement rack are sturdily constructed to meet flight test requirements.

2.4. Target markers

Although stereo measurement is in principle non-contact methods, the stereo measurement requires reference points that are matched in the two cameras' images to obtain their three-dimensional positions. These reference points have to be visually distinct when accurate measurement is required. But because a general wing surface is smooth and uniform color, there are few features that are available as reference points. The use of existing rivets or joint lines between wing components as reference points may be supposed, but it would be considerably difficult to obtain sub-pixel accuracy in the stereo camera measurement.

To overcome this issue, target markers were affixed to the upper surface of the wing to be used as reference points. The target marker is a thin adhesive sticker designed for aircraft. As Fig. 4, target markers were arranged in straight lines along the direction of the wing span near wing spars of front, middle and rear by referencing rivets on the wing upper surface. The positions of the centers of these target markers in the image of the stereo measurement are obtained with sub-pixel accuracy by an in-house image processing tool.

3. Camera Calibration

3.1. Pinhole camera model

The cameras were modeled as a pinhole camera in Fig. 5. In the pinhole camera model, a point in the three-dimensional world is projected to a point on the two-dimensional image.

The pinhole camera model has intrinsic parameters and extrinsic parameters. The intrinsic parameters are the focal length c , the displacement of the principal point (x_0, y_0) and the distortion of the lens. The extrinsic parameters are the orientation of the view $(\omega, \varphi, \kappa)$ and location of the camera viewpoint (X_0, Y_0, Z_0) in world coordinate system.

$$x = -c \frac{a_{11}(X - X_0) + a_{12}(Y - Y_0) + a_{13}(Z - Z_0)}{a_{31}(X - X_0) + a_{32}(Y - Y_0) + a_{33}(Z - Z_0)} + \Delta x \quad (1)$$

Fig. 3. Measurement system installed in the cabin.

Fig. 5. Pinhole camera geometry.

$$y = -c \frac{a_{21}(X - X_0) + a_{22}(Y - Y_0) + a_{23}(Z - Z_0)}{a_{31}(X - X_0) + a_{32}(Y - Y_0) + a_{33}(Z - Z_0)} + \Delta y \quad (2)$$

Equations (1) and (2) describe the relationship between a point in three-dimensional world coordinate system (X, Y, Z) and the location of its projection onto the image plane (x, y) . Correction for lens distortion Δx and Δy is accomplished if required.

3.2. Camera calibration

Camera calibration establishes the relationship between points in the three-dimensional world and corresponding points in the image by determining parameters of the pinhole camera model. While there are many methods for finding parameters, a method using reference points with known positions is adopted in this study. That is, the camera is calibrated by correlating the known three-dimensional locations of reference points in world coordinate system and the corresponding locations of their projections in image coordinate system. A non-linear least-squares method is used to find the intrinsic parameters and extrinsic parameters, which requires an initial value to be assigned to each parameter. Each initial value is found using Tsai's method,⁷⁾ and then each parameter is found by the Levenberg-Marquardt algorithm.

An ideal condition for the camera calibration is where many reference points are distributed uniformly in three-dimensional space around the object to be measured. However, this is not easy to achieve when the measured object is large, such as in the case of an aircraft wing. Furthermore, methods that might damage the aircraft have to be avoided for safety. In this study, the target markers on the wing were used for the camera calibration. However, although the target markers had sufficient horizontal distributions (X_b and Y_b), being distributed over the wing, they had insufficient height distribution Z_b to allow them to be used for calibration alone. Therefore, supplementary reference points on styrene blocks placed on the wing were added to increase the Z_b distribution. Styrene blocks were used since the material is soft and lightweight and so have less risk of damaging the aircraft. The positions of the styrene blocks were given consid-

eration to be set as wide area as possible and to avoid the extrapolation in the camera calibration for measurement positions of the wing deformation.

The positions of the reference points around the object in the camera calibration are measured using a “total station,” which is a surveying instrument with a laser rangefinder and a theodolite. A piece of reflective material is placed at each reference point to allow the total station’s laser rangefinder to determine its distance. Figure 6 shows photographs of the camera calibration. The camera calibration was conducted in a hangar to avoid vibrating of the reference points and the total station from strong wind.

Positions measured by the total station are referenced to its unique coordinate system X_t that has the direction of the gravitational force as one of its axes and the remaining axes determined by the operator. The coordinate system of total station X_t does not coincide with the aircraft’s body axis coordinate system X_b . Because the objective of this research is feedback of the wing deformation in flight to the design technology, the amount of deformation of the main wing should be indicated by the body axis. Thus, the coordinate system of the total station is transformed into aircraft body axis coordinates by translation and rotation by the following equation.

$$X_b = E(X_t - X_{t0}) \quad (3)$$

where E is Euler angles to the aircraft’s attitude (ϕ, θ, ψ).⁸⁾ Generally, because it is too difficult to measure simultaneously the 3 angles of the pitch, the yaw and the roll of the aircraft, the roll angle of $\phi = 0$ deg was established by adjusting the jacks supporting the aircraft. Points of the jacking up are near landing gears. Pitch angle θ was measured using the aircraft’s own inertial reference system. Yaw angle ψ was obtained using a laser-generated reference line aligned with the aircraft’s centerline projected onto the fuselage.

The origin of the total station coordinate system, X_{t0} , is located arbitrarily. In this study, it was set at a point on the aircraft’s fuselage.

When the positions of all reference points had been measured by the total station, images were taken by the CCD cameras that had been fixed to the measurement system rack in the cabin. The focal position and the aperture of the camera lenses were set before the calibration and remained fixed until after the flight tests had finished. The center of each reference point image was obtained at sub-pixel precision by the image processing tool.

Finally, camera calibration was conducted using the three-

dimensional positions of the reference points in aircraft body axes system and their pixel positions in the camera images.

4. Results and Discussions

4.1. Camera calibration

The accuracy of the camera calibration was evaluated by examining the difference between the center of each reference point in an actual image and its theoretical projected position on the image computed using the measured three-dimensional position of the reference point and the pinhole camera model with parameters determined by the camera calibration process.

It was found that the camera calibration had insufficient overall accuracy (approximately 3.9 pixels at 2σ) when using all reference points to determine the camera parameters. Although measurement data have high accuracy in the X_b and Z_b directions, there is insufficient accuracy the Y_b direction. Thus in this study, camera calibration error was reduced by delimiting regions of the wing span and using a different calibration for each region; that is, the wing was divided into regions centered on subsets of the target markers, camera calibration was conducted separately for each region using the corresponding marker subset, and deformation measurement in a region used the corresponding calibration. The accuracy of the camera calibration was thereby increased to about 0.6 to 1.9 pixels at 2σ . Lens distortion was not compensated in the camera calibration and wing deformation measurements.

4.2. Overview of deformation of the wing

Wing deformation measurements were conducted in the following four conditions: 1) on the ground with the aircraft static, 2) in straight and level flight, 3) in level, circling flight at a 45-degree angle of bank, 4) in level, circling flight at a 60-degree angle of bank.

In the on-ground condition, the wing is free from aerodynamic loads but its shape is affected by its own weight and fuel. The main landing gear are housed in the engine nacelles and support the weight of the aircraft on the ground, so there is a bending load on the inner wing.

The straight and level flight condition was flown at three speeds: $IAS = 120, 140$, and 160 mph. Constant bank angle (circling) flight cases were conducted to observe effects of different load factors: $1.4g$ at 45 degrees angle of bank and $2g$ at 60 degrees angle of bank. The circling cases were flown in a counter-clockwise direction (port wing low) to avoid taking images against the sun by putting the sea in the background.

Figure 7 shows images of the wing during flight tests. The line drawn across the images allows the positions of the wing tip to be compared. The increasing deformation of the wing with increasing load is clearly observed from the images.

4.3. Wing deformation measurements

Both wing bending and twist were obtained by comparing the measured positions of target markers between the on-ground condition and each in-flight condition. Measurement data on the X_b – Z_b plane of the aircraft body axes were used to calculate the bending and twist in this study; that is, differences in the Y_b , component of target marker position (along

Fig. 6. Measurement of three-dimensional positions of reference points for the camera calibration. (a) camera calibration, (b) reference points.

Fig. 7. Images of the wing. (a) on the ground, (b) in straight and level flight, (c) circling at a 60-degree angle of bank.

the wing span direction) were neglected as it was assumed that the effects of bending and twist on ΔY_b position change would be much smaller than the Z_b . Approximately, $\Delta Y_b = (1 - \cos \varepsilon)Y_b$, $\varepsilon = \sin^{-1}(\Delta Z_b/Y_b)$, the order of ΔY_b is 10^{-1} mm in ΔZ_b is 10^1 mm.

Figure 8 shows the bending and twist angles measured from the target markers. It is clear from these graphs and the photographs in Fig. 7 that the degree of bending changes according to the load factor. In the Fig. 8(a), changes in speed in straight and level flight do not cause large changes in bending. Random error bar is shown in the Fig. 8(a) for level flight of 160 mph; the error bars are as small as markers. The random error bar is obtained by two times of the root sum square of in-flight and on-ground. Each random error is obtained by the root mean square of 5 time-series data that includes vibrations of the wing in flight and measurement error of the stereo camera measurement. Bias error is neglected because the ΔZ_b is difference between the in-flight and the on-ground.

Figure 8(b) shows the bending at the leading edge is greater than that at the trailing edge. In this aircraft, which has unswept wings; this result in twisting that increases the wing's angle of attack. (Generally, in a wind tunnel model with a swept back wing decreases the wing twist by the load due to the geometric characteristics.^{1,2)})

Figure 8(c) shows twist angles of the wing. Increasing load causes an increase in twist angle as well as bending. There are some scatters in twist angles on each location of the span wise. The reason that causes the scatter is not clear because the twist angles are very small values and the wing structure is not clear. The range of variation of the twist angle was less than 1 degree. The twist angle error bars obtained by the same way in the bending are comparatively large because the twist angle changes are relatively small.

5. Conclusion

The objective of this study is to develop a quantitative measurement technique to determine the deformation of an aircraft's wing in flight. Flight tests using JAXA's Beechcraft Type 65 Queen Air research aircraft were conducted to measure wing deformations under various load conditions.

A stereo camera measurement system with two cameras was developed for flexibility of measurement system, which does not require large modifications for an aircraft. The measurement system measures many points simultaneously, and it has an advantage that gives fewer disturbances to the airflow.

Fig. 8. Bending and twist angle of the main wing. (a) bending at center of code, (b) bending at the leading edge and trailing edge, (c) twist angle; 60 deg is circular flight with 60 deg angle of bank, 45 deg is circular flight with 45 deg angle of bank, others are level flights.

A camera calibration method for a large object like an aircraft is developed in the limited environment of flight test.

It indicates that the measurement method studied in this paper is available to quantitatively measure the wing deformation.

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