Review and Prospect of Wind Tunnel Model Attitude Determination: Past, Now and Future

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Abstract. Analyzed was the effect of wind tunnel model determination accuracy on test data quality. The development was reviewed of wind tunnel model determination methods, principles and applications were compared and analyzed for the accelerometer, gyro, and optical measurement system whose drawbacks and advantages were presented, and future model angle measurement methods were discussed.

Introduction

Wind tunnel model attitude determination uncertainty is one of the key parameters which affect the drag coefficient(C_D) accuracy. The reason why wind tunnel test organizers pay attention to developing high-precision attitude measurement system comes from the energy saving requirements of aircraft makers which is highly dependent on the drag coefficient accuracy. The oil crisis in 1970s compelled the aircraft makers to enhance oil efficiency to save the transport costs. A study[1] has indicated that a 0.0001(1 drag count) decrease in C_D results in a 90kg increase in payload for a large, generic and twin engine transport while the drag uncertainty will be 0.0003 at takeoff conditions with a lift coefficient of 1.7 and an angle of attack accuracy of +/-0.01°. Currently there are mainly four different model attitude measurement systems in use at wind tunnels: the model support system, the servo accelerometer based system, the optical measurement system, the gyro based system. These different systems will be described and compared.

Model support system

The nominal angle provided by a model support system belongs to the control angle not the measurement angle in the strict sense. The nominal angle accuracy is dependent on the control system precision, structure strength(deforming resistance) and joint components(pins, hinges). A model support system can only offer a poor attitude accuracy of 0.1° and unavoidable hysteresis[2], but it can provide the angle of attack angle and sideslip angle simultaneously. Model support systems are still widely employed almost in all kinds of wind tunnels for model attitude solution. A model support system is the main attitude measurement system before 1950s. After 1970s, the angle of attack angle accuracy is required to be 0.01° from 0.1°[3], the servo accelerometer becomes the main measurement sensor. However, the sideslip angle is not easy to be determined which makes the support system be the only choice at many conditions.

Accelerometer

Due to precision requirements and constraint of the wind tunnel model inner space, servo accelerometers have been adopted as the standard angle of attack measuring device. This inertial transducer is used to sense the attitude of the model with respect to the local vertical. An oil-damped, open-loop unit (Lynchmeter) with a strain-gaged cantilever design was developed by NASA in the late 1940s. Three versions have the size of 5.8cm（D）×11.4cm（L）, 2.9cm（D）×11.4cm（L） and 2.9cm（D）×10.2cm（L） separately. The Lynchmeter was used for many years but finally replaced by the servo accelerometer of 0.01° precision for its lower accuracy(0.1°) and oil leaking and air bubble problems.

The servo accelerometer developed by NASAhas three versions: Type I, Type II and Type III. Type I, using the translational suspension, was never adopted to measure model attitude because of the large rectification error. Type II, an oil damped unit, uses a pendulous metallic flexure design with the size of 2.5cm(D)×2.5cm(L). This accelerometer is very strong and never destroyed during its service life. Type III servo has a pendulous flexure made from fused quartz with a size of 2.5cm(D)×6.57cm(L). After the manufacturer incorporated integrated circuits to replace the discrete components in the control circuit, the unit length becomes shorter. This servo is delicate and 15 to 20 were destroyed during the use of 20 years. Based on size, capability and price, NASA currently chose Type III servo accelerometer(Q-Flex) to measure model attitude.

One must keep in mind that the inertial devices are sensitive to sting whip. This will be a big problem in the use of inertial devices to measure model attitude. Removing the centrifugal acceleration caused by a dynamic pitching or yawing motion of the sting-model assembly is very hard or even impossible without the use of additional sensors. Model vibration may result in 0.1°~0.25° offset between the on-board servo-accelerometer and the standard measurement system in a blow-down wind tunne l[5,6].

Selecting the best units or using passive vibration isolation will reduce the rectification error. Although the use of isolation pads makes the package more rugged and more reliable, the loss of structure integrity decreases the accuracy of the accelerometers[3]. Otherwise, a lot of algorithms have been investigated to improve the measurement results, such as considering the effect of rotation angle velocity of a accelerometer during angle of attack resolution[6,7] or employing iterative algorithm[8].

CARDC-LSAI often meets the so–called angular singularity phenomena during use of angle of attack sensor which may have relation to bound for the arcsine function. A preset angle of the accelerometer will resolve this problem.

Another problem is how to calibrate the angle of attack sensor with high quality quickly. Developing a static auto calibration system[9] will help to overcome this obstacle.

Optical measurement system

A laser yawmeter, 0.1°accuracy, was developed in 1980s in the 5 meter pressurised wind tunnel in RAE to resolve the support system deflection problem, 0.8° deflection maximum, which resulted in the test data error[10].

A beam of laser light in the horizontal plane swept the three photodetectors on a model surface through the rotating cylindrical lens. The lens was mounted on a position encoder. The pulse from the detector was used to interrogate the encoder as a trigger and measure the angular position of the three detectors.

The system is complicate to prepare, hard to calibrate, sensitive to vibration and very expensive. In 1990s, CCD camera technology made great progress. A real time position and attitude sensing system based on CCD cameras was applied for the magnetic suspension system[11-15]. Two cameras were arranged perpendicularly, one in the horizontal plane and the other in the vertical plane. Four white mark points were placed on the nose, fuselage and wing tips. A special algorithm was designed to acquire the model attitude. Test results indicated that the angle of attack measurement accuracy was 0.2°.

A OPTOTRAK system was developed based on the two camera principle in DNW[14]. LED mark points and high resolution infrared sensors application make sure that the accuracy of attitude determination can be as high as 0.01°. The system operation is quite simple but not capable of direct measurement and needs other sensors to establish reference base.

In general, Mark points are necessary for optical measurement system which may destroy the airfoil surfaces. Moreover, limited by the CCD pixel resolution, the accuracy of optical measurement system will decrease for large scale wind tunnel application. To alleviate these problems, NASA developed novel optical sensors for the in-situ real-time measurement of wind tunnel model attitude[15]. This system is based on the refraction principle. An incident beam will not be affected when it passes through the medium. However, the beam will be refracted while there is an inclination between the surface and the path. Refraction will leads to displacement of the beam which is proportional to the angle between the surface and the incident beam. Given a material of fixed thickness and refractive index, beam angularity can be determined by measuring the beam displacement using a position sensing detector. It was demonstrated that detectors were capable of 0.006° resolution.

A stereo vision attitude measurement system, developed by Northeast Dianli University, based on cooperative objects also overcome the mark point problems[16]. A cooperative object mounted on the aircraft model generates two bidirectional collimated laser beams projected onto the surfaces of two screens. A pair of binocular stereo vision systems measure the 3D coordinates of the laser points on the wall surfaces to determine the model attitude. Experimental results indicated that the accuracy of angle of attack determination was better than 0.02°.

Gyroscope

Gyroscopes were born for angle measurement. Compared with accelerometers, gyroscopes have the advantages of strong shock resistance ability, long lifetime, better measurement accuracy and reliability while the size limits their use in wind tunnel model attitude determination. In the late of 20th century, miniaturization of high accuracy optical gyroscopes achieved major breakthrough which made the application of gyroscopes for wind tunnel model attitude determination possible. The study of Stuttgart University demonstrated that using a fiber optic gyro and differential inertial measurement technique(DIMT), the difference of incidence measurements between reference and the FOG/DIMT results were below 0.05°[17].

CARDC studied the application of three axis laser gyroscope in FL-13 low speed wind tunnel. Tests indicated that model attitude accuracy was below than 0.02°. Fig. 1 illustrates the angle of attack measurement results comparison between the laser gyroscope and the OPTOTRAK system which shows the good agreement.

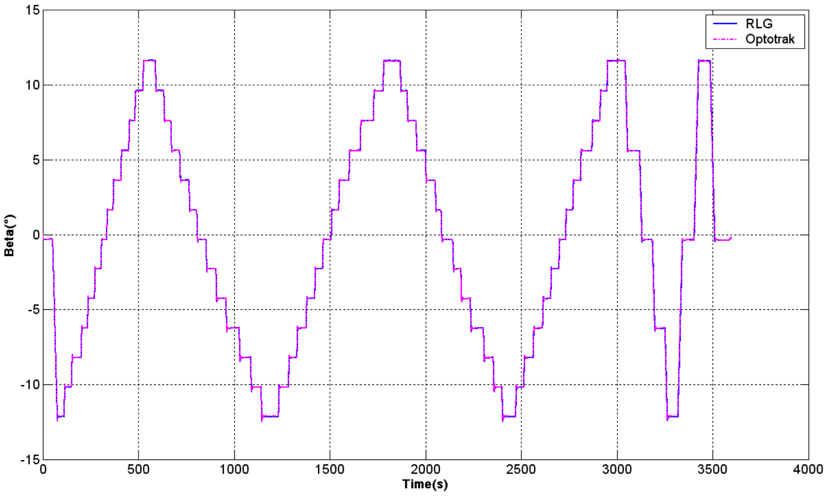

Fig. 1 Angle of attack measurement results comparison

The drawback of a gyroscope comes from the drift which cannot be corrected without assistance of other efficient measurement sensors, especially for yaw angle determination. Moreover, the size of high accuracy optical gyroscopes is still too big for small wind tunnel model and further miniaturization is necessary.

A dynamically tuned gyroscope was successfully used in the Boing Polysonic Wind Tunnel to measure model attitude. Research results indicated that the accuracy of this system was almost the same with the conventional measurement system. There would be small bias from 0.025° to 0.05° in 7 seconds. However, due to the drift, this kind of gyro cannot work a long time which means that it is not a suitable sensor for low speed wind tunnel model attitude determination.

MEMS Sensors

MEMS sensor research has been strengthened because of the special advantages, such as small size, low cost, simple structure. NASA designed and manufactured two types of MEMS accelerometers: capacitive and servo, but the accuracy was not good enough as expected[18]. Old Dominion University developed MEMS based accelerometers and gyroscopes for wind tunnel model attitude determination[19]. Wind tunnel test results demonstrated that the accuracy of the MEMS based accelerometer was below than 0.1° but the MEMS gyro was disappointed due to the unavoidable drift. Although the accuracy of MEMS sensors needs further improvement, the advantages make sure their attractive in the future.

Accuracy comparison among different model attitude determination systems

Boeing Commercial Airplane Group investigated the comparison among the QA-2000 servo-accelerometer, the laser angle meter and the OPTOTRAK real-time photogrammetry system in the mid 1990s[20]. Comparative tests were conducted in the Boing Transonic Wind Tunnel on the Boing737 model and the calibration model mounted on the straight sting, the swept strut and the plat support systems. The former two support systems were employed for an internal strain gage balance while the latter one was designed for the external balance. Test results indicated that at wind-off and wind-on conditions, all three systems produced angle-of-attack uncertainties of less than 0.01° at a 95% confidence level.

NASA tested two optical systems, the video model deformation system(VMD) and the OPTOTRAK system, for measuring model attitude and deformation compared to servo accelerometers[21]. The tests were performed on the sting mounted full span 30% geometric scale flexible configuration of the UCAV installed in the NASA Langley Transonic dynamics tunnel. Results showed that VMD offered less accurate measurements in terms of angle of attack: 0.015° bias for static measurement and 0.03° bias for dynamic measurement. The servo accelerometer acquired the almost same accuracy with the OPTOTRAK system, 0.004° difference for angle of attack determination, which agreed well with the comparative results of Boing.

Conclusions

For conventional force measurements with internal balances in a wind tunnel, C_D accuracy has direct relation with angle of attack determination uncertainty. 0.0001 C_D accuracy means less than 0.01° attack angle uncertainty. To meet this requirement, servo accelerometers, optical systems, and gyros have been developed one by one. It has been demonstrated that different measurement systems will obtain the same accuracy for wind tunnel model attitude determination. Now accelerometers have been the standard measurement sensors in a wind tunnel, optical systems are the most powerful capable of measuring three attitude angle and model deformation during the test but with complicated arrangement and high cost which limits its use. Gyroscopes have the advantages of strong shock resistance ability, better measurement accuracy but needs further miniaturization. MEMS sensors have small size, low cost and are suitable for wind tunnel test. With the development and technology, the accuracy and precision will be improved which will make the MEMS sensor more attractive for wind tunnel model attitude determination.

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