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RLG BASED REAL-TIME MODEL ATTITUDE DETERMINATION SYSTEM DEVELOPMENT FOR LARGE LOW SPEED FACILITY OF CARDC

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Abstract

The national large low speed facility(FL-13 Tunnel) of CARDC has a main test section of 8m×6m×15m. Available attitude measurement systems cannot be used in this facility efficiently because of scope limitation for photogrammetry systems or incapability for accelerometers, especially for sideslip angle measurement. A RLG based real-time model attitude determination system(RRMADS) was developed in CARDC using three orthogonal RLGs for angular rate measurement and three orthogonal servo-accelerometers for error compensation. Test results indicate that this 200mm length, 110mm width, 90mm height packaged IMU can be mounted in most of the models in FL-13 Tunnel, the 0.02° accuracy in angle of attack is comparable to the sensors equipped in the tunnel, and the 0.02° accuracy in sideslip angle can be kept within an hour.

Nomenclature

AOA	Angle of Attack
CARDC	China Aerodynamics Research and Development Center
DAS	Data Acquisition System
IMU	Inertial Measurement Unit
ISM	Inertial Support Module
NC	Navigation Computer
RLG	Ring Laser Gyroscope
RRMADS	RLG based real-time model attitude determination system
g	Gravity
H	Height
L	Latitude
p	Pitch Angle Rate
q	Yaw Angle Rate
r	Roll Angle Rate
α	Angle of Attack
β	Angle of Sideslip
θ	Pitch Angle
λ	Longitude
φ	Roll Angle
ψ	Yaw Angle

1 Introduction

FL-13 Tunnel is a main tunnel in CARDC for aircraft and ground vehicle design checking and finalizing. Besides some special tests such as flutter or dynamic derivative testing, model attitude measurement accuracy is a key factor to the final data quality. Accelerometers are employed to measure angle of attack traditionally in FL-3 Tunnel while cannot be used to determine sideslip angle for insensitivity to the changes in angle when the plane of rotation is perpendicular to gravity. Great efforts have been ever made to develop a suitable system to resolve the sideslip angle problem using photogrammetry systems or the OPTOTRAK system[]1,2,3] but not successful. A RLG based real-time model attitude determination system development was established in CARDC.

2 System Description

2.1 Design Philosophy

To save the limited inner space of a tested article, RRMADS adopts divided and module design style: IMU is mounted on a plate adaptor in the model to sense the angular rate and AOA while NC and Host Computer are located in the control room for model attitude calculation. Meanwhile, IMU is divided into inertial unit module and process circuit unit module. The former consists of three RLG with front-end amplifier circuits and three quartz accelerometers, while the latter is installed on the other side of IMU, including I/F circuit board, computer circuit and interface board, motherboard, power module and power connector. Figure 1 presents the principle of the system. Figure 2 shows the inner layout of IMU.

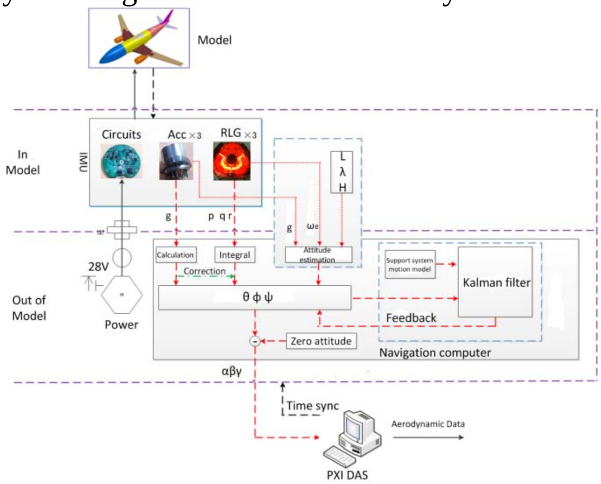

Fig. 1. RRMADS Principle Sketch

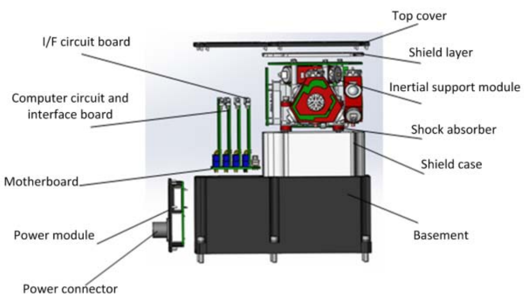

Fig.2. IMU Layout

2.2 IMU

IMU consists of three RLGs, three accelerometers, signal processing computer, RLG control circuit, temperature measurement circuit, I/F circuit, power circuit and struct.

Table 1-2 presents the specifications of three RLGs and three accelerometers. It is stressed here that the performance of the yaw RLG is better than that of the other two RLGs because the latter output can be corrected efficiently using accelerometers while this correction does not suit for the former.

To minimize IMU size, laser shells are dropped. Lasers are directly installed in the framework of IMU. Meanwhile, circuits are integrated and newly designed. The final size of IMU is limited to 200mm×110mm×90mm.

Signal processing computer acquires accurate angular rate signals through phase judgment, count, filter, error compensation, constant period sample to beat signals. Real-time processing software is embedded in the signal processing computer for time sync, and temperature compensation to original RLG and accelerometer output .

Table 1. RLG Specifications

	Yaw RLG	Pitch and roll RLGS
Bias stability	≤0.005°/h	≤0.01°/h
Bias repeatability	≤0.005°/h	≤0.01°/h
Random walk	$\leq 0.005°/h^{1/2}$	$\leq 0.005°/h^{1/2}$
Scale factor	≤5ppm	≤10ppm
Scale factor nonlinearity	≤5ppm	≤10ppm
Magnetic field sensitivity	0.004°/h/Gs	
Dynamic range	±400°/s	

Table 2. Accelerometers Specifications

Range	-20g～20g
Bias	≤2mg
Bias Temperature Coefficient	≤10μg
Scale Factor	1.2mA/g～1.6mA/g
Scale Factor Temperature Coefficient	≤20 μg/℃
Resolution	1μg
Second-order Nonlinear Coefficient	$\leq 10\mu g/g^2$

2.2.1 Magnetic Shield Design

It is necessary to design shield cover for IMU because of the strong magnetic environment from electric motors using in propeller tests or the wind tunnel power section. A special cover, 116mm×104mm×82mm, was designed to shield the ISM entirely by selecting 1J85 shielding material with 0.5mm thickness and 250000 magnetic permeability. Calculation result indicates that magnetic strength will be lessened to about 0.001 of the original value after through this cover. The maximum wind tunnel magnetic strength was tested to be 4.8 gauss when operating four 80kW AC motors plus with maximum wind tunnel fan output. That means the final magnetic, reaching to the inertial devices , strength will be 0.0045gauss which has no significant effect when it is lower than 1 gauss.

2.2.2 Shock Absorption Design

To suppress vibration and shock effect on IMU precision and reliability, great efforts were made to balance the mass distribution of different parts during layout design, so the mass center of the ISM will coincide with its geometrical center. Four couples of T type shock absorber rudder with metal stop shaft are employed to eliminate vibration effect. 3D modeling (Fig.3.) analysis show that the deviation of the two centers is less than 1mm. Further analysis indicates the ISM deformation is less than 4×10^{-3}mm in three directions under 20g shock. The first mode is 1385Hz and the second mode is 1471Hz, which is far higher than the RLG vibration frequency and has no effect on RLG precision.

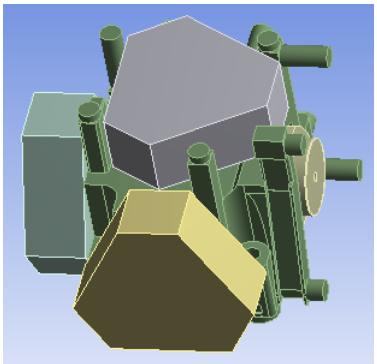

Fig.3. Inertial Support Module Analysis Model

2.2.3 Thermal Design

Three measures are adopted to improve the cooling efficiency. The first is to leave the power module fixed on the side of the basement far away from the ISM. The second is to use thermal gap pad to connect the power module with the side cover. The third is to add heat sinks to the side cover.

2.3 Navigation Computer

NC receives sync pulse from PXI DAS, collects data from attitude measurement result stream, and sends original result to PXI DAS for postprocessing. NC receives compensated inertial acceleration and angle rate measured by IMU to solve pitch angle, yaw angle and roll angle through SINS calculation and Kalman filtering using real time processing software embedded in itself.

2.4 Host Computer

Host computer runs post processing software and monitor software. The former processes original IMU output for more accurate AOA and sideslip angle. The latte connects host computer and NC with COM or UDP protocol, sends command parameters to NC, receives measurement results from NC and monitors NC status.

3 Data Processing

3.1 Wind Tunnel Centerline Azimuth Determination

Wind tunnel centerline azimuth ψ_c can be used to obtain IMU installation error. Firstly, make the y axis (yaw) of IMU be parallel with the tunnel centerline, keep this status for 30 minutes and record the data. Secondly, turn the y axis to the contrary direction, keep this status for the other 30 minutes and record the data. ψ_c can be resolved by average of the two results. For one specific tunnel, these procedures only need to be performed once. Then ψ_c can be loaded as a constant parameter.

3.2 Installation Error Measurement

Pitch error $\Delta\theta$ and roll error $\Delta\varphi$ can easily be calibrated with a accurate inclinometer. Yaw error $\Delta\psi$ can be acquired through the following steps.

Step 1: Measure model roll angle φ_{m0} when nominal AOA is zero.

Step 2: Record IMU output θ_{i0} and φ_{i0}.

Step 3: Adjust model attitude to a 20° above AOA.

Step 4: Measure model roll angle φ_{m1}.

Step 5: Record IMU output θ_{i1} and φ_{i1}.

$\Delta\psi$ can be obtained through the following equation:

$$\Delta\psi = (\varphi_{i1} - \varphi_{i0} - (\varphi_{m1} - \varphi_{m0}))/(\theta_{m1} - \theta_{m0}) \quad (1)$$

3.3 *α* and *β* Solution

θ_{tn-1} , φ_{tn-1}, ψ_{tn-1} are three Euler angles from model body axis coordinate(C_b) to wind tunnel axis coordinate(C_w) at time t_{n-1}, which will be transformed to a quaternion $Q_{tn-1}=[q_0\ q_1\ q_2\ q_3]$ for stable solution. Transformation matrix C_b^w between C_b and C_w can be expressed:

$$C_b^w = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix} \quad (2)$$

The airflow coordinate system will coincide with the wind tunnel coordinate system if we omit the airflow angle deflection effect, then α and β can be derived from the following equations:

$$\alpha = \theta = \arcsin(C_{b32}^w) \quad (3)$$

$$\beta = \psi = \arctan\left(\frac{C_{b12}^w}{C_{b22}^w}\right) \quad (4)$$

The detailed data processing procedure concerns quaternion update, coning compensation, velocity update, Kalman Filter, RLG and accelerometer output compensation, angle rate compensation and lever arm effect compensation. These procedures are beyond the scope of this paper and will not be described here.

4 Tests and Results

4.1 Static Calibration Test

A series of static calibration tests were performed after RRMADS development was finished, including drift tests, turntable tests, and temperature tests. Drift tests were carried out three times and each drift test last one hour. During the turntable tests, angle range varied from -180° to 180°. Each temperature test last one hour at -20℃ and 60℃. Drift data were recorded and averaged during temperature test.
For pitch and roll angle, the drift error is very small. The drift error of yaw angle is 0.01°/h, which is very ideal for a 20 minutes or 30 minutes long wind tunnel test. It can be induced from Table 1. that temperature is not a significant effect parameter for RRMADS, and the 0.002 ° maximum mean error can be directly ignored.
Table 3. presents the some test results.

Table 3. Static Calibration Test Results

	Mean Pitch Error	Mean Yaw Error	Mean Roll Error
Drift	0.0008°	0.01°/h	0.001°
Turntable	0.001°	0.009°	0.002°
Temperature	0.0008°	0.002°	0.0008°

4.2 Wind Tunnel Tests

To evaluate the measurement accuracy of RRMADS in operational environment, wind-on and wind-off tests were performed in FL-13 wind tunnel. RRMADS and a AOA Sensor were installed in the aft part of a transport model(Fig. 4.). The nominal AOA Sensor measurement accuracy is 0.01° for AOA range from -45° to 45°. Another equipment adopted to measure model attitude is the OptoTrak system. The theoretical accuracy is 0.001° for attitude and 0.1mm for displacement measurement. Compared to the large tunnel size, OptoTrak system view of field is too small to cover the whole model movement. So OptoTrak system is only used for wind-off tests. Through adjust of CCD position, it is possible to make the model enter the view of CCD at any time. 10 trackers were pasted on the wings and fuselage to make sure enough trackers light reflect into the CCD.
AOA measurements were performed in sweep mode from -8° to +20°.
Fig.6. shows the AOA measurement comparison results. The bias for RRMADS/OptoTrak comparison is small(0.0007°). The differences for RRMADS/OptoTrak are randomly scattered about the mean. The differences for AOA sensor/RRMADS are relative large because of data from wind-on environment. Model vibration and support system movement seems to result in a larger difference.

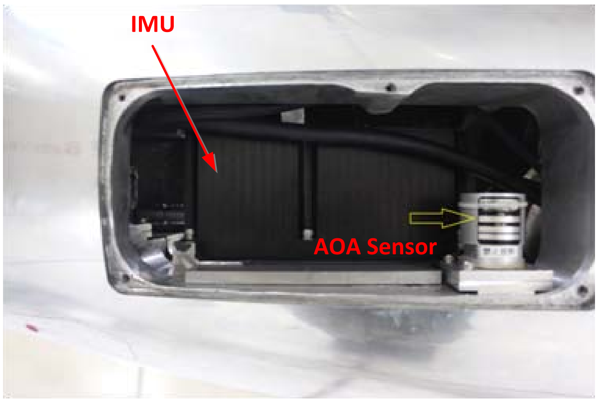

Fig. 4. IMU and AOA Sensor Installation Position

Fig.5. OptoTrak System

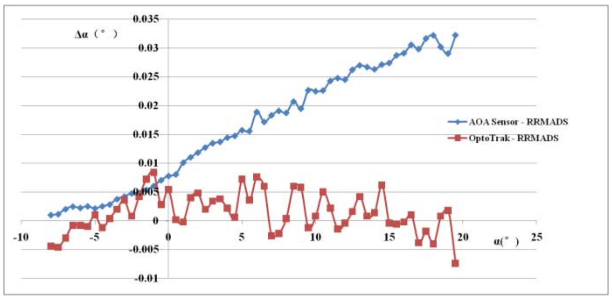

Fig.6. AOA Measurement Comparison Results

Table 4. AOA Measurement Comparison Results

Device Combination	Differences Mean Value	Differences Mean Variables
AOA Sensor/RRMADS	+0.017°	0.0001°
RRMADS/ OptoTrack	+0.0007°	0.00001°

Fig.7. and Table 5. show sideslip angle measurement comparison results. The measurements are carried out in “step-by-step” mode with 5° increment between consecutive data points. Compared with the design specification, the bias for RRMADS/OptoTrak is small(-0.01°). Like the AOA measurement differences, the sideslip measurement differences are also randomly scattered about the mean.

Static calibration tests and wind tunnel tests both prove that the accuracy of RRMADS fulfills the design specifications.

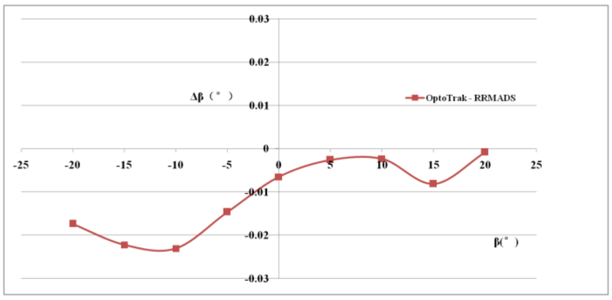

Fig.7. Sideslip Angle Measurement Comparison

Table 5. Sideslip Angle Measurement Comparison

Device Combination	Differences Mean Value	Differences Mean Variables
RRMADS/ OptoTrack	-0.01°	0.00008°

4 Conclusion

A high accuracy model attitude system, RRMADS, was developed in CARDC. The size of this system is 200mm×110mm×90mm which is suitable for most models tested in FL-13 tunnel. The accuracy of AOA measurement is better than 0.02° and of sideslip angle measurement is better than 0.02°/h.

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