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Aerodynamic Database Design and Flight Data Analysis of a Waverider Vehicle

Bingyan Chen, Xinyu Liu, Guowu Xu, Faming Guan
China Academy of Aerospace Aerodynamics
17 West Yungang Rd., Fengtai, Beijing, China

Abstract

Waverider configuration has been studied intensively since the concept was introduced by Nonweiler in 1959. Waverider is believed to be the ideal hypersonic vehicle configuration due to its high lift-to-drag ratio characteristics. However, application of waverider configuration in practical vehicles has yet to be seen. A waverider vehicle was developed as a flight test demonstrator for practical waverider configuration. One of the main purposes of the flight test project is to demonstrate the feasibility of waverider configuration in practical hypersonic applications. The demonstrator was boosted by a solid rocket to hypersonic speed. When the preset flight test window conditions were meet, the demonstrator was released to free flight after the cowling ejection and stage separation. The demonstrator then performed a predesigned flight trajectory with its automated control system. A reliable and accurate aerodynamic database is the key to ensure the demonstrator flies along the predesigned trajectory. In this paper the methodology of the establishment of the aerodynamic database of the waverider vehicle is introduced. The aerodynamic data was mainly obtained with CFD simulations. Wind tunnel experiments were conducted at selected conditions for the validation of the CFD data. Post-fly data analysis was conducted and the analysis results show that the real flight data falls within the uncertainty band given by the aerodynamic database.

1. Introduction

Waverider configuration has been studied intensively since the concept was introduced by Nonweiler in 1959. Waverider is believed to be the ideal hypersonic vehicle configuration due to its high lift-to-drag ratio characteristics. However, application of waverider configuration in practical vehicles is still yet to be seen. A waverider vehicle flight test demonstrator for practical waverider configuration was developed. One of the main purposes of the flight test project is to demonstrate the feasibility of waverider configuration in practical hypersonic applications. Aerodynamic database takes an important role on the conceptual design and optimization design of flight test vehicle, flight performance evaluation, and the analysis of aerodynamic data between flight test and ground prediction, or flight simulation[1]. Therefore the development of aerodynamic database is crucial for the success of the flight test. It was highly valued in the past aerospace flight test programs. For example, the aerodynamic design data book was powered for the development of space shuttle early years in America, and the demonstrator aircraft aerodynamic databases were developed for X-33/ X-34/ X-43A recent decade years[2-3].

In this paper the methodology of the establishment of the aerodynamic database of the waverider vehicle is introduced. The aerodynamic data was mainly obtained with CFD simulations. Wind tunnel experiments were conducted at selected conditions for the validation of the CFD data. Post-fly data analysis was conducted and the analysis results show that the real flight data falls within the uncertainty band given by the aerodynamic database.

2. Aerodynamic database design

2.1 Vehicle configuration

The waverider flight demonstrator is 1.5m long and 0.7m wide. Its total weight is about 170kg. The windward wing surface of the vehicle was designed using the waverider design method based on shock-fitting technique developed by Chen. et al[4]. A fuselage that hold internal components is on top of the wing. The radius of the leading edge is

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3.8mm. The aerodynamic control surfaces of the vehicle consist of a pair of wing elevons and a pair of rudders located at the rear part of the V-shape stabilizers.

2.2 CFD calculations

The main goal of the aerodynamic database establishment is to provide an accurate and reliable aerodynamic model for preflight simulations. The cost of developing the database is also an important consideration for the flight test project. The aerodynamic data of the waverider vehicle were obtained by CFD calculations.
The CFD tool used for the aerodynamic database development is GiAT, a CFD software developed by China Academic of Aerospace Aerodynamics (CAAA). GiAT includes an adaptive viscous Cartesian grid generator[5] and a Roe scheme[6] based Navier-Stokes flow solver. The Spalart-Allmaras one equation turbulence model[7] and several two equation turbulence models, including Wilcox k-omega 1998[8], Wilcox k-omega 2006[9], and Menter SST k-omega[10], are integrated in the solver for simulation of turbulent flows.
The calculated aerodynamic data is presented in the body axes system, as shown in Fig. 1. In this system, the reference point is placed at the center of gravity.

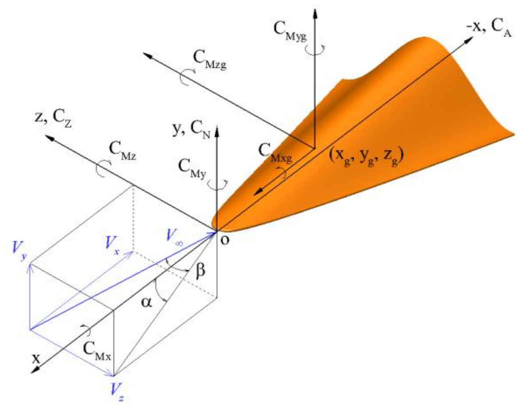

Fig. 1: Definition of the body axes system.

Numerical simulations were conducted using a standard set of simulation guidelines that assured adequate grid resolution and iterative convergence. Two types of grids, i.e. viscous Cartesian grid, which contains subdivided layers near solid walls to capture the boundary layer flow, and multi-block structured grid, were generated for CFD solutions. The y^+ value on the first cell near solid walls was generally keep in the order of 1. The differences of aerodynamic force coefficients calculated using different type of grids falls within 3%.
Free stream and boundary conditions used for numerical simulations are given in Table 1. When free stream Reynolds number based on unit length is greater than 5.0e6, turbulent flow is assumed for the simulation; otherwise, laminar flow is assumed. For turbulent flows, the Menter SST k-omega turbulent model was used. The ideal gas model was used for all the numerical simulations.

Table 1: Free stream and boundary conditions

H [km]	Ma	α°	β°	Re [1/m]	Tw [k]
0	0.4	-2~15	-4~4	9.32e6	300
5	0.8	-2~15	-4~4	1.16e7	300
10	1.1	-2~15	-4~4	9.35e6	300
17	1.5	-2~15	-4~4	4.43e6	300
19	2	-2~15	-4~4	4.32e6	300
24	3	-2~15	-4~4	2.91e6	300
28	5	-2~15	-4~4	2.57e6	700
30	6	-2~15	-4~4	2.26e6	700

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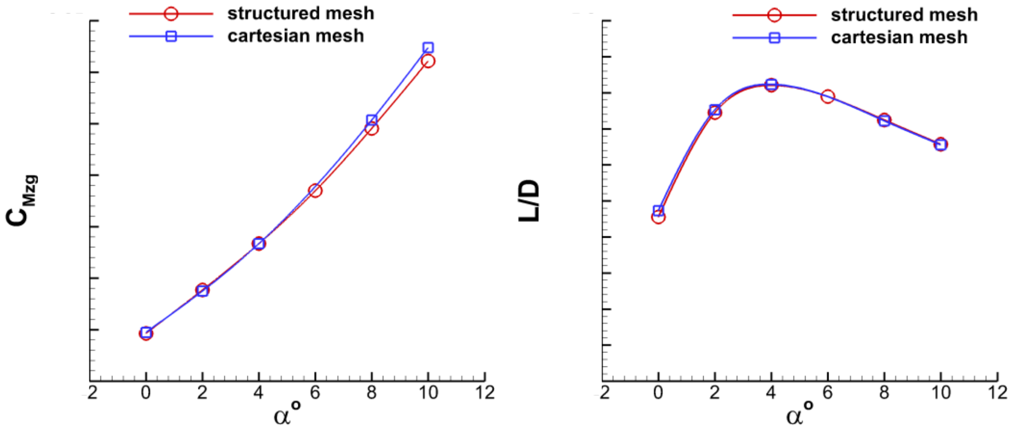
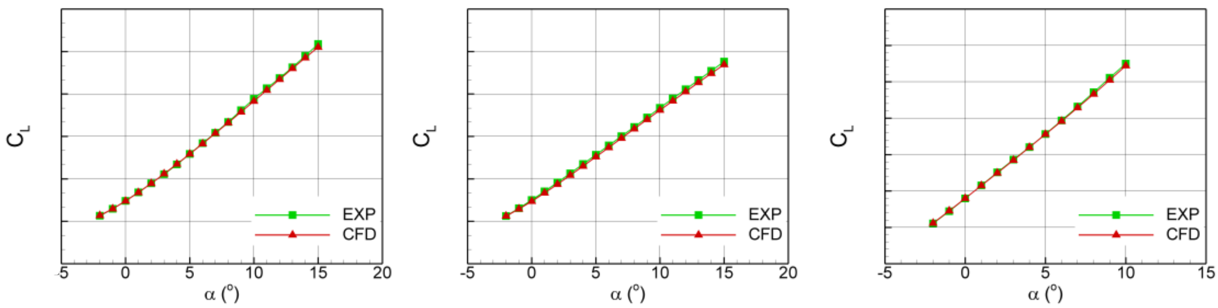


Fig. 2: Aerodynamic coefficients calculation results using different types of mesh

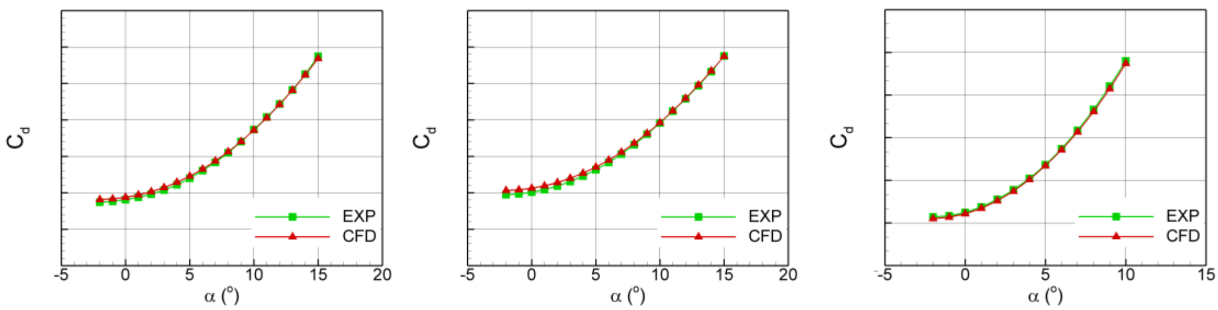
2.3 Wind tunnel tests

In order to validate the numerical data, wind tunnel tests on selected key points were conducted in the FD-06 and the FD-07 wind tunnels at CAAA. The FD-06 is a semi-return-flow intermittent wind tunnel. The cross section dimension of the test section is 0.6mx0.6m. The test Ma number ranges from 0.3 to 4.45. The FD-07 is a hypersonic wind tunnel. The cross section dimesion of the test section is Φ0.5m. The test Ma number ranges from 4.5 to 8. The test model scale ratio is 1:4.2, with deflectable control surfaces that can be set at specific angles.
The following figures show the comparison between the numerical results and the wind tunnel test results for the basic profile test model without elevon and rudder deflection. The green line with solid square represents the wind tunnel test data, and the red line with solid triangle represents the numerical data. As shown in the figure, the lift coefficient and the drag coefficient fit very well for the two set of data in different Mach numbers. For the longitudinal pressure center coefficient and the lateral pressure center coefficient the differences between the numerical data and the test data are less than 2%.



(a) Ma=0.8 (b) Ma=1.5 (c) Ma=5.0

Fig. 3: lift coefficient



(a) Ma=0.8 (b) Ma=1.5 (c) Ma=5.0

Fig. 4: drag coefficient

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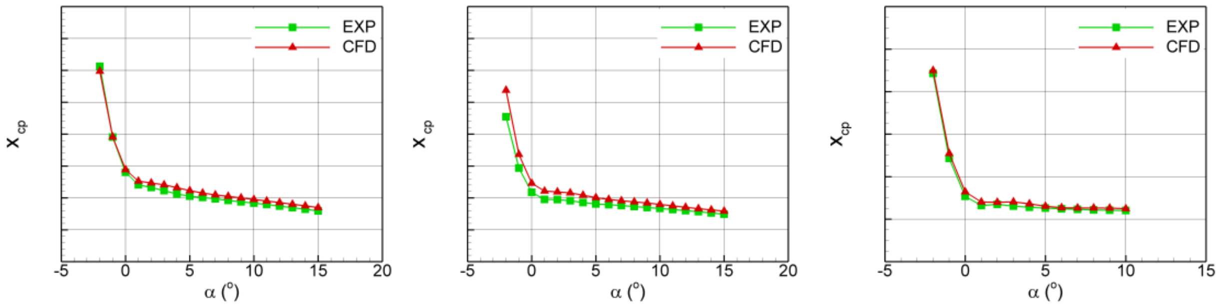
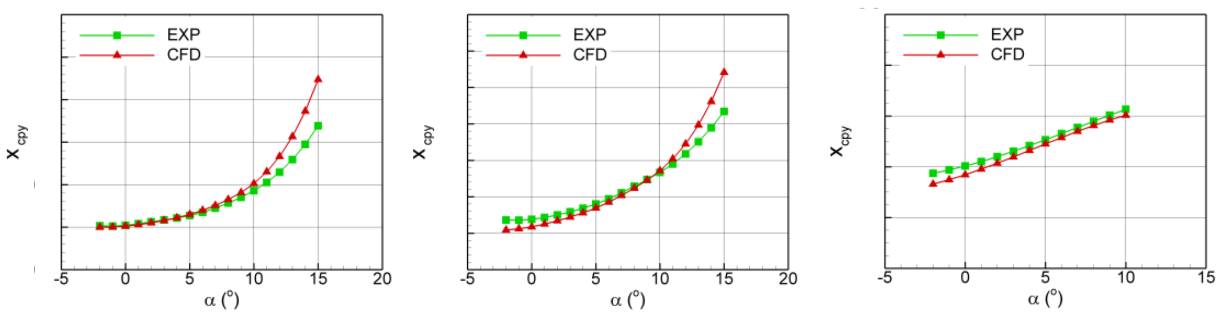


(a) Ma=0.8 (b) Ma=1.5 (c) Ma=5.0

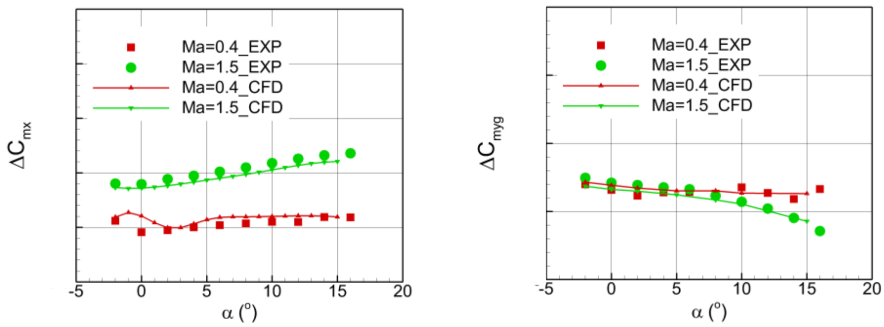
Fig. 5: longitudinal pressure center



(a) Ma=0.8 (b) Ma=1.5 (c) Ma=5.0

Fig. 6: lateral pressure center

The following figures show the comparison between the numerical results and the wind tunnel test results for the test model with elevon and rudder deflections. Fig.5 (a) shows results for the model with -25 degrees left elevon deflection and 25 degrees right elevon deflection. Fig.5 (b) shows the results for the model with 10 degrees left rudder deflection at 4 degree angle of sideslip. The numerical data fit well with the wind tunnel test data in different Mach numbers.



(a) Elevon deflection (b) Rudder deflection

Fig. 7: comparison of the control surfaces effect

Over all the differences between the CFD data and the wind tunnel test data were considered to be acceptable and were accounted in the aerodynamic uncertainties.

2.4 Aerodynamic control surfaces decouple methodology

As mentioned above, the aerodynamic database are composed by massive parallel numerical calculation results, the wind tunnel tests on some key points are used to verify the results and establish the uncertainty band. Such practice can reduce the cost effectively, but even so it is hard to calculate all data points for vaiarious control surfaces combinations. So firstly when considering the single control surface deflection model, we calculate the data points only for the left side deflection model because of the symmetrical characteristics of the vehicle. The data of right side deflection model can be obtained from the above data by symmetric processing. Secondly for multi-control surfaces

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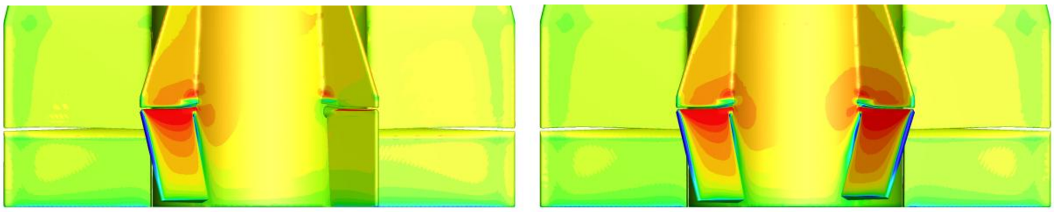
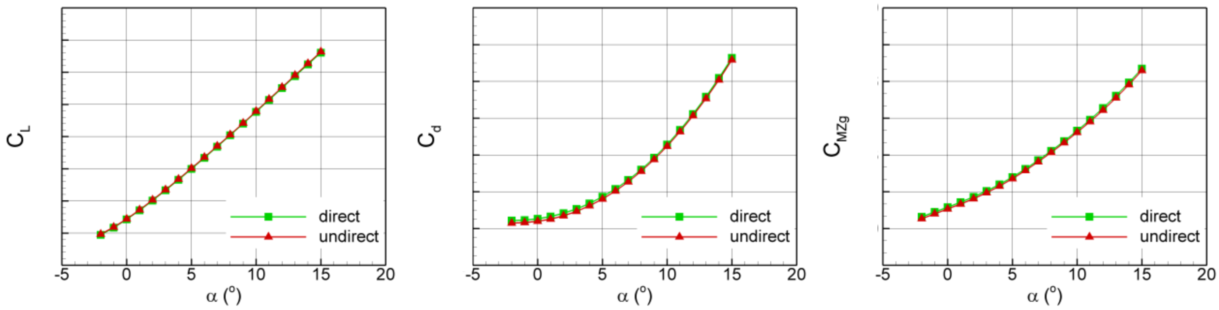
deflection model, the aerodynamic data is calculated by adding the basic model (no control surfaces deflection) data with each individual control surface deflection model incremental data. Specifically, the difference between single control surface deflection model and basic model is taken as the incremental data. Such linear processing method implies an assumption, that is the disturbance between different control surfaces deflections can be ignored. To prove this, we choose the left and right rudder to test the disturbance of 20 degrees deflection by numerical method. Fig. 8 shows the surface pressure contour comparison around the rudder, the model（a） is single left rudder deflection model, while the model（b） is symmetric rudder deflection model. As we can see the pressure distribution around left rudder are basically the same with each other, and it indicates that the deflection of right rudder has little influence on the left rudder. So the method of basic data linearly adding with the increments of each rudder deflection is feasible.



(a) single deflection (b) symmetric deflection

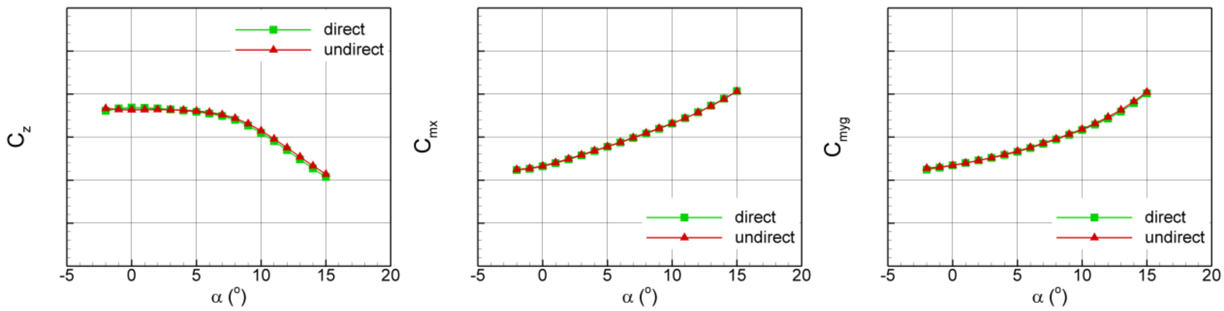
Fig. 8: surface pressure contour of the rudders

Further more, we compare the results between the linear superposition method and directly numerical calculation method. In the following figures, the word undirect represents the linear superposition method, the word direct represents the directly numerical calculation method. Fig. 9 shows the profile of left and right rudder 20 degrees symmetric deflection, while Fig. 10 shows that of 20 degrees asymmetric deflection. As shown in the figures, for the concerned aerodynamic parameters, the undirect results fit well with the direct results, the difference is less than 1%. So it proves the method to construct the database is feasible.



(a) lift coefficient (b) drag coefficient (c) pitch moment coefficient

Fig. 9: 20 degrees rudder symmetric deflection



(a) lateral force coefficient (b) roll moment coefficient (c) yaw moment coefficient

Fig. 10: 20 degrees rudder asymmetric deflection

Based on the basic and single rudder deflection data, the bottom of the database runs a section of code to realize the method. The method can save a great quantity of material resource and time cost, it is the optimal choice under current computational conditions.

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3. Flight data analysis

The effects of the local atmosphere (mainly wind speed and direction) on the angle of attack, α, and angle of sideslip, β, is shown in Fig. 11. The local wind speed and direction was detected by a sounding balloon at the launch site before the flight test. Therefore the wind field data can only reflects the situations of the initial phase of the flight trajectory. For locations far away from the launch site, the wind field data was not accurate.

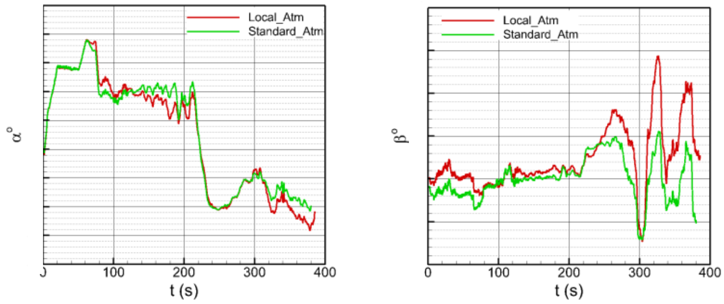

Fig. 11: Effects of local atmosphere on α and β

Fig. 12 shows the comparison of the six components of the aerodynamic coefficients and lift and drag coefficients identified from the flight test results with the prediction of the aerodynamic database. The process results using both the standard atmosphere and local atmosphere are shown in the figure simultaneously. Flight data agree well with database prediction in the early 200s of the flight. After 200s, the discrepency between flight data and prediction results becomes relatively large. The reason for this appears to be the lack of the accurate wind field data.

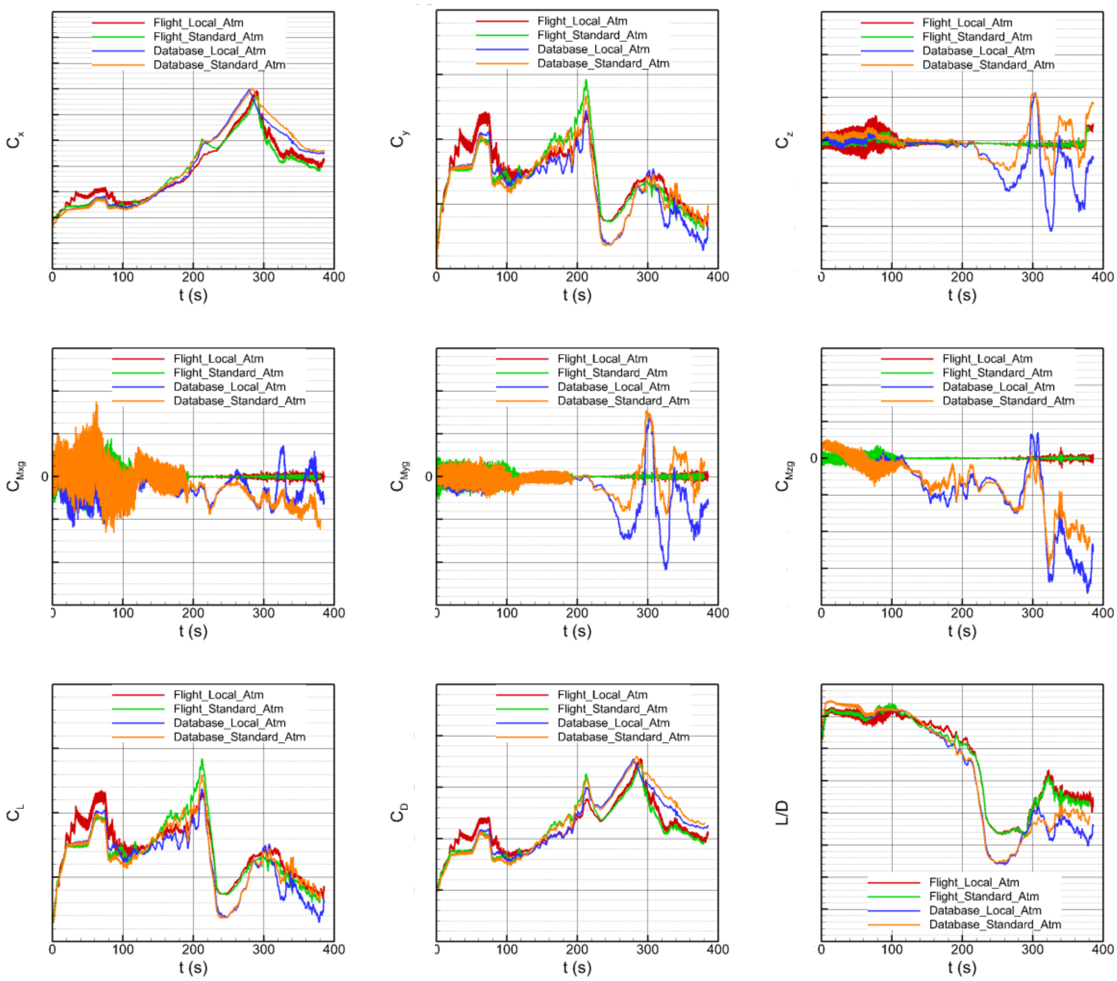

Fig. 12: Comparison between flight data and database prediction

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The comparison between the flight data and the aerodynamic database with uncertainty is shown in Fig. 13. It can be seen that the axial force coefficient, normal force cefficient, rolling moment coefficient and pitching moment coefficient of the flight results fall within the uncertainty band of the database. Due to the lack of the accurate wind field data, the side force coefficient and yawing moment coefficient of the flight results deviate beyond the uncertainty band of the database, especially after 200s.

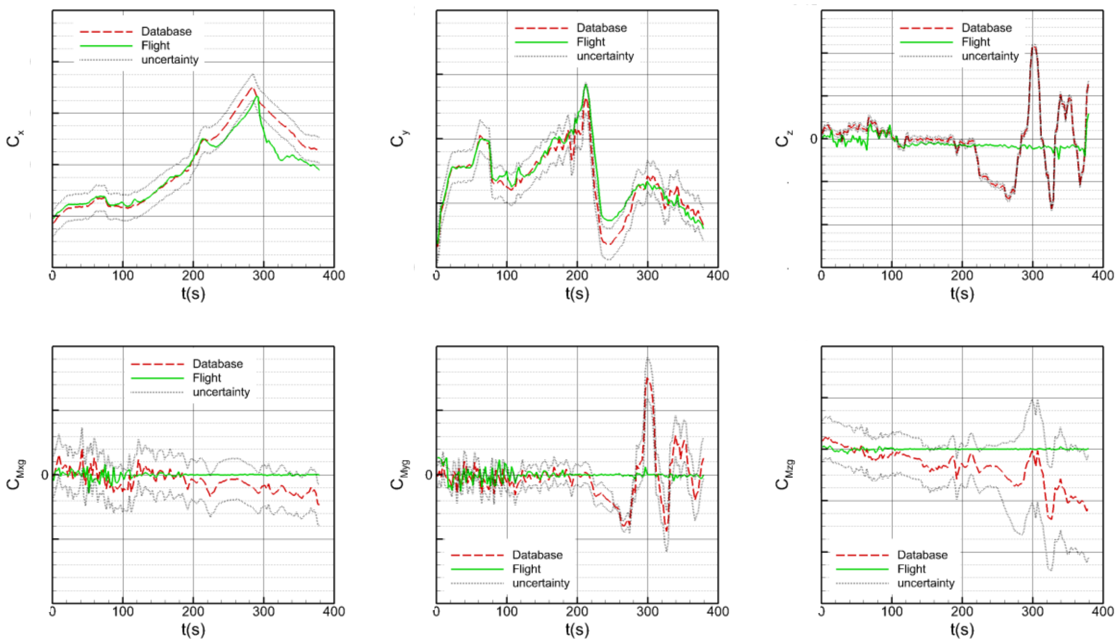

Fig. 13: Comparison between flight data and database with uncertainty

4. Summary

In this paper the methodology of the establishment of the aerodynamic database of the waverider vehicle is introduced. The aerodynamic data was mainly obtained with CFD simulations. Wind tunnel experiments were conducted at selected -conditions for the validation of the CFD data. Post-fly data analysis was conducted and the analysis results show that the real flight data falls within the uncertainty band given by the aerodynamic database.

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