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IN-FLIGHT MEASUREMENTS AND ESTIMATION OF SONIC BOOM SIGNATURE OF SUPERSONIC AIRCRAFT

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Abstract

Sonic boom is one of the key problems to be solved in the development of supersonic civil aircraft. In-flight flow-field signature measurements is the most direct method to study the sonic boom characteristics of supersonic aircraft. Technologies related to sonic boom flight test track planning, ground-air integrated large-scale array sonic boom measurement are developed. The in-flight sonic boom test programme of a supersonic aircraft was carried out, collecting multiple sets of sonic boom signatures in real atmospheric conditions. The sonic boom waveform measured on track has significant correlation. The far-field boom measured data and numerical prediction results are compared and analyzed. When the aircraft flew over the measurement array, the basic shape of the obtained sonic boom signatures is consistent, with relatively close duration time. The relative error between the peak values of the bow shock and the wing leading edge shock is less than 5%. However, due to factors such as the simplification of the simulation model and the nonlinear cumulative effect of the long-distance propagation of the sonic boom, the predicted sonic boom signals have certain differences in local characteristics, which suggested further research on the far-field sonic-boom prediction method in real atmospheric environment.

Keywords: supersonic；sonic boom；flight test；shock；prediction

1. Introduction

Sonic boom is an important research topic in the development of supersonic civil aircraft. There are three main research methods for sonic boom problems, namely numerical simulation, wind tunnel test and flight test[1]. Numerical simulation is affected by factors such as modeling uncertainty and calculation error[2-4], whereas the sonic boom flight test data is required to verify the numerical simulation program[5-7]. Due to the limitation of the test section and model size, the wind tunnel test is limited to study the near and intermediate flow field, which could not represent the real atmosphere[1]. The sonic boom flight test is the most direct method to study the characteristics of the sonic boom signatures. It can obtain not only the near-field and mid-field sonic boom signals, but also all important ground test data. Hence, the generation and propagation process of the supersonic aircraft sonic boom can be understand for cruise state, as well as the maneuvering flight. The measured data can be used to verify the sonic boom prediction method and low sonic boom design technology. Therefore, it is of great significance to carry out sonic boom flight test for supersonic aircraft, aiding the development of sonic boom prediction technology and the design of low sonic boom aircraft.

The United States has carried out lots of research in sonic boom for nearly seven decades[1]. Starting from a large number of sonic boom wind tunnel tests and flight tests, it has gradually developed and improved sonic boom test technology characterized by the capture of over-pressure signals. Combining the abundant measured sonic boom data with the basic principle of sonic boom effect, the theoretical basis for linear and nonlinear sonic boom prediction methods such as the waveform parameter method[8] and the Augmented Burgers equation[9] was established, developing some engineering tools such as PCBOOM and sBOOM. In the field of sonic boom flight test research, the United States has established a rich database of supersonic flow fields, including F-100, B-58, XB-70, SR-71, F-5E/silent cone, SSBD and other typical supersonic vehicles, with near-field, mid-field and far-field sonic boom signatures[1]. The valued database can be used to master and analyze the generation and propagation characteristics of sonic boom signals, which can also support the design of a new generation of low sonic boom supersonic aircraft. Japan's JAXA has carried out series of D-SEND projects[10], aiming to verify the low sonic boom design technology, by dropping the model from a high altitude to reach the supersonic flight state and testing the sonic boom signal. The EU and Russia have also carried out research related to sonic boom flight tests in the RUMBLE project[11]. More details can refer to the our review paper[12].

At the end of 2020, CAE and Aircraft Flight Test Technology Institute successfully carried out a special in-flight sonic boom test of a supersonic aircraft. In this paper, the in-flight test plan and related results are described at first. Then, a comparative analysis is carried out in combination with the numerical simulation results. The obtained in-flight test data are in relatively good agreement with the numerical simulation results, which preliminary verifies the reliability of the sonic boom prediction tool. The research work can provide experience for the follow-up sonic boom flight test of supersonic aircraft, and also can provide technical support for the development of low sonic boom design of supersonic civil aircraft.

2. In-Flight Test Method

According to the in-flight sonic boom signature measurement requirements and the generating aircraft performance to be verified, the flight status of the aircraft when flying over the sonic boom measurement array was designed in detail, including flight attitude, flight altitude, flight Mach number and flight trajectory. As to the designed flight path of the aircraft, sonic boom signature characteristics such as intensity and duration at ground is estimated. Combined with the meteorological conditions such as the local temperature, humidity and air pressure, a sonic boom in-flight measurement system was designed. When the generating aircraft flew over the ground sonic boom measurement array according to the design flight state, the data related to the flight trajectory, sonic boom signal and real-time atmospheric parameters were collected as planed. A large number of important measured data under real atmospheric conditions were obtained.

This series of flight tests mainly conducted ground sonic boom measurements in the state of low-altitude and high-altitude supersonic uniform speed in cruise flight, namely Hp=3km and Hp=11km. The design of flight status was based on the following two points:

(1) Investigate sonic boom signature characteristics of the generating aircraft at different altitudes and different speeds;

(2) Verify sonic boom in-flight measurement program and the related technology.

The flight test measured a wide range of ground sonic boom signals. As to designed flight altitude *Hp*=3km, two flights were performed, and the duration of each test was not less than 120 s. The time periods before and after passing the measurement array remained more than 60 s. As to *Hp*=11km, the in-flight test is performed once, and the duration is not less than 480 s. The related time periods before and after passing the measurement array are maintained more than 240 s.

The generating aircraft flew according to the proposed status, which generated the target sonic boom in the state of stable level flight at different altitudes at a given Mach number. Technologies related to sonic boom flight test track planning, ground-air integrated large-scale array sonic boom measurement are developed. Figure 5 shows a schematic diagram of the in-flight test method. The aircraft flew along the design tracks at 3km and 11km altitudes in the figure respectively. The arrays of sonic boom measurement points were all arranged directly below the flight track, and the main direction of the array was kept parallel to the flight target track. The length of the test array is 1200m along the flight track and 400m in the vertical track direction. A total of 13 test locations were set, associated with a group of microphones for which the separation distance was generally 120m and 200m in each direction. When the flight path entry point is adjusted to the test state as proposed, it is guaranteed to fly over the sonic boom measurement array in the target state. The determination of the entry point mainly considered the basic flight performance, handling stability characteristics and pilot operation efficiency of the aircraft. According to the flight speed and the location of the measurement array, the flight status should remain fairly steady-state flight conditions. The principle of determining the exit point of the track is that the aircraft is as far away as possible from the measurement area, without affecting any other measurement locations, as well as considering the aircraft's supersonic flight performance, airspace limitations, etc. During the test, the test system continuously measured parameters such as sonic boom, ground and air meteorology, flight status, and flight path.

As shown in Table 1, a special in-flight sonic boom test programme was conducted at a nominal Mach number of 1.23 and 1.49. Here, H_p is the pressure altitude of the tested aircraft, and H_G is the altitude of the generating aircraft above the ground. Multiple sets of sonic boom measured data under real atmospheric conditions were collected, which confirmed the rationality of the in-flight test plan. Overall, 3 sets of valid test data were obtained. More details can be found in the journal paper[13].

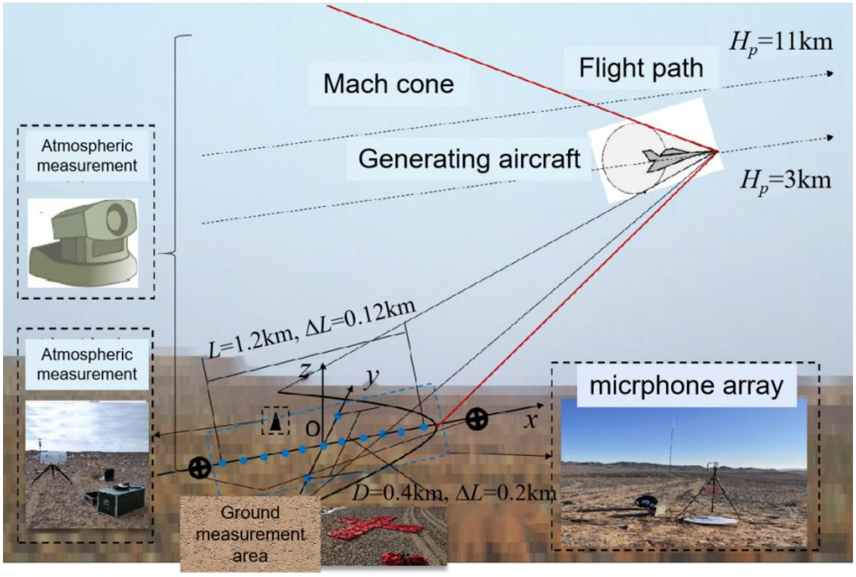


Figure 1 In-flight test method

Table 1 Overview of flight measurement program

No.	Altitude/km	Ma
Fx1	H_p=3.04 H_G=1.72	1.23
Fx2	H_p=3.01 H_G=1.75	1.23
Fx3	H_p=11.0 H_G=8.74	1.49

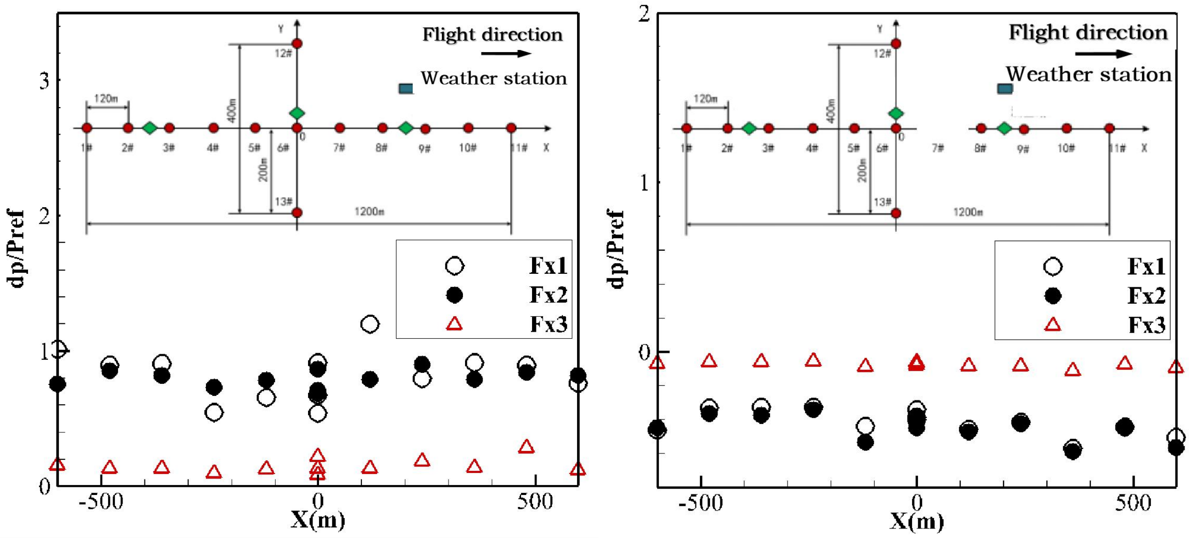
3. Numerical Simulation Method

The well-proven CFD method was used to solve the three-dimensional Euler equation to predict the near-field sonic boom signal. And the far-field propagation program based on the Augmented Burgers equation was used to predict the propagation process of the far-field sonic boom signal, resulting the ground sonic boom signal (ground reflection factor was set as 1.9). The Stevens loudness method was selected as the calculation method for the total loudness level of the sonic boom, carrying out the subjective response evaluation of the ground sonic boom signal. All the above methods are integrated in an in-house code CBoom developed by CAE.

4. Results and Discussion

4.1 Overview of the measured data

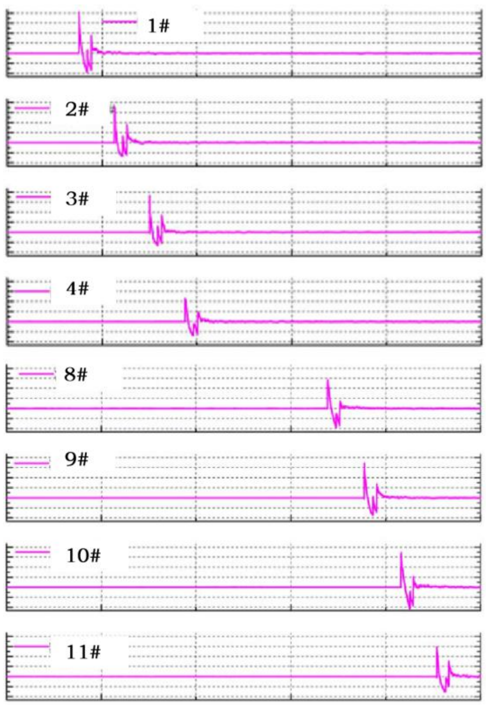
As shown in Figure 2, the sonic boom waveform measured on track has significant correlation. The relative error of the sonic boom signal bow shock peak is about 18%, which of the tail shock peak is about 8%. The duration of the sonic boom signature is around 0.1s.



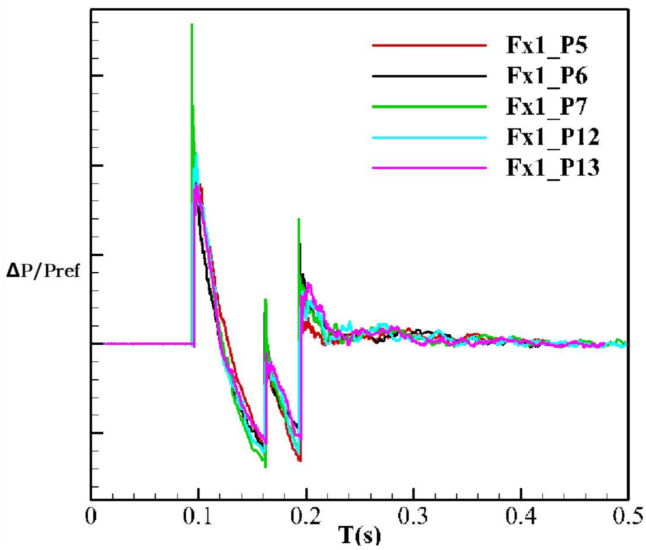
(a) Bow shock (b)Tail shock

Figure 2 Peak over-pressure of the measured sonic boom signature

As to the flight path test data, the test aircraft flew over the test array basically according to the predetermined flight path during Fx1. The Followed discussion will focus on Fx1. Figure 3 (a) shows the sonic boom signals measured from 8 measuring points on track, where the measured signal waveforms have significant similarities. Further comparison regarding to detailed wave shape is presented in Figure 3 (b), showing the over-pressure around the array center, namely 6#. It can be seen that the sonic boom over-pressure peaks measured at those measuring points have changed significantly, which is most likely caused by the change of the sonic boom signal waveform related to atmospheric conditions. It is inferred that the comprehensive influence of the micro-atmospheric effect related to the atmosphere on the sonic boom signal is very important.



（a） Measurement array along *y*=0



（b） Measurement array around the array center

Figure 3 Measured sonic boom signatures

4.2 Comparison of the measured and predicted data

A comparison of flight-test data and the computed pressure signatures at ground are carried out. Figure 4 shows the comparison between the measured data of the flight test regarding to the 6#, 12#, and 13# measurement points during the flight test Fx1 and the corresponding numerical simulation results of CBoom. The basic shape of the sonic boom signatures obtained is consistent, and the duration is relatively close. Meanwhile, the predicted results matched the measured signature in regard to the number, location, and magnitude of the shocks, especially of the nose and wing shocks. The relative error between the peak values of the bow shock and the wing leading edge shock is less than 5%. The solid red line represents the predicted results of the simplified geometry, which simply modify the geometry near the engine tail nozzle, resulting increased the equivalent cross-sectional area. Thus, the resulted tail shock is quite far away from the corresponding measured data. After refining the model geometry, the predicted tail shock agree much better with the measured results, see the dashed red line in Figure 4.

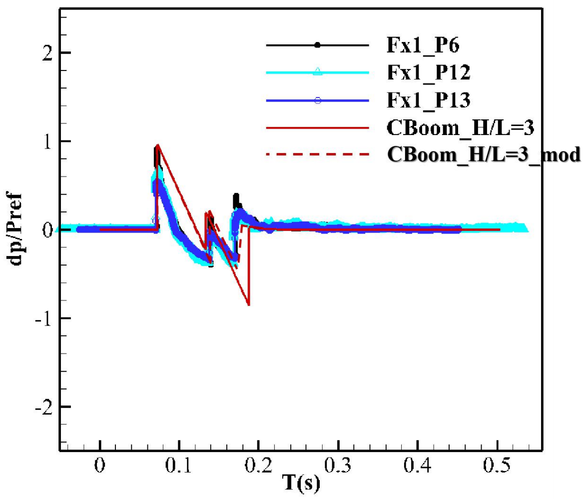


Figure 4 Comparison of over-pressure signatures for ground sonic boom (Ma=1.23)

According to the ground sonic boom signal obtained from the Fx1 in-flight measurement and prediction, the Stevens loudness method was used to calculate the loudness level corresponding to the sonic boom signal propagating from the near-field over-pressure signal on track and off track located at H/L=3 to far-field sonic boom signal. When the aircraft flew over the test array, the ground sonic boom loudness level comparison is shown in Figure 5. The average loudness level of the measured data is 120.3 PLdB, while the averaged loudness level obtained from the predicted data from the refined geometry is 121.0 PLdB. The error is within ±1 PLdB.

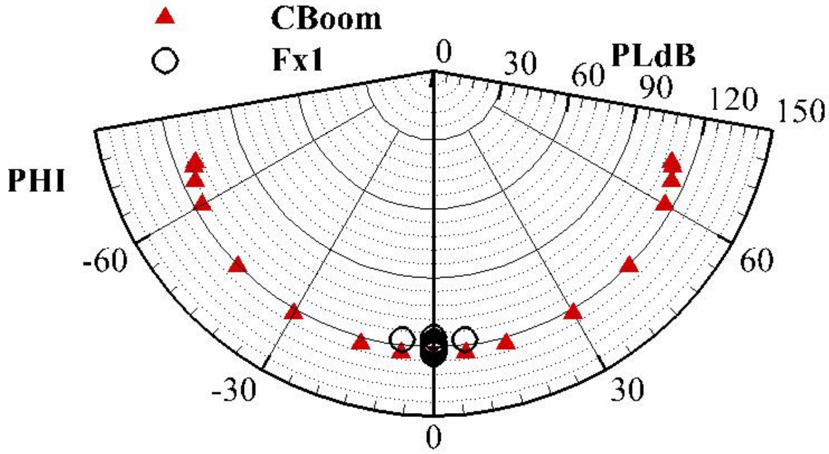


Figure5 Comparison of loudness levels for ground sonic boom signatures (Ma=1.23)

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5. Conclusions

A special sonic boom in-flight measurement of supersonic aircraft was carried out. A large number of important data under real atmospheric conditions were obtained. The measured results were compared and analyzed by combining numerical simulation methods. The main conclusions are as follows:

1) The sonic boom in-flight measurement successfully collected multiple sets of sonic boom signatures, as well as the corresponding atmospheric conditions and flight state data. The measured data verified the rationality of the test plan. Meanwhile, a series of key technologies regarding to sonic boom in-flight test for real aircraft are verified, such as specified flight trajectory planning, low-altitude integrated large-scale array sonic boom measurement, and so on.

2) The measured data of ground sonic boom signals are in good agreement with the overall trend of numerical simulation prediction results. The sonic boom prediction method adopted has certain reliability.

3) There are some differences in local characteristics between the measured data near around, which indicated that the nonlinear cumulative effect of the long-distance propagation of the sonic boom under real atmospheric conditions plays important role.

References

[1] Maglieri D J, Bobbitt P J, Plotkin K J, et al. Sonic boom: six decades of research. NASA Langley Research Center, NASA/SP-2014-622, 2014.

[2] Park M A, Morgenstern J M. Summary and statistical analysis of the first AIAA sonic boom prediction workshop//Proc of the 32nd AIAA Applied Aerodynamics Conference, Atlanta, GA. Reston, Virginia: AIAA, 2014.

[3] Park M A, Nemec M. Nearfield summary and statistical analysis of the second AIAA sonic boom prediction workshop. Journal of Aircraft, 2018, 56(3): 851-875.

[4] Rallabhandi S K, Loubeau A. Summary of propagation cases of the second AIAA sonic boom prediction workshop. Journal of Aircraft, 2018, 56(3): 876-895.

[5] PLOTKIN K J. Calculation of sonic boom from numerical flow-field solutions: MDBOOM version 2.2[R]. Wyle Research Report, WR 92-14, 1992.

[6] MEREDITH K, DAHLIN J, GRAHAM D, et al. Computational fluid dynamics comparison and flight test measurement of F-5E off-body pressures[C]//43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada. Reston, Virginia: AIAA, 2005.

[7] HAERING E A, MURRAY J E, PURIFOY D D, et al. Airborne shaped sonic boom demonstration pressure measurements with computational fluid dynamics comparisons[C]// 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2005. AIAA 2005-9.

[8] THOMAS C L. Extrapolation of sonic boom pressure signatures by the waveform parameter method[R]. NASA TN D-6832, 1972.

[9] CLEVELAND R O. Propagation of sonic booms through a real, stratified atmosphere[D]. Austion: University of Texas at Austin, 1995.

[10]KAWAGUCHI J, SUZUKI H, NINOMIYA T, et al. Post-flight evaluation of the guidance and control for D-SEND#2 2nd drop test[C]//AIAA Atmospheric Flight Mechanics Conference, Grapevine, Texas. Reston, Virginia: AIAA, 2017.

[11]LØVHOLT F, NOREN-COSGRIFF K, PARK J, et al. Building vibration due to sonic boom—Results from simulations and field measurements[J]. The Journal of the Acoustical Society of America, 2021, 149(4): A100.

[12]SONG Y, FAN G, QU L, et al. Progress of Aircraft Sonic Boom Flight Test Technology: Review [J]. Acta Aeronautica et Astronautica Sinica, 2023, 44(1): 626186.

[13]QU L X, HAN S, SONG Y H, et al. Flight tests and predictions of sonic boom signature for supersonic aircraft[J]. Acta Aerodynamica Sinica, 2022, 40(4): 69−80.