ADVANCED SONIC BOOM ANALYSIS USING FULL-FIELD SIMULATION

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Abstract

A full-field simulation method was recently proposed as a new approach to improve the state of the art of sonic boom prediction method. As a result, first-ever direct simulation of sonic boom was successfully performed to reproduce flight tests and to clarify sonic boom phenomena that would be difficult to evaluate using conventional prediction methods, including sonic boom cutoff phenomena in low supersonic flight and waveform transition of sonic boom in hypersonic flow regimes. This paper reviews the full-field simulation method and some simulation results described in [1-6], especially in the doctoral thesis of this author at the University of Tokyo[1].

1 Introduction

Sonic booms generated from an aircraft traveling at supersonic speeds are an unavoidable impediment to realizing advanced supersonic transports [7]. The International Civil Aviation Organization (ICAO) presently deliberates on an international standard in which an acceptable level of sonic boom will be determined to allow overland supersonic flight. However, the lack of scientific data makes it difficult to formulate the clear standard in various flight and atmospheric conditions. Therefore, several flight tests for sonic boom were recently conducted by NASA [8-10] and the Japan Aerospace Exploration Agency (JAXA) [11], and the development of accurate prediction methods for sonic boom is promoted.

Sonic booms are generated not only from an aircraft traveling at supersonic speeds but also from a meteorite falling on the earth. In the Chelyabinsk meteorite observed in 2013 [12], the sonic boom generated from the meteorite falling propagated extensively and produced unexpected damage to the ground. From this fact, the development of accurate prediction methods for sonic boom is required for evaluating not only advanced supersonic aircrafts but also influence of meteorite impact.

The prediction methods for sonic boom have been chiefly developed to evaluate sonic boom noise generated from supersonic aircrafts. These methods are based on the weak shock theory, and even complex phenomena are treated as simplified models. Thus, their applications are limited, and some sonic boom phenomena such as sonic boom cutoff occurring from shock wave diffraction [4] would be difficult to evaluate using the conventional prediction methods. For improving the state of the art, the full-field simulation method was recently proposed by Yamashita R. and Suzuki K. [1-6] The full-field simulation represents the Computational Fluid Dynamics (CFD) analysis over the entire field, consisting of its near field around a supersonic flight object, far field extending to the ground, and caustic-vicinity field in which shock-wave diffraction occurs. In this simulation, the governing equations can be modified to take into consideration effects such as molecular vibrational relaxation, chemical nonequilibrium, and turbulence. Furthermore, the simulation is available for investigating sonic boom characteristics at low supersonic and hypersonic speeds, three-dimensional structure of shock wave, and ground effects. Therefore, the full-field simulation is a powerful tool for reproducing sonic boom propagation in realistic environmental conditions and for analyzing sonic boom phenomena that would be difficult to evaluate using the conventional prediction methods.

What must be necessary for realizing direct simulation for sonic boom is to consider atmospheric effects such as atmospheric stratification, to properly capture shock waves in the entire field, and to reduce the computational load as much as possible. However, because it is difficult to meet all the requirements above, the direct simulation for sonic boom propagation through a real atmosphere had not been realized until the full-field simulation method was proposed. This paper reviews the full-field simulation method that successfully realized the first ever direct simulation for sonic boom propagation through a real atmosphere and some simulation results described in [1-6], especially in the doctoral thesis of this author at the University of Tokyo [1].

2 Full-Field Simulation Method

The full-field simulation based on the compressible CFD analysis was realized by constructing the following three methods: the numerical correction method for considering atmospheric stratification in Sec. 2.2, the method of constructing a solution-adapted grid aligned with shock waves in the entire field in Sec. 2.3, and the segmentation method of computational domain for reducing the computational load in Sec. 2.4. In this chapter, the full-field simulation method [1-6] is briefly presented.

2.1 Governing Equations

Full-field simulation is based on CFD analysis, and the appropriate governing equations can be selected according to applications. The basic governing equations are the primitive equations of fluid dynamics, i.e., the Navier-Stokes equations, and they are modified to consider effects that are required for properly analyzing sonic boom propagation. Note that the minimum required effects should be considered, because the computational cost is increased with increasing the number of effects considered. Assuming steady level flight in an undisturbed atmosphere, analysis of sonic boom propagation must be conducted in consideration of the following five effects:

- Geometrical spreading: the attenuation effect due to the geometrical spreading of wave with increasing distance from the generation source.
- Nonlinearity: the effect of wave steepening that is caused by the difference in the propagation speed of waves.
- Atmospheric stratification: the atmospheric effect due to variation in atmospheric properties with altitude.
- Molecular vibrational relaxation (thermal nonequilibrium): the relaxation effect due to translational-vibrational energy exchange.
- Viscosity: the dissipation effect due to fluid friction and thermal conduction.

In the Navier-Stokes equations, the nonlinear wave steepening and viscous dissipation are expressed by the convective and viscous terms, respectively. The geometrical spreading of waves can be considered by three-dimensional analysis, and atmospheric stratification can be incorporated by adding the gravity term for maintaining the state of hydrostatic equilibrium to the governing equations. In addition, the molecular vibrational relaxation can be considered by adding the thermal nonequilibrium model, in which conservation equations for vibrational energy with respect to oxygen and nitrogen molecules are incorporated and the rate of vibrational energy exchange is evaluated by the Landau–Teller rate model.

2.2 Computational Approach

The governing equations are discretized by the Finite Volume Method (FVM), and the Riemann solver used in compressible CFD analysis is directly applied. However, because the flow field is discretized by the computational grid, the change issued from atmospheric stratification is treated as a discontinuity in the Riemann solver, and as a result, nonphysical waves are generated because the hydrostatic equilibrium cannot be properly maintained. To improve this problem, the numerical correction method, in which the correction term is added for cancelling the discretization error, was constructed. Since the correction term is derived as the constant value depending on the atmospheric condition, the computational cost is hardly changed using the numerical correction method.

2.3 Solution-Adapted Grid Generation

Figure 1 shows an outline of entire computational domain used for analysis of an axisymmetric slender body. In order to precisely predict sonic boom noise, there are three requirements for a computational grid. First, the grid lines in the entire computational domain must be aligned with shock waves whose angles change according to variation in atmospheric temperature with altitude. If the grid lines are aligned with the shock waves, the grid spacing parallel to the shock waves can be set to the relatively large value, except for the surface of body. Second, the grid resolution vertical to the shock waves must be high enough to precisely capture the shock waves. Third, the number of grid points must be reduced as much as possible because the computational domain ranges over several tens of kilometers. For the requirements above, the method of constructing a solution-adapted structured grid in the entire computational domain was constructed. In this method, an initial three-dimensional structured grid is constructed by rotating a two-dimensional structured grid in which the grid resolution is enhanced only near the front and rear shock waves, as shown in Fig. 1. Then, the preliminary computation is performed using the initial grid, and the locations of the shock waves are detected based on the results obtained by the preliminary computation. Thereafter, the grid lines are adapted to properly align with the locations of the shock waves, and the reconstructed grid is used for the final simulation.

2.4 Segmentation of Computational Domain

A computational domain of full-field simulation ranges over several tens of kilometers, and the efficiency of computation must be improved to perform the simulation in reasonable computational time. Therefore, the entire computational domain is segmented into a sequence of subdomains, as illustrated in Fig. 1.

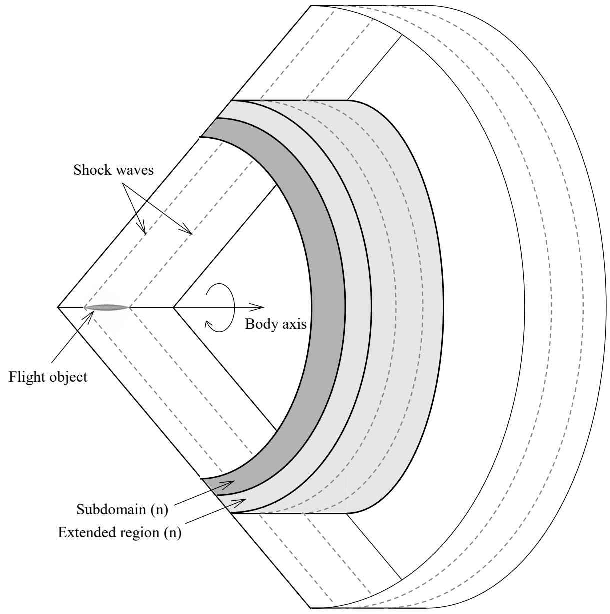

Fig. 1 Outline of computational domain.

Each simulation is performed in the subdomain (n) combined with the extended region (n) for preventing the influence of boundary between the subdomain (n) and subdomain (n+1). The time step in each simulation is changed to perform the efficient computation and is decided by the preliminary computation.

2.5 Computational Procedure

The computational procedure of full-field simulation is divided into two stages. First is the solution-adapted grid generation to properly align the grid lines with shock waves, according to the following procedure:

(i) The computational grid is constructed in the subdomain (n) and extended region (n).
(ii) Numerical simulation is performed.
(iii) The grid adaptation is conducted, and the computation in the same domain is performed again.
(iv) The computational domain is moved to the next domain until the solution-adapted grid is constructed in the entire domain.

Second is the final computation using the solution-adapted grid over the entire computational domain, according to the above procedure except for step (iii).

3 Full-Field Simulation Results

Full-field simulation has been performed to validate accuracy of the simulation [2, 3] and to clarify sonic boom phenomena [4-6] that would be difficult to evaluate using the conventional prediction methods. In this chapter, some computational results obtained in the previous studies [1-5] are briefly reviewed.

3.1 Simulation Accuracy [2, 3]

Accuracy of full-field simulation was validated by comparison with the flight test data that was obtained in the D-SEND#1 (the Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom #1) by JAXA [11]. The results showed that the pressure waveforms obtained by the full-field simulation were in good agreement with the flight test data, and they demonstrated that the full-field simulation properly analyzed sonic boom propagation through the real atmosphere.

3.2 Simulation at Low Supersonic Speed [4]

Full-field simulation was performed to investigate Mach cutoff phenomena of sonic boom. In a stratified atmosphere, shock waves generated by low supersonic flight are diffracted by an increase in atmospheric temperature toward the ground, and they do not reach the ground. This phenomenon is known as Mach cutoff. When Mach cutoff occurs below an aircraft, it may be allowed to make overland supersonic flight. Therefore, the flight test for evaluating cutoff phenomena was recently conducted at NASA [8, 9]. However, the lack of scientific data makes it difficult to formulate the clear standard for low supersonic aircrafts. With this in mind, the full-field simulation was performed to analyze sonic boom propagation generated from a low supersonic flight object. The results showed that an incoming wave generated from a supersonic flight object was divided into an outgoing wave traveling upward and an evanescent wave traveling downward, as observed in the flight test [10]. In addition, the computational results well clarified the detailed mechanism of Mach cutoff, including focusing strength in the cutoff region, propagation characteristics of evanescent wave, and three-dimensional structure of cutoff surface. These results were quite helpful in understanding the characteristics of Mach cutoff that would be difficult to evaluate using the conventional prediction methods, and they demonstrated that the full-field simulation method was a powerful tool for analyzing the sonic boom propagation generated from the low supersonic flight object, including the Mach cutoff.

3.3 Simulation at Hypersonic Speed [5]

Full-field simulation was performed to analyze sonic boom characteristics at hypersonic speeds. Generally, a pressure waveform shaped like “N” (N-wave) is generated from a supersonic aircraft, and an explosive sound occurs twice. However, in the Chelyabinsk meteorite, the explosive sound generated from each meteorite fragment may have occurred only once. Therefore, the full-field simulation was performed to clarify the waveform transition of sonic boom generated from a hypersonic spherical body. The results showed that the sonic boom waveform type was changed from an N-wave type to a caret-wave type as the flight Mach number increased. An explosive sound occurred twice in the case of the N-wave, whereas it occurred only once in the case of the caret-wave; i.e., the number of explosive sounds changed with the flight Mach number. The transition curve that divided an N-wave from a caret-wave was acquired from the full-field simulation, and the critical Mach number at which the waveform transition occurred was clearly shown. These results were quite helpful in understanding sonic boom characteristics at hypersonic speeds, and they demonstrated that the full-field simulation was a powerful tool for analyzing the sonic boom propagation generated from the hypersonic flight object, including the strong shock wave.

4 Concluding Remarks

The full-field simulation method and some simulation results were reviewed. Accuracy of the full-field simulation has already been proven, and this simulation has been applied to sonic boom analysis at all speeds, including Mach cutoff phenomena at low supersonic speeds and unique waveform transition at hypersonic speeds. Although the full-field simulation method needs to be further developed to consider three-dimensional aircraft configuration, unsteady flight, and atmospheric variability, the full-field simulation based on the CFD analysis has the potential for considering various flight, atmospheric, and ground conditions. Therefore, this simulation seems promising for realizing high-accuracy numerical flight experiments, wherein flight tests for sonic boom measurements are precisely reproduced.

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