SONIC-BOOM PREDICTION USING EULER CFD CODES WITH STRUCTURED/UNSTRUCTURED OVERSET METHOD

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Abstract

Sonic-boom due to a supersonic airplane is one of the most serious problems to be solved for supersonic overland flight. Prediction of the sonic-boom on the ground is important to design a low-boom supersonic airplane. Structured/unstructured overset grids method is developed to estimate the sonic-boom on the ground and evaluate the effects of low-boom design concepts. The unstructured grid CFD analysis solves only around the airplane. Then the structured grid CFD analysis is conducted to predict the near-field pressure signatures using the result of unstructured grid CFD analysis. The purpose of this overset grids method is to predict the near-field pressure signatures accurately and efficiently which are used to estimate the sonic-boom on the ground. In this paper, the structured/unstructured overset grids method is applied to the Darden's low-boom axisymmetric configuration and a three-dimensional low-boom demonstrator airplane.

Nomenclature

α	angle of attack, degree
C_D	drag coefficient
C_L	lift coefficient
C_m	pitching moment coefficient
C_P	pressure coefficient
ϕ	angle of circumference, degree
H	distance from fuselage axis
L	reference length
M	Mach number
R	maximum radius of the configuration
X	coordinate value of fuselage axis

1 Introduction

The Silent SuperSonic(S-cube) research program [1] on quiet supersonic airplane design technologies started in 2006 at Japan Aerospace Exploration Agency (JAXA). In this program, the Silent Supersonic Technology Demonstrator (S3TD) (Fig.1) is planned to be built in order to demonstrate the advanced low-sonic-boom design technologies; low-boom design concepts and design/analysis tools.

Both prediction of the sonic-boom on the ground and estimation of the aerodynamic forces are important for design of the low-drag/low-boom supersonic airplane. A multi-block structured grid CFD code can obtain not only the aerodynamic forces but also the near-field pressure signatures for sonic-boom estimation since structured grid is suitable to capture the sonic waves. For this reason, the structured CFD analysis is adopted in the S3TD preliminary design phase to confirm its low-drag/low-boom concepts. However, it takes large amount of time to generate its computational grid. On the other hand, an unstructured grid CFD code is generally suitable to estimate the aerodynamic forces of complicated airplane geometry with less grid generation time than the structured grid while it is difficult to obtain the accurate near-field pressure signatures. The structured/unstructured overset method is developed to utilize both advantages for more accurately and efficiently sonic-boom prediction. The process and the accuracy of the overset method are presented with its application to an axisymmetic and a 3-deimensional supersonic configuration.

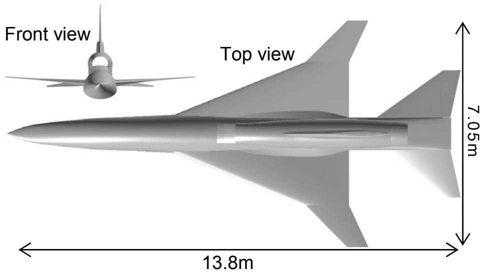


Fig 1. S3TD configuration

2 Structured/Unstructured Overset method

In the structured/unstructured overset method, the unstructured CFD analysis is conducted only around the configuration. Then structured CFD analysis is conducted to obtain the near-field pressure signatures using the result of the unstructured CFD analysis. By this overset method, the near-field pressure signatures for sonic-boom prediction can be obtained with low working load.

Two CFD codes are used in this study. One is an unstructured grid solver called "TAS (Tohoku university Aerodynamic Simulation)"[2,3], which is developed by Tohoku University and modified by JAXA. It can generate triangular surface grid by the advancing front method and tetrahedral volume grid by the Delauny tetrahedral meshing method with its GUI (Graphical User Interface). The TAS code is based on a cell-vertex finite volume method, in which the HLLEW (Harten-Lax-van Lee-Einfeld -Wada) method is used for the numerical flux computations and the second-order spatial accuracy is obtained by a linear reconstruction of the primitive variable. The LU-SGS (Lower/Upper Symmetric Gauss-Seidel) implicit method is used for the time integration.

The other solver is a multi-block structured grid solver called "UPACS(Unified Platform for Aerospace Computation Simulation)"[4], which is developed by JAXA. The UPACS code is based on a cell-centered finite volume method, in which the convection terms of the governing equations are discretized using AUSMDV scheme with MUSCL extrapolation and min-mod limiter. MFGS (Matrix Free Gauss-Seidel) implicit method is used for time integration. Although both CFD codes have Navier-Stokes options, Euler calculation is applied in this study to obtain the near-field pressure signatures.

The process of the overset method comprises following 3 steps. At the first step, the flow field around the airplane is solved by the unstructured grid solver which can be easily applied to complicated airplane geometry. Figure 2 shows the C_p distribution of the unstructured grid CFD analysis which is corresponding to the 1st step of the overset process. Then the result of the unstructured solver is transferred to the corresponding boundary face of the structured grid using interpolation method at the 2nd step. The boundary face might be simple geometry such as a cylinder as shown in Fig.3. This interpolation process is conducted using the commercial visualizing software "Tecplot360". Tecplot360 is used by many CFD users for visualization of their CFD results all over the world. Most CFD solvers have interfaces which can transfer their CFD results from their own formats into the format for Tecplot360. Therefore this process could be applied to any general CFD solvers which can produce data for Tecplot360. At the 3rd step, the boundary conditions obtained from the unstructured CFD result is fixed during the structured CFD analysis after the interpolation process. Finally, the near-field pressure signatures are obtained by the structured CFD analysis without solving flow field around the complicated geometry (Fig.4).

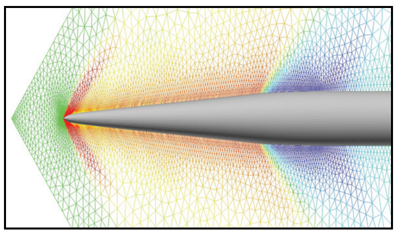


Fig 2. The 1st step of overset process (Unstructured grid)

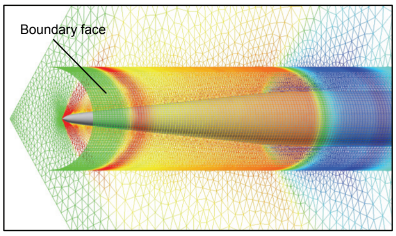


Fig 3. The 2nd step of overset process (Interpolation)

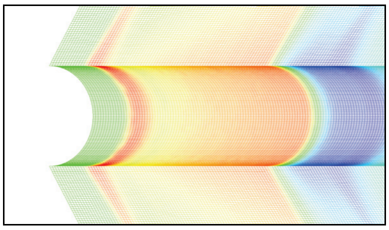


Fig 4. The 3rd step of overset process (Structured grid)

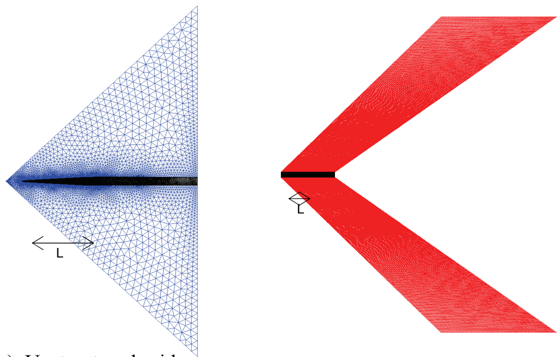
3 Application 1: Axisymmetric configuration

3.1 Testing of the Overset Method

First of all, this overset method is applied to a simple axisymmetric configuration in order to confirm the performance of this overset method. The Darden's low-boom axisymmetric configuration[5], whose cross section area is determined to generate a ramp type low-boom pressure signature on the ground, is applied in this test case, as shown in Fig.5. Its design Mach number is 1.6 and the CFD calculation is conducted at angle of attack of 0 degree. The flow field around the configuration is calculated using the unstructured grid (Fig.6(a)), then the unstructured CFD results are transferred to the cylindrical structured boundary face, as shown in Fig.4. The structured grid (Fig.6(b)) is very easily and simply generated in the near-field (H/L=2.0). In the unstructured grid, the high resolution grid is distributed around the configuration inside the cylindrical structured boundary face. The structured grid is extended along the shock wave from the configuration. Figure 7 shows that the pressure value on the boundary face of the structured grid can be transferred smoothly from the unstructured CFD result. The structured grid is extended three body length away from the body to obtain the near-field pressure signature at H/L=2.0 (Fig.8). Figure 9 shows the near-field pressure signature predicted by the overset method compared to the signature predicted by the panel method with nonlinear modification by area-balancing technique [6]. Some oscillations are observed in the panel method result, which are thought to be caused by its discontinuous connections of the surface panels while the overset method can capture the signature more smoothly. The levels of the fist pressure peaks of the both results are different. This discrepancy mainly comes from the grid dependencies of the overset method. The grid dependency is mentioned in the next section.

These results show that the overset method is useful for low-boom design since it can capture the low-boom characteristics of the model in the near-field.

Fig 5. Darden's axisymmetric configuration



(a) Unstructured grid (b) Structured grid

Fig 6. CFD meshes for Darden's axisymmetric configuration

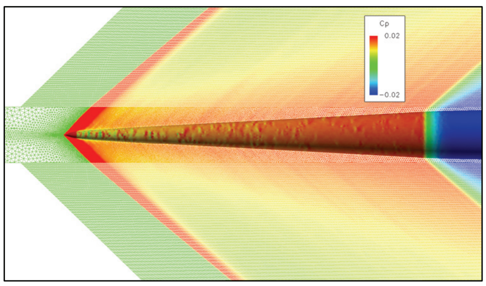


Fig 7. C_p distribution of the unstructured and structured grid results

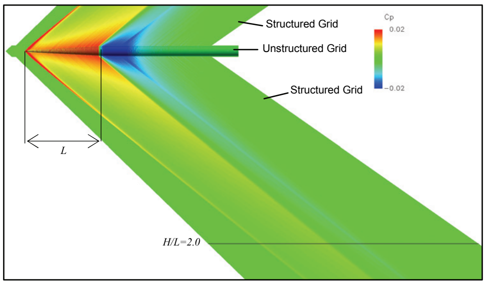


Fig 8. Near field pressure distribution of Darden's configuration

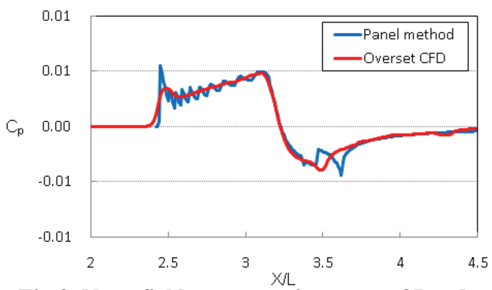


Fig 9. Near-field pressure signature of Darden's configuration at *H*/*L*=2.0

3.2 Grid dependency

The grid dependencies of the unstructured and structured CFD grids are investigated by modifying the grids to obtain sharper pressure signature especially at the first pressure peak than the previous section result. In order to decide the sufficient grid resolution, the grid dependency studies are conducted in the following three steps.

The first step is the unstructured grid dependency study. Table 1 summarizes the results and Fig.10 shows the grid image of the unstructured grid. 4 types of grids are tested; “Coarse”, “Medium”, “Fine” and “Extra-Fine”. Figure 11 shows the near-field pressure signatures at the *H*/*L*=2.0. In these calculations, the structured grid solver uses the same “Fine” grid which is defined later. The oscillations are observed on the “Coarse” grid and “Medium” grid, while the “Fine” grid and “Extra-Fine” grid capture smoother signature. Thus it is found that the “Fine” grid or more should be used to predict the accurate near-field pressure signature.

The second step is the structured grid dependency study. Table 2 summarizes the results and Fig.12 shows grid image of the structured grid. The same “Fine” unstructured grid is used in this study. The inner cylindrical boundary face is located as near as possible to the configuration without touching the surface. As a result, it has a cylinder whose radius is 1.1 times of the maximum radius of the configuration. The grid distribution around the circumferential direction is adjusted as shown in Fig.12. The grid spacing in the lower region is narrower than that in the upper region because the sonic-boom on the ground is estimated from the lower near-field pressure signature. In this grid dependency study, the grid points along the streamwise direction are distributed equally and the number of grid points is increased from the “Coarse” to the “Fine”. As a result, the “Fine” grid has 35points around the first pressure peak at *H*/*L*=2.0. Figure 13 shows the near-field pressure signature of the each structured grid at the *H*/*L*=2.0. The pressure signatures are almost the same except around the first pressure peak. The “Fine” and “Extra-Fine” grid can capture the sharper pressure rise than the others. So it is indicated that over 35 grid points around the first pressure peak are needed to obtain accurate pressure signatures.

The third step is the distance dependency study from the configuration surface to the boundary face of the structured grid. Table 3 summarizes the results. The boundary faces are located from the configuration surface at 1.1*R*, 2*R*, 3*R* and 4*R* (*R* represents the maximum radius of the Darden’s axisymmetric configuration as shown in Fig.12). Figure 14 shows the near-field pressure signature at the *H*/*L*=2.0 of the each structured grid which has different inner boundary face. The fist pressure peak of the shortest distance case (1.1*R*) is sharper than the others.

By the grid dependency study, it is indicated that the more grid points and the shorter distance from the surface are effective to obtain the sharp near-field pressure signature. As a result, the “Fine” grid resolutions are applied to the following 3 dimensional configuration case.

Table 1. Unstructured grids

Grid points	Coarse	Medium	Fine	Extra-Fine
Circumference	10	20	40	80
Stream direction,L	100	200	400	800
Surface grid points	8,300	26,000	100,000	400,000
Total grid points	31,000	150,000	580,000	3,600,000

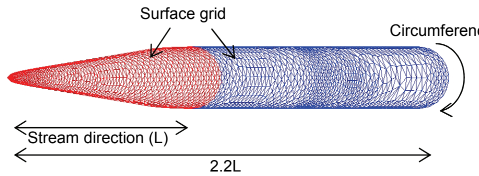


Fig 10. Grid image of the unstructured grid

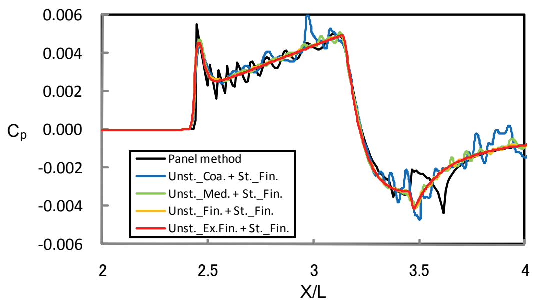


Fig 11. Grid dependency of the unstructured grid

Table 2. Structured grids

Grid points	Coarse	Medium	Fine	Extra-Fine
Circumference	110	110	110	110
Stream direction	300	600	1200	2400
Overset boundary	33,000	66,000	132,000	264,000
Total Grid points	6,900,000	13,800,000	2,760,000	55,200,000
at H/L=2.0				
First pressure peak	18	22	35	63
Δx at boundary face	0.01 L	0.005 L	0.002 L	0.001 L

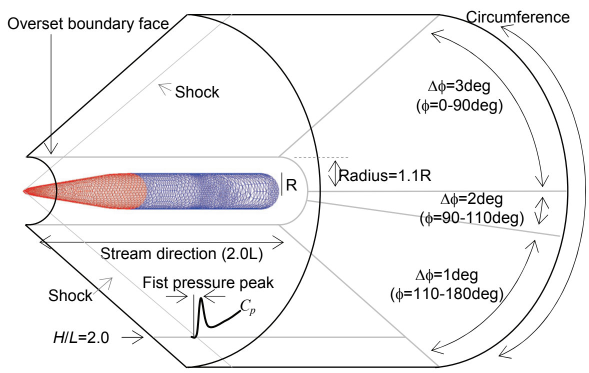


Fig 12. Grid image of the structured grid

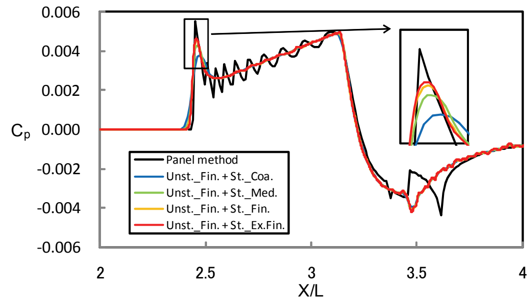


Fig 13. Grid dependency of the structured grid

Table 3. Distance dependency of the boundary face

	Near	Medium	Far	Extra-Far
Radius	1.1R	2R	3R	4R

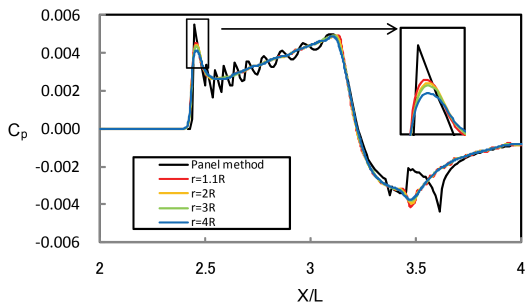
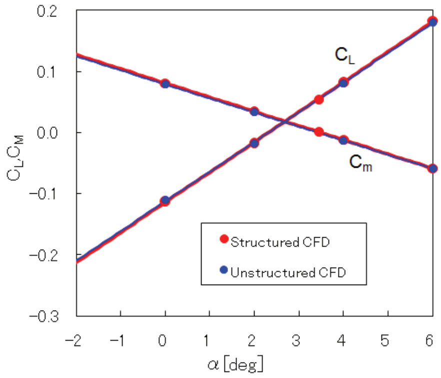


Fig 14. Distance grid dependency of the boundary face

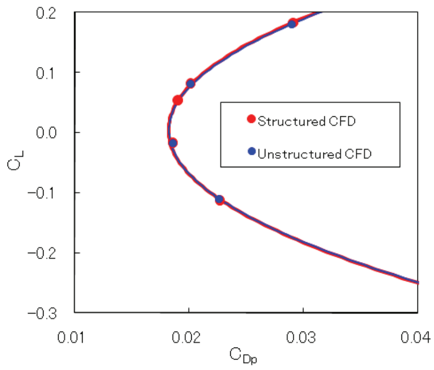
4 Application 2 : the S3TD airplane

4.1 Unstructured Grid Accuracy

Next, the overset method is applied to the S3TD airplane which has complicated geometry with the wing, vertical/horizontal tails and the engine nacelle (Fig.1). The design conditions are the Mach number of 1.6 and the angle of attack of 3.5 degrees which corresponds to C_L=0.055. The S3TD airplane has a jet engine mounted on the fuselage. In this study, the engine is treated with flow-through condition. The authors have been already investigated the jet-on effect on the sonic-boom comparing with the flow-through condition by the multi-block full structured CFD analysis which is used in the S3TD preliminary design phase[7]. Figure 15 shows the aerodynamic forces of the full structured CFD and unstructured CFD results. Both results agreed well each other. It is indicated that using unstructured grid in the overset method is appropriate not only to simulate near-field pressure signatures but also to estimate aerodynamic characteristics.



(a) C_L-α, C_m-α



(b) Drag polar curve

Fig 15. Aerodynamic forces of the S3TD airplane

4.2 Near-field Pressure Signature

The overset grid has the fine grids which correspond to the “Fine” unstructured grid and the “Fine” structured grid defined in the previous section. The boundary face of the structured grid is modified as shown in Fig.16 in order to capture the shock wave near the configuration as sharp as possible. Thus the boundary face is composed of a circular and an oval curve. Figure 17 shows C_p distributions on symmetric plane of the unstructured CFD results and the interpolated structured CFD result. It is observed that the both results are smoothly connected. The near-field pressure signature with the overset grid method is compared to the full structured grid results. Figure 18 and 19 show the near-field pressure signature of the overset method at H/L=1.0 and 2.0(Fig.17) compared to the full structured CFD analysis. It took approximately two months to generate the full structured grid manually which has 58 million grid points. On the other hand, it took less than one week to generate the unstructured grid (6 million grid points) and the structured grid (28 million grid points) for the overset method. As shown in Fig.18 (H/L=1.0), the pressure signature of the overset fine grid is sharper than the full structured grid result. At H/L=2.0 (Fig.19), the pressure signature of the overset fine grid is still sharper than the other except around the middle part. At least the results show that the overset method can obtain the near-field pressure signatures as sharp as the full structured grid with much less computational time.

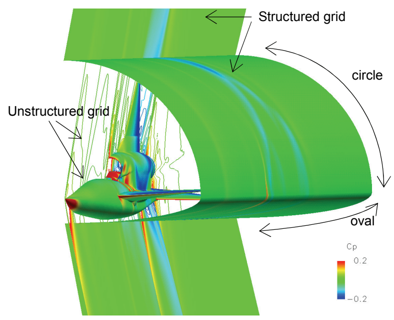


Fig 16. Overset boundary faces

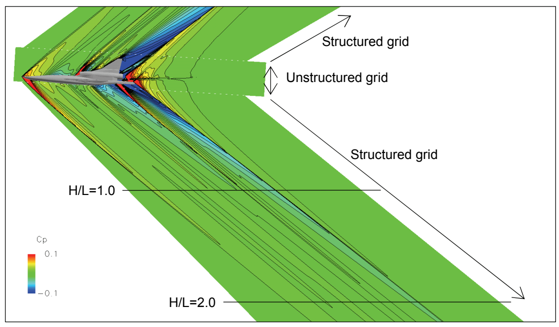


Fig 17. C_p distributions on symmetric plane

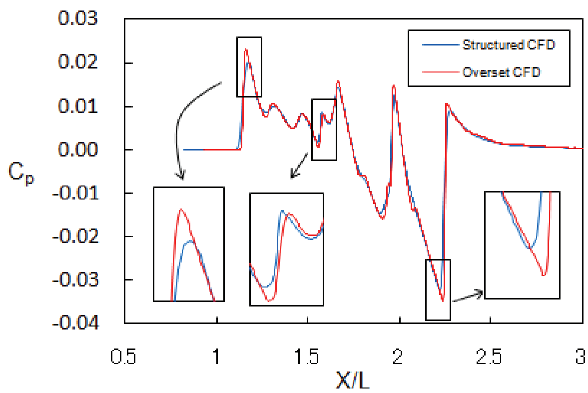


Fig 18. Near-field pressure signature at H/L=1.0

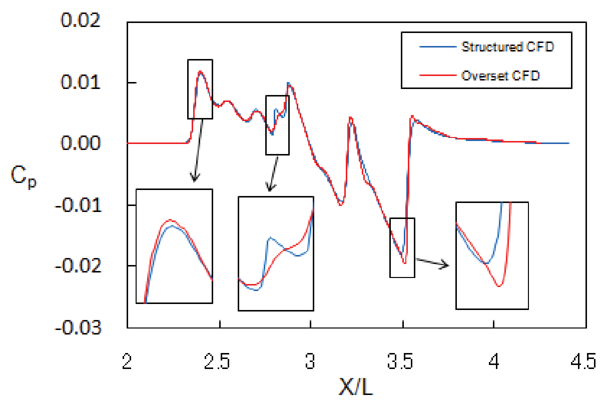


Fig 19. Near-field pressure signature at *H*/*L*=2.0

4.3 Sonic-boom on the Ground

The sonic-boom pressure signatures on the ground are estimated from these near-field pressure signatures at *H*/*L*=2.0 show in Fig.20 by the waveform parameter method (Thomas method)[8]. Figure 20 shows the predicted ground pressure signatures for the flight altitude of 13.4km. The sonic-boom on the ground by using the overset fine grid is almost the same as the full structured grid result. Although the discrepancy is observed on the near-field pressure signature at *H*/*L*=2.0 around the middle part, it is found that this discrepancy does not affect the sonic-boom on the ground. In this case, the overset method can estimate the sonic-boom on the ground with the same accuracy as the full structured grid with much shorter time for grid generation. Thus it is recognized that the overset method is effective for the prediction of the sonic-boom.

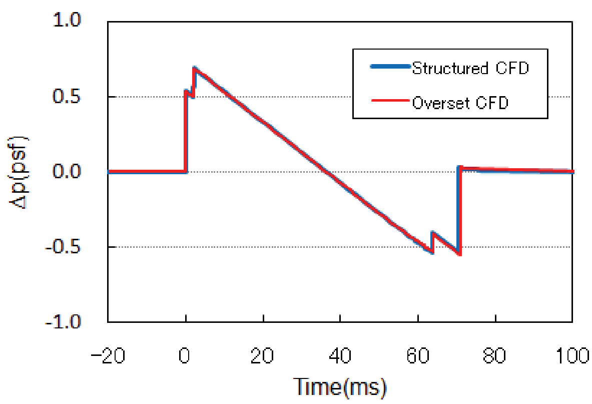


Fig 20. The sonic-boom on the ground

5 Conclusion

The structured/unstructured overset grids method for predicting sonic-boom is developed. This overset method can drastically reduce the grid generation time and obtain the accurate near-field pressure signature. In the S3TD airplane case, it took approximately a week for the overset method, while it took approximately two months for the full structured grid. The aerodynamic characteristics, the near-field pressure signature and the sonic-boom on the ground by using the overset grid method have almost the same accuracy as those by using the full structured grid method. It is found that the overset method is effective for the prediction of the sonic-boom.

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