DAHWIN - Digital/Analog-Hybrid Wind Tunnel

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Abstract

The development of ‘Digital/Analog-Hybrid WINd tunnel (DAHWIN),’ which is an innovative system integrating CFD (Computational Fluid Dynamics) with EFD (Experimental Fluid Dynamics), is presented. The aim of the system is to improve efficiency, accuracy, and reliability of aerodynamic characteristics evaluation in aerospace vehicle developments through mutual support between EFD and CFD. DAHWIN is constructed based on two large facilities, JAXA 2m x 2m Transonic Wind Tunnel for EFD and JAXA Supercomputer System for CFD. The function of this system consists of optimization of test planning, an accurate correction of the wind tunnel wall and support interaction effects, the most probable aerodynamic characteristics estimation based on both EFD and CFD data, and so forth. Key technical challenges in the system development, such as an automatic grid generator, high-speed CFD solver, and a high-speed data processing technique for image measurement data, are addressed. Some preliminary applications of DAHWIN to practical wind tunnel tests showed the usefulness and reliability of DAHWIN.

Key words: EFD, CFD, Wind Tunnel, Database, Data Fusion

Introduction

In order to evaluate aerodynamic characteristics of aircraft and aerospace vehicles, experimental techniques using wind tunnels (experimental fluid dynamics: EFD) were mainly employed as well as theoretical methods till 1970’s. However, since then, computational fluid dynamics (CFD) has been gaining its importance in the aerodynamic prediction with significant advances of CFD techniques and processing speed of computers. At present, it could be addressed that the importance of CFD in aerodynamic design is comparable to that of EFD.

On the other hand, still now, EFD and CFD are usually conducted separately by different groups of experts with relatively weak interaction and collaboration. This situation in the aerodynamic characteristics prediction indicates that as the next step, synergy of EFD/CFD integration is expected to improve the prediction techniques further.

Researches aiming at such real integration of the two techniques do not seem to be matured so far while some trials have been reported with certain degree of success at laboratory condition [1-2]. In particular, practical applications of EFD/CFD integration in industrial aerospace development are very few except the system called ViDI (Virtual Diagnostics Interface System) developed by NASA Langley Research Center [3]. Although the ViDI system was originally developed to aid pretest design of optical fluid diagnostic techniques such as Pressure-Sensitive Paint (PSP), it has the capability of real time comparisons of experimental results with pretest CFD calculations using 3-D graphic feature called Live View 3D. However, the comparisons are done without the EFD/CFD integration only when CFD data are available from users.

Towards the development of future innovative aerodynamic prediction technologies, Japan Aerospace Exploration Agency (JAXA), is developing a practical EFD/CFD integration system called the Digital/Analog Hybrid WINd tunnel (DAHWIN), where ‘Digital’ and ‘Analog’ denote CFD and EFD (or wind tunnel), respectively. The aim of this system is to improve effectiveness, accuracy, and reliability of wind tunnel tests by jointly utilizing CFD as well as some advanced techniques for the EFD/CFD integration. Furthermore, this system is to be used for reliable and accurate prediction of aerodynamic characteristics at real flight condition, based on both ground-based EFD and CFD.

This paper presents the system concept of DAHWIN and technical challenges which should be overcome in the development of this system. Also, described are details of the subsystems and individual technical issues such as a common data format applied to both EFD and CFD data, real-time comparison between wind tunnel test data and pretest CFD data, and so forth. Since the development of DAHWIN is at the final stage, its function, effectiveness, and reliability are being evaluated through applications to some real wind tunnel tests of both aircraft and a space vehicle. The findings in the evaluations are presented, mentioning future upgrades of the system.

Technical Issues in EFD and CFD

For describing the motivation of development of DAHWIN, technical issues in both EFD and CFD, which should be overcome, are surveyed below.

Individual issues in EFD and CFD

EFD using wind tunnels has problems to be solved, such as 1) the compensation of effects due to some differences between flight and wind tunnel test conditions, especially Reynolds number effect, 2) limited flow properties which can be measured by usual measurement techniques, 3) relatively long lead time before a wind tunnel test campaign including model manufacturing and measurement apparatus development, and so forth.

On the other hand, technical issues of CFD include 1) improvement of reliability of calculation results, especially in complex flow cases with turbulence, boundary layer transition, separation, and chemical reaction, 2) relatively long computational time for high-fidelity analysis even using state-of-the-art supercomputers, and 3) difficult, time-consuming grid generation around complex configuration.

In order to solve the remaining tough technical problems described above, some break-through technologies using advanced EFD/CFD integration techniques should be innovated.

Issues in comparison between EFD and CFD

The advancement of CFD has been relying on rigorous comparisons with comparative experimental results for improving accuracy and evaluating applicable range of CFD in terms of flow conditions and model configurations. However, such comparisons are usually conducted by only one side, that is, EFD or CFD side, without a mutual collaboration between both sides. Therefore, it is common that the comparisons are affected by slight discrepancies in flow conditions, model attitude, and model geometry, which are caused by uncertainty of wind tunnel flow condition setting, deflection of balance and sting, and model deformation due to aerodynamic load in wind tunnel tests. In some cases, the experimental data reductions neglect aerodynamic interference effects caused by the wind tunnel wall and model support system. On the other hand, a grid for CFD may not take the wall and support into account. Also, in general, it is difficult to match boundary layer transition location between EFD and CFD. Such various discrepancies encountered in the EFD/CFD comparisons make it difficult to identify problems existing in the CFD technique applied, disturbing the advancement of CFD. To overcome this undesirable situation, a platform which always guarantees the EFD/CFD comparisons at an identical condition is definitely required.

Issues in terms of time-span difference

In general, the time period required for the wind tunnel test model design and manufacturing is long while CFD needs less time for the grid generation as pre-processing. It should be noted that the grid generation time could be significant when many model configurations with various deflections of aerodynamic surfaces have to be treated. On contrary, the computational time required for high fidelity CFD at a flow condition is much longer than data acquisition time for a test point in a wind tunnel test. In addition, recent image-based measurement techniques employed in wind tunnel tests need a relatively long time for the data reduction of huge volume of image data. These differences in time-span between EFD and CFD pose a serious problem when both EFD and CFD should be conducted in a concurrent manner. Therefore, it is needed to shorten the model manufacturing time, the data reduction time of the image-based measurement methods, and the time for the grid generation and high-fidelity calculation of CFD for the concurrent collaboration.

System Concept of DAHWIN

Objectives

The objectives to develop DAHWIN are to comprehensively solve the issues mentioned above by effectively utilizing both EFD and CFD capabilities, resulting in the reduction of design time, cost, and risk and the improvement of design data accuracy and reliability in the aircraft and aerospace vehicle development. In particular, near-term targets are to apply this system to the developments of Japanese regional jet, MRJ (Mitsubishi Regional Jet), which is under development towards the first flight. Also, it is expected that this innovative system promotes the advancement of the CFD technology, leading to acquiring competitiveness of Japan in the design of aircraft against the other foreign countries. Furthermore, it could be possible that DAHWIN will become a typical system of the integration of experiments and numerical simulations, facilitating creation of similar systems in the other technical fields, such as structure, engine, material, chemistry, medicine, biology, and so forth.

Users and functions of the system

We are expecting aerospace engineers as well as researchers as users of DAHWIN. The aerospace engineers of the heavy industries consist of experimental specialists who work near the wind tunnel itself and aerodynamic designers who usually stay at the office of their company far from the wind tunnel. For the designers at remote locations, nearly real-time data transfer capability is incorporated in this system.

Firstly, the system is applied to JAXA 2 m x 2 m Transonic Wind Tunnel (JAXA TWT1) since needs of the industrial users are higher than those to the other JAXA’s wind tunnels covering different speed ranges. Another reason why this tunnel was chosen is that CFD calculation is relatively easy at cruise condition of transport-type aircraft with a simple configuration since the flow is attached to the vehicle with no large separations in contrast to the low-speed flow around a high-lift configuration at stall condition with significant separations. For the next step of the system development, the present system will be applied to the other tunnels such as JAXA 1 m x 1 m Supersonic Wind Tunnel (JAXA SWT1) and 6.5 m x 5.5 m Low-speed Wind Tunnel (JAXA LWT1) in future.

Based on the survey of the technical challenges in the previous chapter and the requirements from the users of the wind tunnels and CFD, the functions of the hybrid wind tunnel were specified as follows:

- ✓ Test planning optimization using pretest CFD calculations in the point of view of the improvement of efficiency as well as the reduction of risk in wind tunnel tests.
- ✓ CAD-based wind tunnel test setting simulation for facilitating the planning of optical aerodynamic measurements before wind tunnel tests.
- ✓ Accurate corrections of aerodynamic interferences due to the wind tunnel wall and model support system using CFD to improve the accuracy and reliability of wind tunnel test data towards the aerodynamic characteristics prediction at real flight condition.

- ✓ Most probable data estimation using both wind tunnel and CFD data considering each error level and reliability.
- ✓ Nearly real-time visualization and comparison of EFD/CFD data and its transfer to allow the remote users the wind tunnel data evaluation in a timely manner, called ‘Virtual participation in wind tunnel test.’
- ✓ Accelerated data processing of the optical flow measurement techniques such as PIV (Particle Image Velocimetry), PSP (Pressure-Sensitive Paint), and model deformation measurement.
- ✓ Refinement and optimization of the CFD parameters like turbulence model and grid.
- ✓ Establishment of a database which consists of EFD and CFD data at perfectly identical condition in order to facilitate improvement of CFD technology.

For enabling the functions shown above, a fast CFD solver in conjunction with an automatic grid generation tool should be developed for the ‘digital’ wind tunnel as one of major subsystems of DARWIN.

System concept

Figure 1 shows the system concept of DAHWIN to realize the functions described in the previous section. After defining a wind tunnel test model geometry in the course of the vehicle configuration design, the ‘digital’ wind tunnel, the right hand side of the figure, conducts pretest CFD calculations in two cases, that is, a test model alone and a configuration including both test model and wind tunnel with a model support system. Then, the CFD results in both cases are transferred to the ‘analog’ wind tunnel, that is, the conventional wind tunnel shown in the left-hand side of the figure. The CFD data are utilized for the optimization of the test planning and model design. Also, the effects of wall and sting interferences can be corrected using the CFD data with and without wall and sting. In the wind tunnel test phase, optical aerodynamic measurement data as well as ordinary measurement data are reduced in a nearly real-time fashion, which are transferred to the remote users as well as the users working at the wind tunnel. The wind tunnel data including the model deformation are sent back to the digital wind tunnel for a revised, detailed CFD analysis for the CFD parameter optimizations, taking the model deformation data into account. At the finish of the wind tunnel test as well as the revised CFD calculations, we can obtain both EFD and CFD data at an identical condition in terms of flow and boundary conditions. Finally, the two data are combined into the most probable aerodynamic characteristics data by using data assimilation (or fusion) techniques, which are stored in the EFD/CFD–combined database.

As shown in Fig. 2, the initial goal of the operation time sequence of the hybrid wind tunnel is that one or two months prior to the start of a wind tunnel test campaign, the pretest CFD is started and the final whole data after the data assimilation are handed to the user about two weeks after finishing the wind tunnel test. In future, the time after the completion of wind tunnel test should be shorten to several days to reduce the aerodynamic design time. It was suggested that this goal can be almost attained through preliminary applications of DAHWIN as presented in one of following chapters.

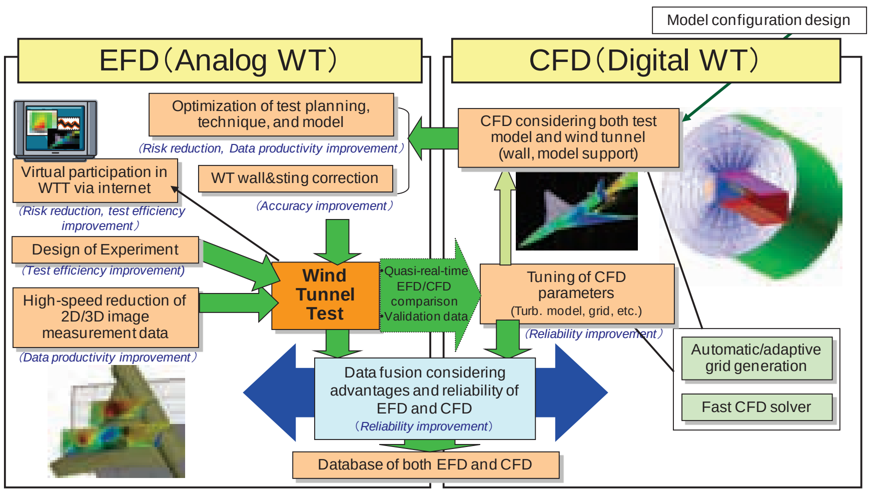


Figure 1 System concept of the Digital/Analog-Hybrid Wind Tunnel (DAHWIN).

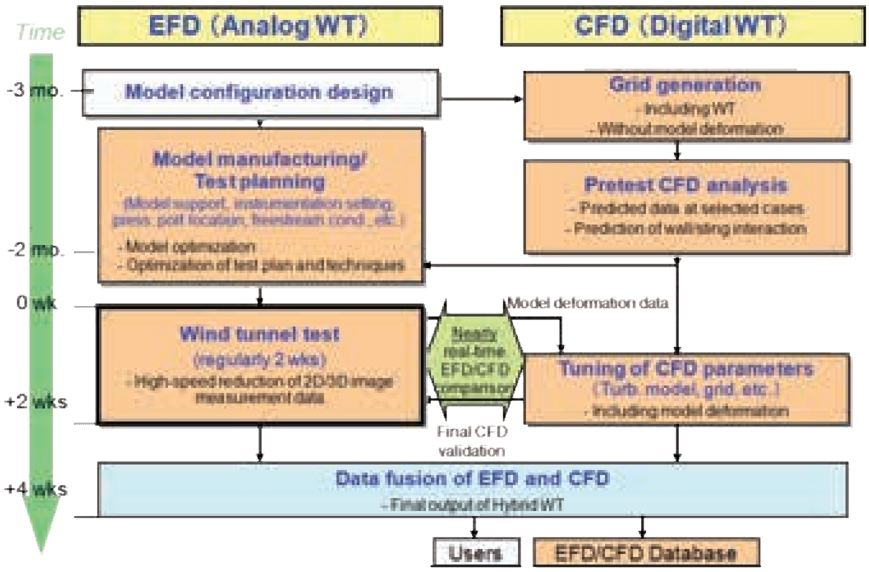


Figure 2 Operation sequence of DAHWIN.

System architecture

Figure 3 presents the system architecture of the hybrid wind tunnel. This system consists of seven servers (web, control, visualization, CAD, SAN, backup, and wind tunnel (WT) servers) and a data storage with SAS and SATA hard disk drives which are connected with each other through 1 Gigabit-Ethernet. The users as well as system administrators have access to this system through the web server. This architecture might be changed or upgraded till the completion of the DAHWIN development through future evaluations of the system in order to keep system reliability and to increase customer satisfaction.

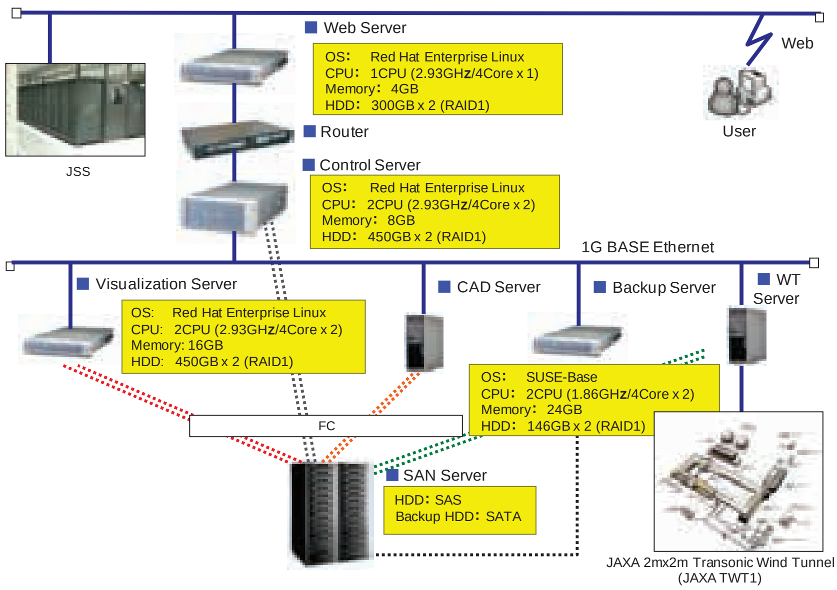


Figure 3 System architecture of DAHWIN.

For the CFD calculations, the supercomputer for the common use in JAXA, JAXA Supercomputer System (JSS), is used as the main hardware of the digital wind tunnel. On the other hand, as the main hardware of the analog wind tunnel, JAXA TWT1 with its data acquisition/processing system is used in conjunction with stand-alone optical measurement systems like PSP, PIV, and model deformation measurement to conduct wind tunnel tests.

First, the EFD/CFD data produced by the analog and digital wind tunnels are converted into a common data format HDF5 (Hierarchical Data Format), which was adopted to facilitate the comparison between original EFD and CFD data with different data format. Next, after the data format conversion, the data are stored in the SAS data storage while the metadata are extracted from the original data and then stored in the database (DB) in the data storage for search purpose. Also, the converted data are sent to the visualization server for displaying the EFD data in comparison with the corresponding pretest CFD data which are automatically chosen in an easy and correct way through database search based on model name, flow conditions, model attitude, and so forth. This integrated visualization feature helps the wind tunnel user to evaluate the validity of wind tunnel data at real-time basis and to understand the overall flowfield which cannot be measured in conventional wind tunnel tests.

The CAD server is used for the wind tunnel test setting simulation [4] before wind tunnel tests and other purposes. Figure 4 shows an example of pretest check of camera field of view and interference between wind tunnel and optical measurement instruments. This feature is useful to reduce time for design of wind tunnel model and optical measurement setup and risk of invalid setting, possibly eliminating an onsite check using real instruments.

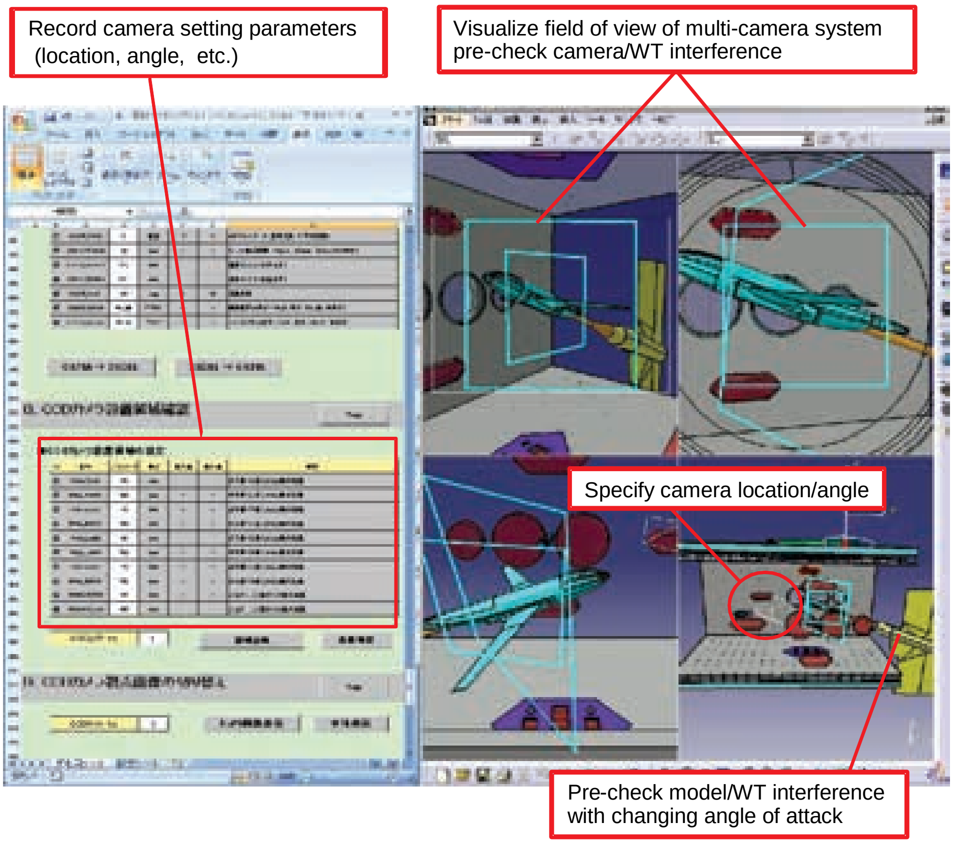


Figure 4 CAD-based wind tunnel test setting simulation.

Key Challenges in Development of DAHWIN

Fast CFD solver with automatic grid generator

For the development of the digital wind tunnel, both features of high-speed performance and high degree of accuracy must be accomplished simultaneously for realizing the timely use of DAHWIN and the high-fidelity wind tunnel data corrections. Mainly, a newly-developed fast CFD solver called FaSTAR (FaST Aerodynamic Routine) for unstructured grid [5] is used in combination with an automatic unstructured grid generator, HexaGrid, using the Cartesian grid generation technique [6-7]. In addition, an unstructured-grid Navier-Stokes solver called TAS (Tohoku University Aerodynamic Simulation) [8], which has been applied to some real aircraft developments such as MRJ, can be used with the user interface being improved as a backup in case that reliability is more emphasized than calculation speed.

Using HexaGrid, it is possible to generate a grid with twelve million cells automatically within an hour by a 64-bit PC around a generic civil transport configuration named NASA CRM as shown in Fig. 5. The generator can densely gather the grid into the regions where a fine grid is needed, such as around the model surface and wing trailing edge. The generated grid has a quality similar to that by the grid generator MEGG3D [9] originally developed for TAS while the number of grid points is comparable between the newly generated grid and the TAS grid by MEGG3D. Difference in drag coefficient between TAS results using the two different grids explained above is about 5 counts (ΔCD = 0.0005) [10], indicating reasonable quality of the grid by HexaGrid for this type of a simple wing-body combination.

An example of grid generation including a wind tunnel model, a model support, and wind tunnel walls is presented in Fig. 6. This result shows that HexaGrid has an ability to automatically generate this type of grid required for the wind tunnel wall/support interference correction based on CFD.

Considering the use of the new CFD solver, FaSTAR, in the pretest CFD calculations, target of its calculation speed performance was set to an hour per case for a grid with ten million cells using a hundred CPUs of JSS. Accuracy of drag coefficient should be less than 10 counts to be used for an industrial vehicle development. Governing equation of FaSTAR can be chosen from Euler and Reynolds-Averaged Navier Stokes (RANS). As turbulence model, Spalart-Allmaras, SST models or so were implemented with their important variations. Although the FaSTAR is still under development at present, its preliminary version has been completed as a RANS solver with two convergence acceleration techniques, that is, the multi-grid technique and GMRES. The preliminary application of FaSTAR to NASA CRM model showed that the difference in drag coefficient between the results FaSTAR and TAS is around 8 counts [10], illustrating acceptable accuracy of this new solver. Incorporating two convergence acceleration techniques shown above has realized four times faster calculation than before, illustrating that the target of calculation speed was accomplished.

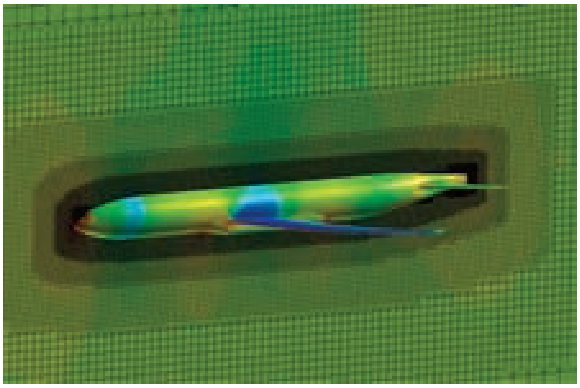
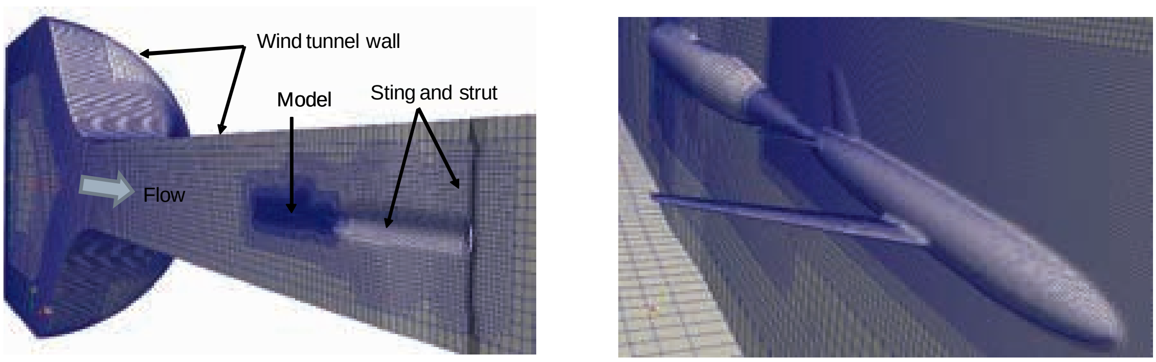


Figure 5 Grid for NASA CRM model generated by HexaGrid (cell number: 12 millions).



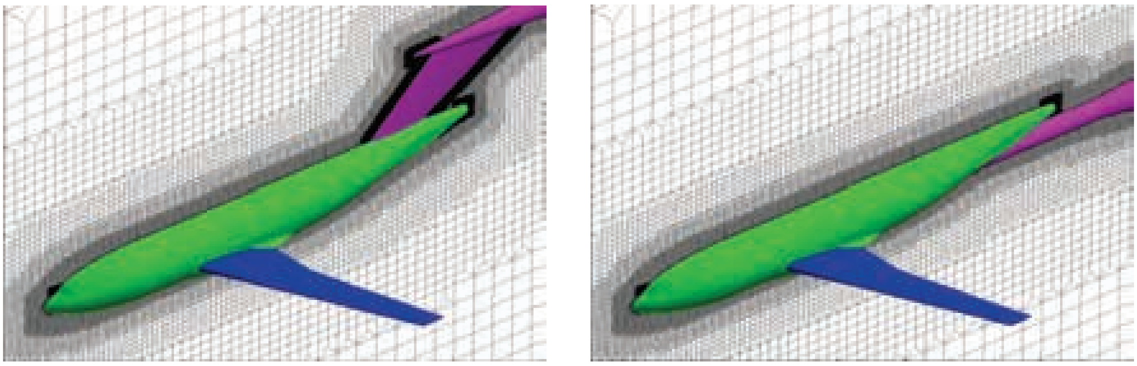
(a) Grid covering flow path of JAXA TWT1.

(b) Grid around model and sting.

Figure 6 An example of automatically generated grid around a generic transport model (ONERA-M5) inside JAXA 2m x 2m Transonic Wind Tunnel (JAXA TWT1).

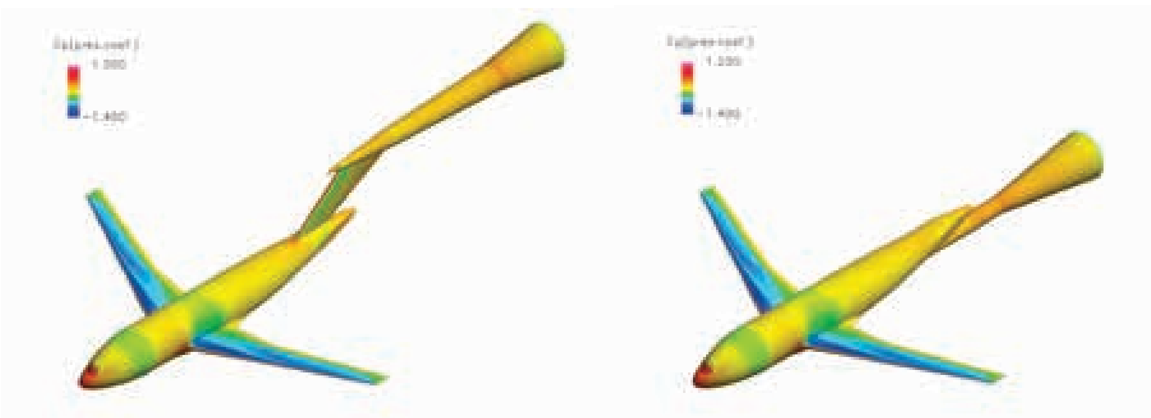
Using the Digital Wind Tunnel, it is possible to count the aerodynamic coefficients of each part of a model, which are constructed from STL data of fuselage, wing, nacelle, pylon, model support, and so on. Therefore, users can examine the influence of each part on aerodynamic characteristics in the pretest CFD calculations.

Before manufacturing a wind tunnel test model and support stings, the digital wind tunnel can be used to evaluate the effects of the configuration of model support on the flowfield around the model. An example of grid generation including two different types of model support, that is, blade-type sting and straight sting, is shown in Fig. 7. Also, corresponding RANS calculation results of pressure distribution (Cp map) on surfaces of the model and sting are shown in Fig. 8. The results of grid generation suggest the robustness of HexaGrid (Fig. 7) while the results of the RANS calculations clearly indicate the model support effect which is seen on the model surface pressure distribution near the junction of the model and support (Fig. 8). Based on these results, the users can choose the best configuration of model support sting without manufacturing several different stings to check the effects of the support configuration during wind tunnel tests. It is significant that this feature of the digital wind tunnel allows aerospace vehicle manufacturers to reduce time and cost for wind tunnel tests during vehicle developments.



(a) Blade-type sting support. (b) Straight sting support.

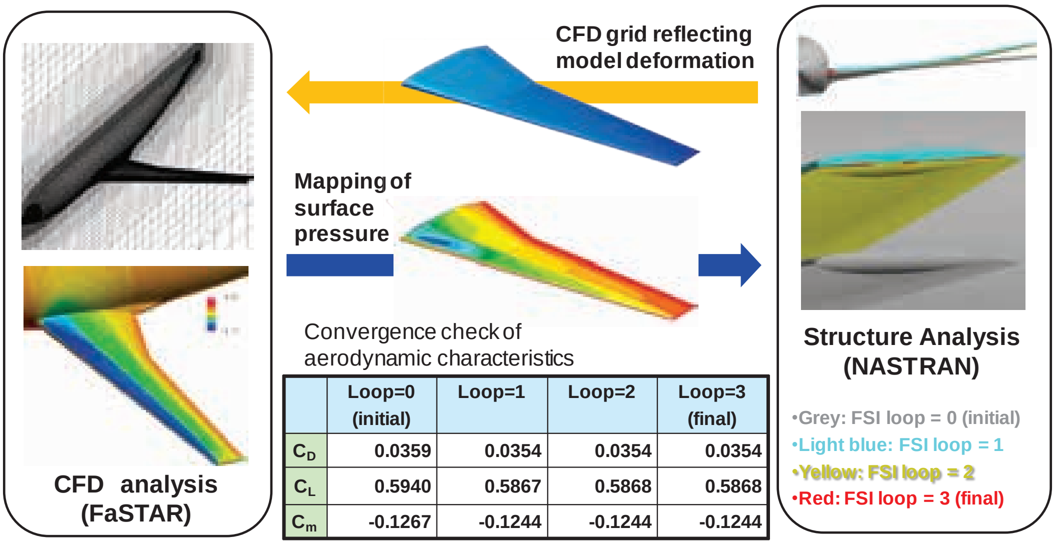
Figure 7 An example of automatically generated grid including two different model supports around the DLR F6-FX2B model.



(a) Blade-type sting support. (b) Straight sting support.

Figure 8 Calculation results of pressure distribution (Cp) on surfaces of the DLR F6-FX2B model.

A newly-developed feature of the digital wind tunnel is the fluid/structure interaction analysis. As described above, the wind tunnel model is deformed by aerodynamic forces acting on the model during a wind tunnel run. As shown in Fig. 9, in this interaction analysis, firstly, a CFD analysis using FaSTAR is conducted for an original configuration with no deformation. Secondly, the surface pressure distribution data obtained by CFD are used to calculate the model deformation by a structure analysis using NASTRAN, which has been widely used in the field of structure analysis. In this structure analysis, the model is assumed to be solid, ignoring the structure inside the model. Thirdly, based on the model deformation data, the CFD grid on the model surface and in flow field is deformed. Then this loop is repeated until a converged result in terms of both pressure distribution and model deformation is acquired. An example of this analysis for a deformed aircraft wing shown in Fig. 9 indicates that two or three loops of analysis are enough to reach a converged result. Using this feature, we can obtain the pretest CFD data which roughly reflect the model deformation, so the comparison of the pretest CFD data with wind tunnel test data during a wind tunnel test becomes more accurate and reliable, decreasing the need of a further detailed CFD analysis which reflects the model deformation measurement data. In future, a test model will be manufactured, considering the model deformation at wind tunnel test so as to form the real flight configuration under the aerodynamic load at wind tunnel test.



	Loop=0 (initial)	Loop=1	Loop=2	Loop=3 (final)
C_D	0.0359	0.0354	0.0354	0.0354
C_L	0.5940	0.5867	0.5868	0.5868
C_m	-0.1267	-0.1244	-0.1244	-0.1244

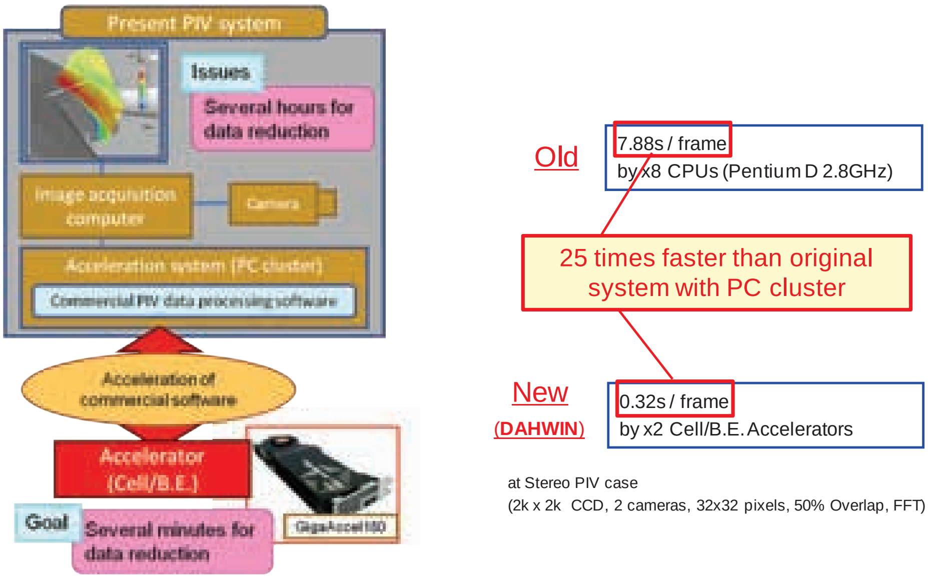
Figure 9 Procedure of fluid/structure interaction analysis.

Acceleration of optical measurement image data processing

Among many types of flow diagnostics in wind tunnels, PIV is one of the measurement techniques which need heavy data processing. Therefore, the acceleration of the PIV data reduction was included in the development of DAHWIN, which is one of key challenges in the improvement of the analog wind tunnel. As shown in Fig. 10, the data processing for a thousand of velocity vector maps usually takes several hours using a PC cluster with eight CPUs while the processing time depends on the choice of data processing algorithm. The goal of the process acceleration in the hybrid wind tunnel is to reduce the processing time by more than one order, resulting in several to ten minutes for the same data processing. As the result, the time needed for PIV becomes not so far from the time for conventional measurement like force balance or pressure measurement, enabling the nearly real-time comparison between the PIV data and corresponding pretest CFD data. To achieve this need, we chose Cell/B. E. as accelerator based on a preliminary evaluation. The system developed with two Cell/B. E. boards resulted in 25 times faster data processing than that of the original data processing system using a PC cluster with eight CPUs [11]. This result means that the goal of processing time less than ten minutes was attained using this accelerator.

Also, acceleration of data processing of PSP measurement [12-13] is being pursued since it is impossible to conduct the processing in a quasi-real-time manner. To overcome this problem, some manual processes such as the detection of position markers on a wind tunnel model surface have to be replaced by new automatic processes.

Model deformation measurement technique using stereo view of position markers on a test model with two cameras was also modified for automation. Similar to PSP, a manual process for finding markers on camera images was successfully automated in order to realize quasi-real-time data reduction.



(a) Concept (b) Effect on data processing speed

Figure 10 Acceleration of the PIV data processing via accelerator.

Examples of Preliminary Applications of DAHWIN

DAHWIN at the final development stage was applied to a series of wind tunnel tests performed at JAXA TWT1 in order to evaluate the usefulness and reliability of the system and find technical items for further improvements towards the complete system. The results are outlined below.

Civil transport-type model test

Firstly, DAHWIN was applied to the wind tunnel test using a civil transport-type standard model (DLR-F6) [14] as shown in Fig. 11. In this test, optical measurement data of PSP and PIV were obtained as well as six-component aerodynamic force and moment and pointwise pressure data. A total of 42 pretest CFD cases (a maximum cell number of 24 millions) were arranged and performed within two weeks. The force/pressure port data obtained by the measurement apparatus were sent to the system and immediately plotted together with the pretest CFD data as seen in Fig. 11 (c). The pretest CFD datasets that have the same flow properties as those in experimental conditions are automatically chosen by the data search function in the database. Real time comparison of the experimental data with the pretest CFD data enables to check the validity of the measurement data during the test period and to rearrange the plan of the subsequent test cases. The comparison of data acquired by PSP and PIV with CFD data is also possible during testing. By the speed-up of the data reduction as described in the previous chapter, these processed data can be obtained within ten minutes after the measurement. As depicted in Fig. 11 (d), by comparing the PSP data with CFD, we can qualitatively check the degree of measurement error and notice significant problems of the measurement techniques as well as the CFD calculations.

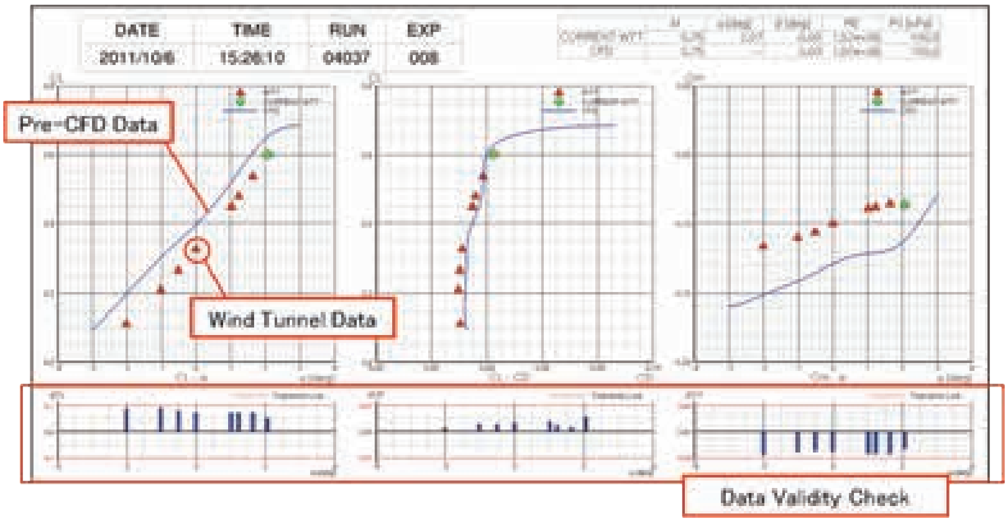
Reentry capsule configuration test

DAHWIN was also applied to a wind tunnel test for a reentry capsule configuration (Fig. 12 (a)) which was conducted as a part of conceptual design of a future space transportation system. Pretest CFD computations of 174 cases (a maximum cell number of 9 millions) were performed within two weeks (Fig. 12 (b)). Computations including a model support system were also made to correct the support interaction effect on the wind tunnel data. At the present system, this was simply done by adding the difference of CFD aerodynamic coefficient data between with and without the support system to the test data. Figure 12 (c) is an example of drag polar plot displayed on the monitoring screen. In this case, it seems that the effect of support interaction was reasonably corrected, using the pretest CFD data. Although in the past, wind tunnel data correction was usually made after the completion of wind tunnel test, it can be made during the test by using DAHWIN. This means that we can readily examine wind tunnel test data without the sting interaction effect.

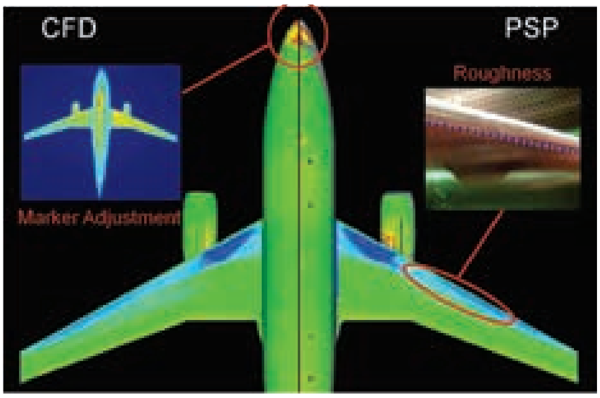
In this test, CFD calculations with different turbulence models were conducted using the fast CFD solver for the cases where the disagreement between wind tunnel test data and CFD data was intolerable. This application of DAHWIN illustrates that it is possible to evaluate the wind tunnel data in comparison with different CFD data in a concurrent manner.

(a) DLR-F6 model mounted in the test section of JAXA TWT1.

(b) Display setting for operation (balance, pressure sensor, PIV, PSP compared with CFD).



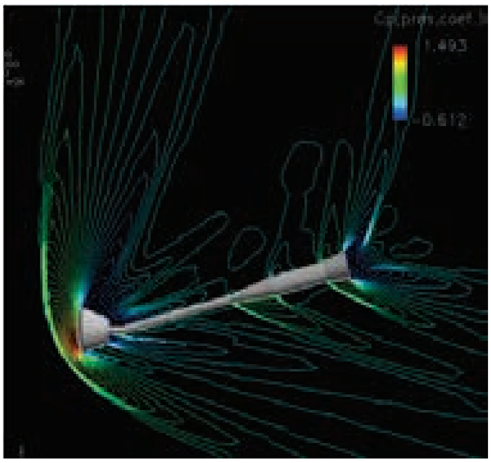
(c) Balance measurement monitoring screen (EFD and CFD with difference (Δ)).



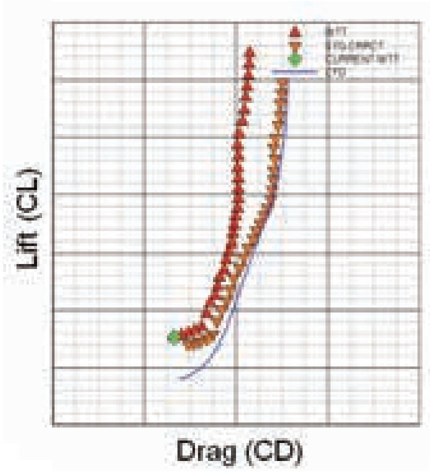
(d) Comparison of pressure distribution by EFD (PSP) and CFD and error sources of PSP measurement.

Figure 11 DLR-F6 configuration tests at JAXA TWT1.

(a) Capsule model in JAXA TWT1.



(b) Pretest CFD results including model support system.

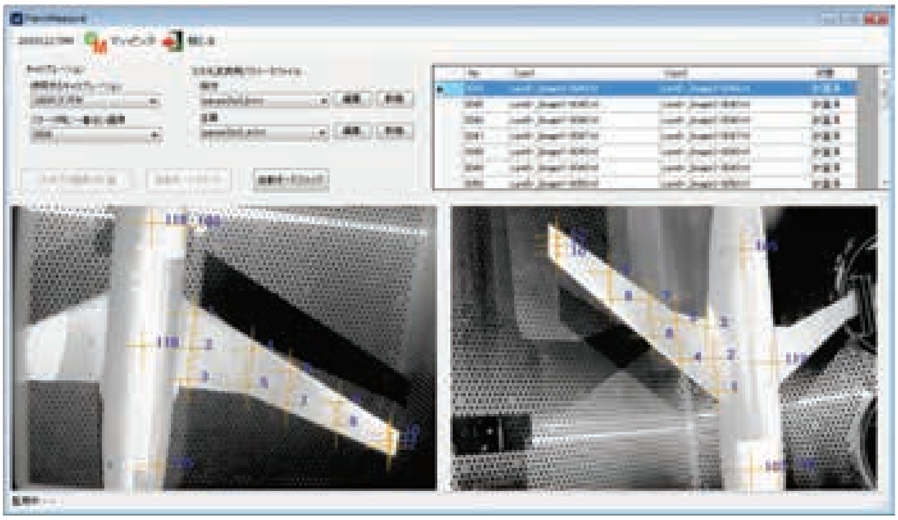


(c) Drag polar plots (comparison between WT data with/without support interference correction).

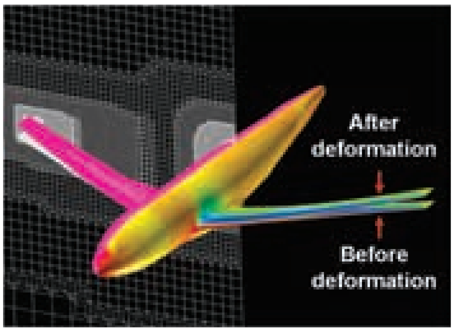
Figure 12 Reentry capsule configuration tests at JAXA TWT1.

High-fidelity CFD using measurement data

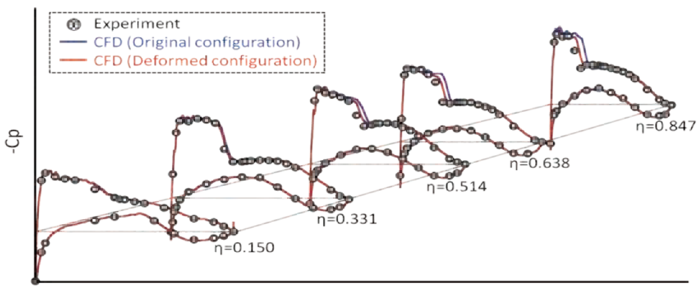
Figure 13 shows an example of the high-fidelity computation using measurement data. Here, high-fidelity computation means that the CFD condition was rearranged so that it becomes almost identical to the experimental condition. In this case, CFD was performed, considering the effect of model deformation caused by aerodynamic load during wind tunnel testing. The model deformation measurement was made using stereo photogrammetry technique with markers located on wind tunnel model (Fig. 13 (a)) [15]. The information of the marker displacement is then used to deform the CFD model surface mesh by applying a simple deformation law with a polynomial approximation (Fig. 13 (b)). The volume mesh for the deformed configuration was obtained by modifying that of the original configuration using the surface influence method. The details of the numerical technique can be found in Ref. 16. As can be confirmed in Fig. 13 (c), the CFD pressure distribution on the main wing shows better agreement with the wind tunnel data when the effect of deformation is taken into account in CFD. The process of the present analysis (measurement data acquisition, surface/volume mesh deformation, and CFD execution) can be made automatically in the system if measurement data as well as pretest CFD data are available. In the complete system of DAHWIN, we will incorporate other conditions which should be matched between wind tunnel test and CFD, such as boundary layer transition location, to realize ideal EFD/CFD comparison under a perfectly matched condition.



(a) GUI of model deformation measurement system.



(b) CFD model geometry before/after the deformation.



(c) Comparison of chord-wise static pressure distribution at five spanwise locations on the main wing.

Figure 13 High-fidelity CFD using model deformation measurement data.

Concluding Remarks

The system concept and development status of the Digital/Analog Hybrid Wind Tunnel (DAHWIN) were presented, whose aim is to improve both EFD and CFD technologies by integrating CFD with EFD, resulting in a significant improvement in efficiency and accuracy of the aerodynamic design of aircraft and aerospace vehicles. At present, the system is at the final development stage, conducting evaluations in some actual wind tunnel test campaigns. The results of the preliminary evaluations showed that the system can be used effectively in industrial-type wind tunnel tests while suggesting various further improvements mainly to increase reliability.

Although the final goal of this type of system is to predict aerodynamic characteristics at the real flight conditions, the present system is mainly focusing on the wind tunnel test conditions since this is a prototype system for future advanced system. As the first step towards the final goal, ability of Reynolds number effect prediction by CFD is evaluated in a limited range of Reynolds number at JAXA TWT1. Then, the CFD solver will be tested in comparison with wind tunnel test results at real flight Reynolds number at a high Reynolds number transonic wind tunnel such as NTF (National Transonic Facility) of NASA and ETW (European Transonic Windtunnel) to confirm the ability of CFD to predict real flight aerodynamic characteristics. Utilizing available flight test data as well as newly acquired data for comparison with various wind tunnel and CFD data is also under consideration.

As mentioned earlier, the EFD/CFD integration technology has not been matured yet, so it is important for the rapid progress in the technology that many researchers and engineers of all types get together to solve various technical challenges. Advanced techniques of the EFD/CFD integration, which will be developed through such cooperation, should be incorporated into DAHWIN in order to add extra values to this system.

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