DAHWIN - DIGITAL/ANALOG-HYBRID WIND TUNNEL - FOR INNOVATIVE EFD/CFD INTEGRATION

Shigeya Watanabe*, Shigeru Kuchi-ishi*, Keiichi Murakami*, Atsushi Hashimoto*, Hiroyuki Kato*, Kanako Yasue*, Hideji Saiki, and Jyun Ogino****
***Japan Aerospace Exploration Agency (JAXA), **Ryoyu Systems Co., Ltd.**

Keywords: *EFD, CFD, integration, database, data fusion*

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 objective to develop DAHWIN 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 as a system seamlessly connecting two large facilities, 2m x 2m Transonic Wind Tunnel for EFD and a 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, quasi-simultaneous monitoring of EFD data in comparison with corresponding CFD data, the most probable aerodynamic characteristics estimation based on both EFD and CFD data, and so forth. Some early applications of DAHWIN to practical wind tunnel tests showed the usefulness of DAHWIN in terms of increasing efficiency and accuracy of both EFD and CFD.

1 Introduction

For evaluating aerodynamic characteristics of aircraft and aerospace vehicles, experimental techniques using wind tunnels (experimental fluid dynamics: EFD) were mainly utilized 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, the importance of CFD in aerodynamic design seems to be 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 illustrates that synergy of EFD/CFD integration is desired to improve the prediction techniques further in future.

Researches aiming at such 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 field are very few except the system called ViDI (Virtual Diagnostics Interface System) developed by NASA [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), developed 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 test), 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 such as data fusion technique for the EFD/CFD integration.

This paper presents the system concept and architecture of DAHWIN. Also, described are details of individual technical functions. Some evaluation results of function, effectiveness, and reliability of DAHWIN are shown as well.

2 Technical 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, and 2) limited flow properties which can be measured by usual measurement techniques, 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 these problems described above, some break-through technologies using advanced EFD/CFD integration techniques should be innovated.

The advancement of CFD has been relying on rigorous comparisons with comparative experimental results for improving accuracy and reliability. 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. 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. 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.

3 Objectives and System Concept of DAHWIN

3.1 Objectives

The objectives of DAHWIN are to 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. Also, it is expected that this innovative system promotes the advancement of the CFD technology. 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.

3.2 Users and major functions of the system

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

At present, the system is only applied to JAXA 2 m x 2 m Transonic Wind Tunnel (JAXA TWT1). A 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 JAXA's wind tunnels with different flow speeds 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).

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 DAHWIN 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.
- 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.
- Accelerated data processing of the optical flow measurement techniques such as PIV (Particle Image Velocimetry), PSP, and model deformation measurement.
- Establishment of a database which consists of EFD and CFD data at perfectly identical condition 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.

3.3 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, 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, measurement data are reduced in a quasi 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 taking the model deformation data into account. At the finish of the wind tunnel test as well as the revised CFD calculations, both EFD and CFD data at an identical condition in terms of flow and boundary conditions can be obtained. Finally, the two data are combined into the most probable aerodynamic characteristics data by using data fusion (or assimilation) techniques, which are stored in the EFD/CFD-combined database.

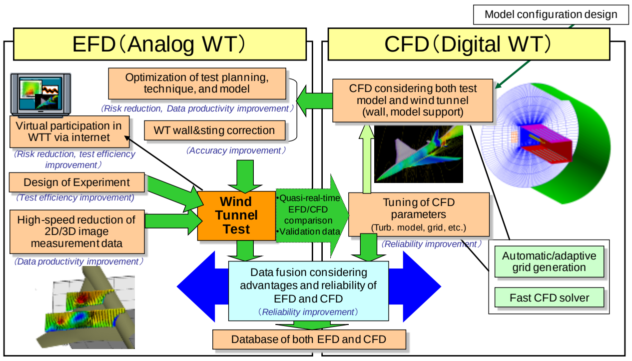


Fig. 1 System concept of the Digital/Analog-Hybrid Wind Tunnel (DAHWIN).

3.4 System architecture

Figure 2 presents the system architecture of DAHWIN. This system consists of eight servers (web, control, visualization, CAD, database, SAN, backup, and wind tunnel (WT) servers) and a data storage with SAS and SATA hard disk drives of 12 TB each which are connected with each other. The users as well as system administrators have access to this system only through the web server.

For the CFD calculations, the JAXA Supercomputer System (JSS) is used as the main hardware of the digital wind tunnel. 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 for other purposes.

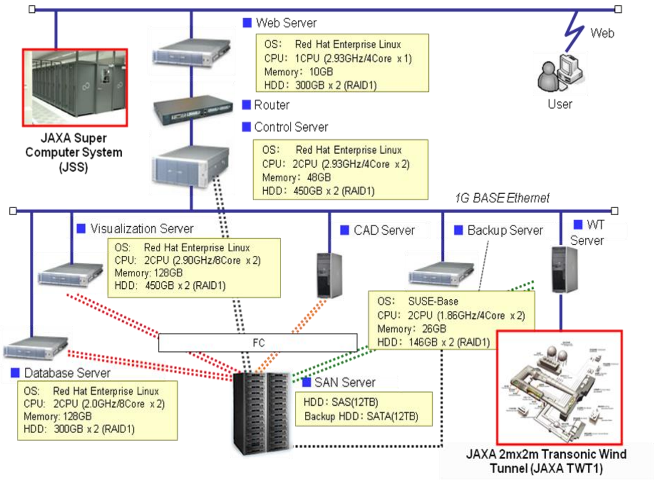


Fig. 2 System architecture of DAHWIN.

4 Major Challenges in Development of DAHWIN

4.1 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, can be used as a backup in case that reliability is more emphasized than calculation speed.

Using HexaGrid, it is possible to generate a grid with ten million cells automatically within ten minutes by a 64-bit PC around a generic civil transport configuration named NASA CRM as shown in Fig. 3. 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 grid by MEGG3D. Difference in drag coefficient between TAS results using the two different grids explained above is about 5 counts (ΔCD = 0.0005) [6], indicating reasonable quality of the grid by HexaGrid.

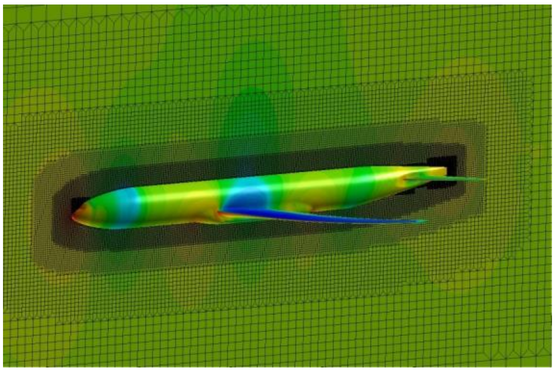


Fig. 3 Grid for NASA CRM model generated by HexaGrid (cell number: 10 millions).

Figure 4 shows an example of grid generation including a wind tunnel model, a model support, and wind tunnel walls. 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.

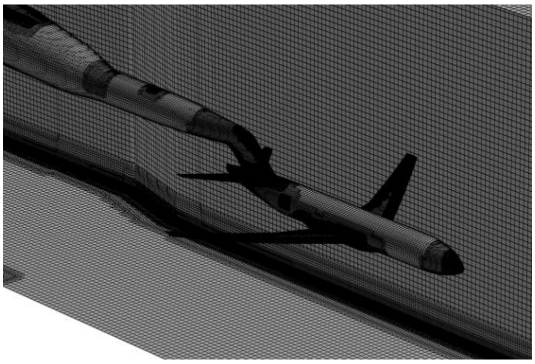


Fig. 4 An example of automatically generated grid around a generic transport model (ONERA-M5) inside JAXA 2m x 2m Transonic Wind Tunnel (JAXA TWT1).

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 a convergence acceleration techniques, the multi-grid technique. The preliminary application of FaSTAR to NASA CRM model showed that the difference in drag coefficient between the results FaSTAR and TAS is less than 10 counts [5], illustrating acceptable accuracy of this new solver. Incorporating the convergence acceleration technique has realized three times faster calculation than before [10], illustrating that the target of calculation speed was accomplished.

4.2 Acceleration of optical measurement image data processing

Among many types of flow diagnostics techniques, PIV is one of techniques which need heavy data processing. Therefore, the acceleration of the PIV data reduction was tried in DAHWIN, which is one of key challenges in the improvement of the analog wind tunnel. As shown in Fig. 5, the data processing for a thousand of velocity vector maps typically takes several hours using a PC cluster with eight CPUs while the time depends on the choice of data processing algorithm. The goal of the process acceleration in DAHWIN 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 for PIV data processing 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. The system developed with two Cell/B. E. boards (Fixstars, GigaAccel 180) resulted in 25 times faster data processing than that of the original data processing system using a PC cluster [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 was 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 model surface had to be replaced by new automatic processes.

Model deformation measurement (MDM) technique using stereo view of position markers on a test model with two cameras [12] 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 [13].

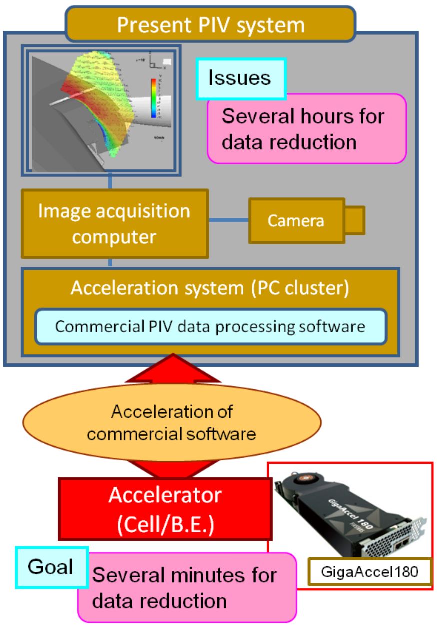


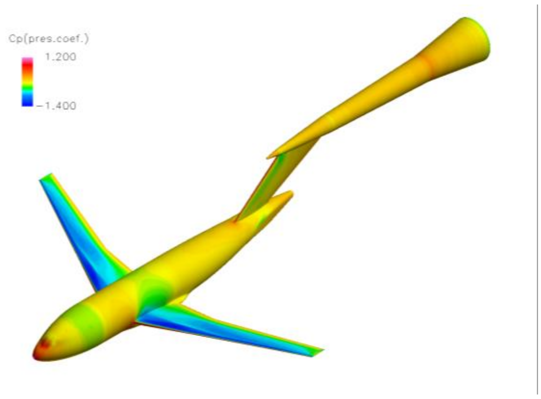
Fig. 5 Acceleration of the PIV data processing via accelerator.

5 Details of Functions of DAHWIN

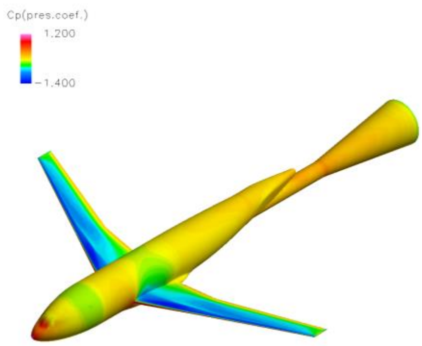
5.1 Pretest CFD

Using the digital wind tunnel, CFD calculations are conducted prior to a wind tunnel test campaign. In the pretest CFD, several configurations with and without wind tunnel wall and support sting are calculated, leading to interference effect corrections based on the CFD technology. Also, these data are utilized as anticipated test data to optimize the wind tunnel test planning and model manufacturing. Based on the CFD data, the type of support sting, such as rear support with straight sting and bottom/top support with blade sting, can be chosen to minimize the sting interference effect. As a result, this feature of DAHWIN allows aerospace vehicle manufacturers to reduce time and cost for wind tunnel tests by reducing the number of the sting support.

An example of RANS calculation results of pressure distribution (Cp map) on surfaces of a model and sting for two different types of model support, that is, blade-type sting and straight sting, is shown in Fig. 6. These results clearly indicate the model support effect which is seen on the model surface pressure distribution near the junction of the model and support.



(a) Blade-type sting support.



(b) Straight rear sting support.

Fig. 6 CFD results of pressure distribution (Cp) on surfaces of the DLR F6-FX2B model.

5.2 Quasi real-time monitoring of wind tunnel test data with pretest CFD data

As presented in Fig. 7, utilizing the accelerated data processing of optical measurement image data processing, wind tunnel test data including balance, pressure sensors, PSP, PIV, and MDM are displayed in a quasi-real time manner on the monitors in the measurement room of JAXA TWT1. Pretest CFD data corresponding to the wind tunnel test data are also displayed in comparison with the test data to detect large problems during the wind tunnel test and to validate the CFD data by the test data. The monitoring data can be distributed via internet with high security level to remote users such as aerospace vehicle design engineers. Using this monitoring function, they can check their expectation on the aerodynamic characteristics and performance, and are able to notice difference between the expectations and real wind tunnel test results for timely change of test cases and finally the configuration of the vehicle.

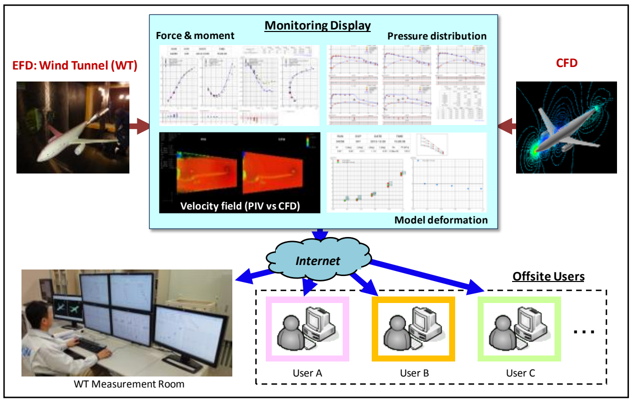


Fig. 7 Quasi-real time monitoring of wind tunnel test data with pretest CFD data.

5.3 High-fidelity CFD corresponding to wind tunnel test results

Following a wind tunnel test, high-fidelity CFD analysis is conducted in the digital wind tunnel considering model deformation measurement results at exactly the same test conditions as the wind tunnel tests. Here, high-fidelity CFD means that the CFD condition including model deformation is almost identical to the experimental condition. In this CFD, the surface and space grids around the vehicle model are deformed to take model deformation into account. The CFD data obtained in this process can be compared with the corresponding wind tunnel test results in a fair manner since all the conditions are matched with each other at this stage.

5.4 Uncertainty quantification for EFD and CFD data

In comparison between EFD and CFD data, it is essential to consider uncertainty for both data individually when judging the degree of agreement. In DAHWIN, uncertainty for EFD data is quantified, following the method recommended by AIAA [14]. For CFD, there is no established methodology to estimate the whole uncertainty so far. Therefore, only uncertainty on grid convergence is estimated by Grid Convergence Index (GCI) [15] and assumed as the total uncertainty of CFD data. Uncertainty data for both EFD and CFD are automatically calculated and displayed by error bar in DAHWIN.

5.5 Data fusion of EFD and CFD data

The EFD/CFD data fusion is one of the most important functions of DAHWIN to realize EFD/CFD integration while this function is not matured well at present. Both EFD and CFD data at an identical condition are delivered to users with uncertainty data and also used to obtain most likelihood aerodynamic characteristics data such as aerodynamic coefficients by a simple algorithm. Using the algorithm, EFD and CFD data are fused to most likelihood data by weighing both data, considering uncertainty level of each data. This function of data fusion should be extended to include flowfield data in the near future.

6 Examples of Preliminary Applications of DAHWIN

6.1 Civil transport-type model test: NASA CRM Pretest CFD

DAHWIN has been applied to a series of wind tunnel tests performed at JAXA TWT1, where the usefulness and reliability of the system are evaluated to extract technical items for further improvements.

The first application of DAHWIN which is introduced here is a test at JAXA TWT1 with a standard model called NASA Common Research Model (CRM; Fig. 8), which simulates wide-body civil transport-type configuration. In this test, measurement items were aerodynamic force/moment measurement by a conventional balance, pressure distribution by conventional pressure sensors, and model deformation. Figure 9 shows quasi real-time monitoring display for force and moment measurement. Since various information is displayed on multi-displays to be examined manually, supplemental data such as difference between CFD and test data are automatically shown on the same displays to facilitate rapid evaluation of the data. It should be noted that test data with wind tunnel wall correction are automatically obtained in DAHWIN to evaluate the aerodynamic effect due to tunnel wall.

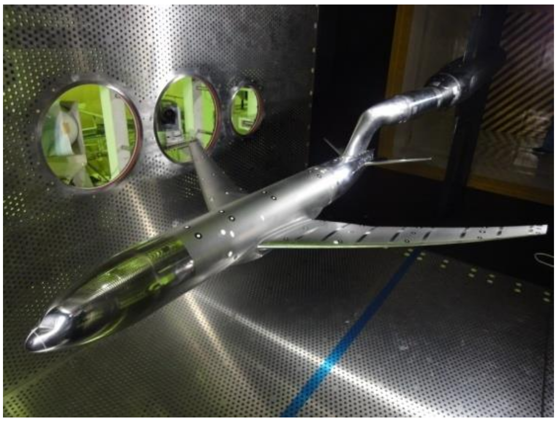


Fig. 8 NASA CRM in the test section of JAXA TWT1.

In this test, the model deformation measurement was made using stereo photogrammetry technique with markers located on wind tunnel model (see Fig. 8) [11]. 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 as shown in Fig. 10. The volume mesh for the deformed configuration was obtained by modifying that of the original configuration based on the surface influence method. The details of the numerical technique can be found in Ref. 16. As can be confirmed in Fig. 11, the CFD pressure distribution on the main wing shows better agreement with the wind tunnel data when the

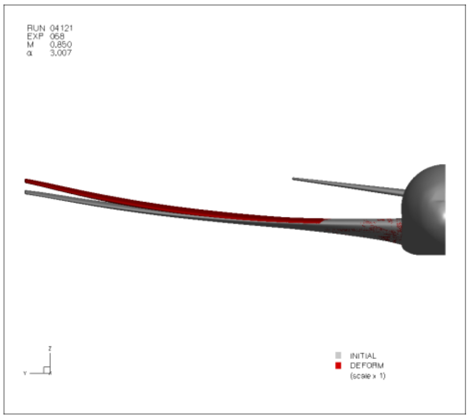


Fig. 10 Deformed wing configuration for CFD based on model measurement data.

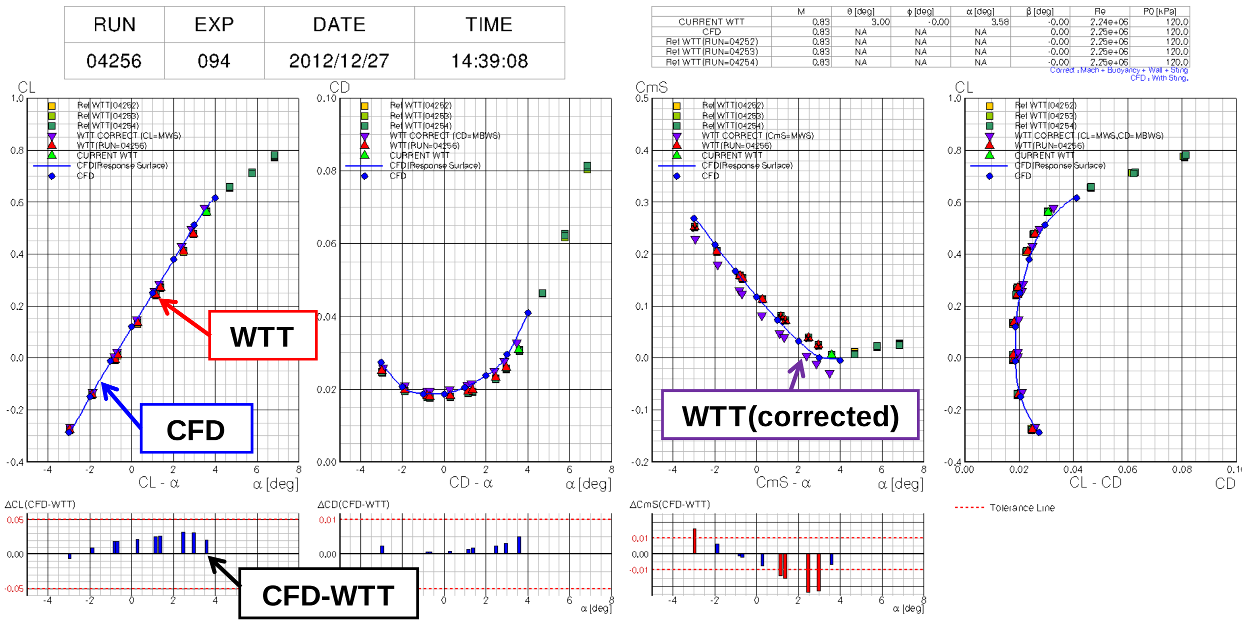


Fig. 9 Monitoring of wind tunnel test data (aerodynamic coefficients) with pretest CFD data.

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.

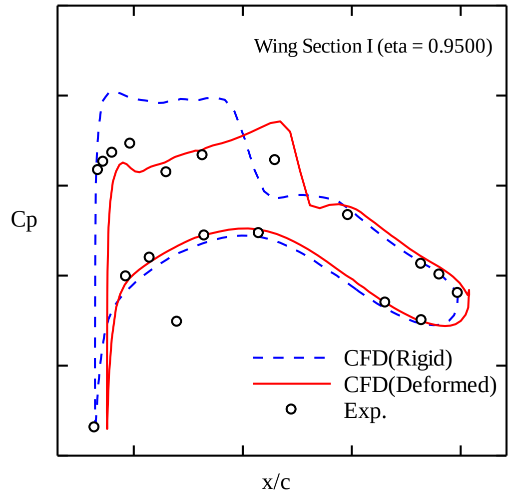


Fig. 11 Surface pressure distribution at wing tip in high-fidelity CFD considering model deformation measurement data.

6.2 Civil transport-type model test: DLR-F6

The second application of DAHWIN is the wind tunnel test using a middle-class civil transport-type standard model (DLR-F6) [17] as shown in Fig. 12. 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 comparison of data acquired by PSP and PIV with CFD data as well as conventional force and surface pressure data was done during the 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. 13, 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.

Fig. 12 DLR-F6 model mounted in the test section of JAXA TWT1.

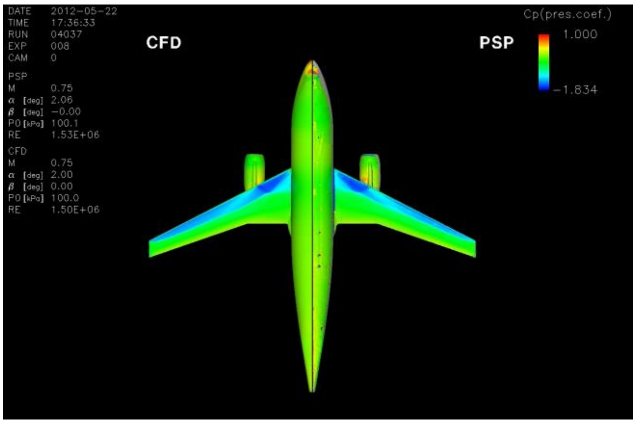
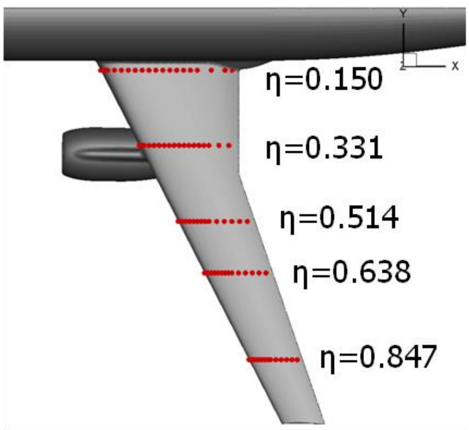


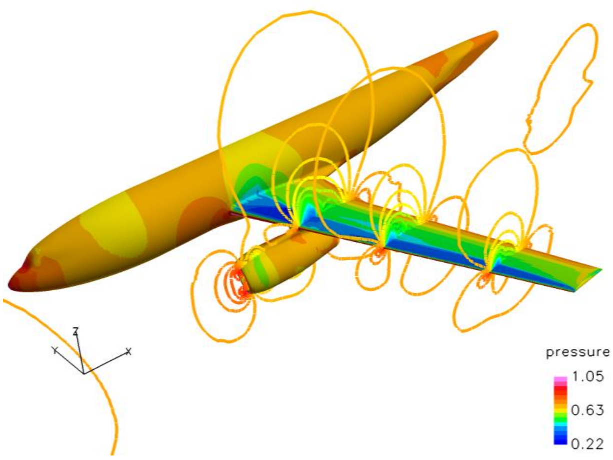
Fig. 13 Comparison of pressure distribution by EFD (PSP) and CFD.

Figure 14 shows an example of the data reconstruction for entire flowfield from measured surface pressure coefficient (Cp) data and several CFD results. In order to understand a flowfield in wind tunnel test in detail using both EFD and CFD data, an EFD/CFD integration technique using Proper Orthogonal Decomposition (POD) [18] was developed for reconstructing a flowfield of measurement data with all quantities obtained by CFD analysis. The POD modes are firstly extracted from several snapshots of CFD solutions using the snapshot POD method. Then the entire flowfield in the measurement can be reconstructed for various variables using the POD modes and limited experimental data sets by applying the gappy POD method. The details of the numerical technique can be found in Refs. 19 and 20. The position of pressure port, which is used for this reconstruction are shown in Fig. 14 (a). The total number of pressure ports is 137.

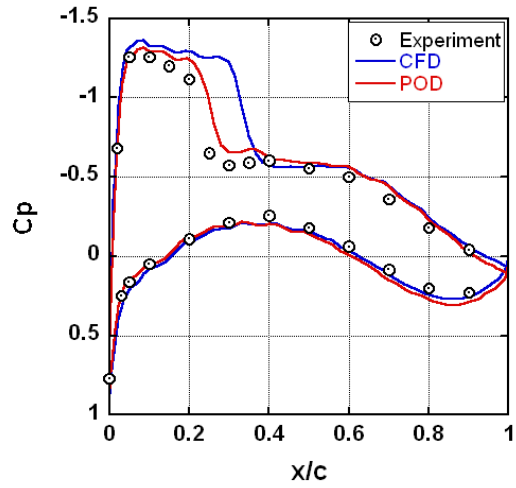
The obtained three dimensional pressure distributions around DLR-F6 model are shown in Fig. 14 (b). By using this POD approach, a three dimensional flowfield of the experimental data, which has same amount of information as a CFD solution, can be obtained from limited experimental data sets. The Cp profiles at η = 0.847 are shown in Fig. 14 (c) with those obtained from CFD analysis under the experimental conditions for comparison. As can be seen, the result of this POD approach agrees with the experimental data much better than that of the CFD. The process of the present analysis can be also made automatically in the system if measurement data as well as pretest CFD data are available.



(a) The position of the pressure.



(b) The obtained three dimensional pressure distributions around DLR-F6 model.



(c) Surface pressure coefficient (Cp) distributions obtained using the POD approach compared with those of the experimental data and the CFD for η = 0.847.

Fig. 14 Data reconstruction technique using Proper Orthogonal Decomposition.

7 Concluding Remarks

The system concept and detailed functions of the Digital/Analog Hybrid Wind Tunnel (DAHWIN) were described, whose purpose 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. After completing the development of DAHWIN, its capability and effectiveness are being evaluated in various wind tunnel test campaigns. The results of these evaluations showed that the system can be used effectively in industrial-type wind tunnel tests while suggesting various further improvements mainly to increase reliability and applicability.

Acknowledgments

The authors are in debt to Dr. T. Aoyama, Dr. N. Fujita, Dr. Y. Matsuo, Dr. T. Hirotani, Mr. M. Ueno, Mr. M. Kohzai, Mr. K. Nakakita, Mr. Y. Suzuki, Mr. E. Nakano, and the other members of Transonic Wind Tunnel Section in JAXA Wind Tunnel Technology Center for their technical support, useful discussions and suggestions. Efforts by members of Ryoyu

Systems Co., Ltd., Quatre-i Science Co., Ltd., Mitsubishi Space Software Co., Ltd., Fixstars Corporation, and Silk Laboratory Corporation in the development of DAHWIN including subsystems are also gratefully acknowledged.

References

[1] Hayase, T., Nisugi, K., and Shirai, A., "Numerical Realization for Analysis of Real Flows by Integrating Computation and Measurement," *Int. J. for Numerical Methods in Fluids* 47, pp. 543-559, 2005.

[2] Crowther, W. J, et al., "A Grid Enabled Wind Tunnel Test System (GEWiTTS): Towards Real Time Integration of CFD and Experiment," Proc. 2nd Symposium on Integrating CFD and Experiments in Aerodynamics, 2005.

[3] Schwartz, R. J. and Fleming, G. A., "Virtual Diagnostics Interface: Real Time Comparison of Experimental Data and CFD Predictions for a NASA Ares I-Like Vehicle," Proc. ICIASF 07, R56, 2007.

[4] Ogino, J., et al., "EFD Setting Simulation on Hybrid Wind Tunnel," Proc. 42nd Fluid Dynamics Conference/Aerospace Numerical Simulation Symposium 2010, JSASS-2010-2079-F/A, 2010 (in Japanese).

[5] Hashimoto, A., Murakami, K., et al., "Toward the Fastest Unstructured CFD Code 'FaSTAR,'" AIAA-2012-1075, 2012.

[6] Hashimoto, A., et al., "Drag Prediction on NASA CRM Using Automatic Hexahedra Grid Generation," AIAA Paper 2010-1417, 2010.

[7] Hashimoto, A., et al., "Validation of Fully Automatic Grid Generation Method on Aircraft Drag Prediction," AIAA-2010-4669, 2010.

[8] Nakahashi, K., Ito, Y., and Togashi, F., "Some Challenges of Realistic Flow Simulations by Unstructured Grid CFD," *Int. J. Numerical Methods in Fluids* 43(6-7), 2003.

[9] Ito, Y., et al., "Unstructured Mesh Generation Using MEGG3D - Mixed-Element Grid Generator in Three Dimensions," Proc. the International Conf. on Numerical Geometry, Grid Generation and Scientific Computing (NUMGRID2008), pp. 5-11, 2008.

[10] Hashimoto, A., Murayama, M., Yamamoto, K., and Aoyama, T., "Turbulent Flow Solver Validation of FaSTAR and UPACS," AIAA Paper 2014-0240, 2014.

[11] Tomita, A., et al., "Quasi-Real Time Data Processing of Stereoscopic PIV using Cell/B. E," Proc. 42nd Fluid Dynamics Conf., 2010 (in Japanese).

[12] Kato, H., et al., "Model deformation measurement for wind tunnel tests using photogrammetry by makers," Proc. 48th Aircraft Symposium. JSASS-2010-5032, 2010 (in Japanese).

[13] Kato, H., et al., "Development of the DAHWIN (Part III): Fast Data Reduction for Optical Measurements in Analog Wind Tunnel," Proc. 45th Fluid Dynamics Conference/Aerospace Numerical Simulation Symposium 2013, 2013 (in Japanese).

[14] Assessment of Wind Tunnel Data Uncertainty, AIAA Standard S-071-1995, AIAA, Washington, DC, 1995.

[15] Roache, P. J., *Verification and Validation in Computational Science and Engineering*, Hermosa, New Mexico, 1998.

[16] Yasue, K., Kuchi-ishi, S., Hashimoto, A., Murakami, K., Kato, H., Nakakita, K., Watanabe, S., and Hishida, M., "High-Fidelity CFD Simulation of a Wind Tunnel Model Using Model Deformation Data," Proc. 15th International Forum on Aeroelasticity and Structural Dynamics, 2011.

[17] Laflin, K. R., Vassberg, J. C., Wahls, R. A., Morrison, J. H., Brodersen, O., Rakowitz, M., Tinoco, E. N., and Godard, J., "Summary of Data from the Second AIAA CFD Drag Prediction Workshop," AIAA Paper 2004-0555, 2004.

[18] Sirovich L., "Turbulence and the Dynamics of Coherent Structures Part I," *Q. Appl. Math.*, XLV(3), pp. 561-571. 1987.

[19] Andrianne T. Yasue, K., Guissart A. Terrapon V. Dimitriadis G. Kuchi-ishi, S. and Watanabe, S., "Integrating Experimental and Computational Fluid Dynamics Approaches using Proper Orthogonal Decomposition Techniques," *Progress in Aerospace Sciences*, 2014 (to be published).

[20] Yasue, K., Kuchi-ishi, S. and Watanabe, S., "Experimental Data Reconstruction Using CFD Results Based on Proper Orthogonal Decomposition," Proc. 5th Symposium on Integrating CFD and Experiments in Aerodynamics, 2012.

Contact Author Email Address

watanabe.shigeya@jaxa.jp

Copyright Statement