A PROTOTYPE SYSTEM TOWARDS EFD/CFD INTEGRATION: DIGITAL/ANALOG-HYBRID WIND TUNNEL

Shigeya Watanabe*, Shigeru Kuchi-ishi*, Takashi Aoyama*
*** Japan Aerospace Exploration Agency (JAXA)**

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Abstract

The development of 'Digital/Analog-Hybrid Wind Tunnel,' which is a prototype system towards integration of EFD (Experimental Fluid Dynamics) and CFD, 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. This hybrid wind tunnel system includes JAXA 2m x 2m Transonic Wind Tunnel for EFD and JAXA Supercomputer System (JSS) for CFD. The function of this system consists of optimization of test planning utilizing pretest CFD calculations, an accurate correction of the wind tunnel wall and support interaction effects through CFD, CFD data refinement based on EFD data, the most probable aerodynamic characteristics estimation based on both EFD and CFD data, database including EFD and CFD data at an identical condition, and so forth. Key technical challenges in the system development, such as an automatic grid generator and high-speed CFD solver, a highly efficient data reduction technique for image measurement data, and techniques integrating EFD and CFD, are addressed.

1 Introduction

In prediction of aerodynamic characteristics of aircraft and aerospace vehicles, theoretical methods and experimental techniques (experimental fluid dynamics: EFD) have been mainly employed. However, since 1970's, 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 evaluated that the importance of CFD in aerodynamic design is comparable to that of EFD. The situational change in the aerodynamic characteristics prediction techniques indicates that as the next step, synergy effects are expected by integrating EFD and CFD rather than only using CFD as the secondary means with EFD as the primary method.

On the other hand, researches for the real integration of the two techniques, which are more sophisticated than just comparisons between EFD and CFD results, do not seem to be matured at present while some successful trials [1-2] have been reported. In particular, practical applications of EFD/CFD integration in the 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.

Japan Aerospace Exploration Agency (JAXA) has been developing both the experimental measurement technologies such as PSP and PIV (Particle Image Velocimetry) and the CFD techniques including computational algorithm and grid generation technique as aerodynamic research and development tools for more than thirty years. Aiming the development of future innovative aerodynamic prediction technologies, JAXA is developing a practical prototype EFD/CFD integration system called the Digital/Analog-Hybrid Wind Tunnel, 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 and some details of the hybrid wind tunnel and mentions technical challenges which should be overcome in the development of the system.

2 Technical issues in EFD and CFD

2.1 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, 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 so forth.

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

Some break-through technologies using EFD/CFD integration techniques would be required in order to solve the remaining tough technical problems described above.

2.2 Issues in EFD/CFD comparison

The advancement of CFD has been supported by the comparison with comparative experimental results in terms of accuracy improvement and evaluation of applicable range 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 control 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. Otherwise, a grid for CFD does 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 comparisons make it difficult to identify problems existing in the CFD technique applied, disturbing the advancement of CFD. To overcome this situation, a platform which always guarantees the EFD/CFD comparisons at an identical condition is required.

2.3 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. Is 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 needs a relatively long time for the data reduction of huge volume of the image data. These differences in time-span between EFD and CFD pose a serious problem when both EFD and CFD are conducted in a concurrent manner. Therefore, it is needed to shorten the model manufacturing time, the data reduction time of the optical measurement methods, and the time for the grid generation and high-fidelity calculation of CFD.

3 System concept of Digital/Analog-Hybrid Wind Tunnel

3.1 Objectives

The objectives to develop the Digital/Analog-Hybrid Wind Tunnel is 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 hybrid wind tunnel in the developments of Japanese regional jet, MRJ (Mitsubishi Regional Jet), and the Silent Supersonic Technology Demonstrator, S^3TD, which are jointly being developed in collaboration between JAXA and Japanese heavy industries. Also, it is expected that this innovative wind tunnel system promotes the advancement of the CFD technology, leading to acquiring Japanese competitiveness in the design of aircraft against the other foreign countries. Furthermore, it could be possible that the hybrid wind tunnel becomes a typical example of the integration of experiments and numerical simulations, facilitating creation of similar concepts in the other technical fields, such as structure, engine, material, and so forth.

3.2 Users and functions of the system

We are expecting aerospace engineers as well as researchers as users of the hybrid wind tunnel. 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 the 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. 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).

Based on the analysis of the technical challenges mentioned 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 and 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, called 'Virtual participation in wind tunnel test.'
- ✓ Accelerated data processing of the optical flow measurement techniques such as PIV, PSP, and model deformation measurement.
- ✓ 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 improve the CFD technology.

For enabling the functions shown above, a fast CFD solver in conjunction with an automatic grid generation tool should be developed as a part of the 'digital' wind tunnel of the hybrid wind tunnel.

3.3 System concept and operation sequence

Figure 1 shows the system concept of the hybrid wind tunnel to realize the functions described in the previous section. After defining a wind tunnel test model geometry in the course of the vehicle design, the 'digital' wind tunnel, the right hand side of the figure, conducts a pretest CFD calculation including both test model and wind tunnel with a model support system. Then, the CFD results 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. In the wind tunnel test phase, optical measurement data as well as ordinary measurement data are reduced in a nearly real-time fashion, which are transferred to the remote users. The wind tunnel data including the model deformation are sent back to the digital wind tunnel for a revised CFD analysis for the parameter optimization, taking the model deformation data into account. Finishing the wind tunnel test as well as the revised CFD calculations, both EFD and CFD data are obtained at an identical condition. Finally, the two data are combined into the most probable aerodynamic characteristics data by using data fusion techniques, which are stored in the EFD/CFD database.

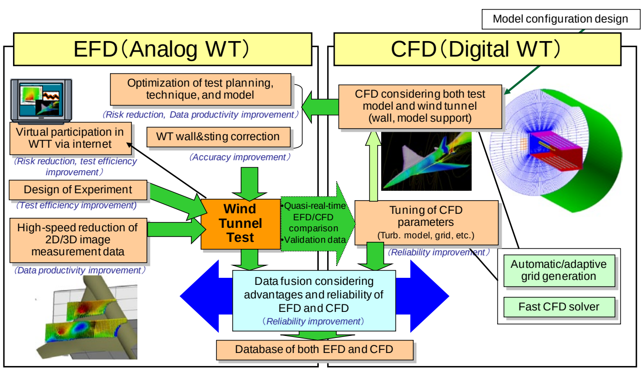


Fig. 1 System concept of the Digital/Analog-Hybrid Wind Tunnel.

The general operation sequence of the hybrid wind tunnel is illustrated in Fig. 2. The goal of the time sequence is that three months prior to the start of a wind tunnel test campaign, the pretest CFD is conducted and the final data after the data fusion are handed to the user about a month after finishing the wind tunnel test. In future, the time after the wind tunnel test should be shorten to around two weeks to shorten the aerodynamic design phase.

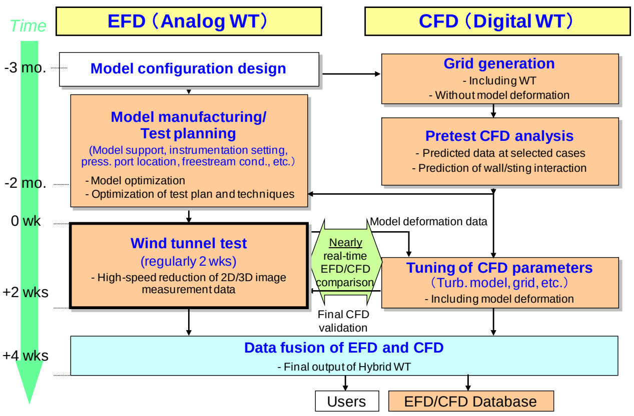


Fig. 2 Operation sequence of the hybrid wind tunnel.

3.4 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 1G-base Ethernet. The users as well as system administrators have access to this system through the web server.

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

First, the EFD/CFD data produced by the analog and digital wind tunnels are converted into a common data format HDF5, 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 future search purpose. Also, the converted data are sent to the visualization server for displaying the EFD data in comparison with the pretest CFD data at the same condition in an easy and correct way as shown in Fig. 4. This integrated visualization helps the wind tunnel user to evaluate the validity of wind tunnel data at real-time basis and understand the overall flowfield.

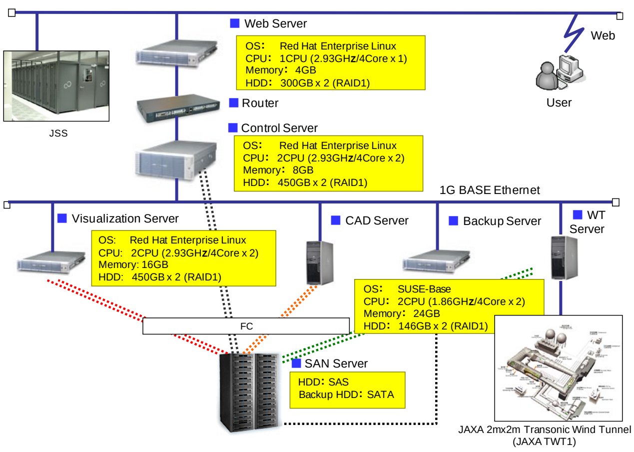


Fig. 3 System architecture of the hybrid wind tunnel.

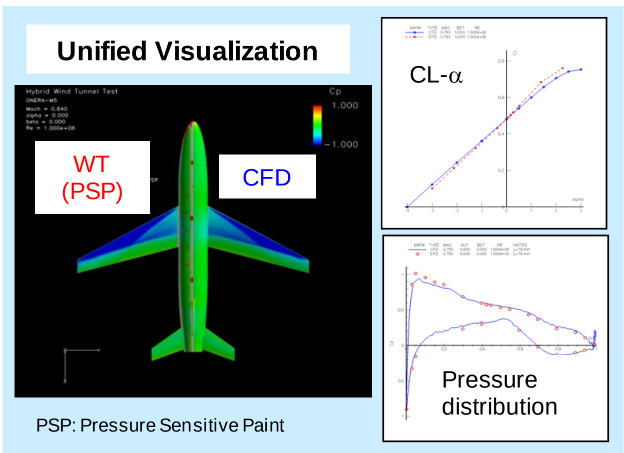


Fig. 4 Unified comparative visualization of EFD and CFD data for ONERA-M5 standard model.

The CAD server is used for the wind tunnel test setting simulation [4] before wind tunnel tests and other purposes. Figure 5 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 wind tunnel model design and optical measurement planning and risk of invalid setting, eliminating an onsite check using real instruments.

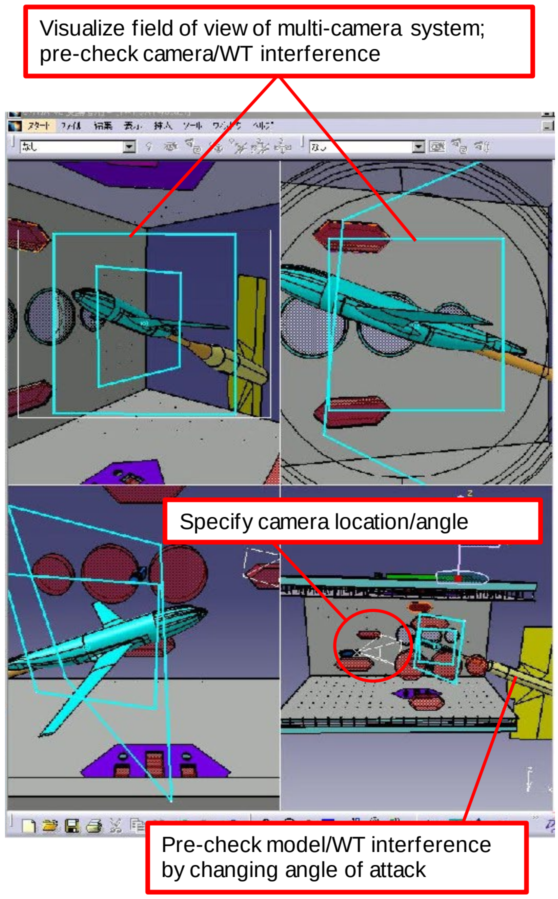


Fig. 5 CAD-based wind tunnel test setting simulation.

4 Key challenges in development of Hybrid Wind Tunnel

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 the hybrid wind tunnel system 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]. On the other hand, an unstructured-grid Navier-Stokes solver called TAS (Tohoku University Aerodynamic Simulation) [7], which has been applied to some real aircraft developments, 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. 6. The generator can 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 [8] originally developed for TAS while the number of grid points is comparable between the newly generated grid and TAS grid. Difference in drag coefficient between TAS results using the two grids above is about 5 counts (ΔC_D = 0.0005) [9], indicating reasonable quality of the grid by HexaGrid.

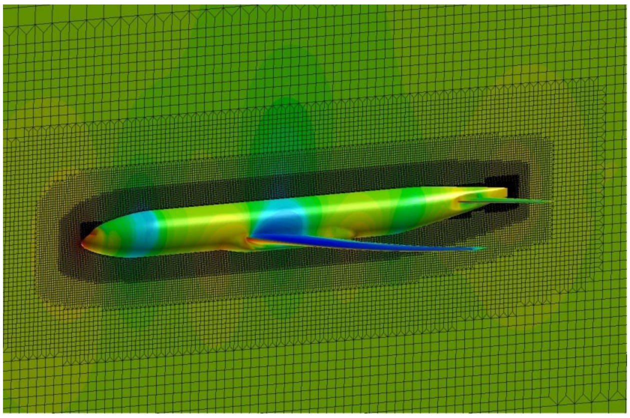
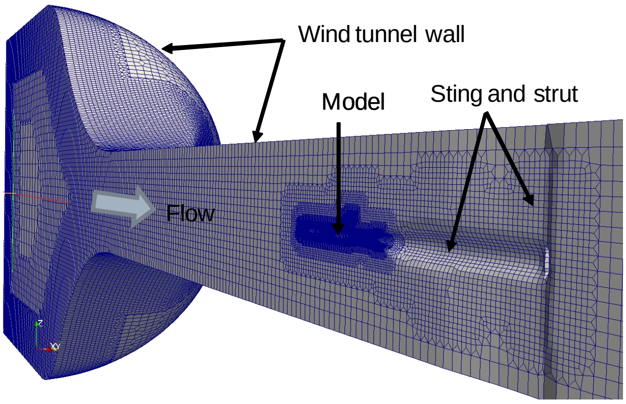
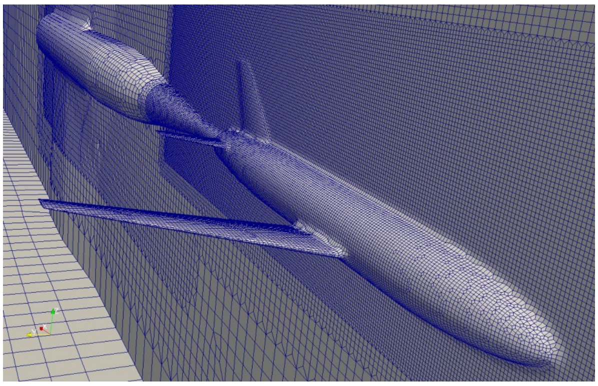


Fig. 6 Grid for NASA CRM model generated by HexaGrid (cell number: 12 millions).

An example of grid generation including a wind tunnel model, a model support, and wind tunnel walls is presented in Fig. 7. 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. However, since there exist some improper grids around characteristic lines like wing-body junctions, improvement of the HexaGrid software has to be done to solve this problem.



(a) Overall grid covering flow path of JAXA TWT1.



(b) Grid around model and sting.

Fig. 7 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 RANS. As turbulence model, Spalart-Allmaras and SST model were implemented. Although the FaSTAR is under development at present, its preliminary version has been completed as a RANS solver while convergence acceleration techniques like the multi-grid technique have not been employed yet. 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 [9], illustrating acceptable accuracy of this new solver. Computation time for 6.7 million grid points was 1.3 hour. Incorporating two convergence acceleration techniques, multi-grid and GMRES, to FaSTAR will realize four times faster calculation than the present code, indicating that the target of calculation speed can be accomplished.

4.2 Acceleration of optical 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 should be incorporated, which is one of key challenges in the improvement of the analog wind tunnel. As shown in Fig. 8, 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. Although the method relying on future advancement of the PC cluster is most reliable, the speed-up rate by PC cluster in several years might be lower than the goal shown above. On the other hand, a preliminary evaluation of an accelerator such as Cell/B. E. and GPGPU (General-purpose GPU) illustrated that the goal of the speed-up in the data processing could be attainable using such accelerator. Considering data reliability and easiness of software optimization for attaining maximum speed, Cell/B. E. was chosen for the analog wind tunnel. The system developed with two Cell/B. E. boards resulted in 20 times faster data processing than that of the original data processing system using a PC cluster with eight CPUs [10].

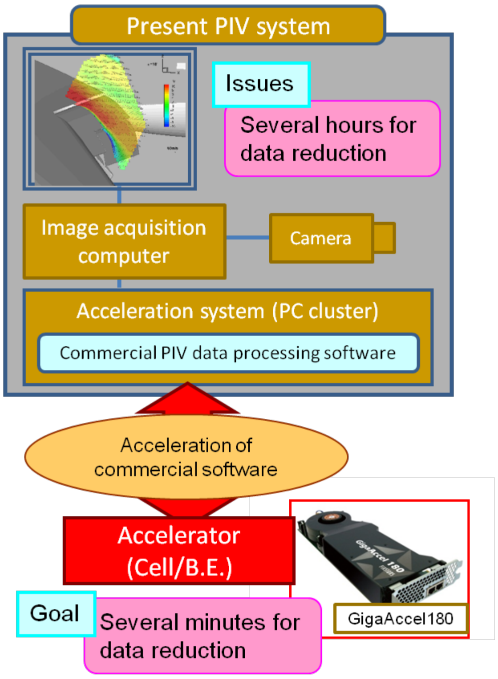


Fig. 8 A strategy for acceleration of the PIV data processing via accelerator.

Also, acceleration of data processing of PSP measurement is to be pursued since it is impossible to conduct the processing in a quasi-real-time manner [11]. 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, for example, utilizing the model deformation data predicted in the pretest CFD calculations.

4.3 EFD/CFD integration techniques

The techniques for the EFD/CFD integration are essential in adding value to the hybrid wind tunnel. The techniques include a wide range of technical fields. In the hybrid wind tunnel, main important techniques would be 1)data comparison technique, 2)data fusion technique, 3)EFD supporting CFD, and 4)CFD supporting EFD.

The purposes of the data comparison in both qualitative and quantitative ways are to support the users to evaluate test data promptly during the wind tunnel test and to find problems which exist in both EFD and CFD technologies for future improvement. One of the key techniques in the quantitative comparison is rapid and accurate data interpolation techniques to make conditions such as flow condition and spatial locations of measurement identical between the EFD and CFD data. In terms of the qualitative comparison, feature extraction methods for flowfields [12] such as edge detection and template matching are important to detect and characterize vortices, separation/reattachment lines, boundary layer transition, shockwaves, or so for finding substantial differences in flow phenomena between the EFD and CFD results.

The data fusion techniques are used to extract most probable aerodynamic characteristics based on both EFD and CFD results which have different uncertainty level and amount of data. Neural network [13] and data assimilation technique [14] might be candidates for the purpose.

In the use of EFD for supporting CFD, optimizations of turbulence model choice [15] and grid distribution refinement are important to improve accuracy and to expand applicable fields of the new CFD code. Figure 9 illustrates an example of the turbulence model selection based on detailed velocity field data measured by the stereo PIV technique. When incorporating this feature to the hybrid wind tunnel, automatic selection of turbulence model should be realized for supporting users to choose the most suitable model quickly.

CFD can support EFD through the high-fidelity interference correction of wind tunnel wall and model support based on the CFD analysis considering both the wind tunnel test model and wind tunnel. A sting interference correction strategy similar to this concept has been demonstrated for civil aircraft development [16]. The correction method could be applied to 2-D or 3-D properties such as pressure and velocity distribution in addition to a scalar property like aerodynamic force and moment. Also, the optimization of the wind tunnel test plan including the test model design and measurement apparatus setting design is categorized as this type of technique.

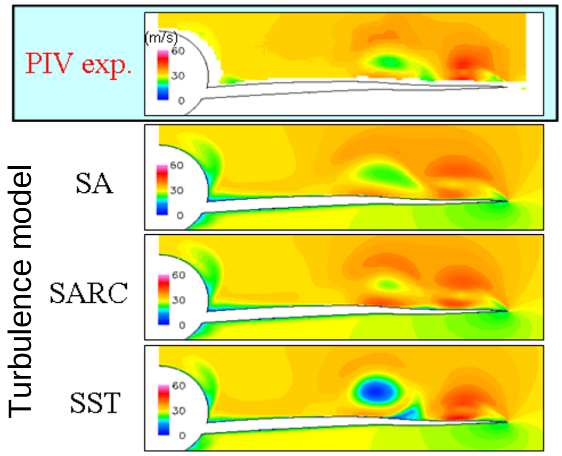


Fig. 9 PIV utilized for turbulence model selection [15] (velocity field around a cranked-arrow wing).

5 Concluding remarks

The system concept and development status of the Digital/Analog Hybrid Wind Tunnel were presented, whose aim is to improve both EFD and CFD technologies by integrating EFD and CFD, resulting in a significant improvement in efficiency and accuracy of the aerodynamic design of aircraft and aerospace vehicles. Based on the system design results of the hybrid wind tunnel, manufacturing of the software and hardware of the system is under way.

Although final goal of this type of the 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 systems. 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 by compared with wind tunnel test results at real flight Reynolds number at NASA NTF (National Transonic Facility) or ETW (European Transonic Windtunnel) to confirm the ability to estimate real flight aerodynamic characteristics.

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 the hybrid wind tunnel in order to add extra value to the system.

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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," 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., et al., "Development of fast flow solver FaSTAR," Proc. 42nd Fluid Dynamics Conference/Aerospace Numerical Simulation Symposium 2010, JSASS-2010-2042-A, 2010 (in Japanese).

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

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

[8] 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), 2008, pp. 5-11

[9] Aoyama, T., et al., "Digital Wind Tunnel Consisting of Automatic Grid Generation Tool and Fast CFD Solver on Work Flow System," Proc. 42nd Fluid Dynamics Conference/Aerospace Numerical Simulation Symposium 2010, JSASS-2010-2080-F/A, 2010 (in Japanese).

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

[11] Kurita, M., et al., "Multi-Camera Pressure-Sensitive Paint Measurement," AIAA Paper 2010-4797, 2010.

[12] Takeshima, Y., et al, "Adaptive Visualization of Measurement-Integrated Simulation of Karman Vortex Sheet Based on Topological Skeltonization," Proc. 5th Int. Sympo. on Advanced Fluid Information, 2005.

[13] Navarrete, J. A. and Meade, A. J., "Fusion of Experimental Data and Mathematical Model in the Simulation of Aerodynamic Coefficients," AIAA Paper 2004-952, 2004.

[14] Nakamura, K., Ueno, G., and Higuchi, T., "Data Assimilation: Concept and Algorithm," Proc. the Institute of Statistical Mathematics, Vol. 53, No. 2, pp. 211-229, 2005 (in Japanese).

[15] Watanabe, S., et al., "CFD Code Validation via Particle Image Velocimetry (PIV)," JAXA-SP-04-012, 2005 (in Japanese).

[16] Stojanowski, M. and Germain, E., "The FALCON 7X: from ETW to flight," AIAA Paper 2008-835, 2008.

Contact Author Email Address

watanabe.shigeya@jaxa.jp

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