The Value of a Computational/Experimental Partnership in Aerodynamic Design

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Abstract

This paper reviews some of the key lessons learned from the past twenty years of Computational Fluid Dynamics (CFD) development. These lessons include the need for careful validation and verification studies, the need for application specialists in CFD and experimental testing areas, and the need for continued improvement in the teamwork between computational and experimental groups. This nature of this teamwork is discussed and several examples are presented to illustrate the broad coverage of problems that a more cooperative approach enables. A good partnership between all required disciplines is suggested to be a key condition necessary for developing tomorrow's competitive air transport designs.

I. Introduction

During the last 20 years, the technology of Computational Fluid Dynamics (CFD) matured to the point where it is now a widely used development tool in aircraft design. In this relatively short time CFD went through several phases of growth during which developers sought proper integration with the more traditional experimental techniques of wind tunnel and flight test. Many lessons were learned and improvements made. Today, a mature blend of both computational and experimental aerodynamic technologies takes advantage of the best capabilities offered. There is still considerable room for improvement, though, and efforts underway are expected to yield even greater benefits. Pacing items, discussed herein, will determine how fast progress is made.

This paper will reflect primarily that area of airplane development with which the authors are most familiar, namely, today's commercial transports having significant transonic flow on wings and tails.

II. Lessons Learned

We have come a long way in the past two decades and we have learned some very valuable lessons. First of all we learned that the validation of new analysis and design tools must be accepted by the ultimate user if they are to be applied routinely. Flight test and the wind tunnel both play an important role in the continuing effort to validate the CFD analysis and design process. This is reminiscent of the early days of wind-tunnel testing. Back then, designers held back, necessitating a long period of validation, before choosing wind tunnels over prototype flight tests as a preferred tool in aircraft development. Now, most CFD computational results are validated by comparing them with wind tunnel experimental data. Computational methods have been improved to the point where, for non-separating flows, they give answers very close to wind-tunnel results. In fact, they may in some cases represent free air conditions even better than fully adjusted wind tunnel results. Still, there is much to be learned. Very few experimental results are available at flight Reynolds Number for comparative configurations. There is a requirement for that validation to be done in detail, and with accountable configurations, to satisfy the ultimate user community.

A second lesson learned is that both computational and experimental data must be understood clearly before meaningful comparisons can be made. Too often an engineer will be painfully aware of the limitations of the experimental data and completely unaware of similar limitations in a code being used for comparison. When a CFD/Experimental data comparison fails, it is usually for one of three reasons: inaccurate application, insufficient input, or slow processing time.

Frequently, the CFD code is used in regions outside the limits assumed in its theoretical development. For example, failure might occur when an inviscid code is used for a problem with significant viscous effects. A second failure mode occurs when geometry definition is insufficient. This is usually because the geometry or grid used in the CFD code did not exactly match the geometry as tested in the wind-tunnel. Thirdly, there is a more subtle kind of failure to be considered, one that occurs not because the solution is incorrect but because it took too long to achieve. When CFD is used in a sequential design process, rapid results are often essential --- a capability that does not fit the timing of the process is no capability at all. Seasoned experimentalists recognize the possibility of similar shortcomings in wind tunnel test results. That is, they must be clearly and rapidly communicated to the designer to allow adequate impact on a rapidly developing design.

A third lesson now becoming clear is that the correct CFD/Experimental blend is more determined by the airplane development process than by the unconstrained capability of either technology. Application specialists, who understand when to use the tools and how to apply them, are a necessary ingredient to ensure a successful design process. While any number of engineers will use these technologies routinely, specialists are needed to help with difficult cases that require an especially in-depth knowledge and to guide the use of the appropriate tools for routine problems. These specialists also bring to the design process an overall knowledge from their respective areas, a knowledge that helps to avoid problems encountered by those less experienced. Specialists not only help to provide a more effective balance of CFD and experimental work, but also help to reach solutions in the most economical manner.

The proper mix of CFD and wind-tunnel testing can minimize the cost of aerodynamic development. Williams[1] illustrated this concept as shown in Figure 1. As more CFD analysis is done, in comparison to wind tunnel testing, the cost of development reduces to some minimum and then begins to grow rapidly. This growth occurs for two reasons: not all conditions are solvable with CFD and the number of cases that must be examined grows increasingly larger. Therefore, even an extreme expenditure on CFD can not provide information necessary for a successful aircraft design. The optimum results will always be gained by combining CFD and experimental test efforts. The challenge for management lies in finding the correct mix for a given set of airplane, market, and manufacturing constraints.

Recent Boeing work on the 777 twin-engine transport and other projects has not only refined the optimum mix of experiment and CFD but also produced an important shift in philosophy. Neither CFD nor experimental capabilities drive the aircraft development process. Instead, the process must

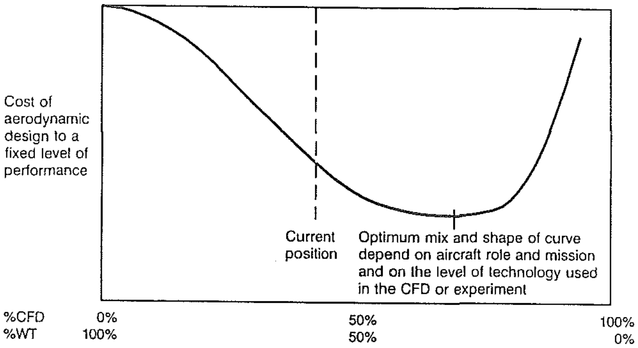


Figure 1. The Relative Cost of Aerodynamic Design Using CFD and Wind-Tunnel Testing

drive the development and use of CFD and experiment. The market sets the introduction date for a new commercial transport and, therefore, timeliness is a key aspect of the development process.

For wind-tunnel testing, timeliness is measured as productivity or through-put from the accurate definition of model geometry to the clear understanding of the data analysis. Similarly, for a CFD code, timeliness is measured as the entire process flow time required to provide an accurate and reliable solution. This includes geometry preparation, grid-generation, and post-processing. Often the speed of the flow solver is only a small percentage of this process time. Therefore, the timeliness of both tools is a key determinant for acceptability by the using aerodynamicist.

III. Current Blend of Computational and Experimental Methods

CFD now plays a vital role in aircraft design. No responsible designer would subject a wing to a wind-tunnel test unless it had been thoroughly analyzed by CFD of some form. Even so, for the foreseeable future, CFD will not replace the wind tunnel. There are still too many flight conditions beyond the reach of CFD. Even when CFD can predict all the conditions of interest, the wind tunnel may still be the most cost efficient source of that information. Most aerodynamic designs are not considered validated unless proven in wind-tunnel tests. The wind-tunnel tests needed for commercial transport development today can number in the dozens per year with several models used during each test period. Obviously, the current blend of CFD and experimental testing requires a large expenditure of resources with careful attention to an appropriate balance of tool usage.

Most aerodynamicists now look at CFD, wind-tunnel testing and flight test as components of a tool box used for aircraft development. Each has its own strengths and weaknesses, but most importantly, each has something to offer toward an improved design.

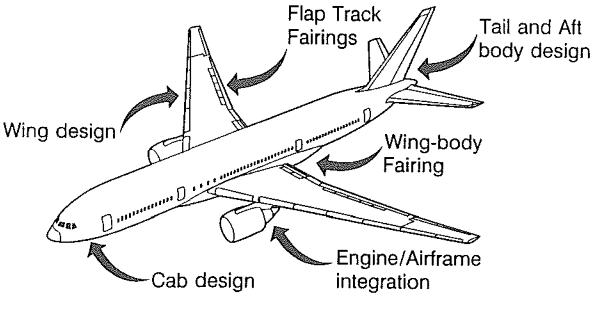
Use of these three data sources in a correctly integrated fashion will produce the best and most robust designs. The integration requires good communication between all those involved. The requirement for innovative design, through application of available resources, is essentially the same as in past aeronautical efforts, but the stakes have changed. The tools are much more expensive; they require greater expertise; and their economic leverage is a very important parameter in the decision.

Two important aspects of today's CFD/Experimental blend must be recognized. First, as has been suggested above, most relatively simple configurations with little or no separated flow can be correctly analyzed --- and often even designed --- with computational methods. However, complex component integration and separation-driven flight boundaries must rely on carefully implemented experimental test programs. Secondly, most aerodynamic development is still done in a sequential or cyclic basis. That is, first the geometry definition is developed by computational techniques and then experimental studies are run, followed by revised computational studies then more testing. Sequential development of this sort often involves three or more cycles. Some examples may help to illustrate the variety of blends being applied today.

Since the time of the Wright brothers, wing design has been a "cut and try" operation, with the "try" taking place in the wind tunnel or in flight. The advent of sufficiently powerful computational methods allowed some the "try" to be shifted to the computer. But, the "cut" was still the designer shaping the wing based on experience and intuition. CFD allows a new approach in which the design engineer specifies to the computer the aerodynamic pressures desired on the wing, and the CFD code computes the geometrical contouring of the airplane surface that will produce those pressures. Engineers do all of the design work and initial evaluation with CFD. Then they pick the best candidates, build wind tunnel models, and test them to validate design performance and to determine off-design performance.

As Figure 2 illustrates, this CFD design approach was used in many areas during the aerodynamic design phase of the new Boeing 777. This was especially true in areas where the flow was attached and not subject to strong viscous interactions. Designing for sub-critical flow solutions not only eliminates the possibility of wave drag, it also allows the use of linear panel methods. An advanced panel method can even do a reasonable solution around the complex geometries of high-lift systems, including multielement systems with flap-track fairings. In the hands of an experienced designer, linear solutions give much insight to guide the design development. Success of such an approach depends on the experimental expertise of the CFD engineer and the degree of collaboration with a specialist in high-lift wind-tunnel tests.

Nacelle integration is a major concern during aircraft development. Integration of the CFM 56 engine on the 737-300 is a frequently cited example of teamwork between CFD and experimental tools. As a result of combining CFD with testing, both the risk and cost of locating the nacelle was reduced. CFD application continues to make good penetration in this area and allowed integration of three different engines during the development of the 777.



Simultaneous design of 3 engine installations including exhaust effects

Figure 2. Areas on the Boeing 777 Where CFD Played a Major Role

An example of a recent validation study shows why CFD is making such an impact on the 777 aerodynamic design process. Two full-potential CFD codes with coupled boundary-layer solvers were evaluated against flight-test data.

Both of these codes are used in aircraft design projects and are capable of producing timely and efficient solutions. The analyses were performed with identical Mach number, angle-of-attack, and Reynolds number as recorded in flight. Figure 3 shows the comparison of A488[2] and TRANAIR[3] (Both full potential with coupled boundary layer codes) with experimental data. A488 uses a familiar Jameson-type finite-volume discretization. TRANAIR uses a Cartesian mesh that refines adaptively in regions of high flow gradients. The agreement with experiment is, in general, excellent with the exception of some minor discrepancies on the wing lower surface. These discrepancies can be attributed to the lack of modeling the wing flap track fairings and other small details of the actual aircraft. Both codes gave comparable results. This case represents about the most complex geometry that the A488 code can currently analyze. The TRANAIR code has more general geometry capability and could model the flap track fairings. Results like these allow the designers to use CFD methods with confidence. Comparisons were also made between wind-tunnel and flight results which further confirmed the validity of the previously used wind-tunnel testing techniques.

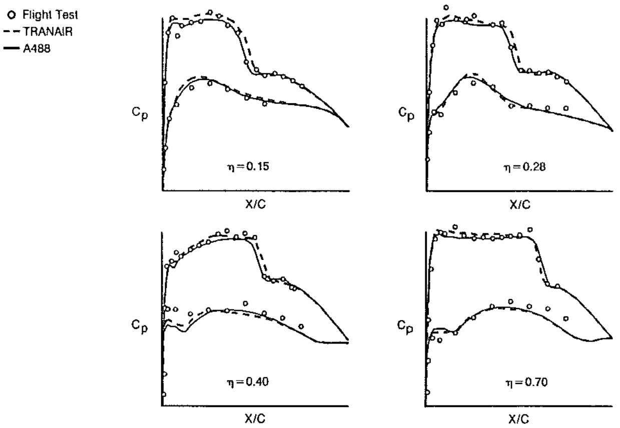


Figure 3. Flight Test Pressures Compared With TRANAIR and A488

A contrasting example shows how CFD solutions sometimes do not require immediate validation due to an established acceptability. Figure 4 illustrates the CFD results from the design of a wing-tip antenna pod for the Navy E-6A, a military version of the Boeing 707. This tip pod was designed and committed to production without wind-tunnel testing. The predicted pressure distributions indicated a rather simplistic flow that was well within the capabilities of the CFD code and, hence, very credible. The flow solver in this case had been developed to a mature state and designers had sufficient confidence in its abilities. In addition, the small size of the pod, relative to the size of the rest of the configuration, would have made meaningful wind tunnel testing difficult.

In another recent study, CFD provided insight into the flow physics of the air circulation in a cabin interior, an area that is difficult to examine experimentally. A Navier-Stokes formulation predicted the circulation streamline patterns shown in Figure 5 which seem reasonable. Navier-Stokes calculations are usually used for problems with strong viscous or boundary-layer flows. In this case, however, Navier-Stokes was used even though most of the flow is not affected by solid-surface boundary-layers because it was felt necessary to predict the entrainment effects at the distribution nozzle. The experimental test results, illustrated in Figure 6, for the same configuration show a good qualitative comparison with the streamlines from the CFD prediction. This is a good example of CFD used in conjunction with a difficult experiment. The computational flow map shows solutions in great detail thereby revealing areas of questionable validity or potential improvement which may warrant further investigation. In this way, an experiment can be done quickly, less expensively, and provide better results.

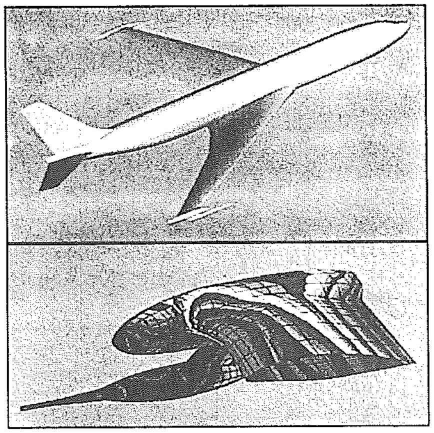


Figure 4. Pressure Contours Used to Design Part of the E-6A Wing Tip Pod

Figure 7 presents results from a similar study. Once more, air circulation in a closed region is the topic, but this time the concern is recirculation in a paint hanger. Recirculation of the air often results in paint over-spray onto other surfaces, thereby forcing a slower painting process or increasing the time spent with additional masking and removal of the overspray. This CFD study gave insight into the possible causes of over-spray. These causes would likely have remained very elusive when investigated by experimental techniques, not to mention the considerable cost involved. Results from this study contributed to the modification of an existing paint hanger, as well as to an improved design for a new paint hanger.

Probably one of the best examples of true computational/experimental blending is the work done by Krynytzky[4] a few years ago to develop installation corrections for a model in the acoustic-wall test section of a transonic wind tunnel. Here an innovative experimental facility was understood only when proper computational analysis of the propfan model installation was done.

Figure 8 shows the steps taken in this correction process, some of which were done with CFD and some from empirical corrections. The first correction was a simple calibration. The next two involved more sophisticated analysis and the last correction, which accounted for the installation of the test article in the wind tunnel to calculate its expected free-air performance, required a full CFD prediction

IV. The Future Blend

To understand where we should be going in this blending of two still-separate subdisciplines of aerodynamics, we must recognize the leverage that aerodynamicists exert on the success of a new airplane program. Figure 9 illustrates the relationship between the design knowledge and the design freedom traditionally available in aircraft design. Most of the aircraft design freedom is lost by the time configuration is frozen. It is lost inversely to cost commitments as more configuration decisions are made. Basic decisions made very early in the program, such as wing planform, chordwise and spanwise thickness distributions, and fuselage area distribution, commit much of the aircraft cost.

Therefore, a confident application of computational design methods, early in the development process, will produce a more refined design at an earlier stage. This, in turn, will contribute to more refined analysis information being available

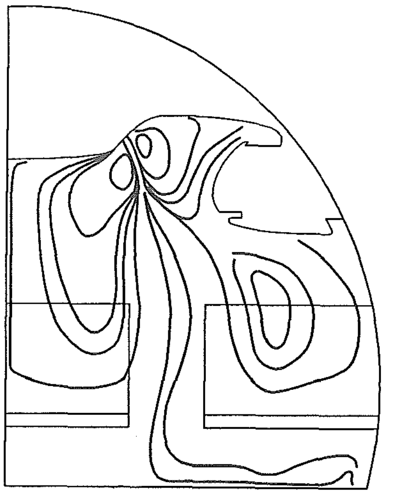


Figure 5. Streamlines Predicted for Ventilation Flow in an Aircraft Cabin

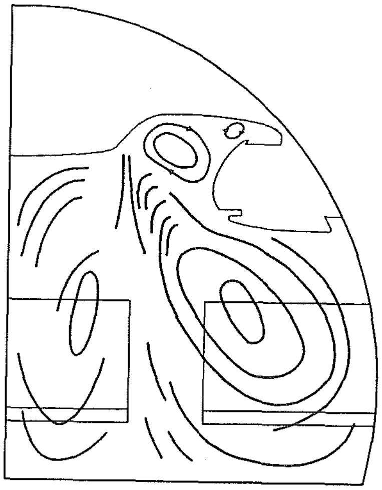


Figure 6. Streamlines Indicated by an Experimental Test

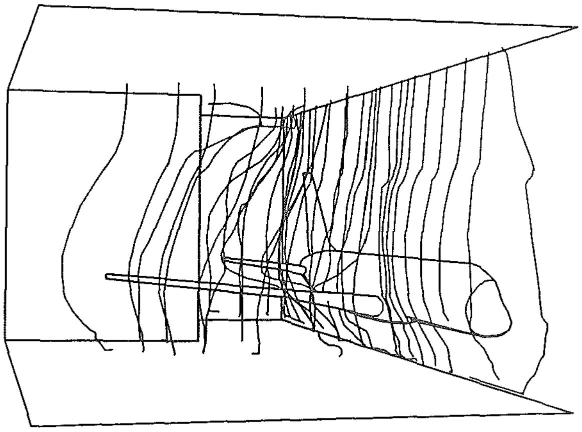


Figure 7. Streamlines Predicted From CFD for Ventilation Flow Over an Aircraft

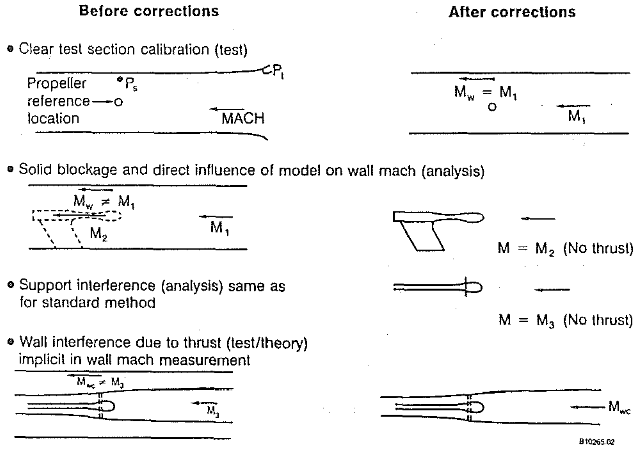


Figure 8. The Steps Applied to Correct the Wing-Tunnel Mach Number to Match That Seen in Free Air

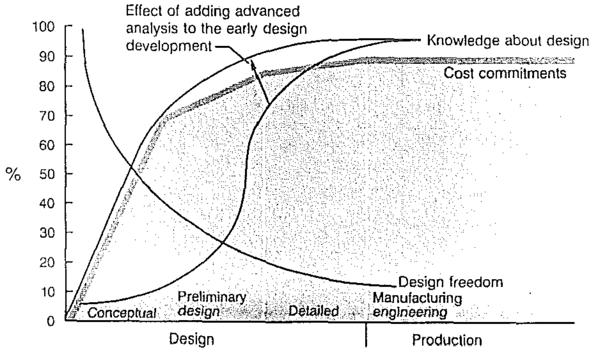


Figure 9. Adding Advanced Analysis Tools to the Early Design Stages Moves the Knowledge Curve Closer to the Costs Committed Curve

during the preliminary configuration design stage. The earlier availability of design knowledge will cause an upward shift in the knowledge-about-design curve so that it is more aligned with the cost commitments curve. Figure 10 illustrates activity peaks in an aircraft design cycle. There is no attempt to show how much effort is expended in each area, only timing. Various efforts start and end in a sequential manner so that design changes in later efforts cannot affect the initial design decisions without serious complications. Figure 11 shows how increased CFD usage in the Preliminary Design stage can better define the aircraft design before the configuration freeze. Having a more precisely defined configuration allows other engineering disciplines, those responsible for structural loads, stress, and control design, to refine their input to the design and work out changes before lines-freeze. Condensing the design process allows more flexibility and confidence in the design at an early stage. This requires improved confidence in the CFD prediction.

We should expect the blend to drift toward Williams' 60 percent to 40 percent ratio over the next decade. Figure 12 shows the trends for the past couple of decades and another view of the future balance between CFD and wind-tunnel testing. As this figure indicates, the requirements added in recent years --- added certification requirements, especially at the flight boundaries; increased competitive pressures; larger size but lower exit velocity propulsion systems; and the like --- have added to the wind tunnel testing requirements. Therefore, as CFD allows a reduction in attached flow testing, experimentalists can concentrate on understanding the results from mixed and complex flows or on refining their measurement techniques.

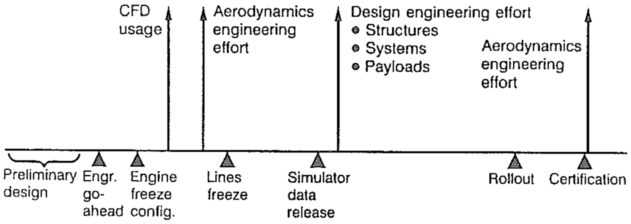


Figure 10. Typical Timings of Peak Efforts for the Areas of CFD, Aerodynamics, and Design Engineering

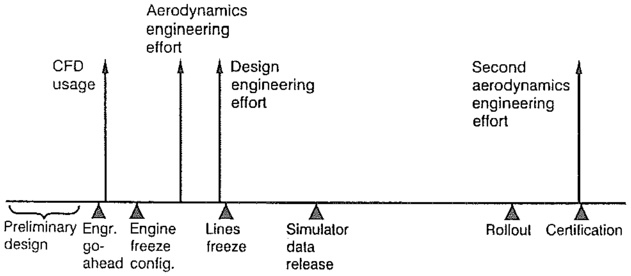


Figure 11. The Earlier Pear Efforts Possible Through Concurrent Design

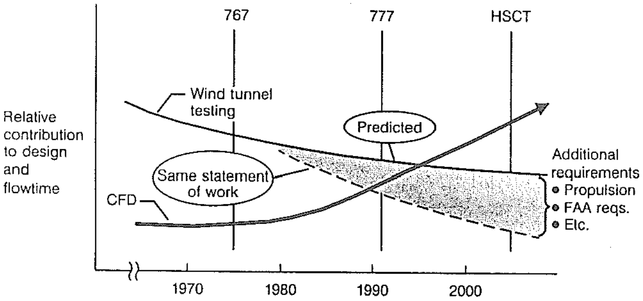


Figure 12. The Trend of the Balance Between CFD and Wind Tunnel Testing

Instead of today's sequential or cyclical approach to design, we must develop an integrated approach to the blending of computations and experiments. Examples of this integration include better wind-tunnel wall and mounting system corrections via CFD. This has been done on a limited basis in the past. Only zeroth order corrections are done today. These corrections change the Mach number, angle-of-attack, and measured quantities, --- sometimes by large amounts --- and they differ with each model, with each Mach number and with each angle-of-attack. Figure 13 shows a typical set of drag corrections applied in steps to a drag polar as an emphasis of the their magnitude. These corrections are very sensitive to model blockage and therefore are more of a problem as model size increases in search of the last bit of Reynolds number capability from current wind tunnels.

The approach currently being used in the porous wall test section of the T-128 transonic wind tunnel at TsAGI is indicative of the direction needed in the future. The ability to do corrections on-line with real-time CFD solutions is within reach of current techniques, thereby allowing corrections in wall suction or wall shape to be made in a timely manner.

As another example of integration, we must begin to rely on the computational surface flow definitions to influence the selection of optimum locations for sensor locations. Sensor density usually varies as grid density in a CFD code. More sensors are desired in regions of strong gradients. Knowledge of the size and location of those gradients, as a function of flight condition, should lead to a reduction in total number of sensors and, therefore, also in model fabrication and check-out time. These improvements should be thought of, again, as contributions to timeliness.

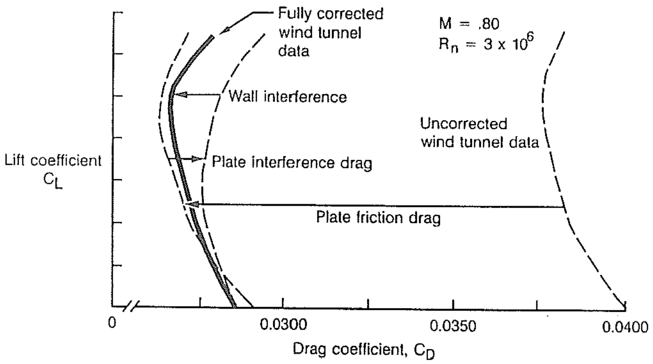


Figure 13. Typical Corrections to Drag Measured in a Wind Tunnel Test

CFD predictions of surface flow fields will be used to increase the confidence level in an experiment. If the prediction is available before the test and accurate tunnel corrections are available on-line, any differences between the observed results and the prediction will allow the expensive test time to be focused on the investigation of anomalies and complex interacting flows.

The area of wind tunnel model design presents still another example of potential benefits available from improved integration of these two subdisciplines. The current trend towards higher tunnel pressures in pursuit of higher Reynolds number will increase model loads and model mounting support sizes. The support can easily become so large as to interfere with the objectives of the test. If a typical factor of safety of 5 is used for model and support design, a support sting can grow to almost the size of the fuselage. To avoid this growth, very expensive materials can be used and/or the factor of safety can be reduced. If CFD can produce accurate design loads, coupled with an accurate finite-element stress analysis, a lower factor-of-safety, maybe as low as 1.5, can be used with much greater confidence than is present today.

The use of pressure-sensitive paints on transonic wind tunnel models is a new technology currently under development. This process was apparently first developed in the early 1980's by TsAGI, of what was then the Soviet Union, followed, independently, by the University of Washington[5] in 1988 and McDonnell Douglas Research Laboratories in 1991. This new technology promises significant improvements in wind tunnel model costs and test flow time. Morris[6] and his coauthors describe general aerodynamic applications of these paints in a recent paper. Briefly, when illuminated with monochromatic light, the reflected light emitted by the paint can be analyzed to provide a continuous definition of surface pressure distribution. Post-processing techniques currently available for visualizing large quantities of comparative CFD output should be modified so as to be useful for visualizing this experimental data. In fact, it has been suggested that the patterns from the two sources could be differenced to allow a very quick assessment of the validity of the pretest load predictions. This developing capability is a great opportunity for CFD specialists to work with instrumentation developers in a synergistic fashion where both groups may realize a greater gain through the sharing of ideas and techniques.

Another opportunity for process improvement through inter-disciplinary efforts relates to aerodynamics and structures. Figure 14 provides a concept for such a collaboration. Not only would the sharing of design data enhance early developmental efforts, but the improved communication between these two engineering functions removes traditional barriers and increases the possibility of breakthroughs in design. This integration of disciplines will be even more productive when these groups more effectively integrate both their computational and their experimental tools.

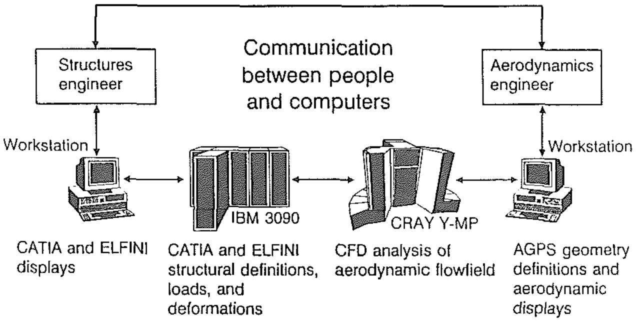


Figure 14. An Example of Parallel Design via Communication

Ideally, many different groups and sub-groups could link through a central designer or integrator. Figure 15 illustrates an idea for teaming computational and experimental people. The integrator, whether person or group, must have a complete understanding of the overall design, as well as the computational and experimental capabilities and requirements, in order to integrate the tools from each component group into an overall design and analysis scheme. Engineers would communicate freely with each other, across disciplinary lines, to provide the integrator with a comprehensive input in the least possible amount of time. NASA's ACSYNT code is an early attempt at providing this type of focussed preliminary design.

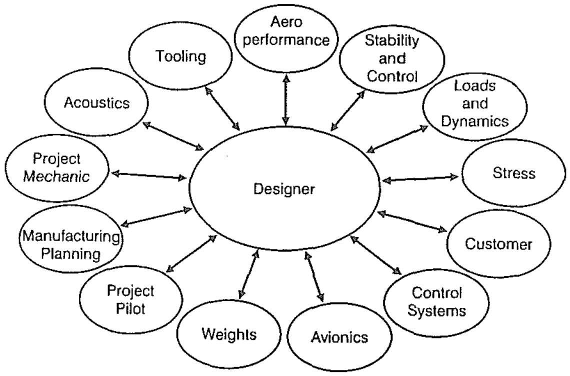


Figure 15. A Concept for Teaming and Coordination Between Several Groups

V. Pacing Items

There are of course some technical innovations and inventions in both areas which are pacing the integrative capabilities of the tools. A better knowledge of turbulence is needed to allow more robust computations of boundary layer transition and separation. And, of course, much more productive non-intrusive instrumentation would allow the acquisition of the detailed structure of high Reynolds Number boundary layers so necessary to computational progress. Then too, computed drag for complex configurations leaves much to be desired. The experimentalist also needs some help in reducing the time and expense of acquiring accurate drag information at high Reynolds Number, both in wind tunnels and in flight.

Yet, the most important pacing items, by far, are not related to the technology but to human nature. Our engineers must be taught and motivated to bring a strong teaming attitude toward their assignments. All of us must continually seek new ways to encourage experienced engineers and to teach young engineers and engineering students to see the more efficient solution of each engineering problem in teamwork.

As the science of aeronautics, at least as applied to subsonic jet transports, is maturing, the world in which it exists is changing. Commercial airways and airports are becoming crowded; the marketplace for our products is undergoing a radical change of character. To succeed in this changing world, we must form teams of engineers, selected for their experience, talent, and insight, and encourage them to question our traditional processes. The computational and experimental blend in aerodynamics and related technologies is one of those process issues. This changing world requires a continual review of the foundational requirements and restrictions on our key processes in order to improve our products.

A specific example of a key process issue, perhaps one of our most pacing items, has to do with the presentation of data for analysis and understanding. By nature, we are able to assimilate information and concepts, as well as to differentiate details, much more readily through integration of visual information than through any other means. Our computational specialists are beginning to capitalize on this capability as they develop new input and output techniques. Other design areas, airplane cockpits for example, are also beginning to reflect an understanding and application of this phenomenon. Yet the widespread application of integrated colored patterns for data presentation is still lacking in most areas. Except for a few innovative experimentalists like Crowder[7], most of us are still tied securely to the traditional alpha numeric or line graph information presentation techniques. The lack of a broadly based, healthy, questioning attitude toward our traditional processes and methods is probably the pacing item most restrictive to the realization of future improvement in aerodynamic design.

VI. Summary and Conclusion

The commercial future of any technological improvement in aerodynamic design tools, either computational or experimental, will be determined by their speed and productivity. Even if a new technology is wonderfully accurate, its timeliness is the vital issue because the real leverage in today's competitive industry comes from productivity. The thousands of computational runs and tens of wind tunnel tests in a typical year are an important ingredient in the design an airplane, but only if they are timely.

Attitudes have shifted toward a more balanced view of the three aerodynamic design tools: CFD, wind-tunnel testing, and flight test. Each is seen as providing a different set of strengths and limitations. Teamwork is now recognized as the only true way to achieve an optimal design in a global market environment that continues to grow more competitive. Additionally, there are considerable benefits available through the linking of efforts by related disciplines, such as those of aerodynamics and structures. By continuing to improve the design and application of computational and experimental tools, integrating their application in a cost conscious manner, and taking a multidisciplinary approach to the improvement of design processes, aerodynamicists can optimize their contribution to world-class products for 21st century markets.

Acknowledgements

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