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Reprinted from

Journal of Aircraft

Volume 45, Number 1, Pages 16-22



A publication of the

American Institute of Aeronautics and Astronautics, Inc.
1801 Alexander Bell Drive, Suite 500
Reston, VA 20191-4344

Engineering Solutions in Support of Supplementary Type Certificate to a Transport-Category Aircraft

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DOI: 10.2514/1.27791

A comprehensive, cost-effective, and accurate method to develop the aerodynamic database in support of structural certification of a transport-category aircraft modification under the Federal Aviation Administration rules and regulations is presented. Although the method in many respects resembles techniques used by the original equipment manufacturer, the emphasis is on the formulation of a process that is eminently suitable for independent or third-party (nonoriginal equipment manufacturer) aircraft modification work. The method is highly integrated in terms of analytical- and test-model development, and analysis-supported test and posttest analyses. The accuracy of the procedure is validated by full-scale aircraft testing and demonstrates that correlation is achieved in an accurate and conservative manner.

I. Introduction

THE aircraft industry consists primarily of original equipment manufacturers (OEMs) responsible for the design and construction of new aircraft. These aircraft are built and certified for operation under a set of federal aviation regulations (FARs). Once approved, a valid type certificate (TC) is issued for the particular aircraft and model(s) being certified. However, a substantial number of third-party (non-OEM) modifications to existing aircraft are being performed and are also typical of the industry. Such modifications are built and certified to the same FARs; however, the actual approval in this instance takes the form of a supplementary type certificate (STC) for the particular modification to specific aircraft TCs. Modifications may include systems changes, performance enhancements, noise abatements, structural modifications, and so on. Common to the TC and the STC design and certification processes is the need to develop the databases used in support of the various analyses and testing deemed necessary in the process of showing compliance with the regulations. By contrast, the TC program is centered on synthesizing a complete aircraft design that matches certain performance criteria, whereas the development of structural modifications in support of an STC merely requires an understanding of the final set of parameters that dictated the design of the aircraft in its original configuration. The OEMs typically invest substantial amounts of resources in developing the databases and consider these highly proprietary. The database is substantial and may encompass several parameters, including, but not limited to a complete description of the structural arrangements, systems description, mass distribution in the aircraft for all operational conditions (center of gravity, payload distributions, fuel distributions, etc.); structural stiffness representation; landing gear characteristics (hydraulic damping, oleo stiffness, tire stiffness, wheel inertias, etc.); design envelope (speed, altitude, Mach range, etc.); control-surface authority, location, operation, performance and stability data; yaw damper and autopilot authority; and distributed aerodynamic loading characteristics.

For the third-party modifier, the traditional venues for obtaining the necessary databases include a licensing agreement with the OEM,

or separately undertaking analysis and testing to develop databases comprehensive enough to allow engineering independence from the OEM. The former approach may not always be available or directly applicable, or it may be prohibitively expensive. For one or more of these reasons, the latter approach has been attempted, although often being incomplete and resulting in inferior STCs. These shortcomings can manifest themselves in operational or performance restrictions and difficulty in providing continued airworthiness, with the final result of erosion in asset value. The reason for these unsatisfactory results is often because of lack of resources, inadequate test and analysis, execution, and/or a combination of these.

As mentioned, the database in support of major modification programs needs to be substantial and often includes some form of aerodynamic design data. Although the aerodynamic database and its development are considered minor tasks in the overall effort, they are nevertheless important components of such programs. Historically, a substantial amount of aerodynamic analyses has been based on component testing contained in Royal Aeronautical Society papers, various NACA reports, the U.S. Air Force Data Compendium for Stability and Control (DATCOM) manuals, and other authoritative sources. Significant to these sources is the fact that they are almost all relying on test data, providing the pedigree necessary for acceptance as part of the basis for certification of an aircraft modification. These methods have been applied with success to a number of small-aircraft programs certified under the CAR 3 (civil air regulation, part 3), FAR 23 (fixed-wing), and FAR 27 (helicopter) regulations. As the industry has become more ambitious and has tackled modifications for which no precedent is available or, if available, is not sufficient for generating the design criteria, various analysis procedures have been introduced as a means of filling this void (see examples in [1–3]).

Although the computational fluid dynamics (CFD) analyses available today are impressive tools in support of synthesizing profiles for optimum performance and are useful in support of preliminary design, these methods are not sufficient in and by themselves for loads development in support of aircraft certifying. It is important to recognize that, whereas the performance issues usually are associated with low angle-of-attack (AOA) conditions (1-g flight), the loads definition entails extreme conditions, including stall, which at present is outside the range of validity for CFD analyses. The problem with the purely analytical approach is that the ensuing analyses that are dependent on a database generated in this fashion are not based on a verified test or other data of authority. For development work or in support of preliminary design, this may not be significant; however, in the context of demonstrating compliance with the FARs, the issue of validation becomes extremely important.

An argument could be made that if the design is based on purely analytical means and is later verified by a flight test, this should be

Presented as Paper 3318 at the 24th Applied Aerodynamics Conference, San Francisco, CA, 5–8 June 2006; received 13 September 2006; revision received 11 March 2007; accepted for publication 19 March 2007. Copyright © 2007 by Leth and Associates. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0021-8669/08 \$10.00 in correspondence with the CCC.

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safe and acceptable for certification. The problem with this argument is that testing to the flight envelope extremes may be unsafe. From a technical point of view, it is simply impossible to separate the effects of Mach, angle of attack or sideslip, dynamic pressure, altitude, aeroelastic deformation, engine power, airplane conditions, control-surface deflections, load factor, and so on, corresponding to all corners of the design envelope to generate a comprehensive database. Measurements from such testing are, at best, snapshot values in response to a complex mix of state variables; they are values that are not easily projected to actual design conditions for the aircraft. Further, if the test shows deficiencies in design, costly redesign and delay in schedule is inevitable. Finally, flight-testing is very expensive because of the cost of amortization of aircraft, fuel, insurance, crewing, instrumentation, and so on. Often, availability of aircraft is a problem. From a risk-management standpoint, reliance on this approach is considered to be imprudent.

Alternatively, it could be argued that the purely theoretical methods can be applied in a conservative manner. Although there are examples in which this can be useful, it is in itself a question as to how to quantify what constitutes a conservative design value. It needs to be remembered that the detailed structure analyst is burdened with demonstrating a sufficient margin of safety. If a "conservative" approach is successfully devised and applied to the extreme, it may result in structure that is too stout. Consequently, this would penalize the aircraft modification by having increased operational empty weights (OEW), which result in reduced payload capabilities.

To close the gap between the analytical procedures and the need for a Federal Aviation Administration (FAA) certifiable aerodynamic database, this paper presents an example of a cost-effective and comprehensive approach to obtaining aerodynamic data in support of certification of a major structural modification of a transport-category aircraft, independent of the OEM. One objective of this paper is to contribute to the advancement of industry standards for STC certification procedures. A further objective is to establish an independent alternative to the OEM for conversion programs, fully using reverse engineering to achieve the third party's legal business purpose. It should be noted that the methodologies employed are similar to procedures widely used by the OEMs and differ only in the execution, thus making the approach a viable alternative in support of STC programs.

The technique presented here was successfully applied in support of the passenger-to-freighter conversion of the Boeing 757-200 aircraft undertaken by Precision Conversion, LLC. This program was completed and received FAA approval under STC no. ST01529SE in June 2005.

II. Method

The present method parallels those techniques traditionally employed for aircraft design and certification by the OEMs, but takes advantage of significant advances in the basic tools of analysis. Thus, the substantial commercial risks often associated with major third-party aircraft modifications may be greatly reduced. Further, by virtue of closely paralleling OEM procedures, there is the potential for acceptance of the third-party modification by the OEMs, leading to continued airworthiness support.

Although simple in concept, it is important that the execution is planned around a small team with cross-technical training and experience. The requirements include, but are not limited to 1) first-hand knowledge of aircraft structures, 2) experience with model design, planning, and conduct of tunnel testing and data reduction, 3) competence in all aspects of computational fluid dynamics, 4) training in the development of design loads and criteria, 5) experience in the application of criteria in the design process and in the details of the structural analysis, 6) experienced planning and management of full-scale flight-testing and flight-test instrumentation, and 7) intimate knowledge of the certification process.

The steps that comprise the present certification procedure are outlined in the following.

- 1) Create a geometry definition.

- a) Obtain outside mold-line (OML) geometry for all airplane conditions required for certification. These may include clean wing (no spoiler, flaps, or control-surface deployment), spoiler deployed (no flap or control-surface deployment), or flaps down (details not included in this paper).

- b) Design and construct a scale aircraft pressure model from measured OML data.

- c) Develop a CFD model matching the scale aircraft pressure model.

- 2) Perform wind-tunnel test.

- 3) Conduct CFD analysis.

- 4) Prepare aerodynamic database.

- 5) Verify analysis via load-survey testing.

In the present approach, the aerodynamic properties of the Boeing 757-200 aircraft with clean wing and with spoilers deployed were each established via wind-tunnel testing on a scale model, dimensionally based on measurement of the full-scale airplane OML, using laser measurement technology. As a complement to these data, a CFD analysis was developed for the aircraft with clean wing and wing with spoilers deployed. Data correlations between test and CFD were used as both a means of calibration and a means of determining the range of applicability of the numerical method. The combined database was used for aircraft performance prediction, which was then confirmed via flight-testing of the actual aircraft.

The combined aerodynamic database in this case consisted of information on tail-plane-off and whole-airplane coefficient data in terms of lift, moment, and drag for a series of Mach numbers and AOAs. In addition, distributed pressures over the fuselage, wing, and nacelle components were established. Posttest analysis was used to prepare the sectional coefficients for the aircraft components. Specifically, the airplane lift data and pressure distributions and their development will be discussed herein. Please note that in most cases, the vertical scale on data plots has been removed because of the proprietary nature of these data.

A. Geometry Definition

Because no geometry is available in the public domain, it was necessary first to obtain the OML by measurement of an existing aircraft. This was accomplished by means of laser-based measurement technology. As this technology is commercially available in several forms, and is in constant development, a detailed description of this method is not included here, except to say that most (if not all) of these methods are based on standard triangulation algorithms.

Following acquisition, the data were immediately downloaded for analysis through a lofting routine. As part of this analysis, all data points were transferred from the elastic state to jig-shape definition. This was accomplished by accounting for sag because of the gravitational force distribution on the aircraft, using the structural stiffness definition and the distributed mass of the aircraft. On large, flexible aircraft, this effect is of sufficient importance to be taken into account. Here, development of the stiffness data was accomplished via ground test involving the flexing of the structure and correlation to a stiffness model. The final result obtained for the reference program is depicted for the clean-wing configuration in Fig. 1.

A scale model of the reference aircraft was constructed with pressure ports installed on the fuselage, the nacelles, and at prescribed body buttock-line (BBL) locations across the wingspan. Although the fabrication of the pressure model is a specialty task, involvement by the structures/loads engineer is required in support of making decisions affecting the accuracy of the model. For example, deflection of the model under load may have to be accounted for in the data reduction, requiring determination of the model stiffness characteristics. The finish of the model and final geometry also has to be verified. In preparation for the testing in the tunnel, boundary-layer trip strips have to be devised and carefully installed.

Generally, it is very important to select a suitable set of pressure ports in terms of number and location to ensure comprehensive test results. For the OEM TC holder, this is normally ensured by using a

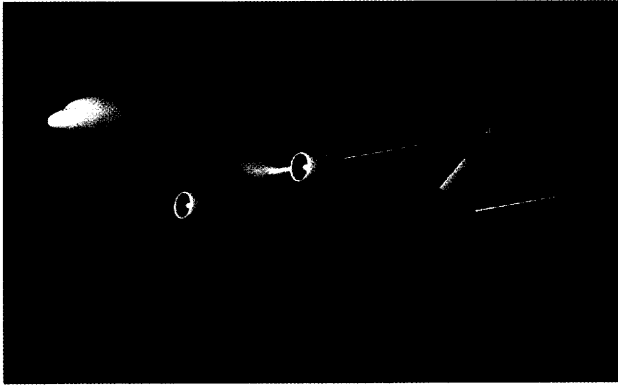


Fig. 1 Image of the subject aircraft as developed from laser-based measurement technology.

large number of ports. For the STC process, the task is not as easily accomplished, as the cost increases rapidly with increasing number of pressure ports. In the present effort, the aircraft analytical model assisted in establishing a set of optimum port locations for the fuselage crown and keel as well as four longitudinal cuts on the nacelle cowl (inboard, outboard, crown, and keel). This approach resulted in sufficient data acquisition at a reasonable cost in terms of model preparation. The wing port locations were dictated primarily by optimization in support of the certification database requirements.

B. Wind-Tunnel Testing

The pressure model was tested in an 8×12 ft transonic wind tunnel (Fig. 2) through a Mach range of 0.30 to 0.91. The angle-of-attack range varied from moderate negative angles through stall. The accumulated tunnel time was approximately 8 h. Data output from the tunnel test included the aerodynamic data for the entire aircraft as established via the balance mount, as well as pressure distributions along the fuselage, nacelle, and at nine spanwise locations on the wing. From these data, total aircraft coefficients, fuselage, and nacelle surface pressures, and wing sectional coefficients were developed for the clean configuration and with spoilers deployed. The flaps-down configuration was not specifically tested because of cost considerations and because other approaches, acceptable for the particular aircraft modification at hand, were employed.

C. CFD Analysis

In support of the wind-tunnel test and posttest data preparation, a computational study was conducted using a method that solves the 3-D Euler equations, which govern inviscid, compressible fluid motion [4,5]. The surface of the configuration is defined by a triangulation, which generally consisted of approximately one million elements. Further, the flowfield was discretized by means of an adaptively

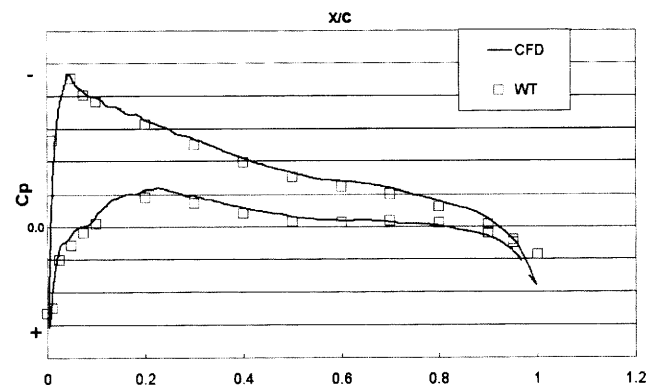


Fig. 2 Pressure model in the transonic wind tunnel.

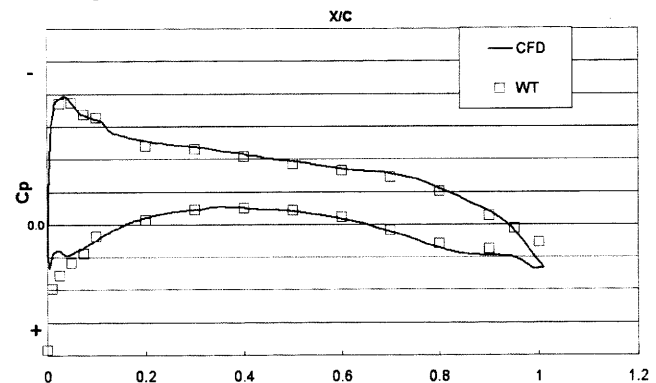
refined Cartesian mesh composed of elements on the order of 10^7 . The aircraft with clean wing, spoiler, and flaps down (not detailed herein) were each analyzed using this technique. Flow conditions for the computations closely matched those of the wind-tunnel investigation in terms of Mach number but were concentrated in the linear range of the lift curve. A level of confidence with the numerical method was gained by direct comparison with the test data across the flight envelope. This gave the investigators the ability to use test and numerical data where it was most appropriate, with the objective of satisfying the database requirements. Results from a low subsonic and a high transonic Mach condition will be presented here for both the clean-wing geometry and the spoiler configuration.

The clean-wing configuration included fuselage, vertical tail, and flow-through nacelles similar to the wind-tunnel geometry. As part of the validation process, the computed results were compared with the wind-tunnel data. The variation in wing upper and lower surface pressure coefficient C_p at Mach 0.30 and 0.82 is shown in Figs. 3 and 4 at an inboard and outboard span location. The computed values are presented as a solid line, whereas the test data are designated by a symbol. The computed aircraft lift coefficient C_L as a function of angle of attack is compared against the test data in Figs. 5a and 5b at a Mach number of 0.30 and 0.82. For wing surface pressures and aircraft lift coefficient, the correlation between test and computation is good at the subsonic Mach number; however, it is worth noting that the neglect of viscous effects is not apparent in the computed results. As expected, the comparison is less favorable at the transonic Mach number because of boundary-layer thickness effects and the occurrence of flow separation. Based upon these comparisons, the test data were used exclusively in the development of the wing sectional coefficients.

The computed variation in fuselage centerline surface pressure coefficient is compared with test data in Figs. 6a and 6b at Mach 0.30 and 0.82, respectively. As previously mentioned, the computed results were available before the construction of the wind-tunnel model and were used to strategically place the pressure ports at the



a) 15% span location



b) 76% span location

Fig. 3 Comparison of computed and experimental wing surface pressure coefficient at Mach 0.30 and AOA of 2 deg for the clean-wing configuration.

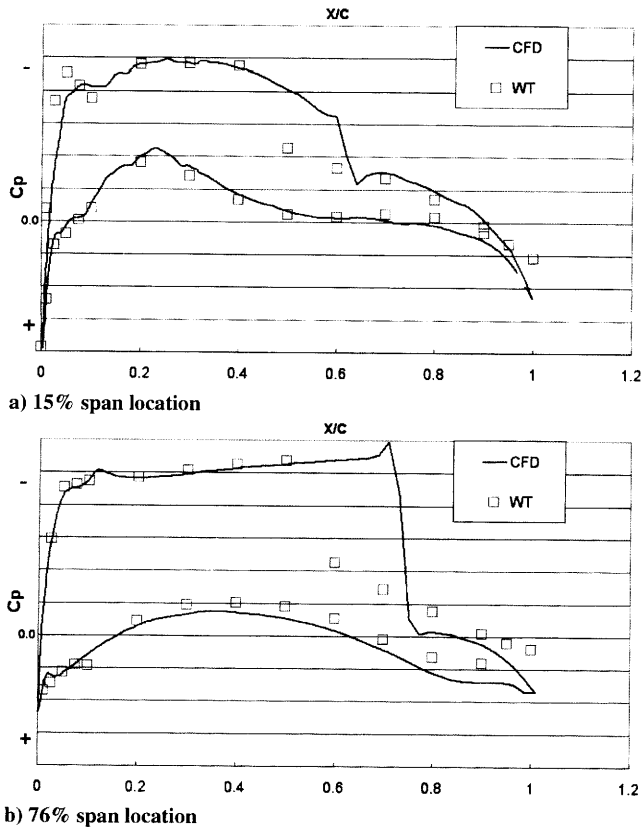


Fig. 4 Comparison of computed and experimental wing surface pressure coefficient at Mach 0.82 and AOA of 2 deg for the clean-wing configuration.

various peaks and valleys in the fuselage pressure distribution. As indicated by these surface pressure comparisons, the benefit of this strategy is clearly evident. Similar good results were obtained for the nacelle surface pressures.

Wing surface pressure coefficient distributions at a midspan location for the aircraft configuration with spoilers deployed are presented in Fig. 7 at Mach numbers 0.30, 0.78, and 0.82. Representative lift-curve data are shown in Figs. 8a and 8b at Mach numbers 0.30 and 0.88, respectively. The comparison between the computed result and the test data is surprisingly good. Given that the computational method is not formulated to accurately model the details of the separated flow region on the downstream side of the spoiler, it is interesting to note that the computed pressure level compares well with the test data in a quantitative sense. Further, as previously shown for the clean-wing case (Figs. 3 and 4), the inviscid Euler technique performed well at the subsonic Mach number, but missed the shock location at the transonic condition. With the spoiler deployed, the shock-boundary-layer interaction was no longer the determinant factor in setting the shock position.

Generally, data correlations between test and computation were used both as a means of calibration and as a means of determining the range of applicability of the numerical method. Once it was established that the computational method was performing up to expectation, the details of the comparison between test and computation was less important. These data comparisons (some of which shown here) indicated that it was valid to use the computed fuselage component and running load as well as the computed nacelle component load in the development of the aerodynamic database. Also, computed wing sectional characteristics with the spoiler deployed were used exclusively.

D. Aerodynamic Database

The aerodynamic data used in support of developing the database were discussed previously. The database may include the pressure data directly as well as sectional and component coefficients.

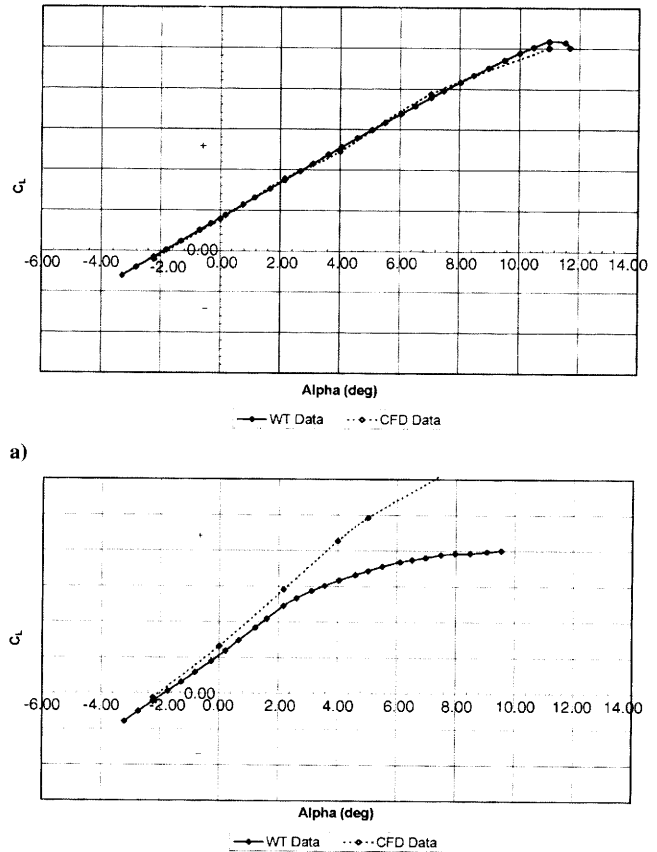


Fig. 5 Comparison of computed and experimental aircraft total lift coefficient as a function of angle of attack for the clean-wing configuration at a) Mach 0.30 and b) Mach 0.82.

Sectional data for the fuselage and the wing are discussed next. These examples demonstrate the engineering tradeoffs that persist throughout the certification process. As these data are of a proprietary nature because they are tied to the particular analysis procedures used in support of certification, only a general discussion will be included.

1. Fuselage Sectional Data

It was highlighted in the discussion in support of Fig. 6 that the predicted pressures match the test values within the Mach and AOA range tested. The significance of this is realized in the posttest data analysis when developing the running load definition in a format suitable for loads development and subsequent structural analyses. Because of the close match between available test data and CFD results, and also because of the relative scarcity of the tunnel model surface pressures, the theoretical approach was used exclusively in developing sectional data as well as the fuselage component force and moment coefficient values.

2. Wing Sectional Data

Using the fuselage data and similar accounting of the nacelle component forces, a proper apportioning of wing component forces was developed. However, because of the discrepancies in theoretical (CFD) and test in the nonlinear range, test data were used exclusively for the development of sectional wing data. This approach demonstrates the need to properly reflect true behavior at the extreme AOA, or operational limits for structural design and certification.

As previously mentioned, no specific flap configuration was tested in the wind tunnel. The CFD analysis, supported by other flap-related data available in the literature, was used to provide the component loads for dynamic landing conditions. The analysis was finally validated by flight-testing similar to what is presented in this paper

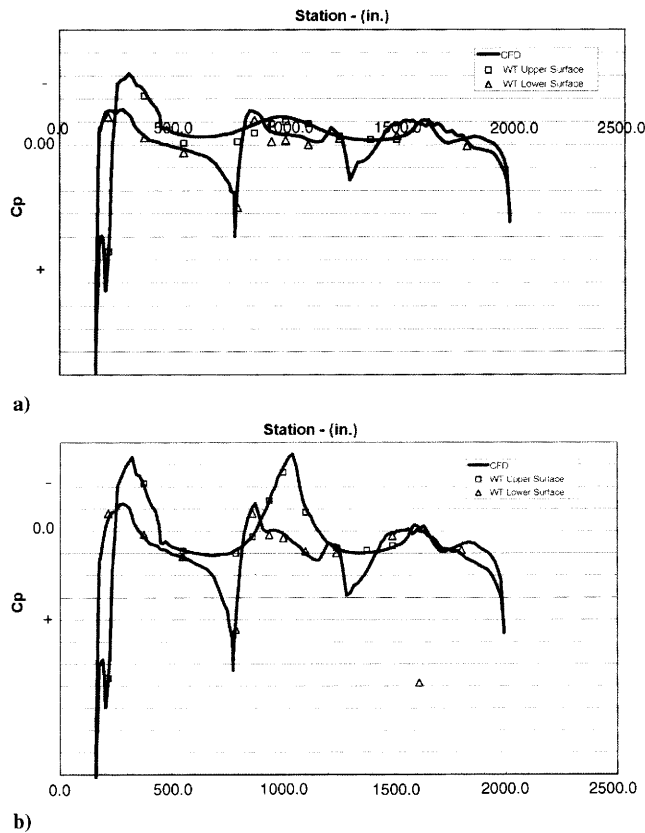


Fig. 6 Comparison of computed and experimental fuselage longitudinal surface pressure coefficient at AOA of 2 deg for the clean-wing configuration at a) Mach 0.30 and b) Mach 0.82.

for the clean-wing configuration. Other flap conditions were less critical and were adequately defined with a simplified approach.

E. Flight Test and Validation

As a component of the certification effort, a flight-load survey program may be considered. Part of such a program is to verify that the aerodynamic analysis stream is correct. This is productively accomplished by showing maneuver loads to be accurately and/or conservatively predicted. For the reference program, correlation to both the wing-bending moment at BBL 100 (corresponding to the wing elastic axis) and the airplane aerodynamic balancing moment (in the form of the aerodynamic balance-tail load applied at the horizontal-tail quarter-chord) are included for one of the flight-test conditions. These data were obtained in flight from load gages at critical locations on the wing root and the horizontal tail. The wing-bending moment close to the wing root at BBL 100 (100 in. from the centerline of the aircraft) was measured using a bending-load gage installed at this location. The gage was composed of axial and shear-strain gages located on the forward and aft spar caps and shear webs, respectively. The method in [6] was used to combine the signals in the form of a load bridge that was calibrated for bending moment. On the horizontal tail, gages were installed on the web supporting the horizontal stabilizer hinge points and on the jackscrew that is used to trim the horizontal-tail pitch angle. Similar to the mathematical procedures applied to the wing gages, the horizontal-tail gages were calibrated to generate horizontal-tail balance load.

The test conditions selected for presentation here consisted of a series of roller-coaster maneuvers. In practice, these are superior to alternative flight maneuvers in part because they offer the ability to generate load-factor g conditions from negative to positive values. Starting from 1- g -level flight, the aircraft was accelerated slightly and subjected to a slight pull-up maneuver. From there, the aircraft was pushed over the top and accelerated slightly, followed by a controlled pull-up to achieve maximum test-load factor. Having

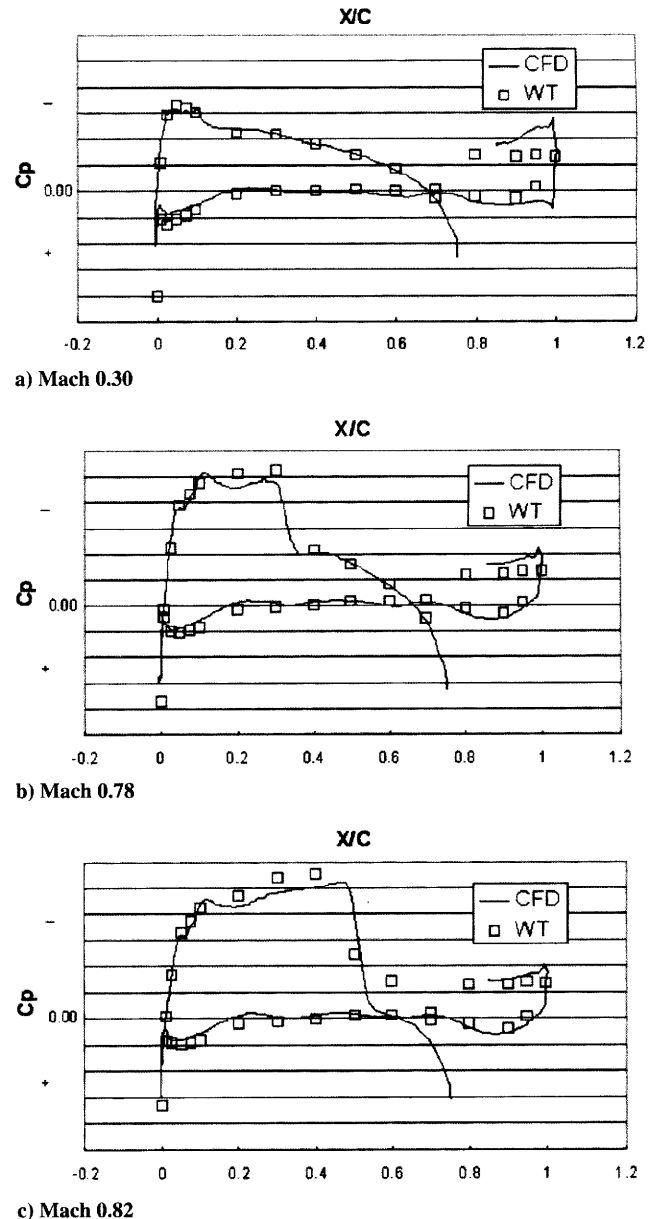


Fig. 7 Comparison of computed and experimental wing surface pressure coefficient at 37% span and AOA of 4 deg with the spoiler deployed.

reached the maximum g , the aircraft was pushed over to the point of near zero load factor (0 g).

The Mach number varied from 0.39 to 0.47 with altitude ranging from 9662 to 11,323 ft throughout the roller-coaster maneuver. The history of maneuver load factor for this flight condition is illustrated in Fig. 9. Note that the aircraft experienced onset of stall slightly after reaching a maximum load factor; this is typical of dynamic stalls for conditions close to the stall line.

Because speed, Mach number, altitude, and thrust cannot be held constant in true flight and pitch acceleration cannot be exactly zero, these flight conditions were approximations of steady-state maneuver conditions. Therefore, accounts of such transient effects need to be considered when comparing flight-test results to analytical prediction.

Figure 10 illustrates the results of the wing and tail load correlations (wing-bending-moment sign convention is positive in the up-bending direction and tail the load is positive in the up-force direction). The tail test values have substantial scatter because of the large variability in conditions during actual test flight and environmental conditions (vortex impingements from the wing at

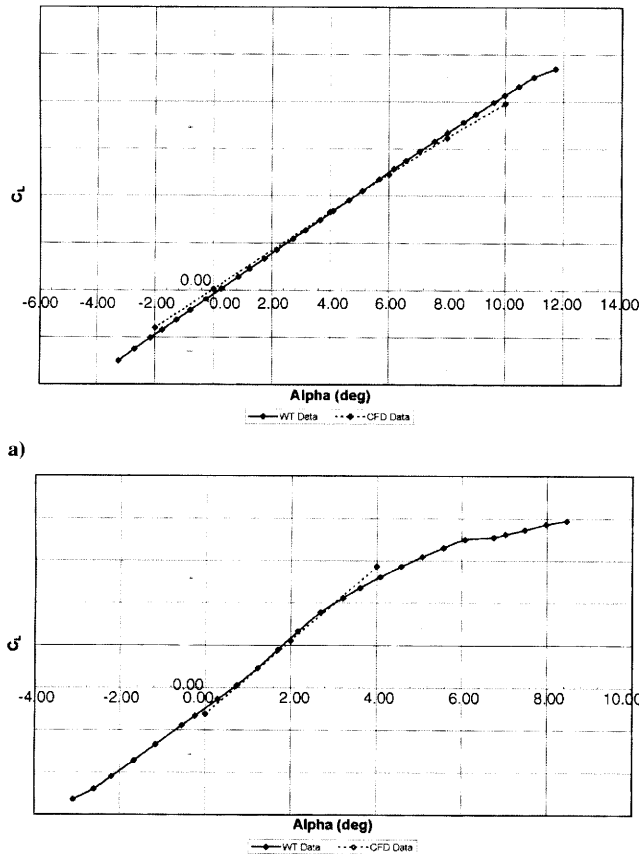


Fig. 8 Comparison of computed and experimental aircraft total lift coefficient as a function of angle of attack for the spoiler configuration at a) Mach 0.30 and b) Mach 0.88.

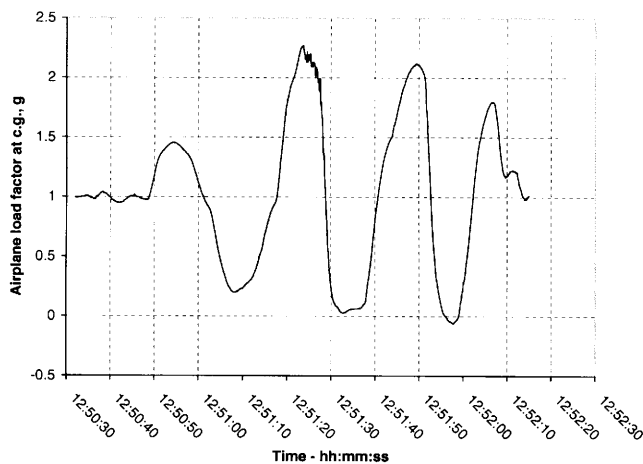


Fig. 9 Typical flight-test maneuver load-factor cycle.

stall and vibrational inertia loads). The comparative study was conducted as a bound analysis through the test range in Mach and altitude conditions. It is seen that the procedure described herein is accurate for the wing loads and is accurate and/or conservative for the balancing-tail load. The latter correlation was not surprising, because a slight conservatism was built into the development of these particular design load components.

III. Conclusions

A comprehensive, cost-effective, and accurate method to develop the aerodynamic database in support of structural certification of a transport-category aircraft modification under the Federal Aviation

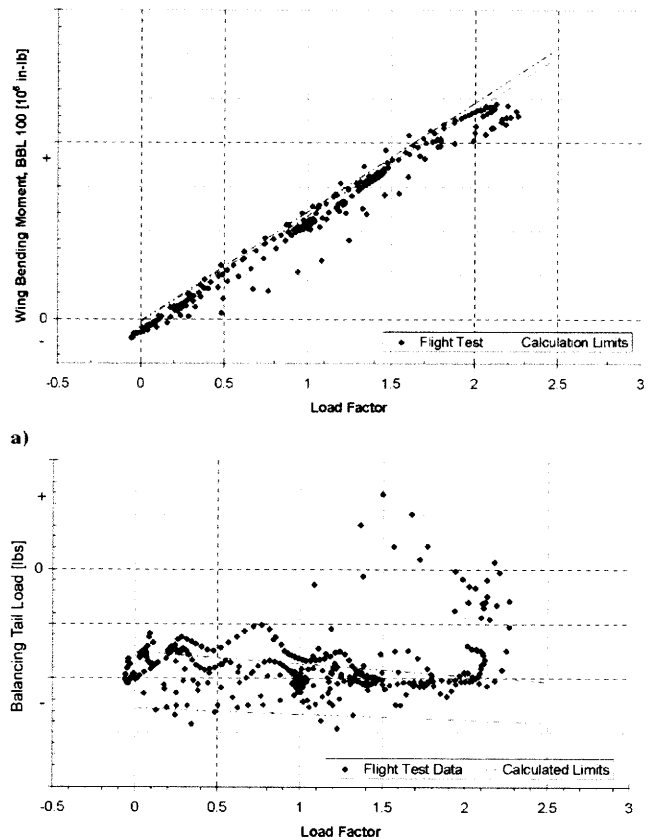


Fig. 10 Comparison of computed and flight-test a) wing-bending moment as a function of the aircraft load factor and b) balance-tail load as a function of the aircraft load factor.

Administration rules and regulations (FARs) was presented. The technique was successfully applied to a major structural modification of a transport-category aircraft, as referenced herein.

The aerodynamic properties of a Boeing 757-200 aircraft with clean wing and with spoilers deployed were each established via wind-tunnel testing on a scale model, dimensionally based on measurement of the full-scale airplane outside mold line (OML) using laser measurement technology. As a complement to these data, a computational fluid dynamic (CFD) analysis was developed for the aircraft with clean wing and wing with spoilers deployed. The combined database was used for aircraft performance prediction, which was then confirmed via flight-testing of the actual aircraft.

Although aspects of the present certification procedure resemble techniques used by the original equipment manufacturer (OEM), the emphasis is on minimum instrumentation, simplified model definition, and highly integrated procedures, which resulted in a methodology that is eminently suited for an STC program when balancing the certification requirement and need for providing continued airworthiness against cost.

Acknowledgments

The authors would like to acknowledge the assistance with the computational model provided by Michael J. Aftosmis; Patersonlabs, Inc. for their craftsmanship with the aircraft pressure model; Rich Hurtig, Leth and Associates (L&A) Instrumentation Manager, for his rigid flexibility; and A. Craig Campbell, L&A Senior Engineer, Flight Test Support. The authors would also like to thank Clive G. Whittenbury and Michael A. Berry for their contributions to the review process.

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