CEAS Aeronaut J (2018) 9:307–317
https://doi.org/10.1007/s13272-017-0250-7

ORIGINAL PAPER

Comparison of the NASA Common Research Model European Transonic Wind Tunnel test data to NASA National Transonic Facility test data

Melissa Rivers[1] · Jürgen Quest[2] · Ralf Rudnik[3]

Received: 8 June 2016 / Revised: 24 April 2017 / Accepted: 14 June 2017 / Published online: 12 July 2017

Abstract Experimental aerodynamic investigations of the NASA Common Research Model have been conducted in the NASA Langley National Transonic Facility and the European Transonic Wind Tunnel. Data have been obtained at chord Reynolds numbers of 5, 19.8 and 30 million for the wing/body/tail = 0° incidence configuration in the National Transonic Facility and in the European Transonic Wind Tunnel. Force and moment, surface pressure, wing bending and twist, and surface flow visualization data were obtained in both facilities but only the force and moment, and surface pressure data are presented herein.

Keywords Transonic · Reynolds number · Wind tunnel · Comparison

List of symbols

b	Wing span
c	Wing mean aerodynamic chord
C_D	Drag coefficient
C_L	Lift coefficient
C_m	Pitching moment coefficient referenced to 0.25 of the wing mean aerodynamic chord
C_p	Pressure coefficient
CRM	Common Research Model
DPW	Drag prediction workshop
E	Modulus of elasticity
$ESWI^{RP}$	European Strategic Wind Tunnels Improved Research Potential
M_∞	Freestream Mach number
NTF	National Transonic Facility
p_t	Total pressure
q_∞	Dynamic pressure
Re_c	Reynolds number based on mean aerodynamic chord
S	Model reference area
T_t	Total temperature
WBT0	Wing/body/tail = 0°
x/c	Longitudinal distance from wing leading edge nondimensionalized by local wing chord
α	Angle of attack, degree
η	Fraction of wing semi-span

1 Introduction

The NASA Common Research Model (CRM) serves as a backbone for providing wind tunnel data for code validation and verification for transonic commercial aircraft. The model has been designed and built as part of the AIAA drag prediction workshop (DPW) introduced with the DPW IV.

The latest use of the model in the European Transonic Wind Tunnel (ETW) is embedded in the framework of the European project $ESWI^{RP}$ (European Strategic Wind Tunnels Improved Research Potential). This so-called infrastructure project is part of the 7th framework program. The objective has been to improve the capabilities of selected strategic wind tunnel facilities in Europe, and, at

This paper is based on a presentation at the CEAS Air & Space Conference 2015, September 7–11, Delft, The Netherlands.

✉ Melissa Rivers
s.m.rivers@nasa.gov

[1] NASA Langley Research Center, Mail Stop 267, Hampton, VA 23681, USA

[2] ETW, European Transonic Wind Tunnel, Köln, Germany

[3] DLR, German Aerospace Center, Köln, Germany

the same time, to provide efficient access to these facilities to academia and research establishments for selected research projects addressing fundamental aerodynamic topics. The focus for the use of the ETW is on improving unsteady testing capabilities for exploring limits of the flight envelope. For this purpose, an international consortium has been formed under the coordination of ONERA consisting of the University of Stuttgart and the German Aerospace Center, DLR (Germany), the Federal State Unitary Enterprise Central Aerohydrodynamic Institute, TSAGi (Russia), the Academy of Sciences (Czech Republic), the Aerospace Research and Test Establishment VZLU (Czech Republic), and the Von Karman Institute for fluid Dynamics (Belgium). The consortium submitted a scientific proposal entitled "Time-Resolved Wake Measurements of Separated Wing Flow & Wall Interference Investigations", which has been evaluated and selected for realization by an expert panel in 2012. The proposal addresses unsteady wake interference effects between the wake of an aircraft wing and the horizontal tail plane. Due to the international character of the study and the intention to provide test data to the general public, NASA's CRM, representing a typical commercial aircraft configuration appears to be an ideal candidate to serve as a wind tunnel model for the experimental investigations as it is also suited for cryogenic testing. Based on a bilateral agreement between NASA and DLR, the model has been provided by NASA, while it is introduced to the consortium by DLR. The overall project is described in Ref. [1].

The background of the experimental activities is the high-speed stall of transport aircraft at the boundaries of the flight envelope, which produces massively separated flow on the wing itself and in its wake. Unsteady oscillating of the separation point and large-scale turbulent fluctuations lead to strong unsteadiness of the wake flow. The relevance to investigate these aerodynamic effects is given by the fact that they bear the risk of exciting structural vibrations due to unsteady air loads in a certain frequency domain. Moreover, they influence the efficiency of control surfaces on the horizontal stabilizer and the elevator. In the case of asymmetry in some separation areas of the wing and the resulting wake, unsteady rolling moments may be excited and induced to the tail plane. These effects of flow unsteadiness at the tail plane can become critical and might require potential load alleviation systems at the tail plane. Thus, the knowledge of the formation, propagation, and impact of large-scale turbulent fluctuations are of interest for the design of commercial aircraft.

A key element towards understanding these effects is time-resolved (TR) measurements in the wing wake. Such measurements, carried out by DLR with a special Particle Image Velocimetry System (PIV), are the main element of the ETW test in the current framework. The corresponding TR-PIV measurements under cryogenic conditions are described in Ref. [2]. Complementary to these measurements, the test provides reference data on the wind tunnel walls, to study wall interference effects and eventually improve wall correction methods.

The tests have been carried out on the wing/body/-tail = 0 (WBT0) degree incidence configuration of the CRM for low and high speed conditions in the linear lift-range up to the highest possible angles of attack. Complementary to the unsteady flow field measurements, classical aerodynamic parameters such as forces, moments, and wall pressure distributions have been recorded. These data are supplemented by wing deformation measurements as the test has been conducted in a low temperature and high-pressure environment to produce flight Reynolds number conditions.

The test matrix has been setup such that a comparison of the ETW test data to existing data from the NASA NTF is possible. The present contribution describes the classical experimental results of the ETW test and compares the data to corresponding results of previous tests with the CRM in the aforementioned facility.

2 Experimental approach

2.1 Facility description

2.1.1 National Transonic Facility

The NTF is a unique national facility (Fig. 1) that enables testing of aircraft configurations at conditions ranging from subsonic to low supersonic speeds at Reynolds numbers up to full-scale flight values. The NTF is a conventional, closed circuit, continuous-flow, fan-driven, pressurized wind tunnel capable of operating in either dry air at warm temperatures or nitrogen from warm to cryogenic temperatures. Elevated pressures in combination with cryogenic

Fig. 1 Aerial view of the National Transonic Facility

temperatures enable testing to the highest Reynolds numbers. The test section is 2.5 × 2.5 × 7.62 m (8.2 by 8.2 by 25 ft) and has a slotted floor and ceiling. In addition, four damping screens in the settling chamber and a contraction ratio of 14.95-to-1 reduce turbulence from the settling chamber to the nozzle throat. Fan-noise effects are minimized by acoustic treatment both upstream and downstream of the fan. Thermal insulation resides inside the pressure shell to aid in maintaining tunnel temperature and thus minimizes energy consumption.

The NTF has an operating pressure range of approximately 103–861 kPa (15–125 psia), a temperature range of 116.5–322.04 K (−250 to +120 °F), and a Mach number range of 0.2–1.2. The maximum Reynolds number is 146×10^6 per foot at Mach 1. When the tunnel is operated cryogenically, heat is removed by the evaporation of liquid nitrogen, which is sprayed into the tunnel circuit upstream of the fan. During this operational mode, venting is necessary to maintain a constant total pressure. When air is the test gas, heat is removed from the system by a water-cooled heat exchanger at the upstream end of the settling chamber. A mixed mode of operation can be used to reach higher Reynolds numbers. This mode uses liquid nitrogen to augment the cooling coil without the expense of fully crossing over into nitrogen mode. Further tunnel details and facility information are provided in Refs. [3, 4].

2.1.2 European Transonic Wind Tunnel

The European Transonic Wind Tunnel (ETW) is similar to the National Transonic Facility, a pressurized cryogenic, closed circuit, continuous-flow, fan-driven wind tunnel. It can be operated in closed and slotted wall configurations for testing full and half-models from Mach numbers of 0.15 up to light supersonic conditions at $M_\infty = 1.35$. Pure high quality nitrogen is used as test gas only. The capability of varying the gas temperature, pressure and speed independently allows for pure Reynolds number and/or aeroelastic investigations. The test-section dimensions are 2.4 m (7.87 ft) in width, 2 m (6.56 ft) in height and about 9 m (30 ft) in length. High flow quality is provided by two filling screens in the wide-angle diffuser combined with a flow straightener (honeycomb) and two anti-turbulence screens followed by a fixed contraction and a flexible nozzle for supersonic operation as illustrated in Fig. 2. Additionally, the tunnel features a second throat downstream of the reentry preventing flow disturbances eventually generated in the high-speed diffuser from propagating upstream into the test-section.

The ETW operating range covers pressures from 110 to 450 kPa (15.95–65.27 psia) and temperatures from 110 up to 313 K (−262 to +104 °F), allowing the achievement of maximum chord Reynolds numbers of 50 million for full models and 90 million for semi-span models at a Mach number around 0.85. While the tunnel shell is internally insulated against heat losses the heat generated by the fan is compensated by the evaporation of the injected liquid nitrogen, which is sprayed into the tunnel upstream of the compressor. Further details about the facility and its operation can be found at http://www.etw.de.

2.2 Model description

The model used in the current investigation was the NASA Common Research Model. This configuration consists of a contemporary supercritical transonic wing and a fuselage that is representative of a wide-body commercial transport aircraft. The CRM is designed for a cruise Mach number of $M_\infty = 0.85$ and a corresponding design lift coefficient of $C_L = 0.5$. A sketch of the CRM with reference quantities listed is shown in Fig. 3. The aspect ratio is 9.0, the leading-edge sweep angle is 35°, the wing reference area (S) is 280 mm^2 (3.01 ft^2), the wing span (b) is 1587 mm (62.47 in.), and the mean aerodynamic chord (c) is 189 mm (7.45 in.). The model moment reference center is located 846 mm (33.01 in.) back from the fuselage nose

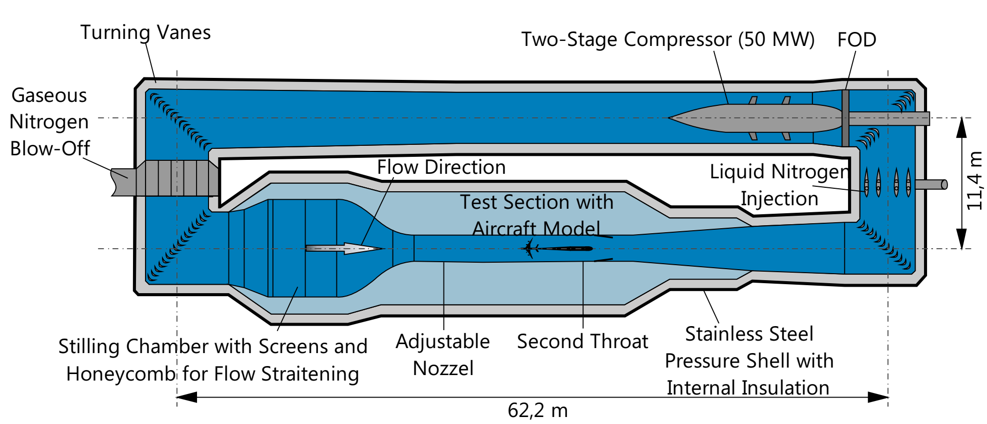

Fig. 2 Sketch of the European Transonic Wind Tunnel aerodynamic circuit

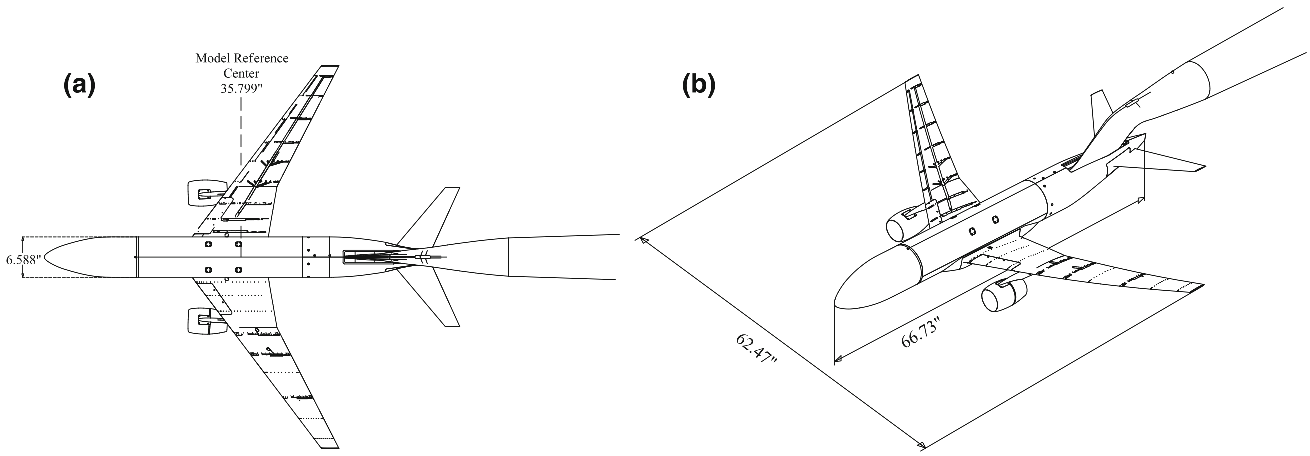

Fig. 3 Sketch of the Common Research Model with reference quantities. **a** Top view, **b** isometric view

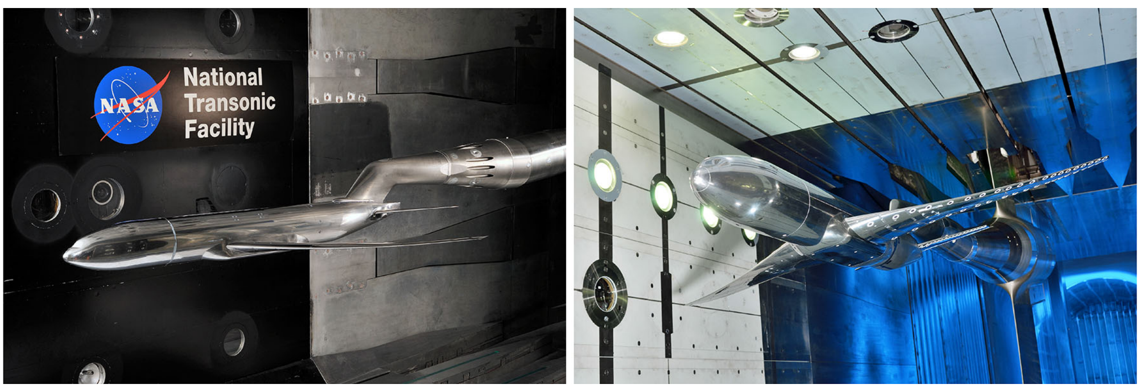

Fig. 4 Photo of the Common Research Model in the National Transonic Facility (*left*) and the European Transonic Wind Tunnel (*right*)

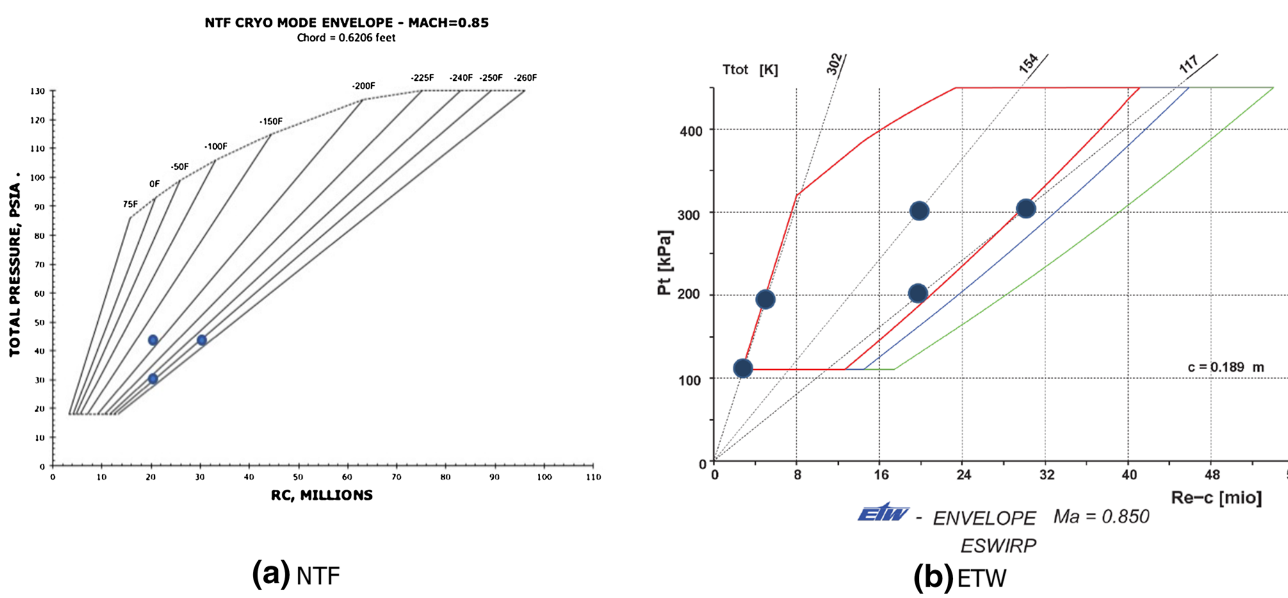

Fig. 5 Test envelopes at Mach = 0.85

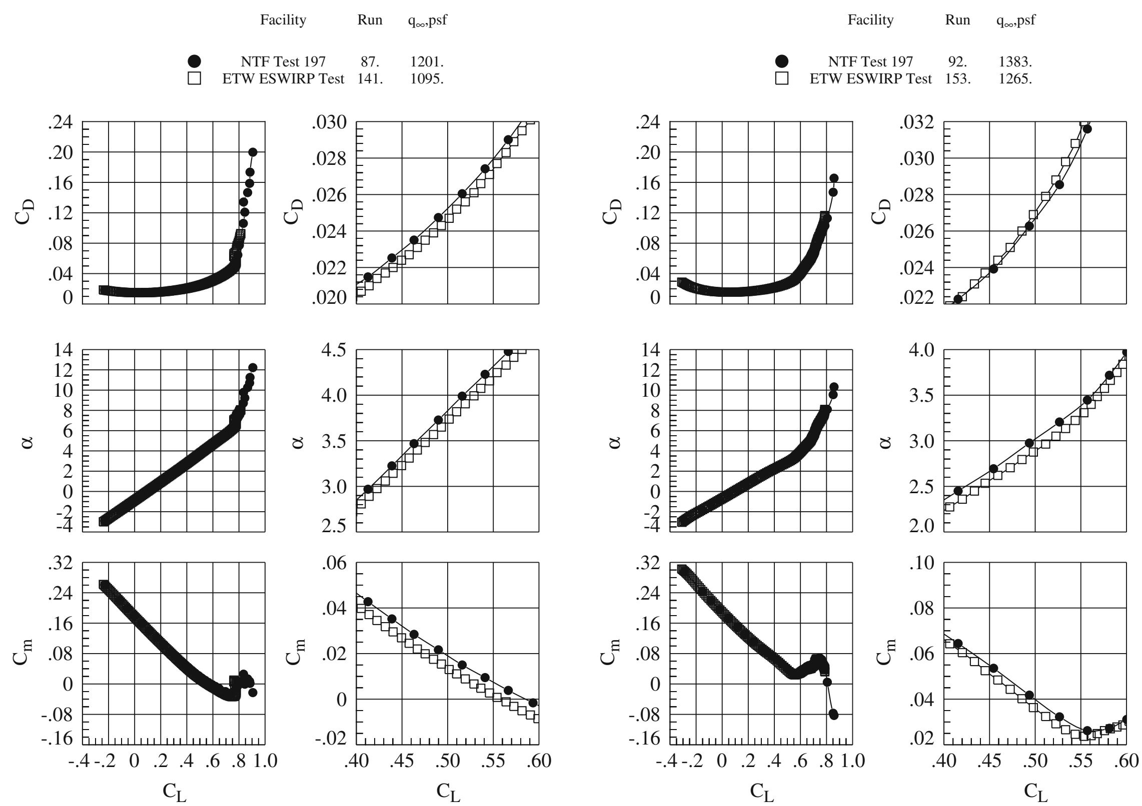

Fig. 6 Lift, drag and pitching moment coefficients, $Re_c = 5 \times 10^6$, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

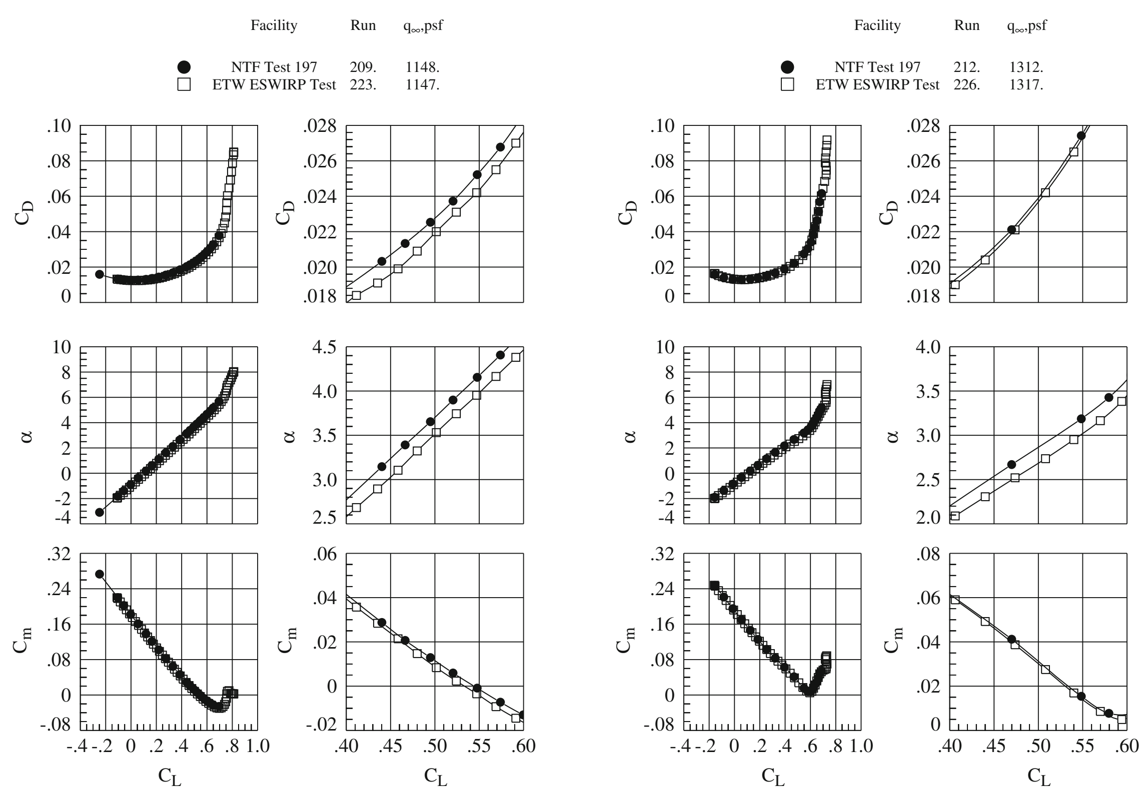

Fig. 7 Lift, drag and pitching moment coefficients, $Re_c = 19.8 \times 10^6$, low q_∞, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

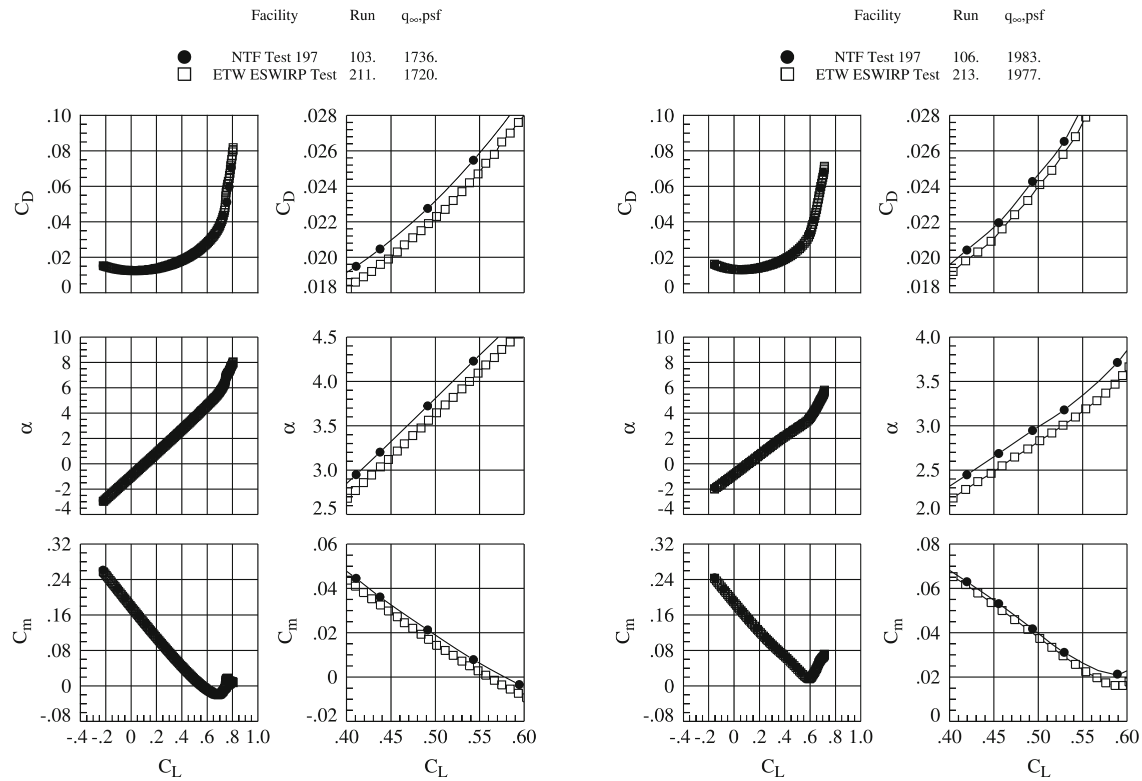

Fig. 8 Lift, drag and pitching moment coefficients, $Re_c = 19.8 \times 10^6$, high q_∞, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

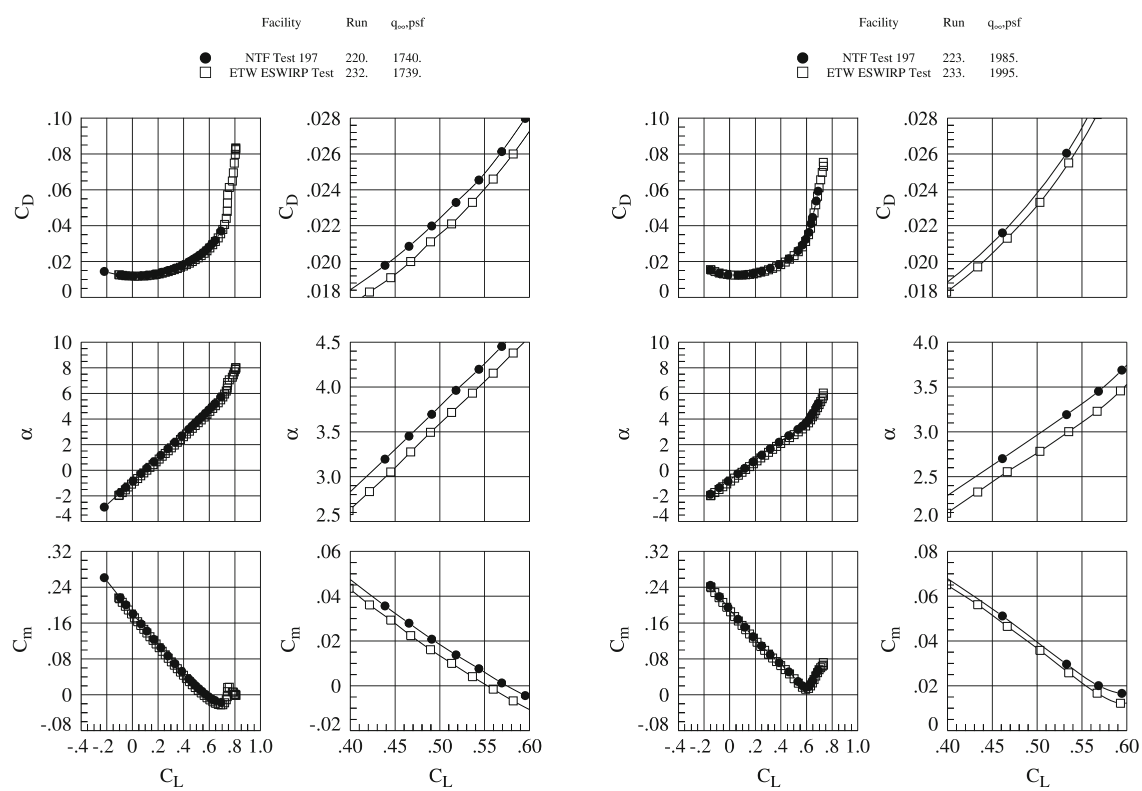

Fig. 9 Lift, drag and pitching moment coefficients, $Re_c = 30 \times 10^6$, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

and 43 mm (1.718 in.) below the fuselage centerline. Forces and moment data were obtained using a facility specific internal balance, i.e., the balance used at ETW was not the same one used at NTF. Pressure distributions are measured on both the left and right wings using 291 pressure orifices located in 9 span-wise wing stations ($\eta = 0.131$, 0.201, 0.283, 0.397, 0.502, 0.603, 0.727, 0.846, and 0.950). All pressure measurements were made using electronically scanned pressure (ESP) modules mounted inside the forward portion of the fuselage. Based on quoted accuracies from the ESP module manufacturer, surface pressure measurements should have no more than ±0.103 kPa (±0.015 psia) full-scale error. This in turn would correspond to a variation of no more than ±0.0026 in terms of C_p. The model is mounted in the wind tunnel using a blade sting arrangement in both tunnels. The difference between the sting arrangement of the NTF and ETW begins downstream of the blade part of the model support system, as shown in Fig. 4. No corrections have been made in either of the data sets for this mounting arrangement. Further details on this geometry are given in Ref. [5].

2.3 Test conditions

2.3.1 *National Transonic Facility*

The investigation, conducted over a 6-week period, provided force and moment, surface pressure, model deformation, and surface flow visualization data. Testing was conducted at 5, 19.8 and 30 million Reynolds number. The 5 and 19.8 million Reynolds number data were collected to provide a comparison to previously calculated CFD results and all of the Reynolds numbers were used to provide an assessment of Reynolds number effects. The 19.8 million Reynolds number data were collected at two different q_∞ levels—a high and a low q_∞ condition. Having two q_∞ levels at the same Reynolds number provides an aeroelastic step in the data. All Reynolds number values presented in this paper are based on mean aerodynamic chord. The data were collected at temperatures ranging from 116.5 up to 322.04 K (−250 up to 120 °F).

All data presented in this paper were obtained at free-stream Mach numbers of 0.7 and 0.85. Data were generally obtained over an angle-of-attack range from −3° to +12°

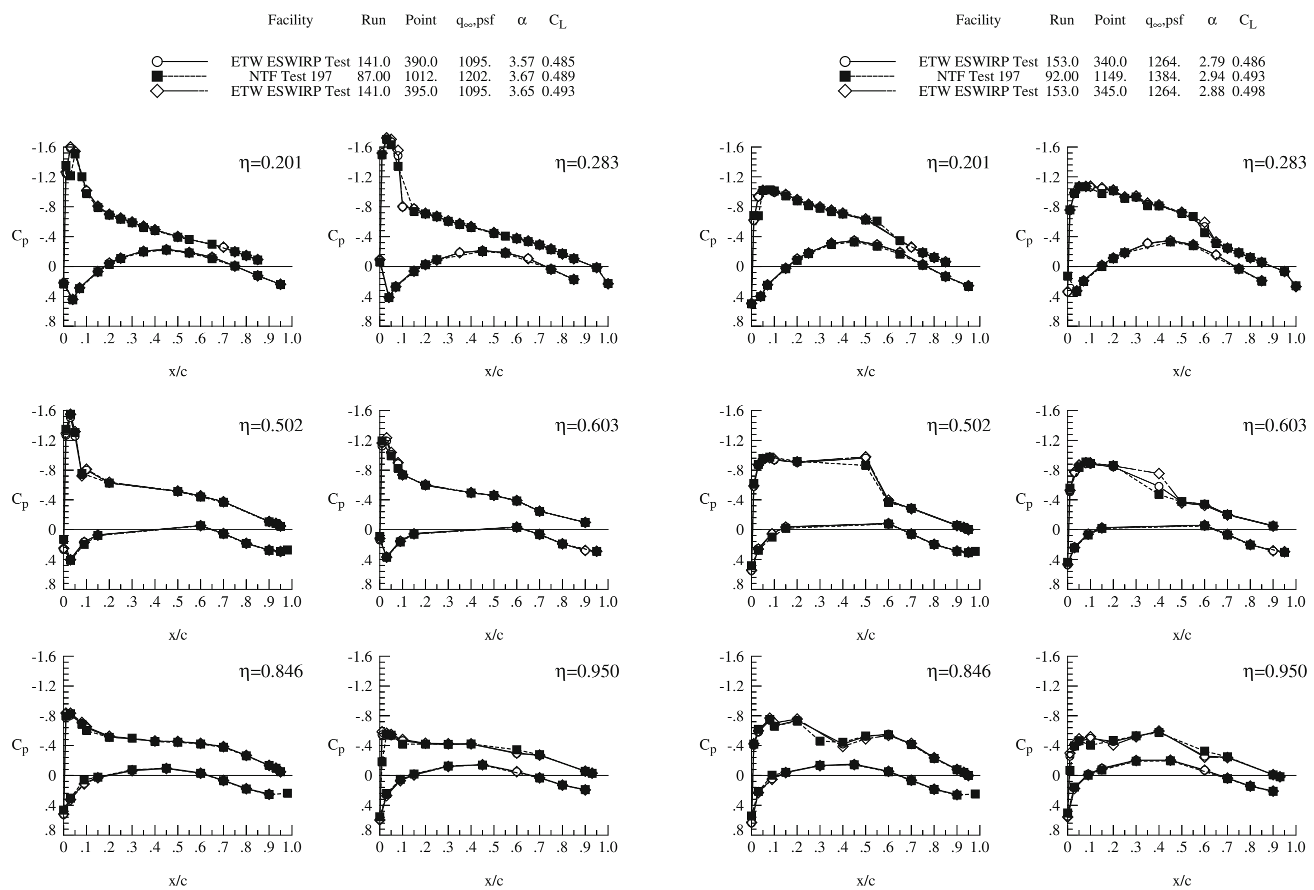

Fig. 10 Surface pressures, $Re_c = 5 \times 10^6$, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

at 5 million Reynolds number and from −3° to +6° at 19.8 and 30 million Reynolds numbers. The reduced angle-of-attack range at the higher Reynolds number was required such that safe model stress levels would not be exceeded. Flow angularity measurements were made and upflow corrections ranging from 0.092° to 0.173° were applied to the final NTF data. Classical wall corrections accounting for model blockage, wake blockage, tunnel buoyancy, and lift interference have been applied according to the methods presented in Ref. [6].

To ensure a consistent and repeatable transition from laminar to turbulent flow and to support the goal of the wind tunnel data being used for CFD validation purposes, it was important to apply a proven and reliable method to fix transition on the model at the low Reynolds number condition. Evercoat trip dots measuring 1.27 mm (0.05 in.) in diameter and spaced 2.54 mm (0.1 in.) apart (center to center) were used for the current investigation. For a chord Reynolds number of 5 million, a trip dot height of 0.089 mm (0.0035 in.) was used from the SOB (side of body) to the yehudi break and 0.076 mm (0.003 in.) was used from the yehudi break to the wing tip. These trip dots were installed at 10% chord. Vinyl adhesive trip dots were applied at the nose of the fuselage and left on for the entire test. When the tails were on the model, trip dots were located at 10% chord and measured 0.076 mm (0.003 in.).

Another important set of data obtained in this investigation was model deformation measurements. Since an effective correlation of computational and experimental data will be directly tied to how well the computational and experimental model geometries match one another, it is important to obtain an accurate definition of the model geometry as tested under aerodynamic loads. To obtain this information, a video model deformation measurement technique has been developed and employed multiple times at the NTF. This system was used in the current investigation to obtain wing deflection and twist measurements due to aerodynamic loading but this data is not presented herein.

2.3.2 European Transonic Wind Tunnel

Since this investigation was funded by the European Commission as part of the ESWI^{RP} project, the available budget only allowed for testing over a limited range of conditions. The test plan for the 5-day test campaign in the ETW was determined based on a compromise between test

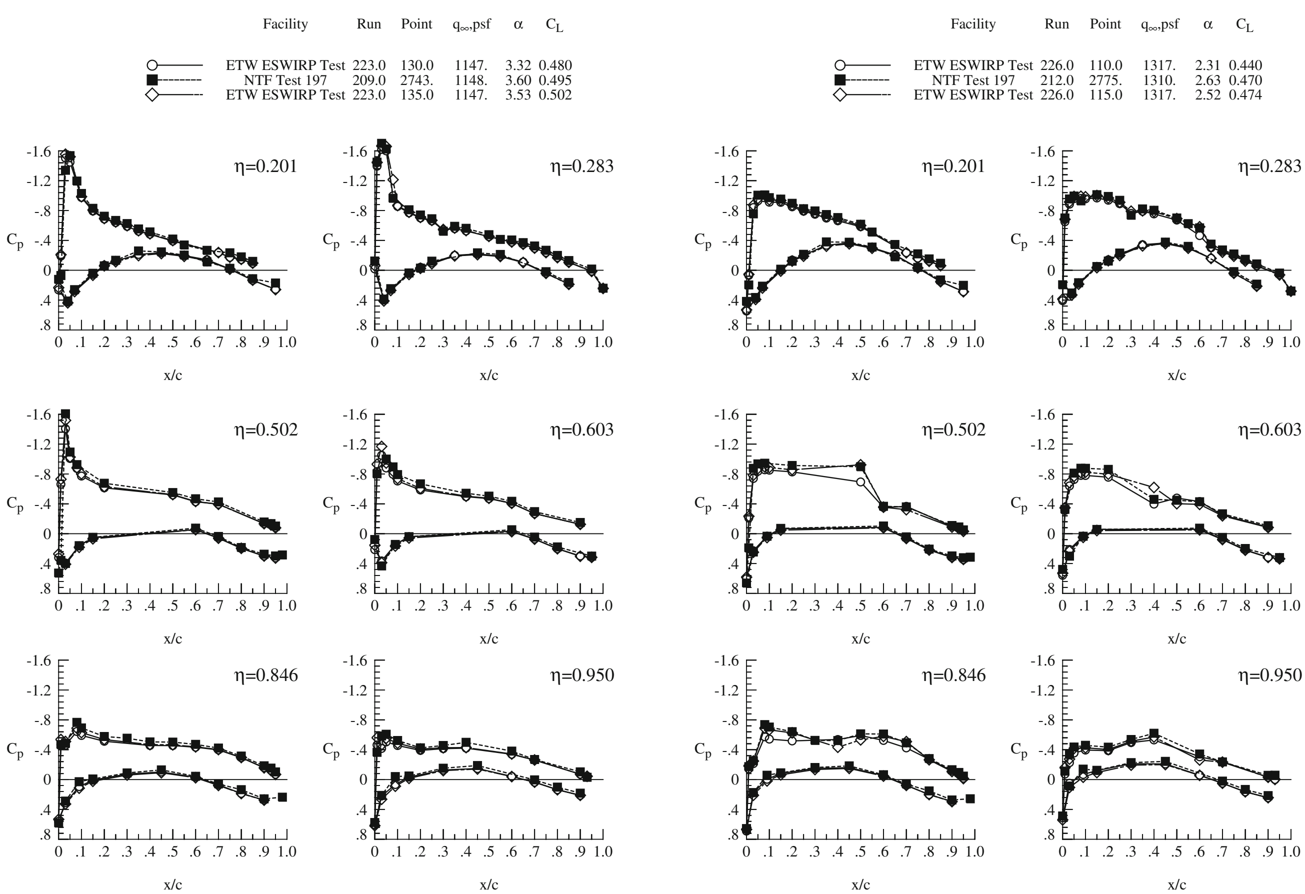

Fig. 11 Surface pressures, $Re_c = 19.8 \times 10^6$, low q_∞, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

requirements from the European project group chaired by J.L. Goddard from ONERA-France which focused on acquiring data for CFD validations of unsteady wake flows and a repeat of the conditions at which the used CRM model had been tested in the NTF. A few polars were added at a very low Reynolds number to provide comparative aerodynamic data for the Japanese research organisation JAXA who have tested the CRM in a down-scaled version in their transonic tunnel.

For achieving the scientific goal of the project, newly integrated measurement capabilities were operated during the campaign: unsteady PIV for wake flow analysis and unsteady and steady model deformation measurements combined with the recording of unsteady balance signals taking the benefit of an upgraded fast high capacity data acquisition system. In the frame of the present paper only aerodynamic data like forces, moments and wing pressure distributions are presented. Although, data were acquired at 12 different Mach numbers ranging from 0.25 to 0.87 the majority focussed on $M = 0.7$ and the model design Mach number of 0.85. So, with respect to the intended comparison of results, the reference test conditions of the NTF at these two Mach numbers were carefully set and controlled. To cover the relevant Reynolds numbers of 5, 19.8 and 30 million the tunnel temperature was varied between 302 and 117 K (83.93 and −249 °F) combined with corresponding pressures between 200 and 300 kPa (29 and 43.5 psia). As can be seen in Fig. 5, the operating envelopes of NTF and ETW do not allow achieving the minimum and maximum Reynolds number at the identical total pressure value. Hence, it was decided to duplicate the 19.8 million Reynolds number at a lower and higher total pressure value allowing an additional comparison of the model deformation assessment as a function of the different aeroelastic effects. By performing lift polars with the model in upright and inverted position the upwash could be assessed as 0.010°–0.015° over the full operating range. The measured data were additionally corrected for wall interference based on the ETW experimental assessment established in the past and presented in Ref. [7]. Extreme care is always given to the measurement of the model angle of attack. Special care was also given to the application of the transition band classically used when testing at a chord Reynolds number of 5 million.

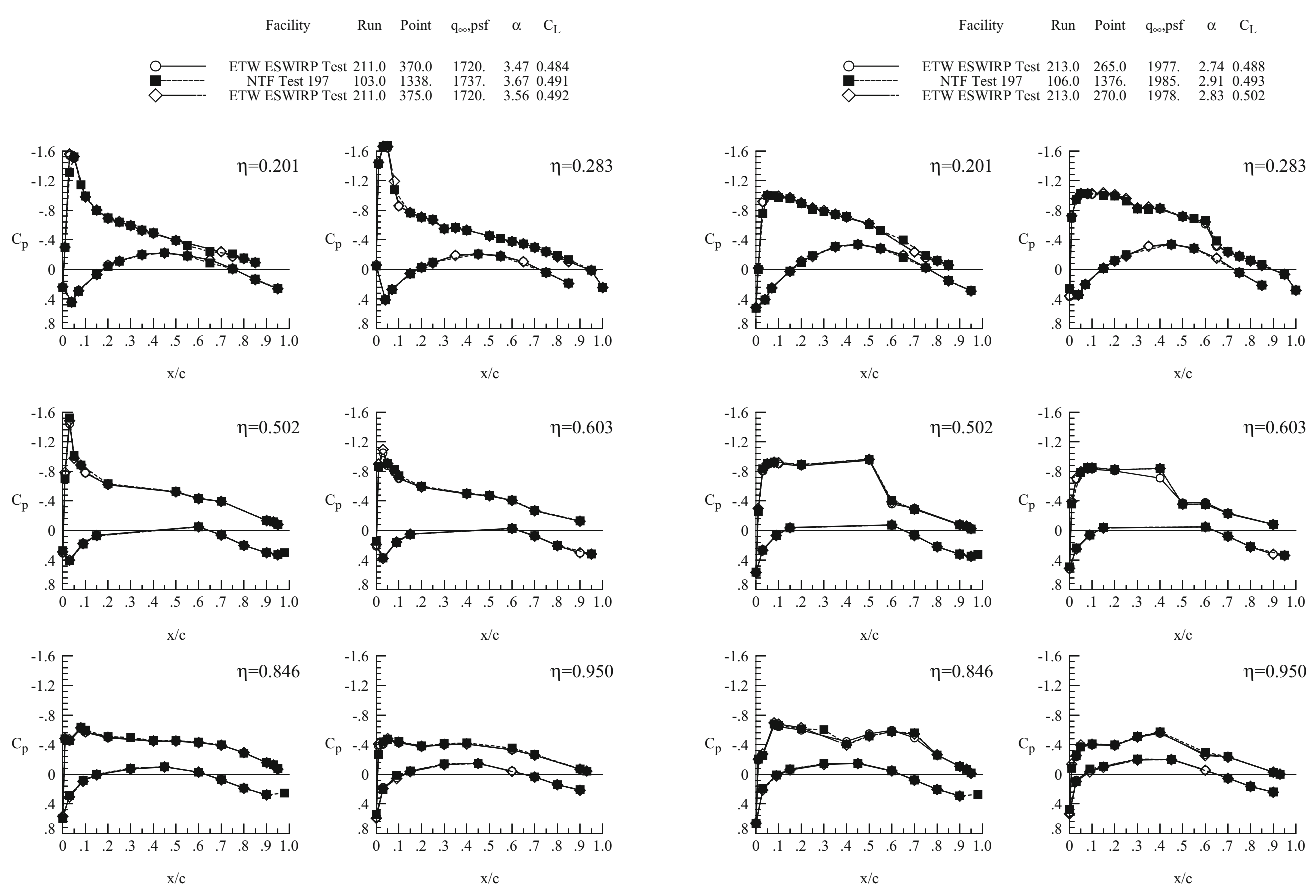

Fig. 12 Surface pressures, $Re_c = 19.8 \times 10^6$, high q_∞, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

Performing this work in close cooperation with the NTF experts minimized the risk for later mismatches in the results originated by this sensitive item.

3 Results and discussion

3.1 Force and moment comparisons

One of the primary purposes of this paper is to compare the data between the NASA wind tunnel and the ETW wind tunnel. First, the lift, drag and pitching moment coefficients are examined. Figure 6 shows the comparisons between both wind tunnels at $Re_c = 5 \times 10^6$ for a Mach number of 0.7 and 0.85. This figure shows that at this Reynolds number, the NTF drag coefficient data is 6 counts higher than the ETW data for the $M = 0.7$ case and the NTF drag coefficient data is 3 counts lower than the ETW data for the $M = 0.85$ case. The NTF lift coefficient data is slightly lower than the ETW data at $M = 0.7$ and lower than the ETW data at $M = 0.85$. The NTF pitching moment coefficient is less nose down than the ETW data for both Mach numbers presented.

Figure 7 shows the lift, drag and pitching moment coefficient comparisons for the $Re_c = 19.8 \times 10^6$ case at a low q_∞ value. At Mach = 0.7, the NTF drag data is 9 counts higher than the ETW data, the NTF lift coefficient data is lower than the ETW data and the pitching moment coefficient is slightly less nose down than the ETW data. For the Mach = 0.85 case, the NTF drag coefficient data is 4 counts higher than the ETW data, the NTF lift coefficient data is lower than ETW and the NTF and ETW pitching moment coefficient values are nearly equivalent.

The results for the $Re_c = 19.8 \times 10^6$ case at a high q_∞ value are given in Fig. 8. For Mach = 0.7, the NTF drag coefficient data is 10 counts higher than the ETW data, the NTF lift coefficient data is lower than the ETW data and the NTF pitching moment coefficient data is once again predicting a less nose down value than the ETW data. At Mach = 0.85, a similar picture is seen. At this Mach number, the NTF drag coefficient data is 7 counts higher than the ETW data, the NTF lift coefficient data is lower than the ETW lift data and the NTF pitching moment coefficient is once again predicting less nose down moment than the ETW data.

At a flight Reynolds number of $Re_c = 30 \times 10^6$, the comparisons show essentially the same differences as for

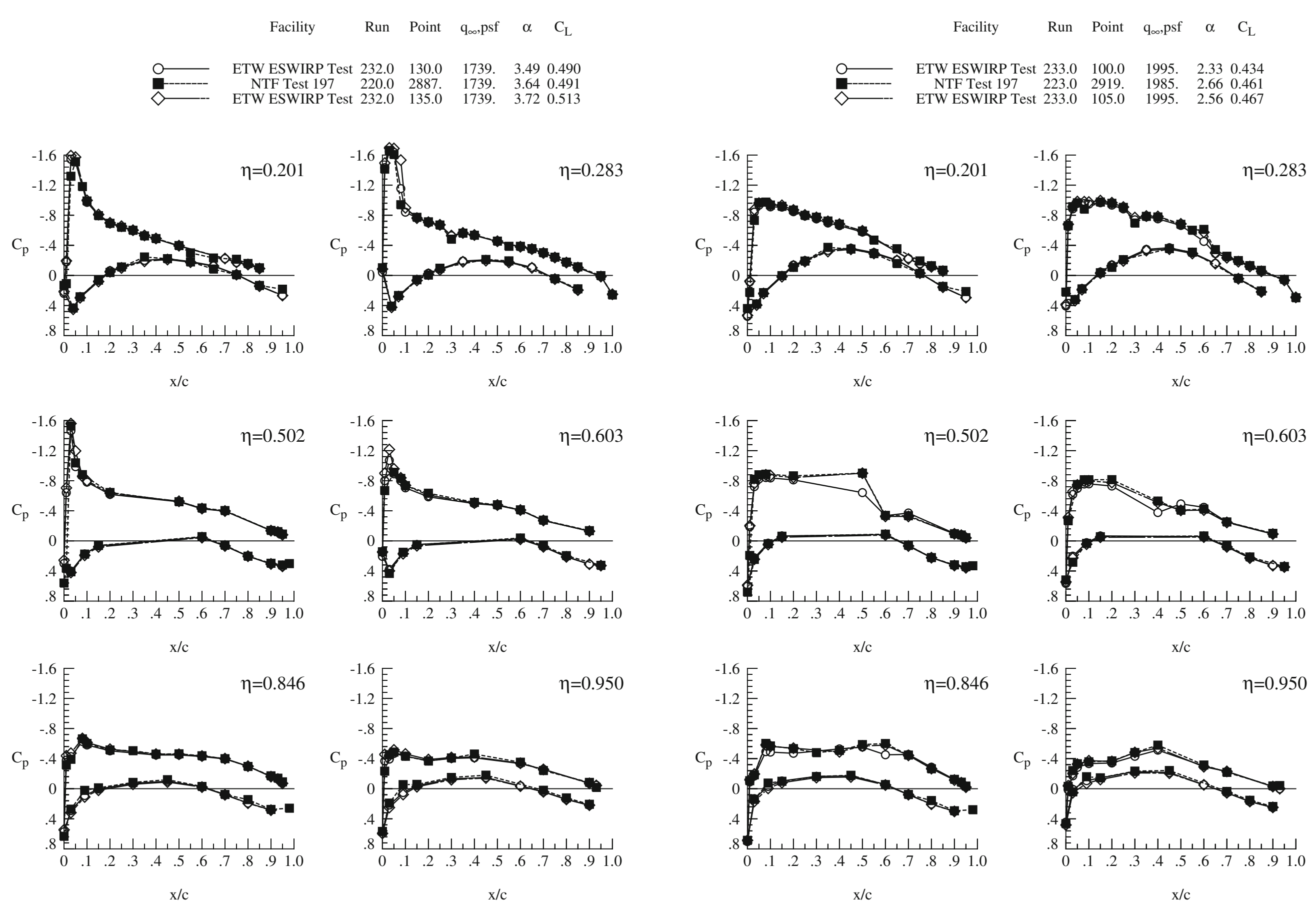

Fig. 13 Surface pressures, $Re_c = 30 \times 10^6$, high q_∞, Mach = 0.7 (*left*) and Mach = 0.85 (*right*)

the $Re_c = 19.8 \times 10^6$ at a high q_∞ case, as shown in Fig. 9. For Mach = 0.7, the NTF drag coefficient data is 9 counts higher than the ETW data, the NTF lift coefficient data is lower than the ETW data and the NTF pitching moment coefficient data is less nose down than ETW. At Mach = 0.85, the NTF drag coefficient data is 9 counts higher than the ETW data, the NTF lift coefficient data is lower than ETW and the NTF pitching moment coefficient data is slightly less nose down than ETW.

3.2 Surface pressure comparisons

Another goal of these investigations was to examine the surface pressure differences between the NTF and ETW wind tunnels. Figures 10, 11, 12 and 13 show the surface pressure distributions for the Mach = 0.7 and 0.85 cases at Re_c = 5, 19.8 and 30 million. In each of these figures, two points are given for the ETW data. These two points were chosen such that they bracket the C_L value of the NTF data. This does result in comparison of different angles of attack but closer comparison of the C_L values. For most of the Mach and Reynolds numbers plotted, the data compares very well across the entire wing. There are several minor differences between the data sets such as seen in Fig. 10. At Mach = 0.85, $Re_c = 5 \times 10^6$, the shock on the wing at $\eta = 0.603$ is possibly located further upstream in the ETW data than in the NTF data. Similar behavior is seen throughout the Reynolds number range.

4 Summary

A successful investigation of the NASA Common Research Model has been completed in the National Transonic Facility and the European Transonic Wind Tunnel. Data have been obtained at chord Reynolds numbers of 5, 19.8 and 30 million for the WBT0 configuration in both wind tunnels. Force and moment and surface pressure comparisons are presented herein. Tunnel-to-tunnel effects have been assessed for all of these data.

1. For all of the data presented herein, the NTF data predicted a lower lift value than the ETW.
2. The drag differences were almost the same across all Mach and Reynolds number conditions. For every case except the Mach = 0.85 and $Re_c = 5 \times 10^6$, the NTF drag data was higher than the ETW by as much as 10 counts.
3. At all three Reynolds numbers tested, the NTF pitching moment was less nose down than the ETW data.
4. All of the surface pressures presented herein shows good agreement between the NTF and ETW data across the wing, with only a couple of exceptions.

References

1. Lutz, T., Gansel, P., Godard, J.-L., Gorbushin, A., Konrath, R., Quest, J., Rivers, S.: Going for Experimental and Numerical Unsteady Wake Analyses Combined with Wall Interference Assessment Using the NASA CRM Model in ETW. AIAA Paper 2013-0871, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine, TX, January 2013
2. Konrath, R.: High-Speed PIV Applied to Wake of NASA CRM Model in ETW Under High Re-Number Stall Conditions for Sub- and Transonic Speeds. AIAA Paper 2015-1095, 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL, January 2015
3. Gloss, B.B.: Current Status and Some Future Test Directions for the US National Transonic Facility. Wind Tunnels and Wind Tunnel Test Techniques, pp. 3.1–3.7. Royal Aeronautical Society, London, United Kingdom (1992)
4. Fuller, D.E. (1981) Guide for Users of the National Transonic Facility. NASA TM-83124
5. Vassberg, J.C., DeHaan, M.A., Rivers, S.M., Wahls, R.A.: Development of a Common Research Model for Applied CFD validation studies. AIAA Paper 2008-6919, 26th AIAA Applied Aerodynamics Conference, Honolulu, HI, August 2008
6. Iyer, V.: A Wall Correction Program Based on Classical Methods for the National Transonic Facility (Solid Wall or Slotted Wall) and the 14 × 22-Ft Subsonic Tunnel at NASA LaRC. NASA/CR 2004-213261, October 2004
7. Gross, N., Quest, J.: The ETW Wall Interference Assessment for Full and Half Models. AIAA Paper 2004-0769, 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2004