20 th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF)
Göttingen, Germany, 25-29 Aug. 2003

MODEL DEFORMATION MEASUREMENT IN ETW USING THE MOIRÉ TECHNIQUE

D. Pallek, K.A. Bütefisch
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Institute of Aerodynamics and Flow Technology
Göttingen, Germany

J. Quest, W. Strudthoff
European Transonic Windtunnel GmbH (ETW)
Köln, Germany

ABSTRACT

A non-intrusive Moiré Interferometry system has been designed and installed to determine the instantaneous deformation of aircraft models during testing in the European Transonic Windtunnel. The present paper describes the principles of the Moiré technique and the experimental set-up of the system. As high accuracy for the measurement of wing twist (< 0.1°) and wing bending (< 0.05 mm) is required, hardware and evaluation software have to be carefully designed. The influence of disturbing effects is discussed in detail, also the solutions to overcome these problems. Measurements of the wing twist of an A 380 type aircraft within the European HiReTT project are described, and results of selected test cases are presented and compared to other experimental and numerical methods.

INTRODUCTION

Up to the mid of the nineties it was thought that typical wind tunnel models are sufficiently rigid to be not exposed to aeroelastic deformation in pressurized facilities. After the European Transonic Windtunnel (ETW) went into operation, the effects of a variation of dynamic pressure on the wing shape could be experimentally proven. ETW, a cryogenic pressurized tunnel for investigations at subsonic and transonic speeds up to true flight Reynolds numbers owns the capability of an independent variation of pressure and temperature. This prerequisite allows the performance of true aeroelastic investigations at constant Reynolds number Re as well as at constant dynamic pressure q in opposite to classical facilities where increases in Re number could only be achieved by an increase in tunnel pressure, hence, a simultaneous variation of the applied model load.

A benefit of this ability has been taken by HiReTT (**Hi**gh **Re**ynolds Number **T**ools and **T**esting), a project funded by the European Commission targeting for the generation of an aerodynamic database up to flight condition for an A 380 type aircraft including the validation of modern CFD tools. Obviously, comparisons of experimental and numerical results will only be meaningful if the correct wing shape gained in the experiment can be provided as input for the numerical calculations. This requirement has driven the application[1] of the **M**odel **D**eformation **M**easurement **S**ystem (MDMS), which is presented here, as well as the development of different methods for prediction, measurement and assessment of wing twist as part of the project.

MEASUREMENT TECHNIQUE

As it has been formerly described,[2,3] the movements, deformations and vibrations of a model in a wind tunnel can be precisely determined by Moiré Interferometry without disturbing the flow. The technique uses the interference of periodic patterns to measure the topology of a given surface.[4,5] The measurement principle is illustrated in Fig. 1:

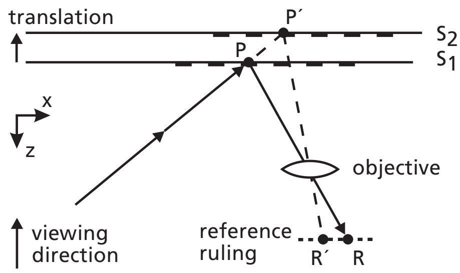

Figure 1: Moiré measurement model for the acquisition of deformations in viewing direction

A Ronchi ruling with parallel black and transparent stripes of equal width is projected onto a plane surface S_1, and the image of the stripes is focused onto a reference ruling. The stripes of the imaged and the reference ruling are parallel to each other, and superimpose to a Moiré interferogram. If the surface is then translated to location S_2, the stripes on the surface move in the x-direction, and a projection ray indicated in Fig. 1 shifts on the surface from P to P´. P´ in turn is now focused onto R´, thus producing an interference pattern with a different intensity.

A translation of the surface in the x- or y-direction does not lead to a shift of the ruling focused onto the surface, and so does not influence the interferogram. The technique is therefore only sensitive to translations in z-direction.

If the observed surface is curved, the resulting fringes in the Moiré interferogram represent lines of equal elevation (Fig. 2 shows the Moiré pattern of the HiReTT model). This implies that large surface gradients lead to large spatial fringe frequencies in the interferogram. The distance in z-direction between two adjacent Moiré fringes is called the layer distance h, which is a function of the optical set-up and usually has to be determined by a calibration measurement. By using image evaluation algorithms the topology of the surface can be determined from the Moiré pattern. Furthermore, if the surface is deformed or shifted in z-direction (e.g. due to aerodynamic load), the change of the z-coordinates of the surface can be calculated by comparing the actual interferograms.

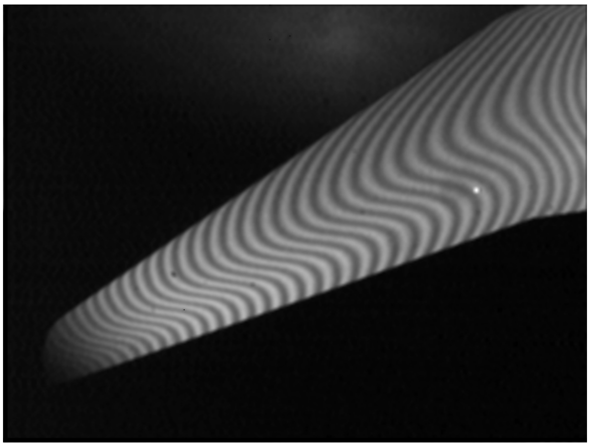

Figure 2: Moiré interferogram of the HiReTT wing

MEASURING SET-UP

Fig. 3 shows the measuring set-up of the DLR Moiré interferometry system MDMS in ETW, which is mounted in the top wall of the test section. It determines the instantaneous wing deformations and movements of full-span aircraft models.

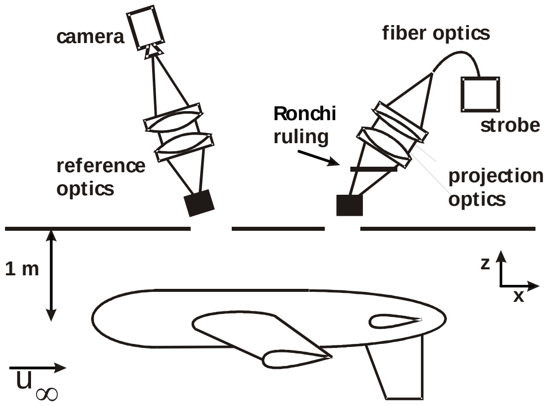

Figure 3: Set-up of the Moiré optics in ETW

The interferometer presented here differs from a conventional Moiré system, as the image of the projection pattern is directly focused on the pixel matrix of the observation camera, without using a reference ruling. The interference pattern is then produced digitally by evaluating every second line of the video picture.

The ETW has a test section of 2.4 x 2 m^2, and runs from Ma = 0.15 to 1.3. Temperature varies from 90 to 313 K, and the total pressure from 110 to 450 kPa. Due to the environmental parameters both optical systems have to be thermally encapsulated and heated.

The present measurements determine the twist and bending of the right wing of an A 380 type aircraft with a full span of 1.58 m. As the lower side of the wing exhibits a smaller surface gradient than the upper side, the model is mounted in the wind tunnel in fin-down position, yielding a higher measurement accuracy.

The observation area of the MDMS is about 0.60 x 0.45 m^2 at an observation distance from 0.9 to 1.1 m from the top wall. The resolution is better than 0.05 mm for wing bending (z-direction) and better than 0.1° for twist.

IMAGE EVALUATION

The z-coordinate of every point in the field of view is computed from the intensity distribution in the interferogram. To achieve this, the straightforward method is: first, the phase angle of the Moiré pattern (a two-dimensional sinus function) is calculated using a Fourier Transform technique[6]. The remaining ambiguity can be resolved with an iterative weighted least squares algorithm (phase unwrapping) based on the discrete cosine transform[7], if the sign of the surface gradient is known in the complete field of view. This sign can be made constant in the complete viewing area by superimposing an additional constant gradient by rotating the rulings relative to another. After applying this procedure, the order of each Moiré fringe is known for every point in the field of view. From this two-dimensional order function and the known layer distance h, the elevation z of each point on the surface relative to a given point can be computed. If absolute z-values are required, the absolute z-coordinate of a single point has to be measured with an additional technique (e.g. triangulation, indicated by the light laser spot in Fig. 2). This is also necessary when a large measurement range in z-direction is required. Then h cannot be assumed to be constant, and is a function of z.

In order to determine the wing deformations (bending and twist) due to aerodynamic load, both surfaces for the no-wind and the on-wind condition have to be calculated. However, it is not sufficient to simply subtract the no-wind surface data from the on-wind surface data. A wing has a curved surface, and if it is just translated in the x-direction, simple subtraction of the two sets of data will suggest a virtual deformation of the model, because different parts of the surface are compared.

In order to achieve the desired accuracy (< 0.05 mm for bending, < 0.1° for twist), all local translations of the wing have to be determined: Under very high loads the model moves slightly (up to 2 mm) downstream due to the bending of the supporting sting. To compensate this effect, each of the more than 500 on-wind wing profiles (separate x-z-planes) has to be shifted in x-direction to its corresponding no-wind profile. By matching the two surface curves, local bending and twist can be calculated.

Also the wing tip is shifted downstream due to the bending of the wing, which brings the tip closer to the fuselage. In the case of the HiReTT wing with its large sweepback and dihedral angles, this effect is relatively strong (up to 4 mm). The amount of this inboard shift can be calculated from the observed wing bending curve, and the wing twist is determined by comparing loaded and unloaded wing sections at the same distance from the wing root (and not at the same span-wise pixel coordinates). To achieve a high accuracy, here an interpolation between adjacent profiles becomes necessary.

Another disturbing effect is due to mechanical vibrations of the wind tunnel under operation. A close examination of the image background showing the tunnel wall opposite the camera revealed movements of the same size and direction as the movements of the model (at low c_L-coefficients). This fact can be explained by a rotational vibration of the camera. Projection system and camera optics being mounted on the same stiff girder, this means that the camera-fixed coordinate system of the MDMS is oscillating (up to 0.2° for cases of high Mach number and large tunnel pressure). Obviously this rotation has a direct influence on the measured incidence angle of the wing and hence on the derived wing twist. The solution for this vibration problem is to determine the translation of the background of each image relative to a reference image (off-wind), then to calculate the corresponding rotation of the MDMS, and finally to rotate the camera system into the wind tunnel coordinate system.

RESULTS

Fig. 4 provides an overview on the test conditions performed in ETW at a Mach number of 0.85, i.e. the design Mach number of the model. It is evident that the test matrix is dominated by quasi horizontally linked points (dashed lines) representing constant values of dynamic pressure divided by the Young's modulus (which is a function of temperature), hence, pure variations of Reynolds numbers, and vertical lines (dotted lines) indicating a variation of load levels. Model deformation measurements with the MDMS-system (black dots) have been performed at 214 and 300 K.

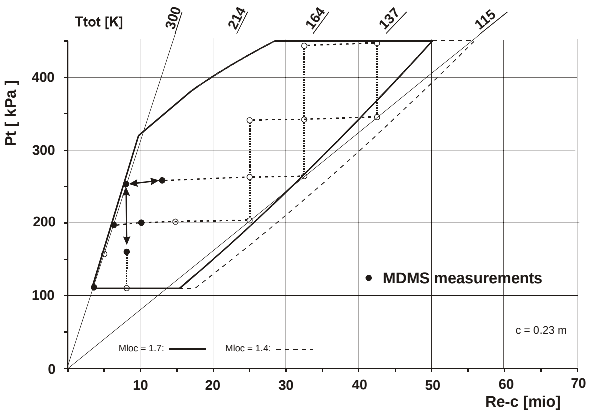

Figure 4: Test envelope for force and model deformation measurements

Wing deformation is presumed to be dominantly driven by aeroelastic loads whereas variations in individual loading due to changes in Reynolds number are suspected to generate only second order deformations. On this basis an assessment of wing twist at ambient temperatures may be valid across the Reynolds number range. Consequently, it was originally only targeted to measure the wing deformation by MDMS at 300 K. Referring to the condition T = 300 K, Re = 8.1 million, pure aeroelastic and Re effects were then investigated.

Comparative measurements with the MDMS system for Reynolds numbers of 8.1 and 13 million at constant levels q/E are given in Fig. 5. Here, positive twist values represent a reduction in angle of attack. Reliable results have been gained between 30 and 90% span. It is evident that they suffer from an increased noise level in the outboard section of the wing due to the short cord length and the reduced illumination in this region. Generally, the results achieved for both Reynolds numbers are in fair agreement for all three lift levels with local differences of up to 0.1° which reflects the expected accuracy of the system.

It should be noted that for a lift coefficient of 0.5 the assessed wing tip twist is about 1.8° for a tunnel pressure of about 250 kPa, hence, the wing suffers already a remarkable deformation.

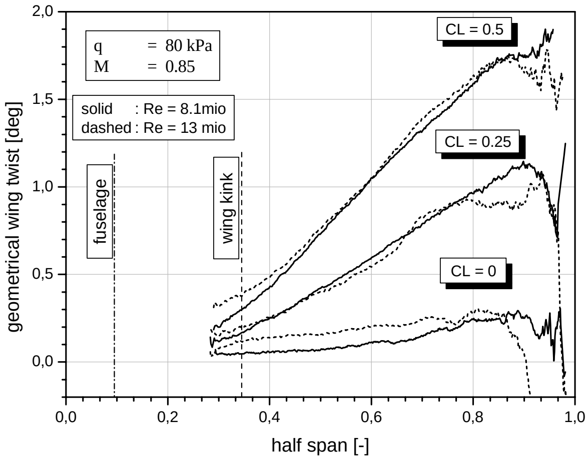

Figure 5: Effect of Reynolds number variation on wing twist measured by MDMS

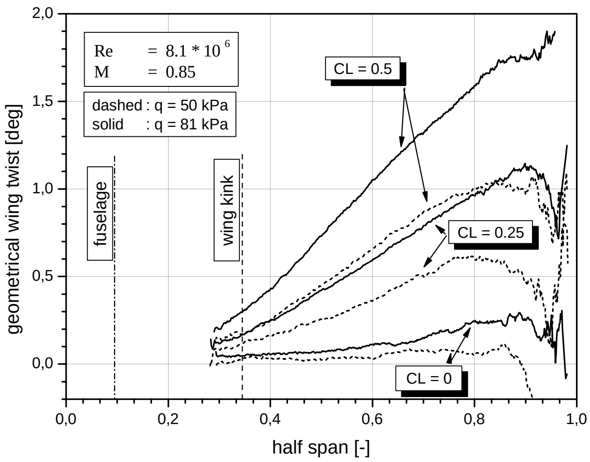

Figure 6: Effect of q–variation on wing twist measured by MDMS

Fig. 6 represents the effect of a variation of the dynamic pressure caused by an increase in tunnel pressure. Raising q by about 60% leads to growing twist levels amplified by the lift level. As ETW is capable to operate at q levels of up to 120 kPa at a Mach number of 0.85, changes of 3° in wing tip twist have to be considered for high lift loads.

Driven by the need to deliver the true wing shape in the early stage of the HiReTT project and to gain confidence in the MDMS results, alternative methods for twist prediction and assessment had been developed.

The Technical University of Aachen (RWTH) successfully established a coupled code combining a RANS 3d flow solver with a structural insert based on the Timoshenko beam theory to predict wing twist and bending.[8]

AIRBUS-UK have used the wing CP-distributions gained by the wind tunnel entry in ETW to convert them into single point loads to be subsequently attached as weights to the individual cross sections in a laboratory set up.[9]

ETW developed a method for twist evaluation based on measured wing CP-distributions at different q-levels.[10] It presumes that the effective twist on a wing is a function of lift and dynamic pressure and, hence, matching two CP-distributions measured at the same span-wise wing section at identical Mach and Re-numbers allows to work out the difference in effective twist. The induced twist is subsequently calculated based on classical theory to gain the geometrical twist required for CFD input.

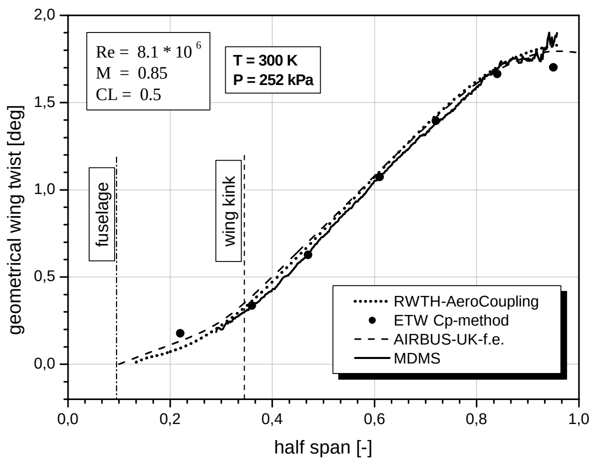

Figure 7: Prediction and measurement of wing twist by various methods

Fig. 7 impressively demonstrates that all results achieved by the different methods agree within less than 0.1°.

CONCLUSION

In the presented experiments, the DLR Moiré system MDMS in ETW has proven to be a valuable instrument for measuring wing deformation. Even under the critical environmental conditions (high tunnel pressure, cryogenic temperatures, mechanical vibrations) the wing twist of an A 380 type aircraft with a full span of 1.58 m has been measured locally in more than 500 individual sections of the wing with an accuracy of better than 0.1°.

In order to receive such a high resolution, careful design of the experimental set-up has to be guaranteed. Just as necessary is the development of complex image evaluation software considering all appearing disturbing effects.

REFERENCES

1). Wright, M.C.N., Strudthoff, W. 2003, "HiReTT Task 1.1.2 MDMS: High speed wind tunnel tests on the full-span model N44", *Technical Report HIRETT/TR/ ETW/MCW/250403/1*

2). Baumann, P.H., Bütefisch, K.A., 1997, "Measurement of hinge moments and model deformations in wind tunnels by means of Moiré interferometry", *SPIE* ***2546***, pp. 16-32

3). Pallek, D., Baumann, P.H., Bütefisch, K.A., Kompenhans, J., 1999, "Application of Moiré interferometry for model deformation measurements in large scale wind tunnels", *Euromech* ***406***, pp. 167-170

4). Kafri, O., Glatt, I., 1978, "The Physics of Moiré Metrology", John Wiley & Sons, New York

5). Grauer-Carstensen, H., 1978, "Eine Messeinrichtung zur Verformung eines Modells im Windkanal", *DFVLR-AVA Bericht 251 78 G 02*

6). Takeda, M., Mutoh, K., 1983, "Fourier transform profilometry for the automatic measurement of 3-D object shapes", *Appl. Optics* ***22***, pp. 3977-3982

7). Ghiglia, D.C., Romero, L.A., 1994, "Fast two-dimensional weighted und unweighted phase unwrapping that uses fast transforms and iterative methods", *J. Opt. Soc. Am.* ***11***, pp. 107-117

8). Braun, C., Boucke, A., Ballmann, J., Hanke, M., Karavas, A., 2003, "Numerical prediction of the model deformation of a high speed transport aircraft type wing by direct aeroelastic simulation", *Technical Report HIRETT/TR/RWTH/CB/18032003/1*

9). Lopez-Calleja, F., 2003, "Supply of full-span model wing deformations", *Technical Report HIRETT/M/ BAES/FLC-TG/011200/1*

10). Gross, N., 2002, "ETW analytical approach to assess the wing twist of pressure plotted wind tunnel models", *AIAA 2002-0310*