DESIGN AND QUALIFICATION CONCEPTS FOR FLEXIBLE WIND TUNNEL WING MODELS

Manuel Kämpchen , Wolfgang Jung , Athanassios Dafnis , Hans-G. Reimerdes
Department of Aerospace Structures - Light Weight Construction, RWTH Aachen

Keywords: *wind tunnel test, flexible wing model, aeroelasticity, structural concepts, measurement techniques*

Abstract

Flexible wing models are used to examine aerostructural dynamical, aeroelastical and flight mechanical problems.

Furthermore currently elastic models are being used to validate coupled software for direct simulation of flow-structure-interaction, particularly in the subsonic (start, landing) and in the transsonic region (mid-cruise). Sufficient deformation data should be made available for the wing models within the operating limits of the respective wind tunnels, without overstepping the linear-elastic region of the material.

For the theoretical layout of the flexible, load carrying structure of the wing models, special software has been developed under consideration of the properties of open and closed beam-sections and geometric non-linearities (caused by large wing deflections, following forces).

The effort taken in technical measurement (for example interface load information at the clamping fixture, strain gauges, acceleration sensors, pressure sensors) to describe the static and dynamic structural behaviour under wind-on as well as wind-off conditions is outlined. Furthermore, methods of wing qualification are elaborated on. Experimental data is presented for a comparison with theoretical results obtained by direct simulation (computational aeroelasticity) methods.

1 General Introduction

For aerodynamic and structural (aeroelastic) phenomena often scaled configurations of original aircraft wings are used. These investigations do not consider preliminary the properties resp. restrictions of special wind tunnels. At the Department of Aerospace Structures an unscaled, high elastic wing model has been designed and manufactored to study the aero-structural wing behaviour and enable a validation for numerical computations on idealized wing models. The requirement of precise description of the static and dynamic behaviour of the wing model demands a high flow quality and a high accuracy of the different applied measurement techniques. The latter one is crucial under wind-off and wind-on conditions. In this paper a methodology for the specification, qualification and validation of high flexible wings is presented and experimental results are given for a rectangular spar wing model. For theoretical studies a beam like structure is assumed. For the investigation of planned swept wing wind tunnel models with closed section geometry, extended structural concepts are developed.

2 Concepts for Flexible Wind Tunnel Wing Models

2.1 Theoretical Investigation in Structural Concepts of Flexible Wing Models

For the preliminary analysis of the structural behaviour of wings beam models are often used.

The determination of stresses and displacements produced by axial loads, shear forces and bending moments and torsion is based on the classical Euler-Bernoulli beam theory. The Timoshenko beam amplifies the latter by considering displacements caused by the work of shear forces. For the investigation of non-swept open section wind tunnel wing models (see fig. 3) the Timoshenko beam theory has been used. Depending on different flow velocities the influence of geometrical non-linearities together with the effect of following forces (see fig. 1) result in an increase of wing tip deflection and wing tip torsion as shown in tab. 1.

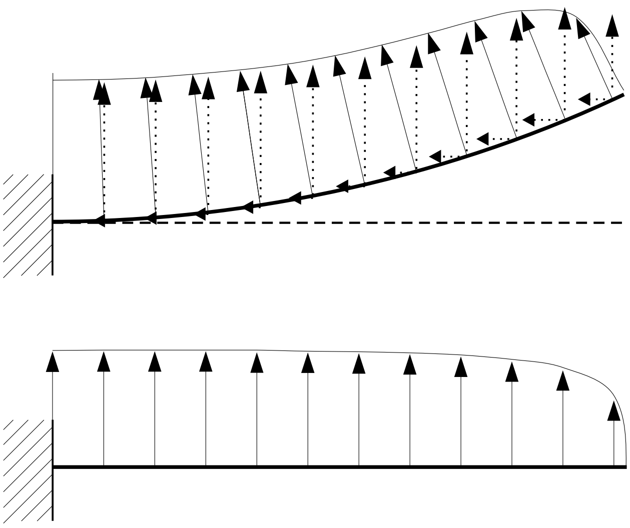

Fig. 1 Effect of Following Forces

Flow velocity [m/s]	45	65	85
Increase of wing tip deflection [%]	.35	1.38	5.81
Increase of wing tip torsion [%]	.37	.94	3.49

Table 1 Influence of Nonlinearities

Especially when dealing with closed section wing models, used in real aircraft wings or scaled wing models, effects like taper, restrained warping, different materials, rib effect and sweep must be considered. For this reason an idealized wing model has been established, which assumes a thin-walled mono-cell wing box with parabolic covering skin panels (see fig. 2). The wing box is

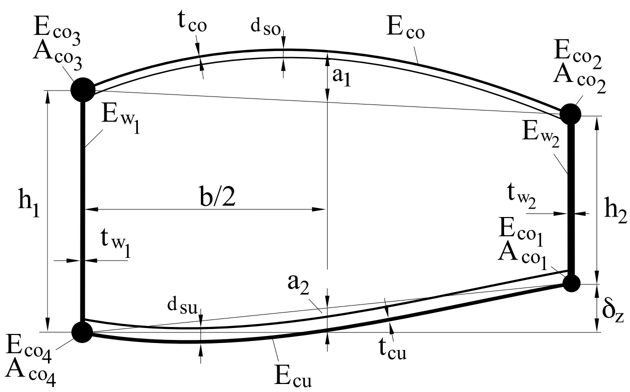

Fig. 2 Effect of Following Forces

stiffened by smeared internal and discrete corner stringers as well as by smeared ribs, where the latter ones are positioned normal to the spanwise direction. The Timoshenko beam was extended in regard to wing taper, rib effect, warping restraint and the effect of different materials of the structural elements. First results are given in [5].

2.2 Design and Experimental Investigation of a Flexible Wind Tunnel Wing Model

The high elastic wing models investigated at the Department of Aerospace Structures differ in some aspects from the rigid wing models, which are normally used for wind tunnel tests. Due to the large static deformations (particulary twist) of the wing under aerodynamical forces, it is no longer possible to accept these loads for a rigid wing model in the early stage of preliminary design. This is especially relevant (regarding the applied airfoil) for the angle of attack adjusted at the wing root, at which the total lift of the wing becomes zero. Furthermore elastic wing models have to be designed in view of their dynamic behaviour due to the mass distribution.

The specimen introduced below is a rectangular wing model with a 1*m* semispan and a chord length of 222*mm*, which has the same airfoil and the same aspect ratio as the reference configuration defined in the Collaborative Research Center (SFB401) [8] and which did not have to meet any other criteria of similarity. It was designed for large deformations with respect to the capabilities of the wind tunnel without exceeding the linear elastic material behaviour of the aluminium wing spar. Additionally the rectangular wing model was designed to have low eigenfrequencies and a low structural damping.

2.2.1 Design, Sizing and Construction

To realize these requirements of the high elastic wing model, it was preferable to use a hybrid construction in contrast to the in [7] introduced compact construction and the in [1] introduced construction of a shaped plate. This hybrid construction can be subdivided in the different assemblies:

- wing spar
- ribs
- aerodynamic shape
- measurement instrumentation

For the specification of the static elastic properties it was sufficient to consider first the mechanical characteristics of the wing spar (cantilever beam). For the dynamic behaviour of the wing model it was also necessary to take the other assemblies mentioned above with their mass distribution into consideration.

The cross shaped wing spar shown in fig. 3 was appropriate for the elastic wing model. The bending and torsional stiffness could be influenced by a combination of width, length and the geometry of the vertical and the horizontal notches of the cross-shaped spar. In this way a more or less strong coupling of the wing movement (plunge, twist) was reached. A low torsional stiffness was specially required to initiate both high static elastic deformations under the aerodynamic loads and close coupled eigenmodes caused by unsteady aerodynamics.

Different material properties (steel, titanium, aluminium) have been looked at in the design process with respect to their influence on the static and dynamic deformation behaviour [4]. For this first elastic wing model only metallic materials were evaluated, because of their relatively low structural damping (hysteresis) as opposed to (fibre-reinforced) plastics, so that the aerodynamic damping influence became obvious.

At the Department of Aerospace Structures a program based on the Timoshenko beam-theory has been developed for the theoretical determination of wing spar deformations and stesses. By a simple strip-theory approach for the aerodynamic forces with 2D-correction [8], it was possible to fix the cross section of the wing spar as shown in fig. 3. This spar geometry allows such large deflections to the elastic wing model, that non-linear geometric effects (following forces) are not negligible any more. The aerodynamic forces calculated for the deformed wing model had been verified with a "Vortex Lattice"-method. For further investigations of swept wing models, this aerodynamic method was linked with a commercial finite-element program. It predicts with high accuracy the deformations and stresses in an early stage of the design process. In fig. 10 and 11 the results of the iterative approximation of the "design tool" are shown in comparison to the wind tunnel tests and the numerical direct simulation.

The wing spar mentioned above thickens towards one end and is fitted to a rigid flange, which is part of a piezoelectric 6-components-balance for measuring the reaction forces/moments of the clamped support. At 16 positions in spanwise direction strain gages are applied to measure bending and torsional strains. The cross-coupling of which is negligible because of the specific cross-shape of the spar.

An aerodynamic shape had to be found, which causes only low changes in the elastic behaviour of the spar and at the same time transfers the aerodynamic loads by means of ribs to the spar without any local deformations (airfoil variance). 21 aluminium-ribs of appropriate profilation stiffen the foam covering the spar, of which two were prepared for the reception of in-situ pressure transducers for the measurement of transient pressures. The spaces had been filled with

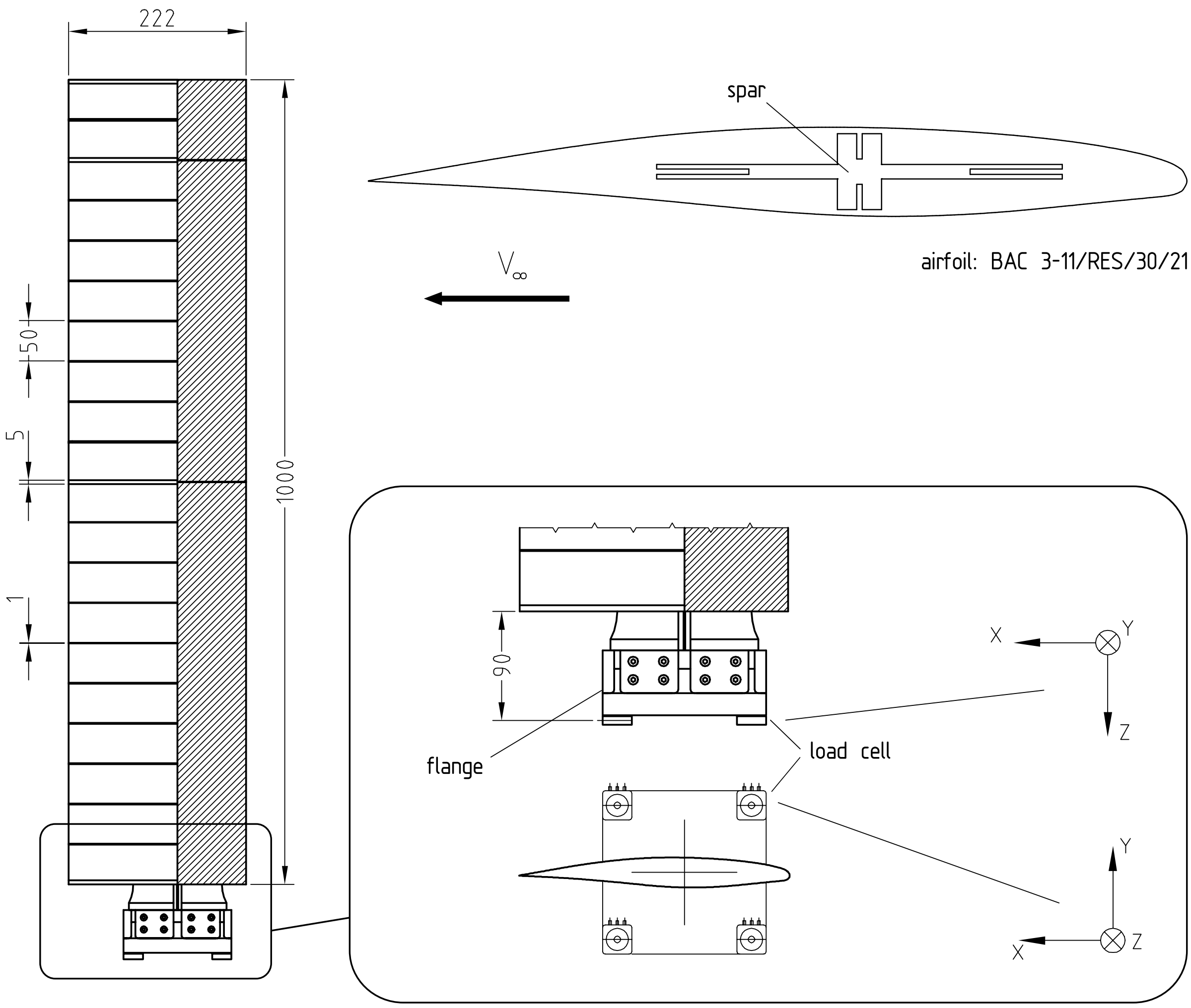

Fig. 3 Shape of the Flexible Wind Tunnel Wing Model

polyurethane-integral-foam pieces, providing a surface without poriosity and the proper profile.

A pair of accelerometers was each placed on 5 different span positions, for the evaluation of the scheduled dynamic tests [6].

2.2.2 Wind-off Structural Identification

In order to evaluate the wind tunnel tests, it was necessary to first make a structural identification of the elastic wing model under wind-off conditions. For extraction of its elastic properties the wing model was clamped to a holding fixture designed for introducing loads as well as integration of distance measurement techniques. It allows both the loading of a shear force resp. a pure torsional moment and the non-contact three-dimensional measurement (laser-optical triangulation) of an arbitrary number of points on the wing surface. By means of this device it was possible to evaluate the elastic line of the wing, which approximately coincides with the elastic line of the spar. Furthermore the stiffness matrices in bending and torsional direction were evaluated (tab. 2).

Flap Bending	Lag Bending *)	Torsion
$5.864 \cdot 10^8$	$2.178 \cdot 10^{10}$	$1.4133 \cdot 10^8$

*) calculated stiffness

Table 2 Measured/Calculated Stiffness of the Flexible Wing Modell in Nmm^2

Apart from this information essential for the numerical simulation, a calibration of the strain gages was done concerning the section moments as well as the deflection and the twist.

A software based on the phase separation technique was used for the total determination of the wing models eigenmodes. The wing model was excited by the impact method and the modal structural parameters (eigenfrequency, eigenform and damping) in a frequency range up to 300Hz were determined by using internal accelerometers (tab. 3).

Wing Model's Eigenfrequencies [Hz]			
	1st Bending	2nd Bending	1st Torsion
test	8.82	54.05	49.67

Table 3 Measured Eigenfrequencies

Along with the mass matrix composed by superposition of the discrete masses it was possible to take this information to control the implemented wing model's properties in the simulation.

To specify the wing model's properties, data was transferred to the simulation taking into account the shape (airfoil, outline of the wing) the measured flap-bending and torsional stiffness matrices, the measured mass matrix as well as the calculated lag-bending stiffness.

2.2.3 Wind Tunnel Testing

The first step in testing highly elastic wing models must be the determination of the root angle of attack of zero-lift depending on the flow speed as reference item determined by the piezo-electric balance. The moment of the here used non-symmetric BAC 3-11 airfoil twists the wing model proportionally to the dynamic pressure. This also appears if the total lift is vanishing. In order to keep the total lift of the wing equal to zero while increasing the flow speed it also necessitates increasing the angle of attack at the wing root (fig. 4). At the inner section the flexible wing model produces positive lift which is balanced by the negative lift in the outer section of the wing.

Fig. 5 shows the elastification of the wing model by the given experimental boundary condition powering up and down the wind tunnel continously. This phenomenon is typical for high elastic wing models during static aerodynamic investigations and can be explained as follows:

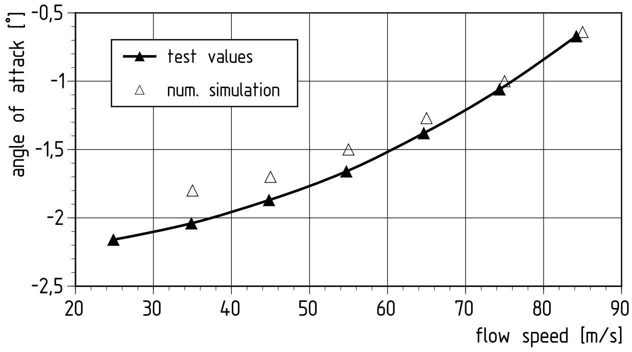

Fig. 4 Angle of Attack of Zero-Lift vs. Flow Speed

The overall lift force increases at first, until the wing is twisted at higher flow speed so much that the lift force decreases down to (approximately) zero. The small lift force of about 1N left in fig. 5 is caused by the limited adjustment of the angle of attack. It doesn't allow adjustment to the exact angle of attack with vanishing total lift.

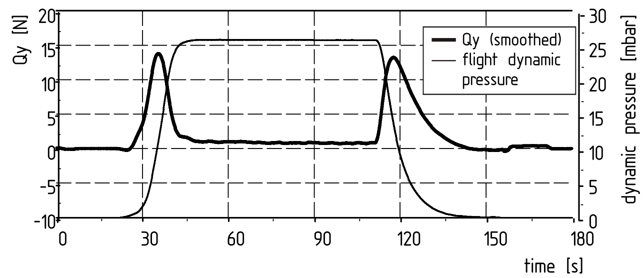

Fig. 5 Zero-Lift at $V_\infty = 65m/s$ ($\alpha_w = -1.33°$)

Starting with the measured angles of attack of zero-lift wind tunnel tests were done at different angles of attack ($\Delta\alpha_W = [-2,2,4,6,8]°$) at the respective flow speeds ($V_\infty = [25,35,45,55,65]m/s$). The angle of attack $\Delta\alpha_W$ represents the difference between the angle adjusted at the wing root and the angle of attack of zero-lift measured at the respective flow speed. It was ascertained , that no flow separation occurred in the investigated field of angles of attack, even regarding the elastic deformation of the wing model.

The wind tunnel available in Aachen is a closed loop atmospheric wind tunnel with an open test section. Due to this configuration the high turbulence level excited the high elastic wing model to acyclic vibrations of relevant amplitude. This caused in all measuring signals a superposition of the static value with a high dynamic response and thus complicated the analysis of the steady state flow tests. The analysis of the dynamic tests (twang tests) was made impossible by the high signal-to-noise ratio. On this account new tests took place in the DNW–LST of the NLR in Emmeloord, a closed loop atmospheric wind tunnel with a closed wall test section. Thanks to its proven low turbulence level the problem of the wing vibrations was eliminated. There appeared no more visible movement of the elastic wing model and the measuring signals were only disturbed by a low signal-to-noise ratio.

The signals of the bending and torsional strain gages, the reactions of clamped support and the pressures in one airfoil section were recorded at all tests with a sample rate of 600Hz. The data collected from the strain gages allows to analyse the spanwise deformations and the section moments in view of the gage calibration. To verify the indirect evaluation of the deformations several twice-exposed photographs were analysed, on which the elastic wing model is pictured with and without incoming flow (fig. 6). Analysing these photographs might help to determine the deflection and the twist at the wing tip.

Apart from the tests under steady state flow conditions some twang tests were done at different angles of attack ($\Delta\alpha_W = [0,6]^\circ$) and flow speeds ($V_\infty = [25,35,45,55,65]m/s$) for the purpose of the extraction of the damping characteristic under wind-on conditions. Additionally it was made possible through the twang tests the validation of the time-dependent behaviour of the modeling by the numerical simulation.

After determining that the structural modelling (stiffnesses, masses, eigenfrequencies, modal damping) and the aerodynamic boundary conditions (geometry, airfoil, flow speed, air density) for the numeric simulation corresponded to the conditions during the wind tunnel tests, the test results were compared step-by-step to the numerical simulations (fig. 8). If necessary, they had to undergo an error analysis at wide differences. The dotted boxes "dynamic" and "successful validation" indicate topics which are not yet finished.

In chapter 3 the final result of this validation is presented by some randomly selected examples.

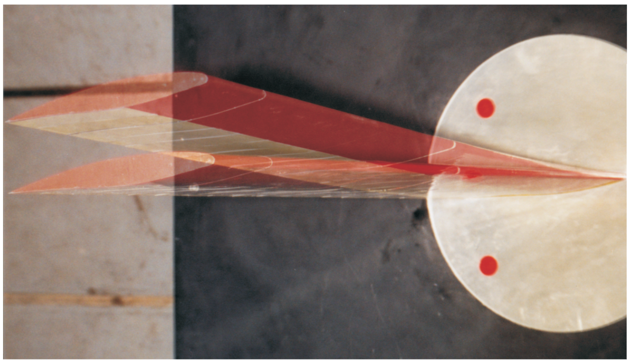

Fig. 6 Flexible Wing Model under Wind-off/Wind-on Conditions

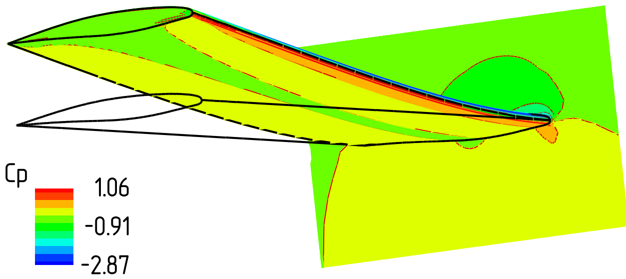

Fig. 7 Numerical Simulation ($V_\infty = 65m/s$, $\alpha_W = 6.93^\circ$

2.2.4 *Numerical Simulations*

For the numerical direct simulation the SOFIA code is used in which higher order programs for the aerodynamics and the structure dynamics are coupled. For the flow analysis of the available calculations the implicit Euler-method INFLEX was used, alternatively the utilistion of the

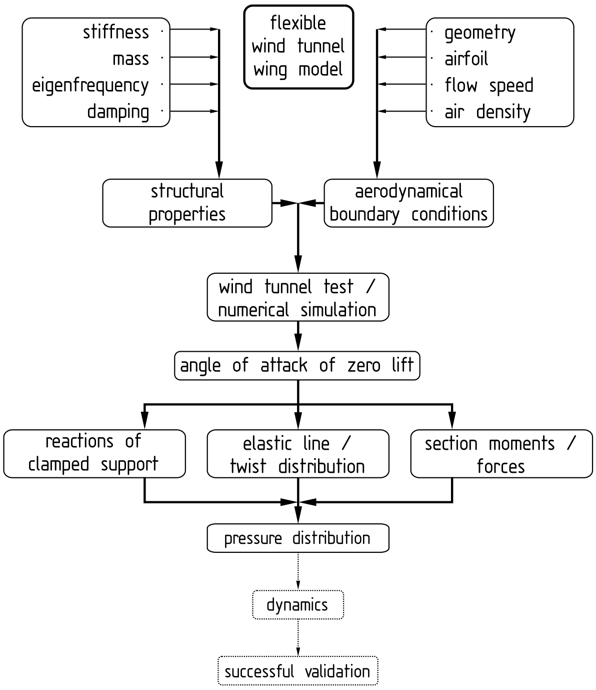

Fig. 8 Schedule of the Validation

Navier-Stokes-method FLOWer would be possible. For the structural analysis a reduced one-dimensional FE-beam-model is used. Therefore a Timoshenko-beam with arbitrary oriented axis of bending stiffness, torsional stiffness and mass inertia is applied under assumption of a rigid aerodynamic cross section. Within the code SOFIA the coupling was realised iteratively in such a way that the structure's new velocity and deformation conditions can be calculated, based on the previous time step, and with it the new aerodynamical loads. This procedure will be repeated for the current time step until convergence is achieved. A detailed description of this method is given in [2, 3].

3 Results

The first step in the validation process was to verify the effect of elastification by the numerical simulation, as the main static elastic and aerodynamic effects of the flexible wing model become visible by this phenomenon (fig. 4). The phenomenon of elastification also becomes obvious in the numerical simulations, but the results differ more at lower flow speeds. The reason is probably numerical errors, which appear at small forces and deformations.

In the following step both the reactions of clamped support measured with the piezoelectric balance and the elastic deformations were experimentally determined and compared with the respective numerical simulations. At this point the elastic deformations were extracted indirectly from the calibrated signals of the bending-strain gages. The comparison of fig. 6 and fig. 7 illustrates the good qualitative correspondence between the experiment and the numerical simulation.

Here are given the results of the test at $V_\infty = 45m/s$ and $\Delta\alpha_W = 08°$ measured in DNW–Low-Speed-Tunnel (LST) in Emmeloord representative for the large number of tests under varying flow conditions, compared to the numerical results. The following diagrams show that the deviations between the numerical simulation and the experiment are in the scope of the measurement inaccuracy.

Lifting Force		Torsional Moment	
test	num.	test	num.
$204.30N$	$212.97N$	$-4.03Nm$	$-3.72Nm$

Fig. 9 Responses at Clamped Support at $V_\infty = 45m/s$ and $\alpha_W = 6.6°$

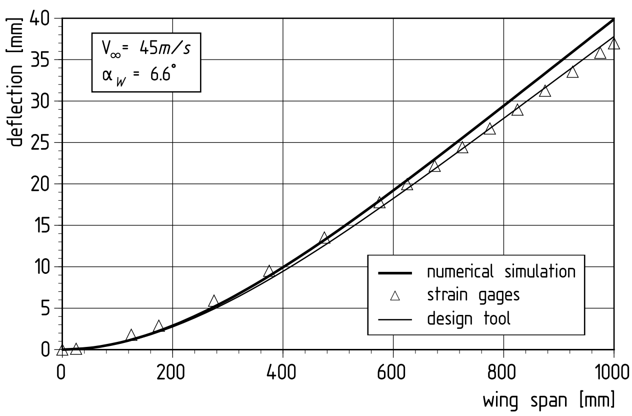

Fig. 10 Deflection Line of the Flexible Wing Model

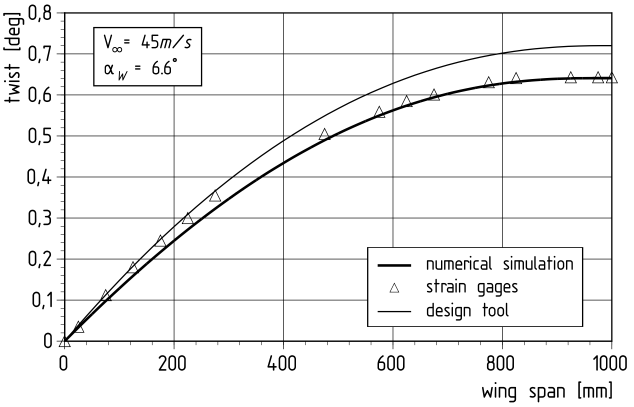

Fig. 11 Twist Distribution of the Flexible Wing Model

The good results of the measured and the calculated deformations, become also obvious comparing the measured and the calculated pressure coefficients in the airfoil section at 50% semispan as shown in fig. 12.

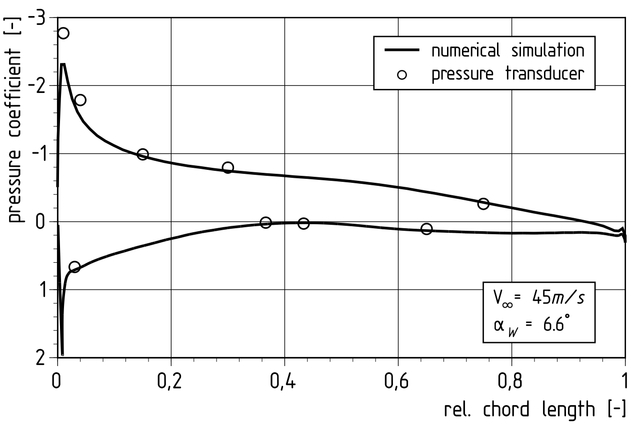

Fig. 12 Pressure Distribution at 50% Semispan

A comparison of the dynamic wind tunnel tests (twang tests) is presently being investigated. For example the decaying oscillation of the 1st bending mode is shown under the flow conditions $V_\infty = 45m/s$ and $\alpha_W = 6°$ during the twang test (fig. 13). One identifies the strong decaying oscillation of the 1st bending vibration (8.9Hz) superimposed by at least one vibration of higher frequency and large amplitudes.

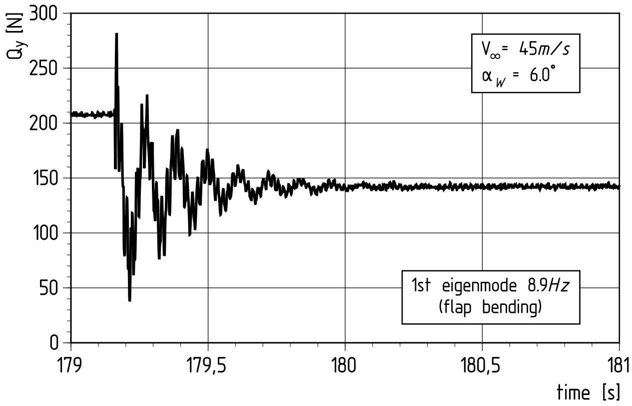

Fig. 13 Twang Test, Excited at the Wing Tip

4 Conclusion and Outlook

The good agreement of the results to the numerical simulations of all tests seems to indicate that the identification of the properties of the flexible wing model was of high quality. Further on the flexible wing model was proved to be qualified for the scheduled wind tunnel tests and was able to fulfill the predetermined requirements entirely.

It remains to be seen at the validation of the time-dependent behaviour (e.g. twang tests) of the flexible wing model, whether concerning the dynamic behaviour similarly good results will be archieved. The structural modal parameters of the flexible wing model required for the numerical simulation and part of the twang tests are already evaluated.

Presently a swept wing model is planned in approximation to the shape of a commercial aircraft, which however will have a spanwise constant chord lenght. The purpose of this likewise highly elastic wing model will be the correct specifcation of the effects of the bending-torsion coupling in the design stage, the identification of these effects under wind-off conditions and finally experimental investigations in the wind tunnel. For the wind tunnel tests a contactless direct measurement of the deformations using laser or picturing methods (interferometry) will supplement the indirect evaluation of the deformations using calibrated strain-gages. In addition the results of the wind tunnel tests with the new swept wing modell will give a further validation of the method of the numerical direct simulation.

5 Acknowledgements

The research work presented in this paper was mainly achieved within the Collaborative Research Centre (Sonderforschungsbereich) 401 "Modulation of Flow and Fluid-Structure Interaction at Airplane Wings" at the Aachen University of Technology (RWTH). We are grateful to the German Research Association (Deutsche Forschungsgemeinschaft) for their support.

References

[1] Bendiksen O and Hwang G.-Y. Nonlinear flutter calculations for transsonic wings. *Proc CEAS Forum on Aeroelasticity and Structural Dynamics*, Rome, 1997.

[2] Britten G and Ballmann J. Navier–stokes based direkt numerical aeroelastic simulation. *Proc 22nd International Congress of Aeronautical Sciences*, Vol. ICA0477, 2000.

[3] Britten G, Hesse M, Grotowsky I, and Ballmann J. Berechnungsverfahren für die aerostrukturdynamik von tragflügeln. *Proc SFB 401, Arbeits– und Ergebnisbericht 1999*, Vol. Teilprojekt B1, pp 227–250, RWTH Aachen, Germany, 1999.

[4] Dafnis A, Jung W, and Reimerdes H.-G. Auslegung elastischer windkanal-flügelmodelle zur validierung aeroelastischer berechnungen. *Proc Aeroelastik-Tagung der DGLR*, pp 261–316, Göttingen, Germany, 1998.

[5] Jung W and Reimerdes H.-G. Ein beitrag zur aeroelastischen untersuchung mit idealisierten tragfl"ugeln. *Proc DGLR Jahrestagung*, Vol. 3, pp 1371–1378, Berlin, Germany, 1999.

[6] Kämpchen M, Jung W, Dafnis A, and Reimerdes H.-G. Entwicklung elastischer flügelmodelle und experimentelle untersuchungen im windkanal sowie konzepte und modellierung der tragstruktur elastischer flügel. *Proc SFB 401, Arbeits– und Ergebnisbericht 1999*, Vol. Teilprojekt B7, pp 343–386, RWTH Aachen, Germany, 1999.

[7] Lee-Rausch E and Batina J. Wing flutter boundary prediction using unsteady euler aerodynamic method. *Journal of Aircraft*, Vol. 32, No 1, pp 416–422, 1995.

[8] Özger E and Jacob D. Wirbelbeeinflussung von tragflügeln. *Proc SFB 401, Arbeits– und Ergebnisbericht 1999*, Vol. Teilprojekt A1, pp 7–48, RWTH Aachen, Germany, 1999.