Design Considerations for a UCAV Wing for Subsonic and Transonic Aeroelastic and Flight Mechanic Wind Tunnel Tests

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SUMMARY

In the German Aerospace Center, DLR, an internal project has been launched to investigate different UCAV configurations. One aspect, covered by the Institute of Aeroelasticity and the Institute of Aerodynamics and Flow Technology, is the wind tunnel test of a UCAV wing in subsonic and transonic flow. The model shall show measurable static aeroelastic deformations. Main goals of the tests will be the study of vortex-dominated flow on aeroelastic deformable wings, and the generation of data for the validation of numerical fluid-structure coupling for delta wings at various points of the operational envelope. At the same time, a new active wind tunnel support will be build to include a means of investigation into the flight mechanics of such a configuration. Contrary to many aeroelastic experiments, flutter tests are not part of the test program.

The report will give an overview of the design considerations for an aeroelastic UCAV wing model, discussing requirements coming from the validation of numerical simulations, leading to an investigation of various planforms for suitability with respect to the requirements of the project and the selection of sensors for the model. Aspects of safety criteria for operation of aeroelastic models in the wind tunnel will be considered, regarding requirements for flutter models vs. those for static aeroelastic models. The outline of the structural design of an aeroelastic UCAV wing for the analysis of deflections and transient motion is given, along with some words on the role of an active wind tunnel support.

As the project has just been launched, the wing model is currently in the concept stage. Final model design is expected to be finished at the end of 2007, the experiments are due to be performed in early 2009.

1.0 INTRODUCTION

1.1. Motivation and Background

The coupling of aeroelasticity and flight mechanics is an important factor for the design and analysis of manned and unmanned aircraft. A number of approaches are used; yet, a generally accepted integrated approach does not exist. Wind tunnel data for validation is hardly available. In the German Aerospace Center, DLR, the internal project UCAV 2010 has been launched to investigate different UCAV configurations. One aspect, covered by the Institute of Aeroelasticity and the Institute of Aerodynamics and Flow Technology, is the design and construction of a representative UCAV wing model for wind tunnel tests wing in subsonic and transonic flow. The model shall show measurable static aeroelastic deformations. At the same time, a new active wind tunnel support will be build to include a means of investigation into the flight mechanics of such a configuration.

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Main goals of the tests will be the study of vortex-dominated flow on aeroelastic deformable wings, and the generation of data for the validation of numerical fluid-structure coupling for delta wings at various points of the operational envelope. The focus is on the validation of methods for the analysis of static and transient aeroelastic phenomena, but also on new aeroelastic concepts including active aeroelastic control. Contrary to many aeroelastic experiments, flutter tests are not part of the test program.

1.2. Technical and Scientific Goals and Basic Requirements

It is one of the main intentions of the work to provide an integrated experimental and numerical approach for aeroelastic investigations. Requirements for the model design should come to an essential part from the numerical simulation. The original goals of the work are:

- The investigation and validation of approaches for stationary and instationary (transient) fluid-structure-coupling;
- The validation of methods and codes for CFD, structural dynamics and fluid-structure coupling;
- An investigation of unsteady lift development of vortex dominated flow for fast pitching motion of the wing;
- Investigation of aeroelastic / flight mechanics coupling;
- Creation of experimental data base as solid basis for validation;
- Investigation of new aeroelastic concepts including active aeroelastic control, active load distribution, alternative structural design concepts.

However, the goal of the work is NOT:

- A design study with implications for a near-term technical product,
- A flutter investigation.

The technical and scientific goals lead to the following basic requirements for the experiment:

- Well defined and well known aerodynamic and strutural properties;
- Simple structure with clear boundary conditions; linear properties as far as possible, well defined non-linearities;
- Simple model with limited functionalities;
- Highly reproducible measurements;
- Basic validation of transient motion, e.g. time response to fast change in angle of attack;
- Different redundant measurement techniques;
- Wing sweep > 53° to reach stable flow properties at large angles of attack;
- Subsonic and transonic measurements.

It has to be taken into consideration that limits in the design freedom are posed due to the limited cross section of the wind tunnel available for the project.

In the framework of AVT, other efforts on the investigation of the properties of UCAVs are ongoing. To increase communality between the models, the configuration selected for the aeroelastic analysis will be compatible as much as possible with the German input to the RTO/AVT Group 161 – “Assessment of Stability and Control Prediction Methods for NATO Air & Sea Vehicles”.

1.3. Experience from DLR Wind Tunnel Experiments

As the original facility for aeroelastic investigations in Germany since the 1930ies, DLR has acquired considerable experience in aeroelastic experiments. For the current project, a study of recent experiments has bee performed under the following points of interest: What has been investigated? / Which data were collected? / Could the data be used for aeroelastic validation?

Three major recent projects have been subject to a closer review – the AMP project Figure 1, [1], the Aerostabil project Figure 2, [2], and the experiments of the AeroSUM project and its follow-up, SikMa Figure 3, [3]. In AeroSUM and SikMa, investigation of aeroelastic effects have not been one of the original aims, but proved to be crucial for the understanding of the results.

AMP Wind Tunnel Model:

- Test program AMP (Aeroelastic Modelling Programme, [1])
- Duration: until 1990
- Partners: Airbus, DLR, ONERA
- Model: steel wing spar, carbon-fibre skin, rotational excitation (hydraulic)
- Equipment: 290 pressure sensors in 10 sections, 12 accelerometers in 6 sections, optical deformation measurements (10 glass fibre light points in 5 sections)
- Wind tunnel: ONERA transonic wind tunnel S2MA, subsonic and transonic measurements

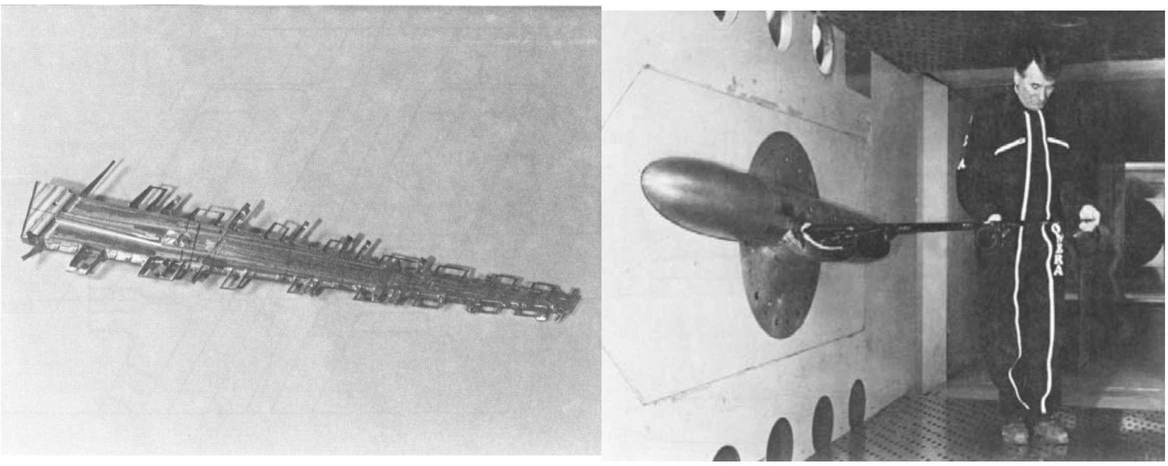

Figure 1: The AMP model in the ONERA S2MA wind tunnel

AEROSTABIL Wind Tunnel Model:

- Test program AEROSTABIL (Aeroelastic Stability in the Transonic Flight Regime, [2])
- Duration: 2000-2002
- Partners: DLR, DNW
- Model: carbon-fibre wing spar, glass-fibre skin, rotational excitation in two axes (hydraulic)
- Equipment: 90 pressure sensors in 9 sections, 6 accelerometers in 3 sections, optical deformation measurements (Moiré)
- Wind tunnel: DNW TWG, subsonic and transonic measurements

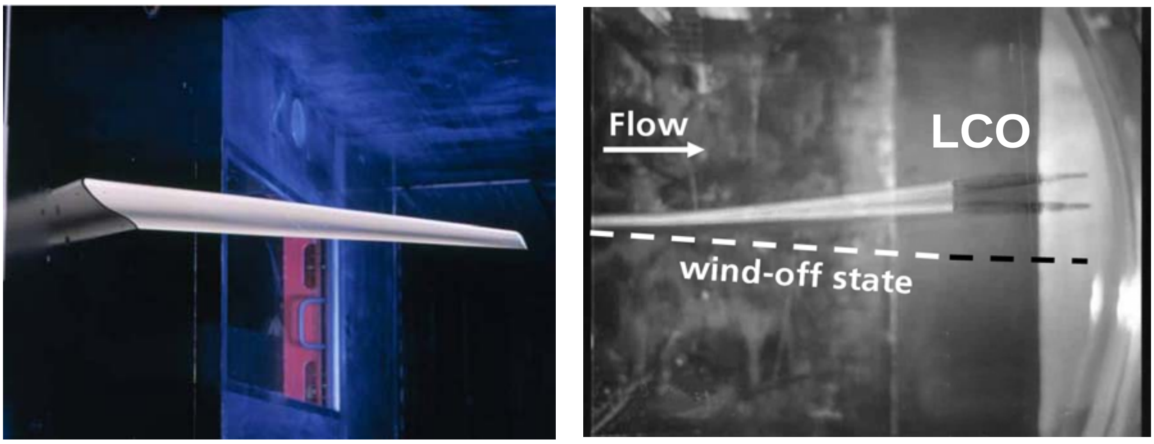

Figure 2: Limit Cycle Oscillations displayed by AEROSTABIL-wing

AeroSUM Wind Tunnel Model:

- Test program AeroSUM (Numerical Simulation of Manoeuvring Fighter Aircraft, [3])
- Duration: 1998-2001
- Partners: several DLR institutes
- Model: carbon-fibre structure on an aluminium frame, spindle drive for flaps, rotational guided and free-to-roll motion on sting (electric)
- Equipment: >30 pressure sensors in 2 sections, accelerometers
- Wind tunnel: DNW TWG, subsonic and transonic measurements

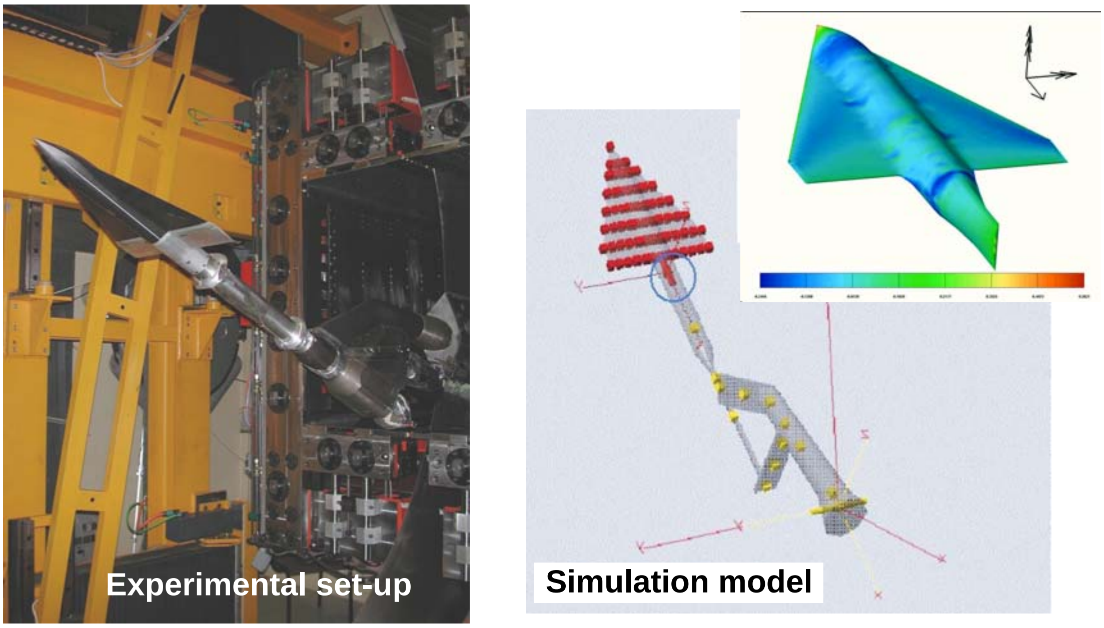

Figure 3: AeroSUM experiment and simulation models

To briefly summarize the review, it can be stated that all projects showed a high expertise in model design and construction. All experiments has been very extensively documented in all steps and provided a wealth of data. From the point of view of validation of numerical aeroelastic analysis methods, however, some lessons learned could be identified. First, static and dynamic properties of the models were sometimes not as well known as necessary for high-fidelity numerical aeroelastic validation. Sometimes, model properties changed during the test campaigns, and not all changes could be tracked. Second, not all measurements desirable for numerical validation (even though principally available) had always been taken, because numerical analysis had not been part of the measurement definition phase. Furthermore, models with too many functions (e.g. control surfaces) often lead to ambiguous dynamic results, meaning that the origin of a certain observed behavior often could not be identified.

1.4. The Wind Tunnel

The wind tunnel available for the investigation is the Transonic Wind Tunnel Göttingen (TWG) of the German Dutch Wind Tunnels (DNW). It is a continuous, pressurized wind tunnel with three exchangeable test sections for subsonic, transonic and supersonic speed range. The possible Mach numbers are 0.3 ÷ 0.9 with adaptive walls, 0.3 ÷ 1.2 with perforated walls, and 1.3 ÷ 2.2 with a flexible Laval nozzle. The pressure range is $0.3*10^5 \div 1.5*10^5$ Pa. The 4 or 8 stage axial compressor has an electric power supply of 12 MW; an auxiliary suction plant with radial compressors for the transonic test section (perforated walls) is available. The equipment includes air-cushion transport system for all test sections, model support and nozzles. The wind tunnel cross section is 1 m x 1 m, allowing a maximum model wing span of approx. 70 cm.

2.0 CONSIDERATIONS ON THE CONFIGURATION

2.1. Existing Fighter Aircraft and UCAV Wing Configurations

The planform and general layout of the aeroelastic wind tunnel model should represent a realistic configuration. On the other hand, understanding the physical interactions and the requirements of the numerical validation are the key drivers of the final design, rather than imminent implications for a near-term technical product. Thus, the model will be as generic as possible, and as similar to a realistic, flying design as necessary.

For current designs of fighter aircraft, two types of wing shapes are common. First, a trapezoidal wing (e.g. at the F-16), see Figure 4 left, second a delta wing (e.g. the X-31), see Figure 4 right. Both designs have benefits and disadvantages from the point of view of aeroelastic validation. The trapezoidal wing has a higher aspect ratio, allowing large deflections (aeroelastic interest). However, it has only a small region of stable vortex dominated flow (aerodynamic interest). The delta wing, on the other hand, has a stable vortex dominated flow for a large region of angle of attack. However, because of its low aspect ratio, only small deflections can be expected.

The shape of current high-speed UCAV configurations is determined to a large extend by measures to minimize visibility of the aircraft both for radar as well as for infrared sensors. Figure 5 shows a number of selected recent UCAV configurations (by no means intended to be a comprehensive overview).

A common design characteristic is the diamond-shape with a leading edge sweep angle between 40° and 60° or a so-called lambda wing with a diamond-shaped fuselage section and wings with a parallel leading and trailing edge. Evidently largely for reasons of stability and control of the aircraft, the lambda wing has been the preferred solution for the majority of suggested or tested UCAV designs.

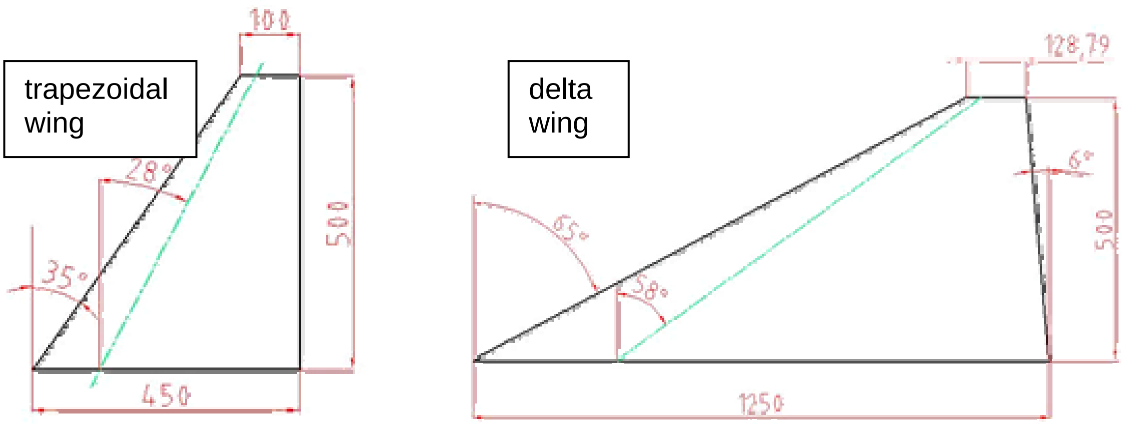

Figure 4: Basic wing shapes of fighter aircraft, design studies of wind tunnel models

- nEUROn: European UCAV technology demonstrator [4]
- X45: Boeing X-45A Unmanned Combat Aerial Vehicle concept demonstrator [5]
- X47A / X47 B: Northrop Grumman Unmanned Combat Aerial Vehicle demonstrator [6]
- Seraph: Denel low-observability, high-speed stealth drone [7]
- Lockheed Martin Generic UCAV Concept [8]
- DARPA smart wing project [9], [10], [11]

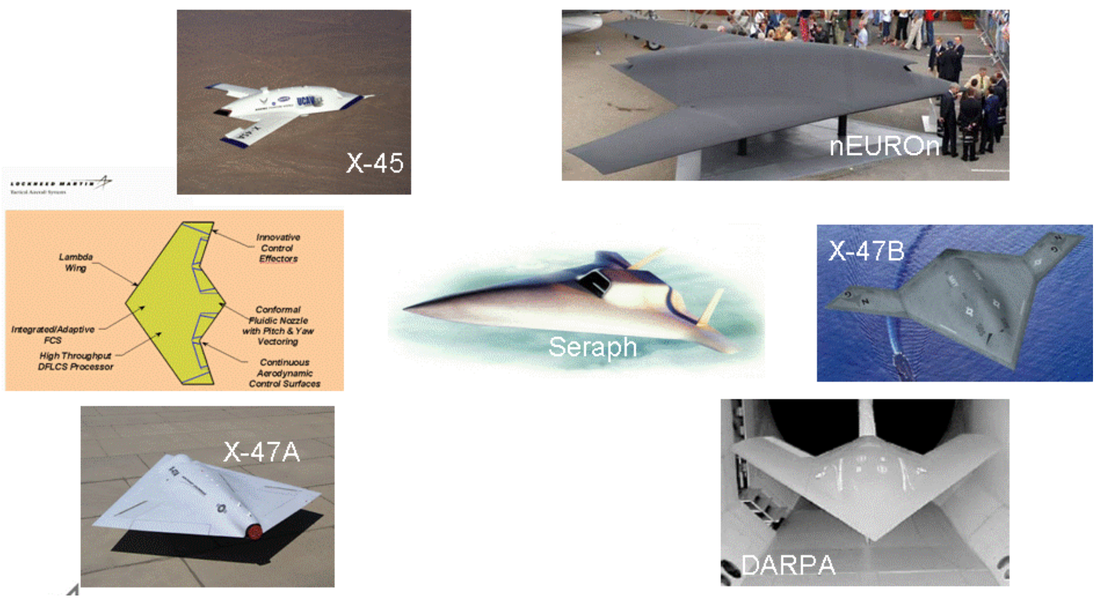

Figure 5: Existing UCAV designs

2.2. Selected configuration

The configuration selected as a basic for the design is a compromise driven by the two requirements of high aspect ratio and stable vortex dominated flow. It consists of a lambda wing with a relatively high aspect ratio. Originally, mostly for aerodynamic reasons and to maximize the wing length for high elastic deflection, a sweep of 65° had been chosen. To come closer to the German configuration proposed to AVT 161, “Assessment of Stability and Control Prediction Methods for NATO Air & Sea Vehicles” [12], Figure 6, the sweep has finally been reduced to 50°. Because of the limited cross section of the wind tunnel, and again to allow a maximum wing length, a half model rather than a full model is preferred.

The wing profile will have a relatively sharp leading edge, being almost symmetric with a slight S-shape for overall vertical flight mechanic stability. The thickness of the profile cannot be much less than approximately 12% the wing chord, as sensors will have to be incorporated. The wing will consist of a parallel leading and trailing edge. Since the wings will be thin, as many of the sensors as possible will be moved to the fuselage section.

The wind speed will be Ma 0.4 to Ma 0.8. The angle of attack is planned to vary between 0 and 20°. The model will be actuated with an active wind tunnel support. Whether the model shall have an additional aileron or a split flap is still under discussion. On the one hand, such a control surface would increase the range of possible maneuvers. On the other hand, an actuation device in the wing will increase the model complexity considerably and very probably stiffen the wing considerably.

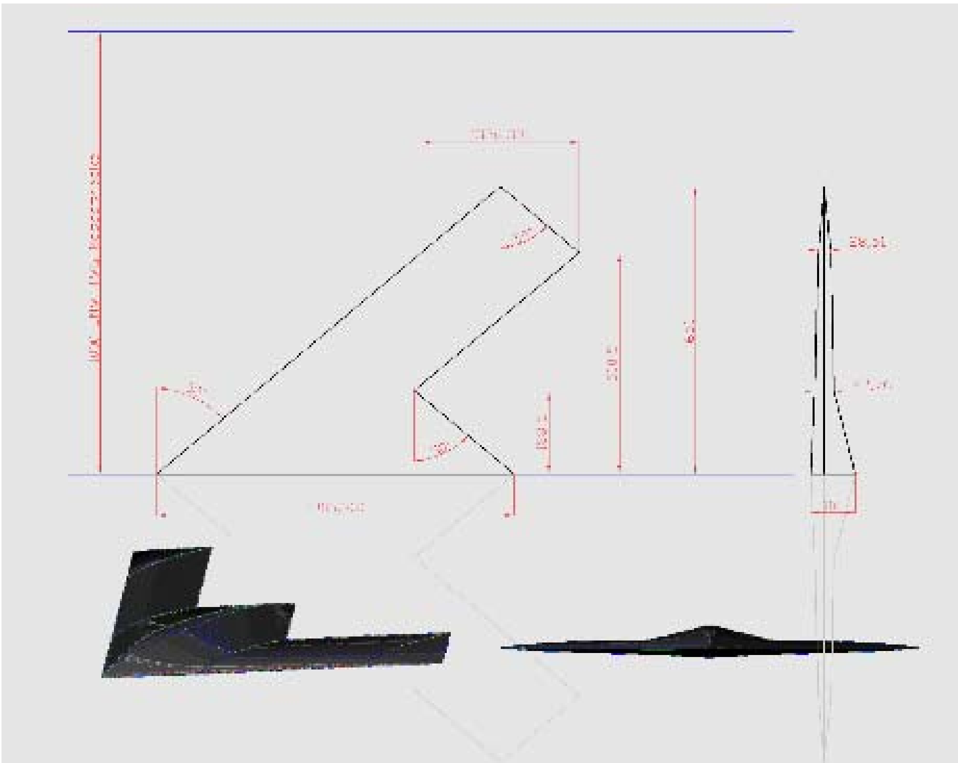

Figure 6: Desing modifications in accordance with suggested AVT 161-model

3.0 STRUCTURAL DESIGN

3.1. Requirements for Flutter Model vs. Static / Transient Aeroelastic Model:

Flutter models and models for the investigations of static or transient aeroelastic behavior have different requirements.

Flutter model:

- Main interest: prediction of flutter points for variable configurations
- Prescribed ratio of structural natural frequencies, possibly scaled
- Relatively thin wing
- Relatively stiff design -> usually small deflections
- Usually low angle of attack

Static / transient aeroelastic model:

- Main interest: large deflections, low frequency motion
- Deflection possibly scaled
- Relatively soft design for large deflections
- High aerodynamic loads -> conflict
- Higher angle of attack

3.2. Structural Design

The structural design of the UCAV model will be driven by the need to obtain a simple, well known structure with little internal damping. The structure should show either little or at least well-defined non-linearities with respect to excitation force level and deflection.

The design will be that of a (double) rib /spar support structure of steel with an aluminum or a carbon fibre skin. The placement of sensors and possibly actuators in the wing is challenging. Loads for the sizing will come from low-order aerodynamic calculations for a first design, and from Euler and RANS calculations for the final design.

Design loads come from the test program. Cornerstones are the requirements for the cases of α = 20°, Ma 0.4, P = 60 kPa, and α = 4°, Ma 0.8, P = 150 kPa. Especially the investigation of dynamic lift development of vortex dominated flow for the pitching wing will be subject of numerical analysis before the final design.

3.3. Safety Criteria for Operation

From these requirements for aeroelastic models, some considerations for safety criteria for operation can be deduced. For static wind tunnel models, traditionally a safety factor of 3 required [13]. This can usually be obtained by heavy design, if necessary, or by a selection of a stiff material. However, this might not be possible for requirements of high deflection, where stiff materially might not yield sufficient deflections, while flexible materials might be too weak. One solution might be the use of high-tensile material, e.g. the use of CrMg4-steel. Such a choice might depend on the manufacturing facilities and price limits and might therefore also limit the design freedom.

4.0 MEASUREMENTS AND ACTUATION

4.1. Test Cases

For the tests, several types of experiments are planned. First, steady aeroelastic deformations will be tested for varying operational conditions. Second, transient motion, i.e. pitch of the wing, will be performed, both sinusoidal and in various steps or ramps. Third, wind tunnel motion coupled to a parallel dynamic flight simulation will be performed (see section 4.3 below). Before the wind tunnel tests, extensive ground vibration tests of the model will be undertaken.

4.2. Sensors / Measurements:

The following measurements will be taken:

- Static deflection
- Transient deflection and motion
- Dynamic pressure
- Flow field
- Model deflection

The deformation of the structure will be measured using laser equipment, accelerometers, strain gauges and the wind tunnel balance. Aerodynamic measurements will be performed with pressure transducers and by optical methods, both particle image velocimetry (PIV) and pressure sensitive paint (PSP).

4.3. Active Wind Tunnel Support

The wind tunnel model will be subject of stationary measurements and transient motion. The model will be measured at various angles of attack and at various reduced pitch frequencies and amplitudes. In addition, a new active wind tunnel attachment will be used. This attachment is capable of real-time motion of arbitrary control inputs. This enables the use of the model in a Software-in-the-Loop environment, where a simulation model of a real aircraft is run and the resulting motion is the input for the actual wind tunnel pitch motion. On the other hand, forces and moments measured in the attachment can be directly played back into the simulation to be used in the next time step. This attachment, working with a high-efficiency electric drive, can be used to simulate small scale motion, e.g. free play or spring characteristic, as well as large scale motion (flight mechanics).

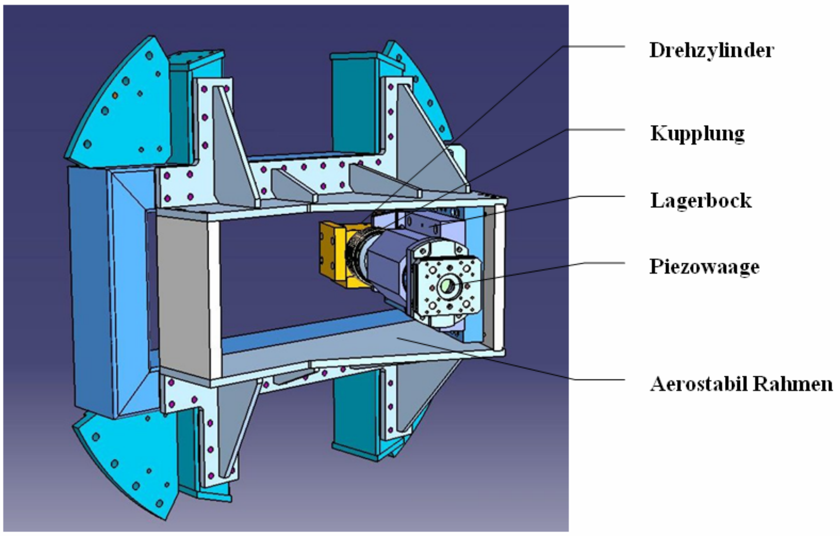

Figure 7: Active wind tunnel attachment

5.0 OUTLOOK

The design of UCAV wind tunnel model used for static and transient aeroelastic investigations has been presented. Main drivers are validation aspects for numerical fluid-structure coupling and investigations of vortex-dominated flow on elastic wings. The work is supported by numerical analysis, both with medium complexity and high fidelity methods. Additionally, multidisciplinary simulation and optimization approaches will be used for fine-tuning the final design and sizing. Model design freeze is foreseen for the end of 2007. Manufacturing will take place in 2008, the wind tunnel campaign is planned to be in 2009. Numerical validation calculations will follow in 2009 and 2010.

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