Study on Unsteady Vortex Behaviour of a Rolling 65° Delta Wing at M=0.8 Using Pressure Sensitive Paint (PSP)

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Abstract

Since the need for improvements in high angle-of-attack maneuverability of aircraft's in transonic flight was of concern, a model was rotated around its longitudinal body axis with a dimensionless rolling rate of ω = 0.0762 (10 Hz), resulting in flow conditions with extensive vortical behavior and strongly non-linear, wing/vortex interference effects.
This paper deals with validation experiments performed at the DLR Göttingen. The objective of this activity was to provide experimental data for comparison with numerical calculations performed within the international WEAG TA 15 group: Alenia (Italy), DERA (United Kingdom), DLR and EADS (Germany), and NLR (The Netherlands). A special 65° delta wing, the DLR PSP-model, was designed, manufactured and finally tested in the transonic 1mx1m wind tunnel DNW-TWG in Göttingen. A rolling apparatus was built up to enable roll rates up to 10 Hz. A new sting concept was developed as elastic simulations showed dangerous problems associated with the rolling model exposed to the periodic aerodynamic load. The experiments were carried out at angles of attack α=10° and 17°, M=0.8, Reynolds number of 5.3 Mio in the case of steady and 2.2 Mio for unsteady conditions.
The model was equipped with only a few pressure taps for PSI and Kulite sensors, as surface pressure distributions of the model should be obtained using the pressure sensitive paint (PSP) technique, to measure the pressure all over the whole surface of the model. As the model was rotating an unsteady PSP technique had to be applied. Several steps had to be considered in order to finally use the measured pressure distributions for comparison with numerical predictions. In the case of steady conditions the results compare quite well with the conventional pressure taps and numerical calculations, in the case of the spinning model discrepancies between Kulite values and PSP as well as numerical results could be stated. Vortex breakdown predicted by the Euler calculations can be confirmed by the experiment.

Introduction

One important question when developing numerical codes on vortical flow fields around delta wings is to understand the influence of vortex stability and vortex breakdown on the aerodynamic quantities [11]. It was expected that experimental surface pressure distributions would provide the necessary input whether or not Euler calculations would be able to capture the correct results. But when applying conventional pressure gauges only a small number of gauges can be implemented into the model. As a consequence it is somewhat uncertain whether the required information will be available. Pressure sensitive paint (PSP) seems to be the appropriate technique as the pressure data are collected all over the entire surface of the model. For steady applications the technique is well known. But for application to unsteady aerodynamic problems the technique is quite new [5]. Especially for vortical flow conditions no experience was available. Thus the objective of the experimental

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14. ABSTRACT

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activity has been twofold: firstly to check on whether the PSP technique is able to provide the necessary data and secondly, whether the experimental results confirm the results obtained by Euler calculations. This report will deal with details of the experimental effort, whereas the detailed discussions on the numerical methods will be presented in a separate paper at this symposium [1].

Experimental work on high angle-of-attack aerodynamics requires also advanced experimental simulation techniques. These include the ability to adapt the wind tunnel to the needs of unsteady flow investigations. The transonic wind tunnel DNW-TWG in Göttingen fulfils the requirements. Adaptive walls and specially developed adaptation procedures minimized the influence of the walls, since the model was rather big, the angle of attack was chosen up to 17°, and the rolling model created unsteady flow conditions.

Wind tunnel

The experiments were conducted in the 1mx1m transonic wind tunnel DNW-TWG in Göttingen [10], a closed circuit wind tunnel for sub-, trans- and supersonic flow for M= 0.3 - 1.2. For this test campaign, the wind tunnel was set up with the 'adaptive test section' , the '3D-support' for proper adjusting a special roll apparatus together with the model. For all cases the Mach number was 0.80 at stagnation pressures up to 100 kPa, resulting in a Reynolds number up to Re=5.3 Million for steady and 2.2 Million for unsteady conditions, respectively.
To generate a continuously rolling of the model at 10 Hz a new apparatus had to be designed and manufactured. In figure 1 a sketch of this apparatus shows some details. Due to a 10° crank the driving motor of the rolling apparatus could be brought into the wake of the sting. Hence the disturbance of the flow could be minimized. The angle of attack of the model was limited to α=17°.

The delta wing model

The model design and manufacturing was carried out in co-operation with the DNW BU GUK, the Institute of Aeroelasticity in Göttingen and the DLR Technical Service of Göttingen/Braunschweig. The 65° delta wing model was equipped with sharp leading edges to provide stable separation conditions. For the force and moment measurements with an internal balance as well as for the instrumentation to use pressure sensors inserted in the model a fuselage is needed. At the rear part of the model a fairing is needed to get a smooth transition of the fuselage-wing combination to the circular sting. This fairing has to be separated either from the delta wing model for not influencing the force measurements and from the sting, because the model and the fairing rotate with respect to the sting. For proper operation of the internal instrumentation like Kulite sensors and amplifiers even the model is rotating a slip connector ring transforms the power and the signals from the rotating model to the non-rotating part of the sting.

Satisfying all the above mentioned, the design of the model ends up as shown in figure 2. A delta wing configuration with 65° swept leading edge, a length of 420 mm, a span of 333 mm, and a diameter of the fuselage of 60 mm, spinning at a frequency of 10 Hz (corresponding to a dimensionless rolling rate of ω=0.0762) was achieved. The location of the pressure holes were defined to provide reference data for PSP measurements.
The complete description of the model is found in [1]. For steady force and moment measurements a six-component TASK balance was used. Local steady pressure measurements were performed using PSI technique. In the case of unsteady pressure measurements the model was equipped with 4 Kulite pressure sensors. Care was taken to keep the volume of the connecting tubing small, figure 3, in order to obtain a small response time. The data were taken with the data acquisition system IDA [12], a new system for unsteady measurements with a maximal sample frequency of 50 kHz per channel at 16 bit accuracy. These pressure data served as reference data for the PSP measurements carried out in parallel.

Sting concept

In order to ensure a safe operation of the rotating model various vibration simulations were performed. As a first attempt set up it was envisioned to have a model at the end of a long sting being operated at a roll rate up to 10 Hz. It can be expected to have a oscillating and somehow rotating lift vector producing two force peaks per revolution which lead to the necessity of having the lowest eigenfrequency located well above 20 Hz. With this in mind a redesign of the model sting was made which lead to the layout depicted in figure 1.
Substantial feature of this new design is a hollow sting that houses a torsional drive shaft. With this a safe operation is ensured as far as a vertical motion of the model (due to elastic bending of the support) is concerned. Horizontal motion is fundamentally determined by the torsional stiffness of the angle of attack sword. For this narrow plate-like structure torsional stiffness is significantly smaller than the in-plane shear stiffness. A shorter sting was not acceptable in order to minimize support interferences. It was therefore decided to use 2 positive loaded anchoring wires that significantly raise the support stiffness in horizontal direction.

A system identification based on a ground vibration test which was performed directly in the test section of the wind tunnel ensured the correctness of the predicted dynamic behavior. Because of the importance of the wire integrity for a safe operation of the model the dynamic wire forces were critically monitored during whole the testing time by 2 load cells.

Pressure sensitive paint PSP technique

The determination of instantaneous two dimensional pressure distributions on the surface of a model in wind tunnels by the application of a pressure sensitive paint can be construed as a major advancement in the field of non-contacting measurement technique in aerodynamics [2],[3]. This method facilitates not only qualitative pressure surveys but also quantitative distributions of the absolute pressure values at every position of the surface of the model captured by CCD-cameras, without introducing flow-disturbing probes or affecting the surface of the model. The conventional pressure measurement methods based on pressure sensors installed at discrete locations of the model may show locally a higher accuracy of measurement, but the 2D information obtained by the PSP-method has definite advantages. Firstly, in case of conventional techniques there are restrictions when creating pressure taps to thin wall of the model; secondly due to desired high number of holes the model experience a deformation depending on the aerodynamic load.

The pressure measurement technique is based on a oxygen-quenching process realized by deactivation of photo-chemically excited molecules with oxygen, resulting in which makes different degrees of luminosity recognizable on the surface of the model. Such a fluorescent image arising under the flow conditions in a wind tunnel can be recorded using CCD-cameras. From this a final pressure map is deduced using complex image processing techniques.

The sensitivity of the employed PSP technique is optimized in the pressure range of 0.3 - 1.5 bar, typically for flow conditions in the DNW-TWG if the stagnation pressure varies. By this procedure for steady flow conditions, the normally used “binary paint ” yields a pressure resolution of around ± 1.5 mbar with a response time of the order of 0.5s. The envisaged unsteady measurements need much higher temporal resolution. Thus a quite other paint had to be applied.

The Stern-Volmer (SV) equations, quantitatively relating lifetime and luminescence intensity to quencher concentration, can be expressed for the intensity method for non time resolved measurements as:

$$\frac{I_{(p=0)}}{I} = 1 + k_{SV} \cdot p \qquad (1)$$

where

$I_{(p=0)}$ - intensity for vacuum conditions, k_{SV} - Stern-Volmer constant, p - local pressure.

An ideal sensor based on Stern-Volmer kinetics requires minimal calibration because the response to the quencher concentration is linear. Although static quenching, inhomogeneous systems and short lifetimes can pose significant barriers, numerous sensors are based on this scheme.

Principally, as mentioned earlier, the optical pressure sensor must be quenchable with oxygen for the application in test facilities like wind tunnels and at the same time enable the measurement of partial pressure of oxygen. Therefore, it is clear that such a sensor must consist of two parts, namely, a binder which is permeable for the diffusion of oxygen and a luminophore for quenching. The diffusion of oxygen is a time-dependent process, in which the thickness l of the polymer layer of the sensor significantly affects intensity of emission. This can be described for polymer binders as follows:

$$t_{relaxation} = \frac{4 \cdot l^2}{\pi^2 \cdot D} \qquad (2)$$

where D is the oxygen coefficient of the binder, i.e., the polymer layer. The permeability of the binder should not be too high to ensure that all the excited luminophores are not quenched by oxygen. Besides, it must be ensured that the luminophores can be quenched by the oxygen diffused through the binder within their lifetime τ [4], [7], otherwise, no pressure-dependent intensity variation can be observed. It gives then an optimum characteristic of the optical sensor for the different cases of application with reference to the maximum pressure changes to be expected (transonic range 0.3 to 1.5 bar) both for the selection of the binder as well as for the

number of luminophores in the binder. In order to achieve the highest possible detectable intensity, the number of the luminophores should be high. They should not react with each other, otherwise, it can lead to irreversible processes. In addition, the sensor must withstand wind loads and the surface has to be flat and smooth to have uniform characteristics over the entire surface of the model. For obtaining a smooth optical sensor on the entire surface, a spray gun is usually employed; mono layer technology to obtain a uniform pressure sensor is under development.
The paint sensor typically consists of three polymeric layers, which are applied consecutively to the models surface as shown in figure 4. They are:

- Screen layer
- Contact layer
- Active layer with different luminophores.

The screen layer is composed of a special white paint which creates an optical uniformity on the model surface, which is independent of the model material and it also enhances reflection of excitation light. The contact layer is applied to ensure adhesion between the screen layer and the active layer. The active layer consists mainly of three components: a polymer layer highly permeable to oxygen (binder), pressure sensitive luminophores dispersed within the polymer and finally, intensity sensitive luminophores which are sensitive only to illumination intensity and insensitive to pressure and temperature for intensity correction of the non homogeneous distribution of illumination.

6.1 Characteristics and calibration of the pressure sensors

Pyrene belonging to a group of aromatic hydrocarbons is well known as a luminophore in optical sensors. UV light of the wavelength λ=330±20 nm from a Xenon flash lamp can be used to excite these types of luminophores.

The characteristics pyrene and ruthenium as luminophores with respect to their sensitivity to pressure become clear from their calibration curves shown in figure 5. In this particular case the calibration curve of pyrene has a more linear behavior than that of ruthenium. The pressure sensitivity of ruthenium based paint appears to be larger than pyrene based paint. The error due to the temperature effects for pyrene is about <0.3%/ °C compared to >3%/°C for ruthenium at atmospheric pressure condition.

A calibration of the optical pressure sensor is necessary for reconstructing a quantitative pressure image from the initial qualitative image of the flow phenomenon on the surface of the model. This can be done mainly in two different ways. In the first one, a test specimen is calibrated parallel to the model paint and subsequently, subjected to known pressure and temperature in an external calibrating chamber. In the other case, the entire model can be calibrated in the wind tunnel itself, provided pressure changes can be statically produced at constant temperature in the test section. In the external calibration chamber the pressure and the temperature can be varied and consequently the described temperature-dependent calibration constants can be determined and related to pressure reconstruction. When there exist large temperature distribution effects on the model surface it is necessary to correct the pressure computations using thermo-couples or IR-cameras. As already mentioned, this is much more easier using pyrene based paint than ruthenium based paint because of the temperature sensitivity. The disadvantage of an external calibration procedure consists in the fact that the test specimen can indeed be painted simultaneously with that of the model, but definitely will not possess identical optical properties as that of the model, typically due to possible differences in the thickness of the layer. Therefore, if possible, the direct calibration of the model is always preferable, since automatically the peculiarities of the model geometry and the layer thickness are taken into account. In addition, for every angle of attack of the model a separate calibration data set can be calculated. The procedure leads to a calibration for each pixel of the obtained image of the wind tunnel model and therefore, a higher resolution of the pressure data is possible.

The local accuracy obtained using the PSP-method is about 1% in comparison to less than 0.02% of the conventional pressure measurement methods for an absolute pressure of 1 bar. As the DNW-TWG is a closed wind tunnel the pressure of the test section could be varied in the range of 0.3 - 1.5 bar. By carefully observing the temperature and maintaining the line of sight of the camera fixed for every angle of attack each pixel was calibrated individually.

6.2 Components of the DLR PSP system

The PSP system is mainly composed of CCD cameras, carefully distributed illumination devices, local data acquisition system, and the on-line evaluation computer [6].

A sophisticated acquisition and processing subsystems is required including camera boards, synchronization units for 4 cameras, light source trigger, a 120 Gbyte hard disk for data storage. A software package, running under Windows95/98/NT has been developed in order to facilitate management of all the tasks executed not only during the wind tunnel test but also for post processing. This software allows extraction of the absolute values of the measured pressure distributions by means of processing the acquired data together with the calibration data.

With the aid of the pressure tap instrumented model in the wind tunnel, shown in figure 6, it is possible to compare the PSP measurements with simultaneous pressure measurements using the conventional pressure tap data for a comparative assessment.

The PSP data was taken by using two CCD cameras with high pixel resolution; one camera to obtain the "pressure image" and the other to take "intensity image" simultaneously on the binary paint-coated model.

6.3 Response time investigations

Experiments in a shock tube have been performed to measure the response time of two different pyrene based paint samples, the binary paint for steady measurements with the active layer thickness typically of about 20µm and the "fast binary paints" with thickness of about 2µm. The measurement results in the shock tube using these paints (figure 7 and 8) show the response time for steady paints and unsteady fast binary paints. The figures also give a comparison between Kulite measured and the PSP measured pressures. Using fast binary paint, with short response time only allows time resolved measurements up to 10Hz. The figures clearly show that at this frequency the paint can hardly resolve harmonics of the shock tube characteristics.

6.4 Processing PSP images

The final data processing took into account the 3D surface of the model in contrast to the 2D image of the model surface obtained by a single camera. Markers on the model surface provided reference points for appropriate transformation procedures.
Firstly steady cases were investigated in order to check for proper experimental conditions [8],[9]. Various sting configurations and paints for the pressure measurements have been tested. In these cases, four conventional pressure taps in the model served for calibrating the PSP system and also for correcting for unwanted light contributions due to light scattered from the walls of the test section. In the case of unsteady measurements, the conventional pressure sensors were replaced by Kulites.
Each measurement consisted of two images, one for each of two sides. All the images together provided the pressure information from the top side of the model. Alignment of corresponding images was performed using the markers on the model surface. After this step, taking into account the reference pressure values and the calibration images, Cp fields were obtained and high frequency noise was removed by appropriate filtering. Finally the Cp fields were resected on the actual model geometry.

The goal of approximation applied to the PSP images is to reduce the huge number of local pressure data provided by the about 500 000 pixel of the CCD-cameras to the much smaller number of the grid points used by numerical codes. Approximation functions were chosen to correspond to the physical model of the process under study. As a periodical process is present it is quite obvious to use harmonical analysis. Moreover such approach provides as a global result amplitude and phase distributions as function of the rolling angle. The accuracy of the measured data is determined by the accuracy of the amplitude as well as the unknown distributed time-response function of the PSP layer.

The general concept includes to use Kulite data as reference for evaluation of the PSP time response function in the vicinity of the Kulite measurement point. Using estimations of the relative paint thickness - the main parameter governing PSP response function - the response function distribution on the total model surface should be obtained. Due to a systematic error in PSP measurements, from Kulite data also the calibration and offset curves have to be taken. If the paint response time is short enough and small in comparison with rotation period of 100msec, the influence of the dynamic behavior of the paint should be negligible. The inaccuracy should then be due to static measurement errors.

7. Experimental Results

7.1 Results based on conventional pressure measurements

The conventional steady pressure measurements using the PSI system were carried out simultaneously with those of PSP measurements, having the same time order of magnitude with reference to their integration times.

The data in figure 9 represent data for different sting configurations, a straight sting and the cranked sting with rolling apparatus, at discrete roll angles of the model. Small differences represent the different magnitude of interference effects if the blockage of the stings is changing. They seem to be acceptable as these differences correspond to about $\Delta Cp=0.1$ regarded today as the overall accuracy of this kind of test. Additionally in the case of steady flow conditions force and moment measurements were performed.

Figure 10 shows for the pressure tap K4 (see figure 2) located where vortices are expected a typical curve for the unsteady case in comparison with data for a sequence of discrete roll angles. The rolling rate of 10 Hz results in a shift of about 10°. Moreover although the rolling rate is rather small the two kinks, at roll angles of – 45° and + 45° show already real unsteady effects.

7.2 Steady conditions

Typical results at steady conditions for Ma=0.8 and α = 10° are presented in figures 11 and 12 and for Ma=0.8 and α = 17° in figures 13 and 14. The integration time of the PSP system was about 10s using the UV illumination device as described before. Fluctuation in the intensity of the light source easily can be corrected with the help of the reference molecules which are not sensitive to temperature or pressure.

Although the necessary “data reduction” from about 500 000 individual pressure values originating from the pixel measurements has to be reduced in our case to about 10 000 grid points of the model surface and results in some smoothing, the surface pressure distribution contains scatter. This is a large disadvantage using rough grid nets of CFD because eminent pressure information can be lost. In particular close to wing body connection and at the central part of the fuselage pressure “jumps” of about $\pm \Delta Cp = 0.1$ are sometimes visible. These refer to well known errors originating from reflections and from fitting together two individual images of the two cameras. Some improvement of the evaluation procedure already under way will remove these errors in future.

Figure 15 shows a typical comparison between Euler code calculations and PSP measurements. The discrepancies between measurements and calculations are obvious. In fact, PSP measurements are an excellent tool for modeling the initial and boundary conditions for numerical calculations because the flow in leading edge region and at the cropped area are not well calculated.
The overall statistical measurement accuracy can be estimated as $\Delta Cp=0.03$, whereas the local inaccuracy may increase up to $\Delta Cp=0.1$ for the wing area.

7.3 Unsteady conditions

Figure 16 and 17 show a comparison between PSP and Kulite data at a cross section of x/c=0.42 for different roll angles. The PSP data represent fairly well the Kulite data. This is not surprising as the Kulite data are used as reference for offset correction when the PSP measurements are evaluated. But note, reference data are only collected for the one half of the surface. As a result the PSP evaluation of the other half of the surface is completely based on the reference data collected on the first half of the surface. From this point of view the evaluation procedure looks very powerful, that there are still discrepancies can be accepted after this first measurement campaign. Again as mentioned before, improved evaluation procedures and moreover, newly developed paint for application in unsteady aerodynamics can overcome this inaccuracies.

Figure 18 shows for example, the resulting unsteady surface pressure distribution for the rolling model at an angle of attack of α=17° and a rolling angle of ϕ=30°. The PSP measurement reveals the complex structure of the flow field very clearly. The result has been used for comparison with that of the Euler calculations, see [1]. As mentioned above final evaluation procedures, already well known for steady PSP measurements like lens and offset correction etc. are necessary. Due to the results of the Kulite sensors at the position x/c=0.42 a correction procedure for the PSP measurement can be developed, see figure 16 and 17. This PSP correction procedure leads to a satisfying agreement between the experimental and numerical result at the chord length position x/c=0.42, see figure 19. In [1] this correction has not been applied which would mainly result in a shift of the hole data of about –0.1 to 0.2. As in the steady cases the measured pressure suction peak values along the vortex axis are lower. A detailed discussion will be found in the second contribution to this symposium dealing with the numerical results [1].

7. Conclusions

The successful test campaign on the steady and unsteady vortical flow behavior of an highly inclined delta wing at M=0.8 in the transonic wind tunnel DNW TWG was possible by the collaboration of the different groups of the

institutes for Fluid Mechanics and Aeroelasticity, DNW BU in Göttingen and the Technical Service in Göttingen/Braunschweig.
Strategies to set up a rolling apparatus, to acquire data even the model is rolling, and to perform adaptations of the wall of the test section although unsteady flow conditions are present, had to be developed.
For the first time the PSP technique for surface pressure measurement has been applied to an international project. As demonstrated by the steady results, this technique is capable of providing quantitatively information about the flow behavior for comparison with results obtained by Euler calculations. PSP obtained pressure distributions allow a much better analysis of the flow field than conventional pressure tap techniques. The overall statistical measurement accuracy can be estimated as ΔCp=0.03, whereas the local inaccuracy may increase up to ΔCp=0.1 for the wing area.
It has been shown that the intensity PSP system can also be used for unsteady pressure measurements in transonic wind tunnels. As a general result it could be shown that the PSP technique not only offers quantitative pressures but also gives useful initial and boundary conditions necessary for numerical flow simulations.

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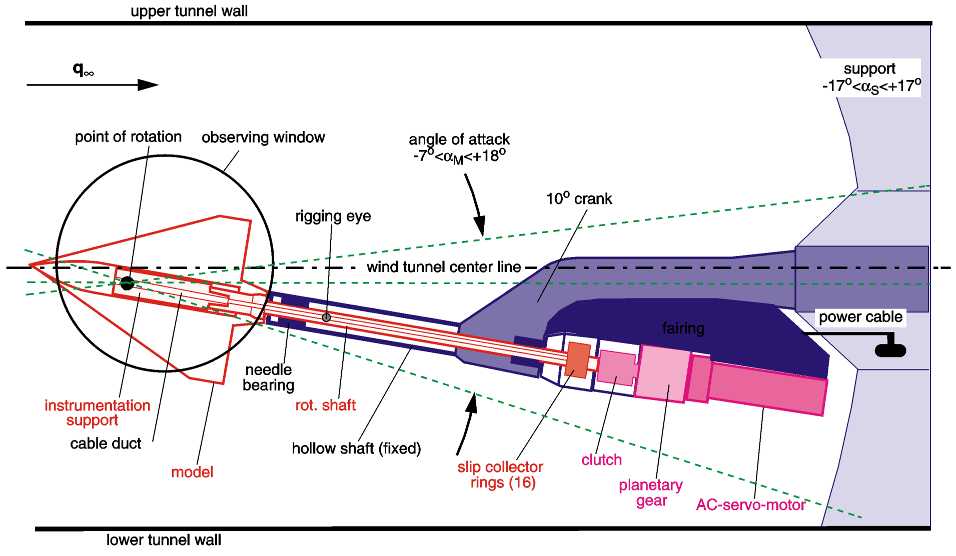

Figure 1. Sketch of the rolling apparatus with mechanical and electrical details

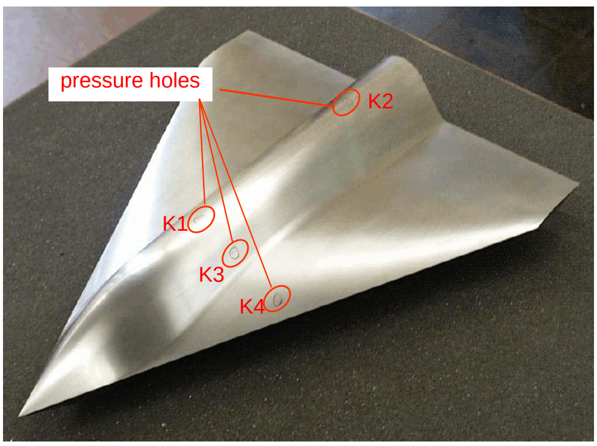

Figure 2. Photo of the DLR-PSP-model with pressure holes

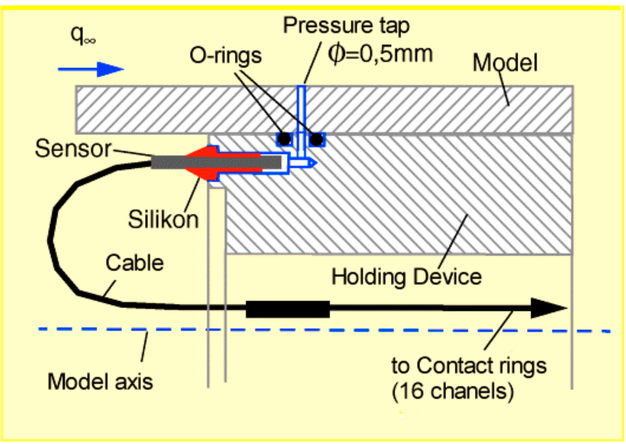

Figure 3. Connection from pressure tap to Kulite sensor in the spinning model

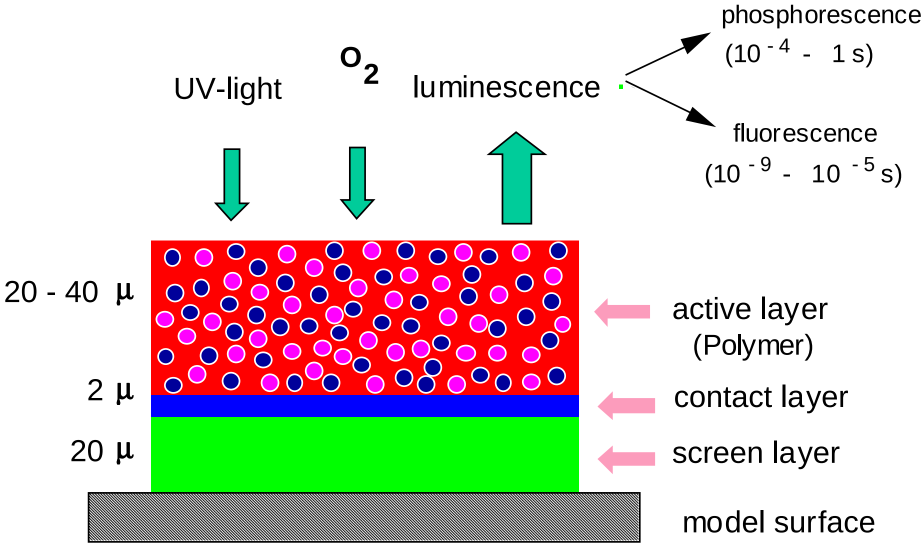

Figure 4. The different layers for coating the model surface with "binary paint"

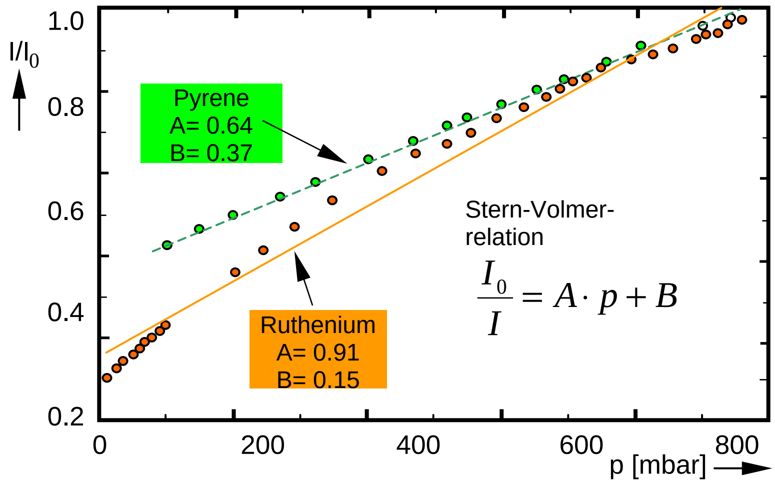

Figure 5. Typical Calibration curves for two different types of luminophores

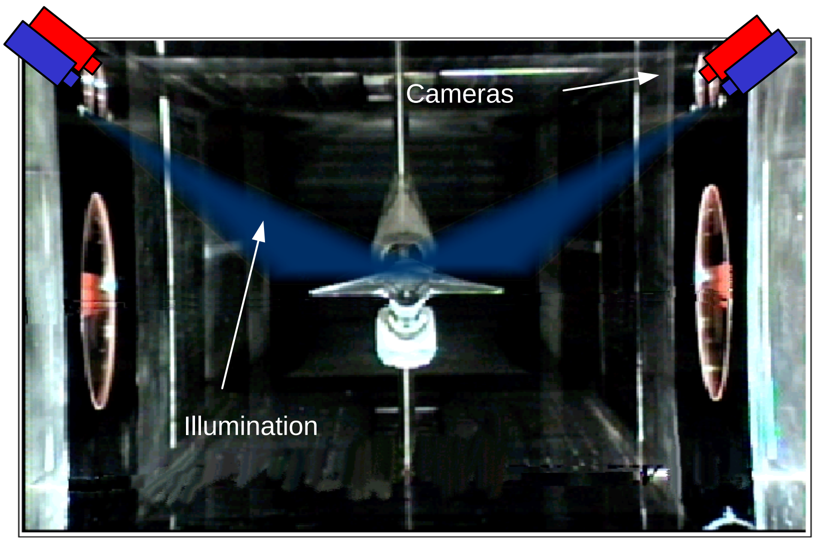

Figure 6. PSP model in the test section the adaptive wall and position of the cameras in the TWG for unsteady measurements

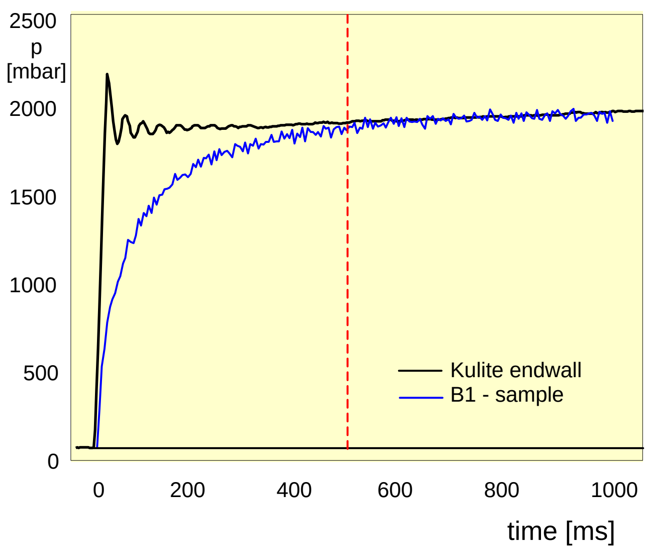

Figure 7. Response time τ for steady binary paint

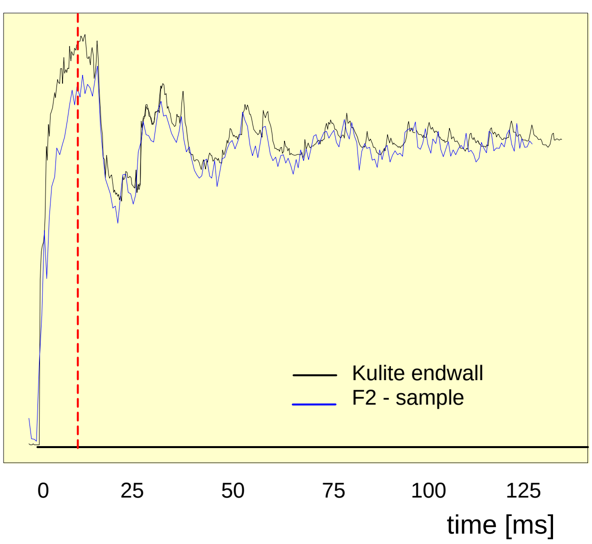

Figure 8. Response time τ for fast binary paint

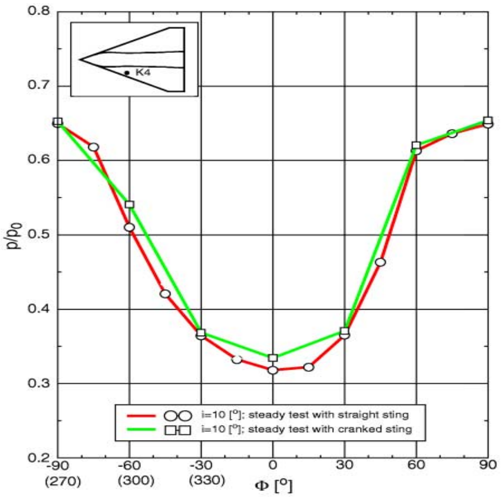

Figure 9. Comparison of pressure data for different stings (steady tests).

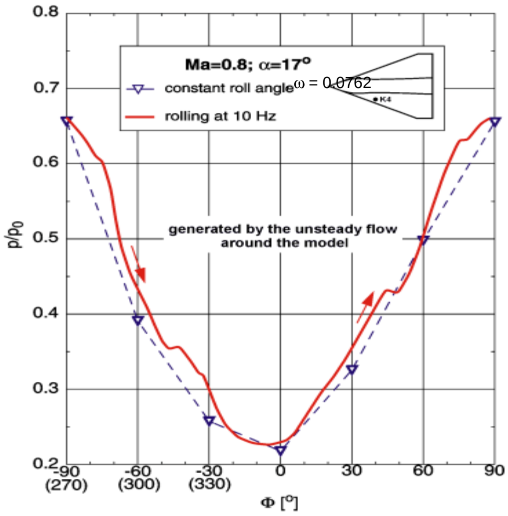

Figure 10. Comparison of steady and unsteady pressure data at tap location K4

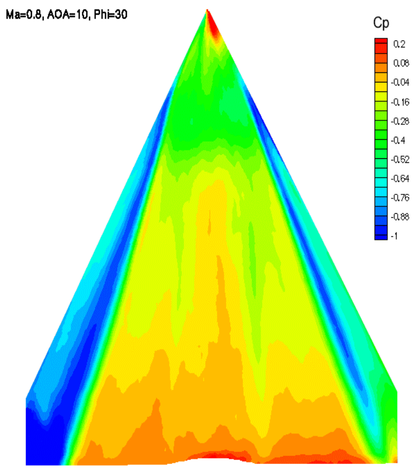

Figure 11. PSP pressure distribution at Ma =0.8, α =10°, Φ =30° for steady condition

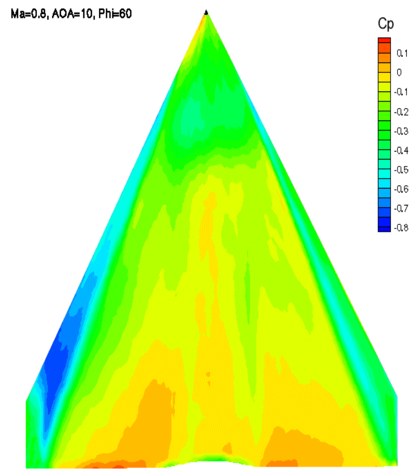

Figure 12. PSP pressure distribution at Ma =0.8, α =10°, Φ =60° for steady condition

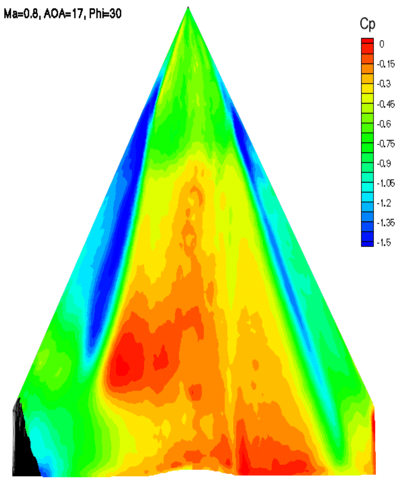

Figure 13. PSP pressure distribution at Ma= 0.8, α =17°, Φ =30° for steady condition

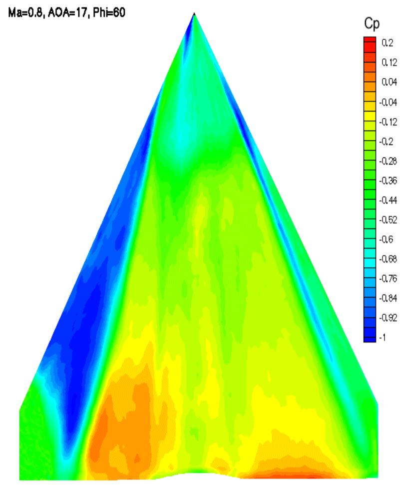

Figure 14. PSP pressure distribution Ma =0.8, α =17°, Φ =60° for steady condition

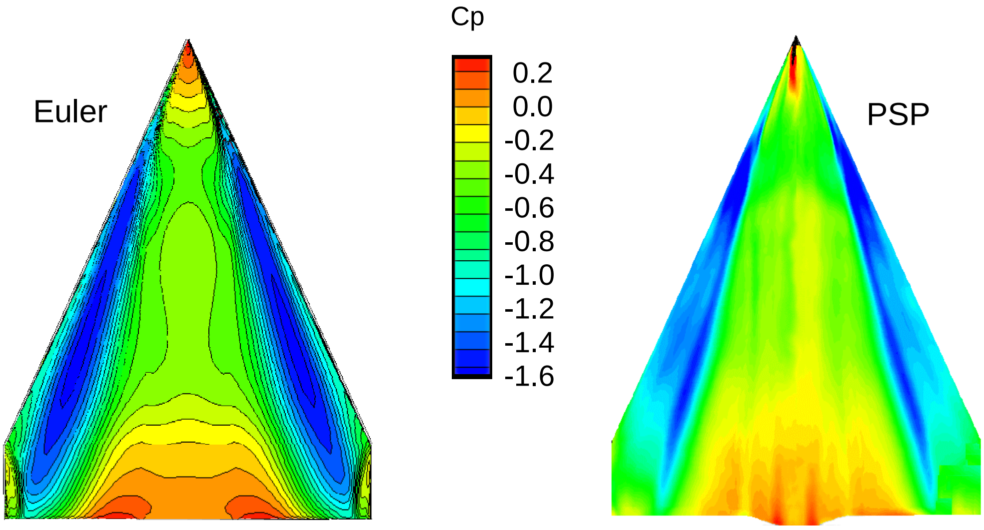

Figure 15. Comparison of Euler - calculation and PSP - measurement at Ma =0.8 , α =17° for the PSP model, measured in the TWG for steady conditions

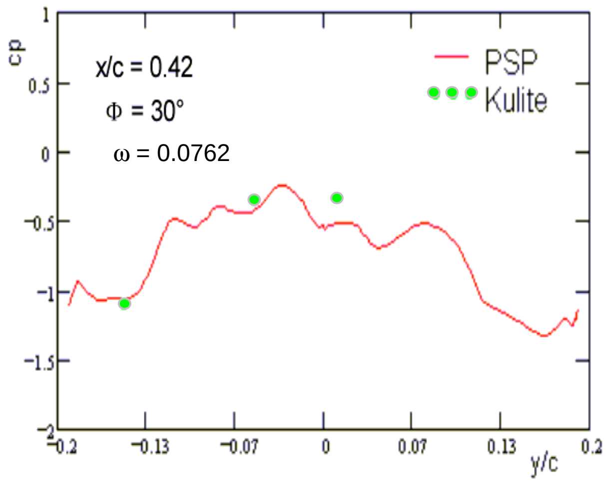

Figure 16. Comparison between PSP and Kulite Ma =0.8, α =17°, Φ =30°, x/c =0.42 for unsteady condition

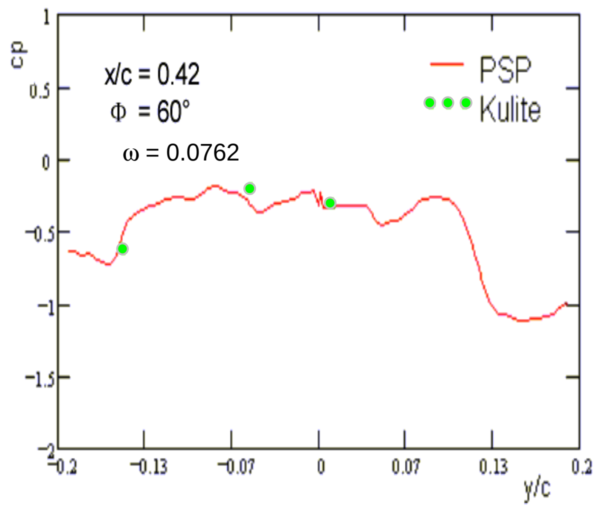

Figure 17. Comparison between PSP and Kulite Ma =0.8, α =17°, Φ =60°, x/c =0.42 for unsteady condition

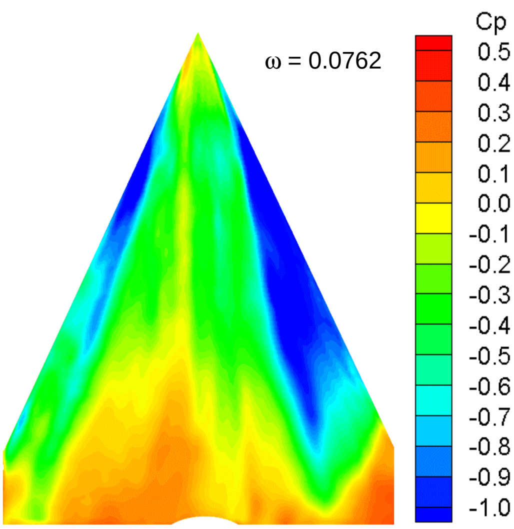

Figure 18. PSP pressure distribution at Ma =0.8, α =17° and Φ =30° for unsteady condition

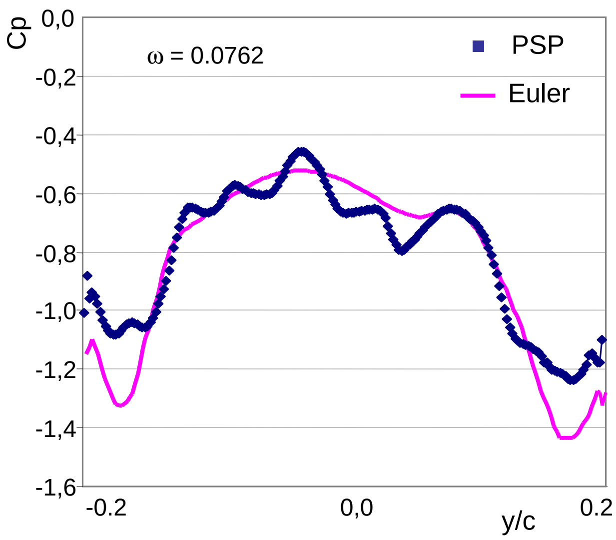

Figure 19. PSP and Euler comparison for Ma =0.8, α =17°, Φ =30°, x/c =0.42 for unsteady condition

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