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Method of optical tracking to determine forces on free flying models in hypersonic flow

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Abstract The accurate measurement of aerodynamic forces and moments in high enthalpy short duration hypersonic facilities has traditionally been a very challenging task. The short measurement time intrinsic to these facilities entails that stress equilibrium can typically not be established during the test duration, neither within the model nor the supporting sting. This matter makes measurements through conventional force balance techniques almost impossible. An elegantly simple alternative to force balances is to allow the model to fly freely in the flow and to determine the forces from the resulting motion. Additional advantages of this free flight technique are the flexibility of model design, and the ability to omit the sting support and accompanying sting/base-drag interference. The induced accelerations can be either measured directly, using internally mounted accelerometers, or derived from displacements inferred from a visual record of the model trajectory. A sequence of images is acquired at high speed capturing the model movement. An algorithm is used to match the model contour in the images with the known model contour. From the resulting model displacement over time, aerodynamic forces and moments can be determined. The development and implementation of this technique at the High Enthalpy Shock Tunnel Göttingen (HEG) of the German Aerospace Center (DLR) is described and exemplified using an experiment with a free-flying capsule model.

Keywords: hypersonic flow, high enthalpy, forces, moments, optical tracking, contour tracking, high speed flow visualization, capsule, Schlieren, edge detection

1 Introduction

The short time span, typically a few milliseconds, during which a steady flow state is maintained in a high enthalpy shock tunnel, complicates the accurate measurement of aerodynamic forces and moments acting on a wind tunnel model. Conventional force measurement approaches rely on the establishment of stress-equilibrium within the model and its support, and are thus impractical for short-duration hypersonic facilities such as the High Enthalpy Shock Tunnel Göttingen (HEG) as already described in [1]. An elegantly nonintrusive approach to obtain aerodynamic force and moment measurements in these types of facilities is the so called free-flight technique. Free-flying in this context means, that after the detachment of the model from an initial support, it is allowed to move freely in the flow during the test time. Translational and angular accelerations of the model can be measured and allow a subsequent calculation of the aerodynamic forces and moments when knowledge of the center of mass and mass is given. One way to record the model acceleration is by instrumenting it with internal acceleration sensors and and on-board data loggers. This approach has been implemented and successfully tested at high-enthalpy shock tunnels as reported in [2]. It eliminates interference with supporting structure (e.g. stings) but requires intricate model design and a soft catching mechanism to safely retrieve the model after the test. At HEG, optical tracking of the model movement is employed to evaluate experiments using the free-flight technique. For this, the model movement is recorded by optical means during the flight phase. By using contour tracking algorithms, the rate of change of the model's position and orientation over time is obtained from the recorded images. This measurement method is suitable for short duration tests and allows for great flexibility in the model design. Main stages of the development of force measurement techniques at HEG are outlined in this paragraph. Early experiments to obtain force and moment measurements (namely lift, drag and pitching moment) in HEG were realized through the development and application of a three component short duration force balance as reported in [3]. The measurements were based on evaluating the dynamic response of the model through the propagation of stress waves, known as Stress Wave Force Measurement Technique. Strain gauges were used to record the time history of strain in five oriented bars connecting the test model with a supporting sting. A deconvolution calculation of the strain signals in combination with the impulse response function of the model (to be determined separately) yielded the aerodynamic force in an experiment. This technique allowed force measurements on short time scales (milliseconds and below) within appropriate uncertainties. Unfavourable characteristics of this technique were the need to adapt the force balance to each new model and the required extensive calibration. The presence of a sting carried the inherent danger of interference with the flow field. Based on previous activities at the T5 shock tunnel of GALCIT by [4, 5, 6], optical tracking was developed and implemented at HEG [7, 8]. In this context, algorithms for contour detection and tracking were derived and implemented in the HEG data evaluation software. In subsequent measurement campaigns, optical tracking was used in combination with models that involved stings or other support methods serving as catching mechanism to secure the test model after flight [8]. This was typically achieved through providing sufficiently deep cavities in the model and aligning them with a male counterpart on the support structure. During the test time, the model can move with the flow and afterwards, it is pushed onto the support structure in which it retains thereafter. This technique showed to be very suitable for axial flow cases and also holds the option of transmitting signals to the outside from internal model sensors through cables in a hollow sting. However, due to the close proximity of the model and its retainer (in some setups, a support sting intruded into the model), interference effects still remain a concern. It should also be noted, that large variations of the angle of attack require modifications to the model and/or the support with this approach. With confidence in the accuracy of the optical tracking technique gained through these experiments, the last step toward an entirely free flight was to eliminate the sting support and let the models fly freely in the flow altogether. This requires means of aligning the model in the tunnel test section as well as model release and catching mechanisms. A simple but effective model hold and release option is to suspend the model in the tunnel test section using weakened strings, which are sliced and carried away by the onset of the hypersonic flow [9]. This technique showed good results in HEG, providing a suitable way to align the model and disconnect from it timely, while imposing no additional significant forces and moments.

2 Optical Tracking Technique

Using the free-flight technique paired with optical tracking involves three major activities: acquiring high-contrast images of the model during free flight, detecting the model location and orientation in these images and evaluating the detected model shift and rotation to obtain aerodynamic force and moment measurements. This section elaborates on these steps and outlines how they are currently implemented in the experimental routine at HEG. For the optical tracking method applied images of the model during free-flight are required to allow distinct identification of the model contour. Such high-contrast images are obtained using a z-type Schlieren setup shown schematically in Fig. 1. The beam emitted from the light source is collimated by a spherical mirror (H1) and passes through the test section via two circular windows. On the opposite side, it is re-focused by an identical mirror and after reflection of a secondary mirror (M) is focused on the chip of a high-speed camera by using a lens (L), or lens system. At the focal point, a vertical knife edge (R) may be placed to visualize the flow structure and allow determination of shock shape and standoff distance. The focal plane (FP) of this setup is usually out in the vertical centre plane of the model.

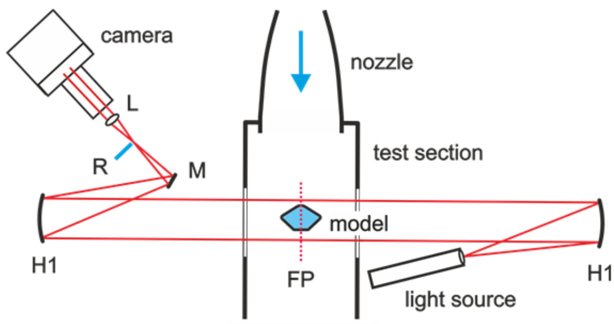

Figure 1. Setup of the HEG Schlieren visualization system used for optical tracking experiments.

For the experiment discussed in this paper, a Phantom v1210 high-speed camera is used to acquire a sequence of Schlieren images, including the steady test time. Images can be recorded with varying resolution and framerates, while, as with most digital high speed cameras, higher framerates can be achieved by lowering the resolution. The lowest possible value for the camera exposure time is 0.468 µs. As a light source, a Cavilux Smart laser is used. It provides repetitive 10 ns light pulses with a wavelength of 690 nm. To exclude extraneous light (e.g. self-luminosity from the flow and unwanted stray radiation) a narrow band-pass filter is placed in the optical path before the knife edge. The main purpose of the tracking algorithm applied at HEG is to match a given model geometry with the recorded Schlieren images and provide values for the position, angle and scale of the model in each respective frame. A detailed discussion of possible algorithm concepts is given in [5, 6, 7] for multiple stages of development. Here, the algorithm is presented in the latest form currently implemented at HEG, including additional routines for outlier removal. The main steps of the iterative tracking algorithm are: Compute gradients of the Schlieren image; mark pixels of high intensity; subpixel refinement of edge points; compare analytic model description with edge points; iterative optimization of fit and removal of outlier pixels. From the recorded Schlieren video, the frames of interest are selected by the operator and handed over to the automated tracking routine, along with an initial guess for the free parameters in the first frame: model horizontal position x, model vertical position y, angle of attack α, and scaling factor f_S. As first step of the contour detection routine, the recorded images are treated with a Canny edge detector [10]. On the resulting gradient image, the model contour is given by pixels of high intensity and thus easily accessible. Those pixels with intensities above a given threshold are marked for further consideration. Through an optional subpixel detection routine, the accuracy with which the edge points can be located on the acquired images can be improved from pixel level to sub-pixel precision. This is achieved by replacing actual pixel locations with virtual positions calculated by making assumptions on the light intensity gradient behavior at contour edges. One example for this is a routine previously described in [11]: Each marked pixel is compared to its eight neighbouring pixels and the direction of the intensity gradient (orthogonal to the edge) is determined. A quadratic function is then fitted to the intensity gradient along this direction and the new edge point is set at the location of its maximum. Multiple subpixel detection routines were implemented at HEG and evaluation of the most suitable is still ongoing. The initial guess for the free parameters (x, y, α, f_S) is used in conjunction with an analytic description of the model contour to obtain an expression for the theoretical model radius $r_a(\theta)$ as a function of the internal polar angle θ. Subsequently, the marked edge points P_i are also transformed to polar coordinates and compared to the analytic contour. The root mean square (RMS) residual is used as indicator for the quality of the fit $RMS = \sqrt{\sum_i \left[r_i - r_a(\theta_i)\right]^2}$.

Fig. 2 shows the known analytical model contour expected to be found in the Schlieren images (blue). Its position and orientation is given by the initial guess or the last available set of the four free parameters. The goal of the following calculations is to shift, tilt and scale this description (i.e. to optimize x, y, α, f_S) to create a best match with the identified edge points P_i and thus obtain an updated description of the model location and orientation on the respective image (grey).

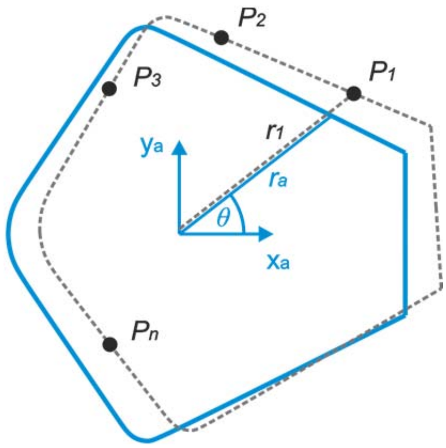

Figure 2. Analytical model description (blue) and reconstructed tracking object location (grey).

This optimization is achieved by applying a Levenberg-Marquardt solver [12] within an iterative routine that alters the free parameters (x, y, α, f_S) in order to improve the quality of fit, lowering the RMS (Eq. 1). This solver was found to converge within a few iteration steps. Pixels that lie further away from the detected contour than a user-defined fraction of the variance of all determined summed squared differences are considered to be outliers. By gradually excluding these in the convergence process, the number of considered pixels is further reduced until an optimum is obtained, where all considered edge points fall within this threshold. After this converged solution is found, the procedure is re-started for the next image, using the last obtained set of the free parameters as new initial guess. The results of the optical tracking algorithm combined with the time stamps provided by the high-speed camera yield the time-resolved model displacement in x- and y-direction, as well as the change in angle of attack. If the calculated displacements are very noisy, an optional Savitzky-Golay filter [13], based on fitting a low-degree polynomial to segments of successional data points, is employed to smooth the data for visual inspection. Its advantage over other smoothing techniques (e.g. moving averages) is that it does not cut off high frequencies but incorporates them in the calculation. The Savitzky-Golay filter does not introduce major distortions and preserves features like local peaks. The test time window is chosen in such a way that the flow conditions are approximately stable throughout. Differentiation of the displacement record with respect to time yields the velocity and acceleration of the model. Additionally, assuming a constant acceleration during the test time and least-squares-fitting the time-displacement profile using a quadratic function yields the model acceleration from the fit constant c: $a = 2c$. Aerodynamic forces (i.e. lift, drag) are then obtained by multiplication with the known model mass. The residual of the fit serves as error estimate. Changes in angle of attack are evaluated likewise and multiplication with the corresponding rotational inertia yields the pitching moment.

3 Experimental Setup

The High Enthalpy Shock Tunnel Göttingen (HEG), operated by the Institute of Aerodynamics and Flow Technology of the German Aerospace Center (DLR), represents one of the major European hypersonic test facilities. This free-piston-driven shock tunnel is capable of providing stagnation pressures of up to 200 MPa and stagnation enthalpies of up to 23 MJ/kg, allowing ground-based simulation of spacecraft re-entry and hypersonic flight up to Mach 10. In HEG, driver gas is compressed by a pressure-accelerated piston until a primary diaphragm bursts. The expanding driver gas compresses the test gas in the shock tube by a strong shock wave, which traverses the shock tube, filled with the test gas, and after reflection at the end of the shock tube provides a high-temperature, high-pressure reservoir in front of the convergent-divergent hypersonic nozzle. Fed by gas from this this reservoir, the nozzle then delivers the hypersonic gas flow to the test section. The start of the usable test time is determined by the establishment of steady flow conditions, and its end is usually driven by contamination through the arrival of driver gas. Further details on the tunnel and its operating conditions are given in [14]. To illustrate the operating principle and capabilities of the optical tracking technique, an exemplary evaluation of an experiment with a free-flying capsule model in HEG is described below. The experiment presented in the following represents one run of a recently conducted measurement campaign, in which the effect of a capsule's varying forefront steepness on the shape and standoff distance of the bow shock was analyzed depending on the kinetic free stream energy. We show the processing on one of these experiments exemplarily. Numerous capsules were manufactured that featured a spherically blunted cone front and a truncated frustum back, interconnected by a radius that provided steady transition between both shapes. The models differed with regard to the half angle of the front part. Each capsule's cross section, an example was already shown in Fig. 2, may thus be analytically described by a collection of circular arcs and straight lines. The capsule model for the selected run was manufactured by turning and featured a 56° half angle on the windward side. It was made from aluminium and possessed a mass of 515 g. Separated by 60° along the waist circumference; two small holes with diameters of 0.6 mm were drilled into the model and thin Kevlar® threads glued into these holes. Both threads were then used to attach the model to the HEG test section's ceiling, as shown in Fig. 3.

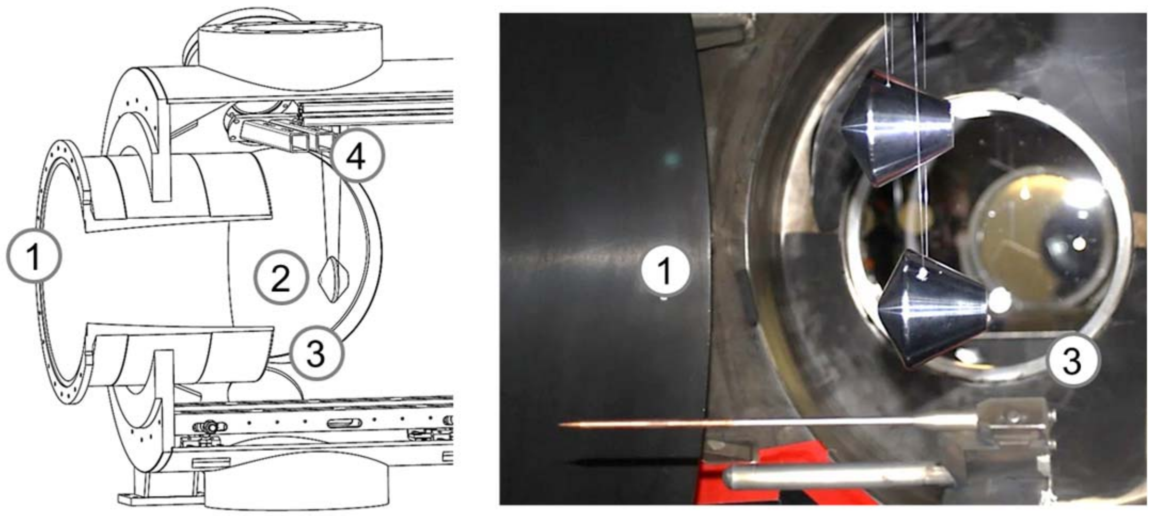

Figure 3. Capsule model mounted in HEG test section (left): 1:wind tunnel nozzle; 2:capsule mode; 3:test section observation window; 4:thread support structure. Photographic view of two capsule models installed simultaneously in the test section (right)

The experiment was performed using HEG condition XIII, which features a specific stagnation enthalpy of 3.2 MJ/kg (low enthalpy condition) at a Mach number of 7.4. The free stream pressure for this condition is 2030 Pa, the free stream temperature 264 K and the free stream density is 0.0270 kg/m^3 at a flow velocity of 2400 m/s. These values are partly measured with free stream and nozzle stagnation probes and partly calculated by numerical simulation. High speed Schlieren images were recorded (resolution of 640x512 pixels; framerate of 32,000 fps) as described in section 2.1. With the onset of the flow, the threads experienced force applied from the flow causing a deflection, which in turn causes the threads to detach from the glue points on the model. By the time a steady flow is fully established, the beginning of the measurement time window, the threads have already travelled downstream and out of sight. The sample images given in Fig. 5 show the recorded sequence exemplary before flow start, shortly after the model's detachment from the strings and the free floating capsule during the test time. For each run, a new capsule model was used, so that a soft capturing mechanism was obsolete. The models traversed the test section and were caught with rubber mats glued to the adjoining dump tank walls.

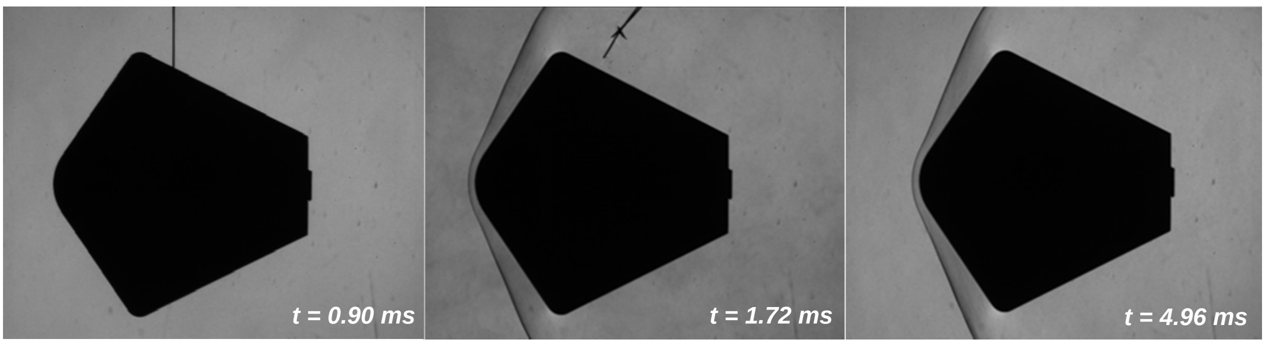

Figure 4. Capsule model before the test (left), after detachment (middle) and during free flight (right).

After the experiment, the captured Schlieren video was analyzed using the optical tracking technique steps described above. For this a file with an analytic description of the model contour and an initial guess for the free parameters that specify the approximate model position at ax and y, angular orientation α and scaling f_S in the first frame is provided to the solver. With these inputs, the algorithm now automatically optimizes x, y, α and $f_{S,}$ for all frames within the desired range of the Schlieren sequence. In the presented case, an axially symmetric model was used with no angle of attack. Therefore, only the obtained variation in x position is of relevance. Subsequently, using pressure measurements taken in the nozzle reservoir and in the test section, the time during which steady flow was present is identified.

Results

The tracking result of the model displacement profile for the representative experiment described above is shown in Fig. 5 on the left. The obtained displacement from the optical tracking algorithm is drawn in black color. The corresponding velocity and acceleration, which are obtained by successive differentiation are given in the plots in the middle and on the right in Fig. 5; here again plotted in black color. The actual test time of the facility is determined on the basis of different pressure and heat flux measurements obtained on probes in the test flow and on the startup behavior of the tunnel nozzle. Since the test time was selected as such that the pressures remain constant, constant model acceleration and thus a quadratic model displacement is expected within this time period. Consequently a quadratic polynomial was fitted to the displacement profile during the test time (shown in red) in the least-squares sense. The coefficient c of this fit gives half of the acceleration which the model encounters. The calculated acceleration during the test time amounts to a = 2c = 1031.88 ± 3.56 m/s².

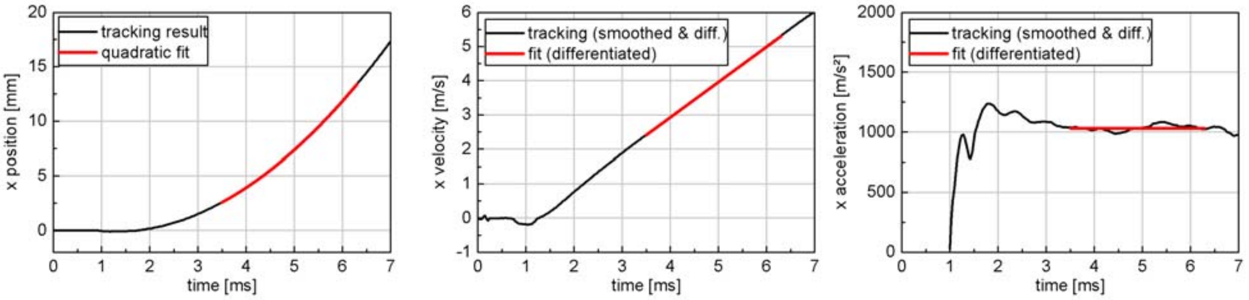

Figure 5. Tracked model position, velocity and acceleration over time (black) and quadratic fit (red).

The aerodynamic force in flow direction is obtained by multiplying the mean acceleration with the model mass $F_x = m\,a = 531.4$ N and the corresponding force coefficient is determined to be $C_{drag} = 2\,F_x/\rho_\infty {u_\infty}^2 A = 1.415$. For visualization purposes in Fig. 5, the obtained quadratic fit was differentiated and the resulting linear velocity and constant acceleration are shown in red. The resulting fit to the model displacement record includes an uncertainty of 0.34% for the quadratic coefficient c. This uncertainty can be considered as an measure to what extent the model movement during the test time follows the assumption of an constant applied acceleration on the model. The small uncertainty of the standard deviation shows that the tracking result behaves very much like a displacement for truly constant acceleration during the selected test time. To access the accuracy σ(a) for the obtained acceleration it can be shown [6] that it is represented by $\sigma(a)/a = \sigma(x)/x * \sqrt{1/n}$, where n is the number of images taken during the phase of constant applied acceleration a. In the case described above, we optically resolve 1 mm with 10 pixels giving a nominal s(x) of 0.1 on the apparatus side. We don’t consider the fact, that we are actually determining the movement of the model´s center of mass which again is determined by roughly 3500 individual points giving a much better σ(x). Nevertheless, with the framing rate of 30 kHz, we obtain a σ(a)/a of 0.21%. So we can finally conclude that the accuracy of the system is good enough to resolve the fit, which assumes that the movement of the model fulfils the criterion of a constant applied acceleration.

Conclusions

To determine forces and moments in the High Enthalpy Shock Tunnel Göttingen (HEG) of the German Aerospace Center (DLR) a free-flight technique paired with an optical tracking algorithm was developed and implemented. This technique can be applied measurement times in the order of a few milliseconds inherent to a short duration facility like HEG. The technique itself is now being used as nonintrusive measurement technique for forces and moments on hypersonic configurations. Its main advantages are the ease of use, the suitability for short duration, the avoidance of flow interference through the absence of support structures and the flexibility in the model design. The implementation presented allows the simultaneous determination of three components, e.g. lift, drag and pitching moment. This requires the model to be symmetric with regard to the vertical centre plane in flow direction and side force, yaw and roll to be negligibly small. Future work will include the addition of a second optical detection path in a direction perpendicular to the original one. This will allow for simultaneous measurements of side force and yawing moment.

References

[1] Hannemann, K. & Martinez Schramm, J. (2007). Short-Duration Testing of High Enthalpy, High Pressure, Hypersonic Flows. In Springer Handbook of Experimental Fluid Mechanics (Eds. C. Tropea, A.L. Yarin & J.F. Foss), Springer-Verlag, Berlin, Heidelberg, Germany, pp1081-1125.

[2] Tanno, H., Sato, K., Komuro, T., Takahashi, M., Itoh, K., Fujita, K., Laurence, S. & Hannemann, K. (2011) Force Measurements using non-restrained Models in a Shock Tunnel. 7th European Symposium on Aerothermodynamics for Space Vehicles, Brugge, Belgium, 9-12 May 2011.

[3] Robinson, M.J., Martinez Schramm, J. & Hannemann, K. (2011). Design and Implementation of an Internal Stress Wave Force Balance in a Shock Tunnel. CEAS Space Journal 1(1-4):45-57.

[4] Laurence, S. J. (2006). Proximal bodies in hypersonic flow. Dissertation (Ph.D.), California Institute of Technology.

[5] Laurence, S. J. & Hornung, H. G. (2009). Image-based force and moment measurement in hypersonic facilities. Exp Fluids 46, 343-353.

[6] Laurence, S. J. & Karl, S. (2010). An improved visualization-based force-measurement technique for short-duration hypersonic facilities. Exp Fluids 48(6), 949-965.

[7] Laurence, J.S. (2012). On tracking the motion of rigid bodies through edge detection and least-squares fitting. Exp Fluids 52(2), 387-401.

[8] Laurence, J.S., Martinez Schramm, J. & Hannemann, K. (2012). Force and Moment Measurements on a Free-Flying Capsule Model in a High-Enthalpy Shock Tunnel. 28th Aerodynamic Measurement Technology, Ground Testing, and Flight Testing Conference, New Orleans, USA, 25-28 June 2012, AIAA 2012-2861.

[9] Bernstein, L. (1975). Force Measurements in Short-duration Hypersonic Facilities. AGARDograph No.214.

[10] Canny, J. (1986). A Computational Approach to Edge Detection. IEEE Trans Pattern Anal Mach Intell 8(6), 679-698.

[11] Jain, R., Kasturi, R. & Schunck, B.G. (1995). Machine Vision, McGraw-Hill, New York, USA

[12] Moré, J.J. (1978). The Levenberg-Marquardt Algorithm: Implementation and Theory. In Lecture Notes in Mathematics 630, (Ed. G. Watson), Springer, Berlin, Heidelberg, New York, pp105-116.

[13] Press, W.H., Teukolsky, S.A., Vetterling, W.T. & Flannery, B.P. (1992). Numerical Recipes in C: The Art of Scientific Computing, Second Edition, Cambridge University Press, pp650-655.

[14] Hannemann, K., Martinez Schramm, J. & Karl, S. (2008). Recent Extensions to the High Enthalpy Shock Tunnel Göttingen (HEG), Proceedings of the 2nd International ARA Days “Ten Years after ARD”, Arachon, France, 21-23 October 2008.