Application of a digital high speed camera and image processing system for investigations of short-term hypersonic fluids

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ABSTRACT

The design and application of a digital high speed image data capturing system with a following image processing system applied to the *Bremer Hochschul Hyperschallkanal* BHHK (University of Bremen hypersonic wind tunnel) is the content of this presentation. It is also the result of the cooperation between the departments *aerodynamic* and *image processing* at the ZARM-institute at the Drop Tower of Bremen. Similar systems are used by the *combustion* working group at ZARM and other external project partners [1]. The BHHK, camera- and image storage system as well as the personal computer based image processing software are described next. Some examples of images taken at the BHHK are shown to illustrate the application. The new and very user-friendly Windows 32-bit system is capable to capture all camera data with a maximum pixel clock of 43 MHz and to process complete sequences of images in one step by using only one comfortable program.

Keywords: high speed imaging, hypersonic, wind tunnel, image processing

2. THE UNIVERSITY OF BREMEN HYPERSONIC WIND TUNNEL (BHHK)

The BHHK is based on the principle of a high pressure charge tube which was described first by Ludwieg in 1955. Basically it is a pressure storage channel with a storage tank shaped as a long tube. Within his work titled *Der Rohrwindkanal* [2] Ludwieg mentioned that because of the requirements of higher Reynolds- and Mach numbers the construction and operation of ordinary wind tunnels increase the costs for these facilities enormous. Due to that fact he proposed a new kind of wind tunnel, which is also the fundamental design of the BHHK. Dr. G. Koppenwallner took the ideas of Ludwieg and by doing some modifications he designed and constructed the BHHK and other similar wind tunnels. The BHHK wind tunnel is easy to operated and has low maintenance costs. Because of these reasons, facilities like the BHHK are interesting for small companies and universities in general terms. The arrangement of the sub systems and main devices is shown in fig. 1. Fig 2. shows a picture of the completed wind tunnel installed in the ZARM-institute experiment hall.

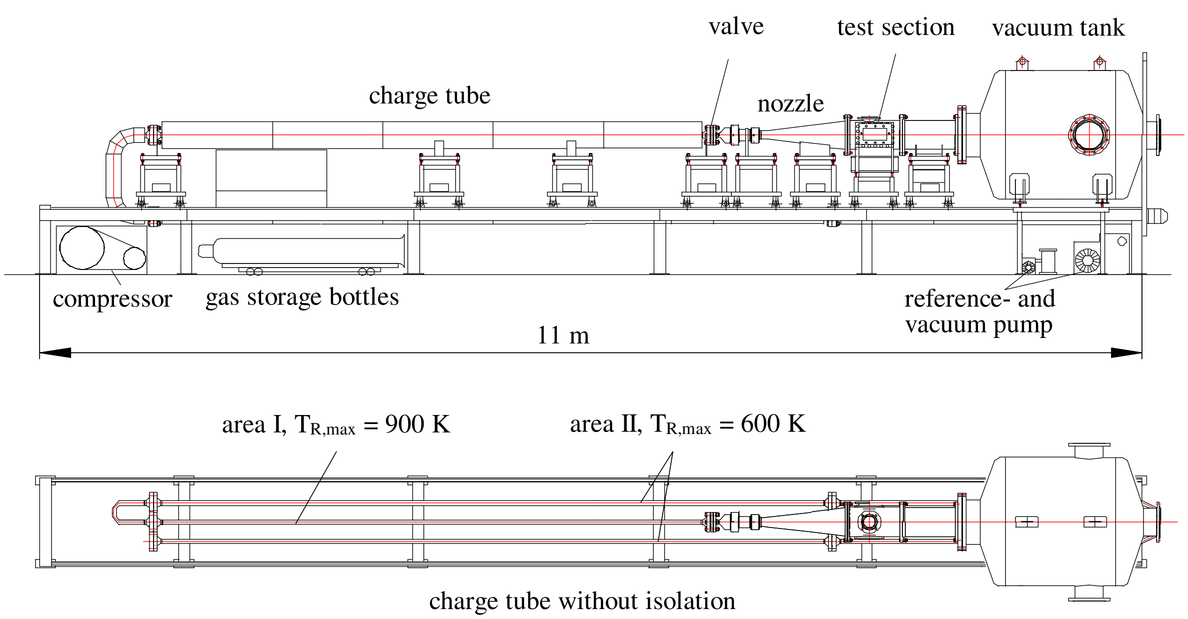

Fig. 1: Construction scheme of the University of Bremen hypersonic wind tunnel (BHHK)

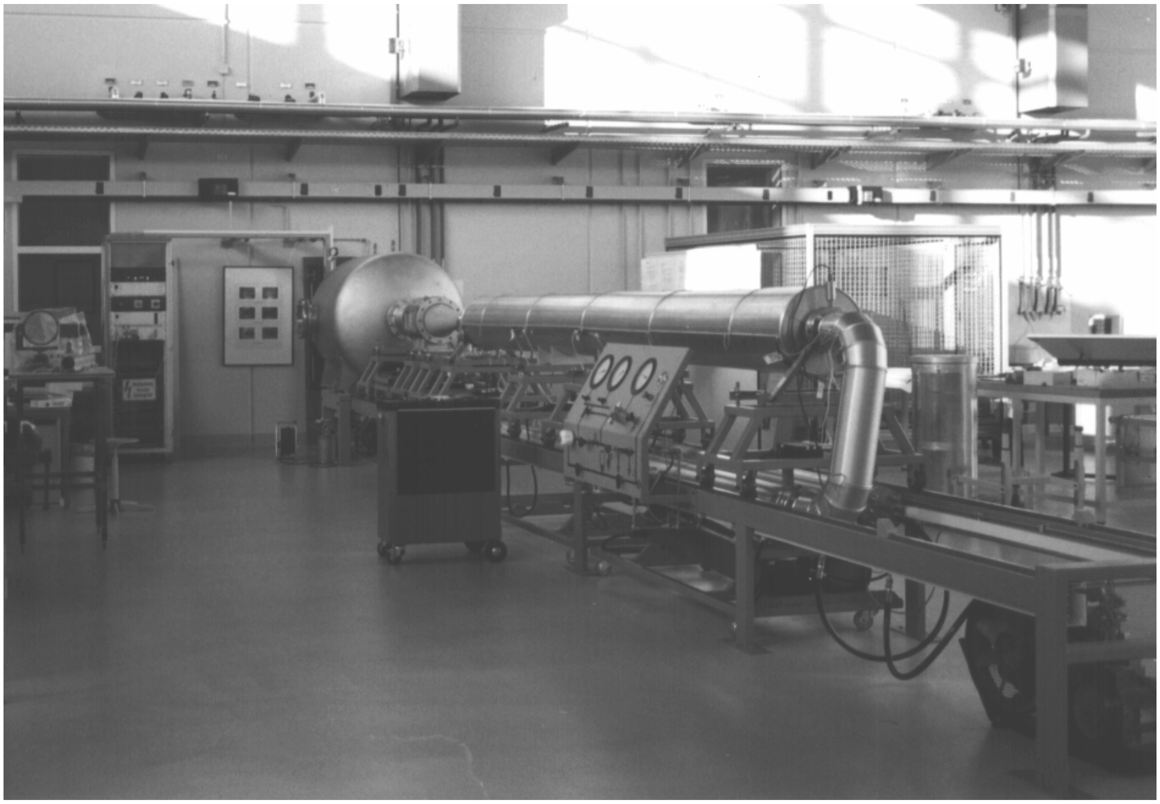

Fig. 2: The University of Bremen hypersonic wind tunnel (BHHK)

The winding charge tube (area I in fig. 1) has a length of 24 m in total and contains the test gas under the conditions of high pressure (up to 100 bar) and high temperature (up to 900 K). At the same time area II (consists of the vacuum tank, nozzle and test section) is evacuated. By separating area I and II via a valve we get a big difference of the gas pressure to start the wind tunnel experiment next. The valve is released and an expansive wave is running from area I to area II. The expansive wave is reflected at the end of the vacuum tank and runs back to the test section and valve area. At this moment the valve is closed to save the energy of the remaining gas (90%) in area I for the next experiment. At least a period of 0.08 - 0.13 seconds is performed to investigate the hypersonic flow around the test body within the test section. A special Laval-nozzle allows to get instationary fluid conditions during the test phase up to 11 times speed of sound (Mach 11). The test section has a diameter of 250 mm and has 2 optical accesses with the dimensions of 120 mm * 300 mm. More details on design and properties of the BHHK wind tunnel were written by Friehmelt, Koppenwallner and Müller-Eigner [3]. Some basic measurement techniques are necessary to carry out useful experiments. At the moment the BHHK is equipped with the following tools:

- Device to alter the angle of attack
- Pitot pressure recording system for wind tunnel calibration
- 32 channel pressure aquisition and recording system
- Schlieren optics
- High speed imaging system (image capturing and image processing)

The next chapters explain the topics *schlieren optic* and *high speed imaging system* more detailed.

3. SCHLIEREN OPTIC

Density gradients close to test body are intensive enough to be visualised by using monochrome laser light and optical systems like the schlieren optic system performed by Toepler [4]. The principle of the optical schlieren system of Toepler is shown in fig. 3. The monochrome light source is placed in the focal point of the concave mirror 1 to ensure parallel light rays through the test section. After passing the test section with the test body the light is focussed by concave mirror 2. A picture is imaged in the second focal plane at B_2 to be captured by the CCD-camera. In areas within the test section where the density gradient varies, the original parallel light is deflected and did not pass the focal point exactly. A schlieren edge is placed close to the focal point and to iris out these rays. Because of that there is a change of the light intensity. This effect is proportional to the change of the density within the test section.

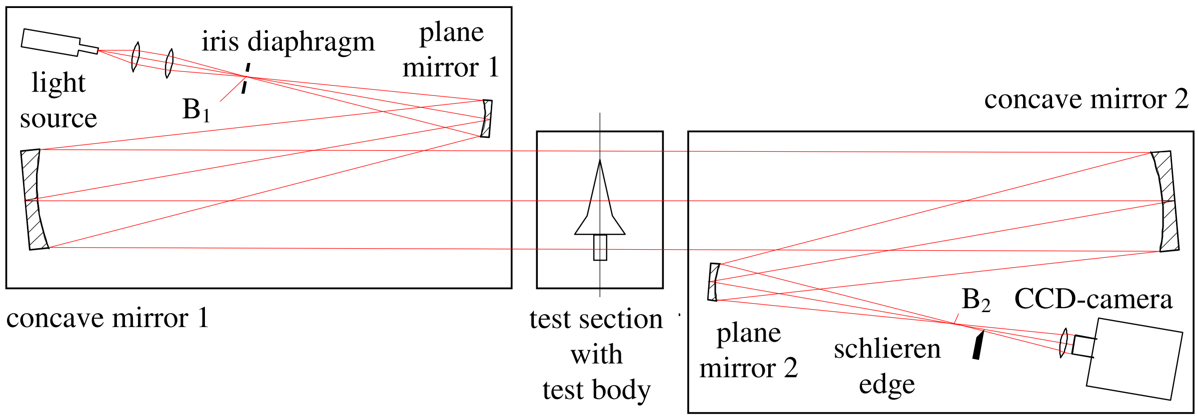

Fig. 3: Path of light rays through the schlieren optic system

4. IMAGING SYSTEM

Due to the short time of stationary conditions (up to 0.13 seconds) during the hypersonic fluid at about Mach 11 it was necessary to use a high speed imaging system to capture pictures of the test body and the density gradient pattern around. Ordinary video (according to CCIR-standard) with 25 or 30 pictures per second will have only snapshot character. An analog camera from DALSA was selected to provide up to 226 images per second respectively a sequence of 30 images during the 0.13 seconds of stationary conditions. The spatial resolution of the CCD-sensor is 256 by 256 pixels. The analog pixel stream of about 14.8 MHz is input to a 8-bit analog-/digital converter of a small image storage system with 16 MByte DRAM memory (upgradable to 96 MByte). So an image sequence of 1.1 seconds is recordable with enough time before and after the experimental phase to capture background images for calibration reasons as an example. Next step is to transfer the digital sequence of image data from the external storage device into a personal computer via SCSI-connection to save and to process the image data. Then the memory of the image storage system is released and a new experiment can be performed. Fig. 4 shows an overview of this old but still working imaging system which mainly consists of a personal computer and the external image storage system.

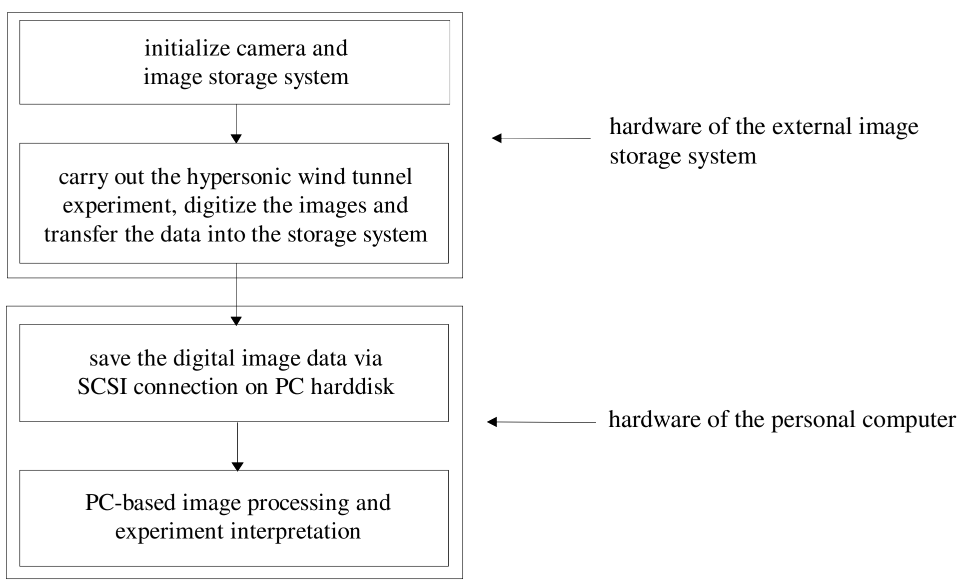

Fig. 4: Overview of the old imaging and image processing system

Recently we completed another system with an improved and only personal computer based imaging, image data storage and image processing system. To capture the image sequences an universal four-channel frame-grabber is used and adjusted to the DALSA high speed camera is this case. The digitized image data are stored within the conventional RAM area (with a maximum memory capacity of 512 MByte) of the personal computer first and on harddisk later. The modern PCI-bus technique allows image data transfer (DMA-transfer) in a real-time mode and a maximum data transfer rate of 43 MHz.

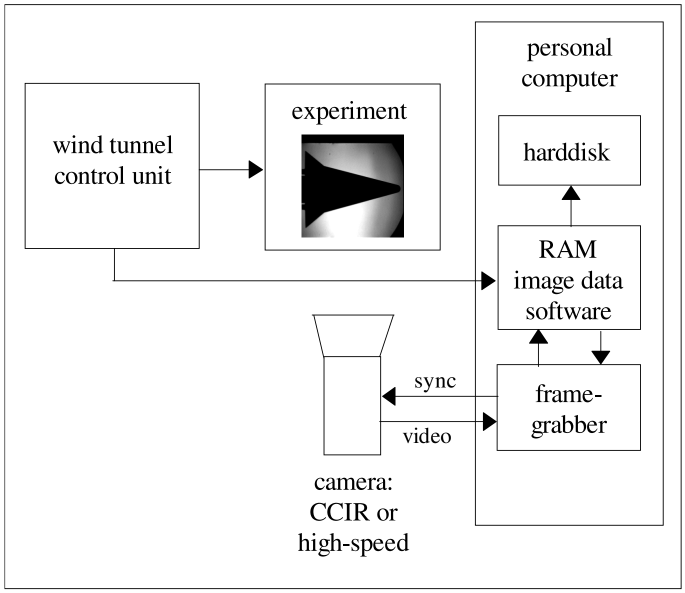

Fig. 5: The new and only on personal computer based imaging and image processing system

5. IMAGE PROCESSING SYSTEM

A variety of software programs is available to interpret the image data. By using the operating system DOS a program called *HAMADIMO* [5] provides the largest collection of image processing possibilities [6]. Because of the minimal system requirements of *HAMADIMO* this program is interesting for space applications at the ZARM-institute too. This program was supplemented continuously with filters or special tools on user request. Since 1997 a very user-friendly Windows 32-bit program called *DIGHISPEED* [8] is available. This software contains a lot of image processing tools and has also the capability of camera guidance and image data digitization by using the universal frame-grabber. A library of camera configuration files adaptes the frame-grabber to the selected camera. An example of the desktop of *DIGHISPEED* is shown in fig 6. The most important image processing functions and tools applicable to single images or image sequences are:

- Convolution with delta-x, delta-y, gaussian, laplace, average, median, gradient, minimum, maximum and other operators by using 3x3, 5x5, 7x7 convolution kernels
- Modification of the gray value distribution, contrast enhancement, area segmentation, etc.
- Tools for image flip, rotation, calibration with background images, zoom, false color, contour measurement, object tracking, image export (bmp, tiff), etc.

New functions can be added to all software packages very easy. Finally there is a program to interpret the distribution of pressure values measured by special sensors fixed on the test bodies surface in relation to the imaged pictures.

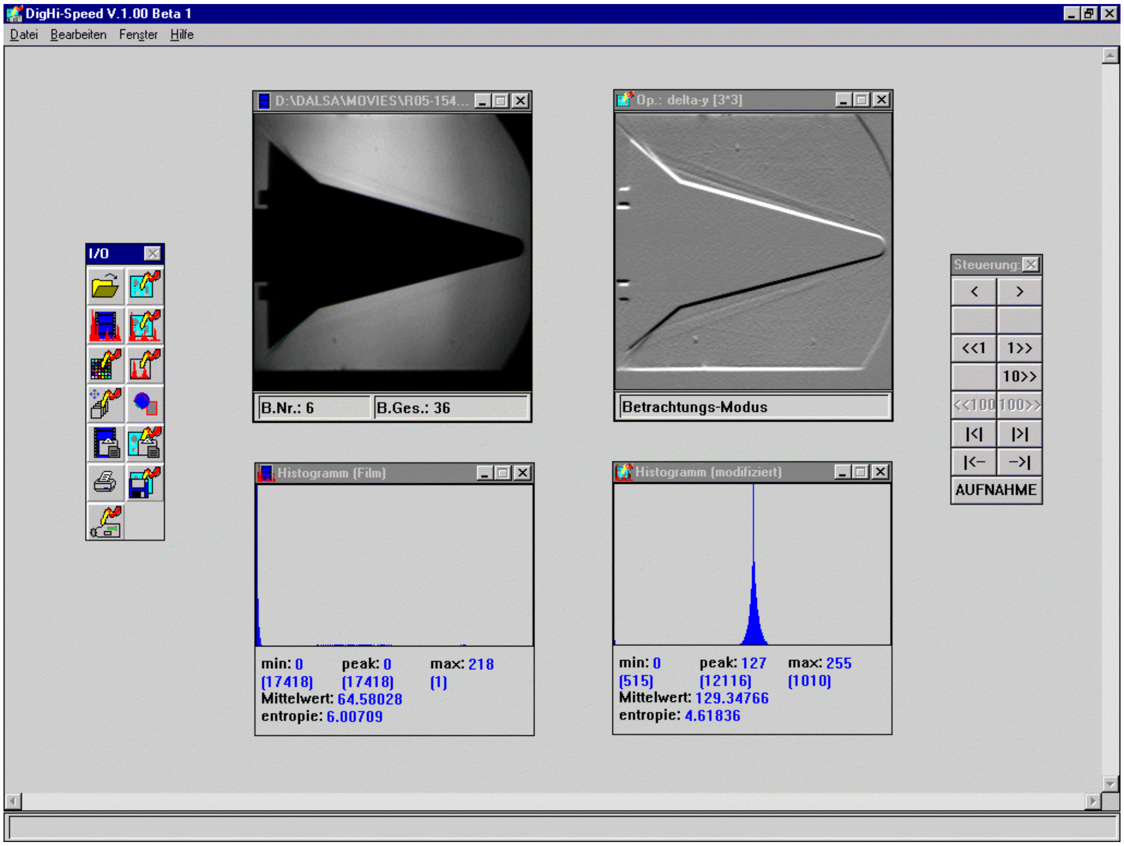

Fig. 6: Desktop of the Windows 32-bit software *DIGHISPEED* with an applied gray value gradient operator (delta-y)

6. SCIENTIFIC OBJECTIVES

The flow around vanes like elevator and side rudder or within engine units is very interesting for re-entry- and hypersonic spacecrafts. In these cases the interaction between interface and compression shock can cause a reduction of the rudder efficiency or causes less power of the engines. One important problem to be discussed is the separation of the interface in the area of the compression edges. The basic research on hypersonic fluids defines simple body configuration to make possible experimental and numerical investigations. The range of test bodies includes plates, compression ramps, axis symmetrical hyperboloids or delta shaped bodies. Double cones were selected for this presentation to investigate the influence of the leading-edge radius. A series of 27 different double cones was generated with three model parameters subdivided into three steps. The first parameter is the leading-edge radius R_N (0 mm, 5 mm, 10 mm), the second and third parameter are the angles of opening of the cone ϑ_1 (10°, 15°, 20°) and ϑ_2 (30°, 40°, 50°) as shown in fig. 7.

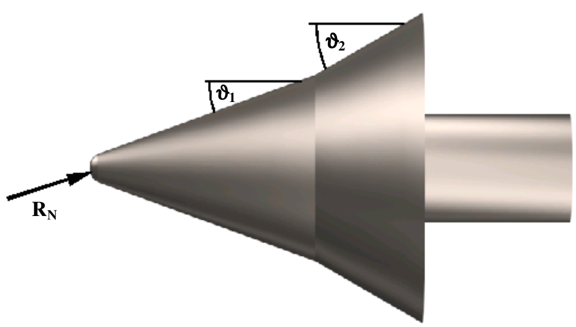

Fig. 7: Nomenclature of the double cone with the three parameter R_N, ϑ_1 and ϑ_2

In particular phenomena like the creation of the compression shock or the resultant flow separation around the compression edge are important to watch and to be investigated. The two most interesting areas for the optical analysis are marked in fig .8.

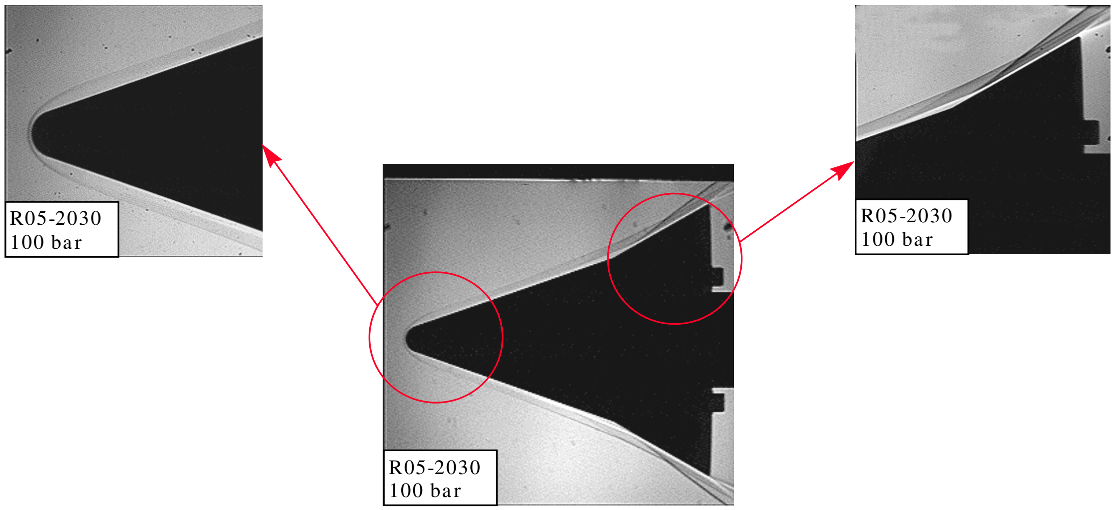

Fig. 8: Flow at the leading-edge and at the compression edge of the test models

7. EXAMPLES

All models mentioned within the last chapter were investigated under the conditions of four different Reynold-numbers but without a variation of the angle of attack. Exemplary two image sequences with their original data and their processed data (delta-y operator) to intensify the density gradient are shown in fig. 9 and 10. In fig. 9 the leading-edge radius varies from 10 mm down to 0 mm (as seen from the top to the bottom). The model family is called RXX-2030. The name stands for the two fixed angles of opening ϑ_1 = 20° and ϑ_2 =30° and the varied leading-edge radius XX. The change of the shape of the compression shock related to the shape of the leading-edge is good to see. There are also different interferences visible around the second cone. The optical effects are better to see by processing these pictures with the delta-y operator to intensify the value of the gradient in y-direction as seen to the right. Next step is to measure the geometry of the compression shock and the interference zones.

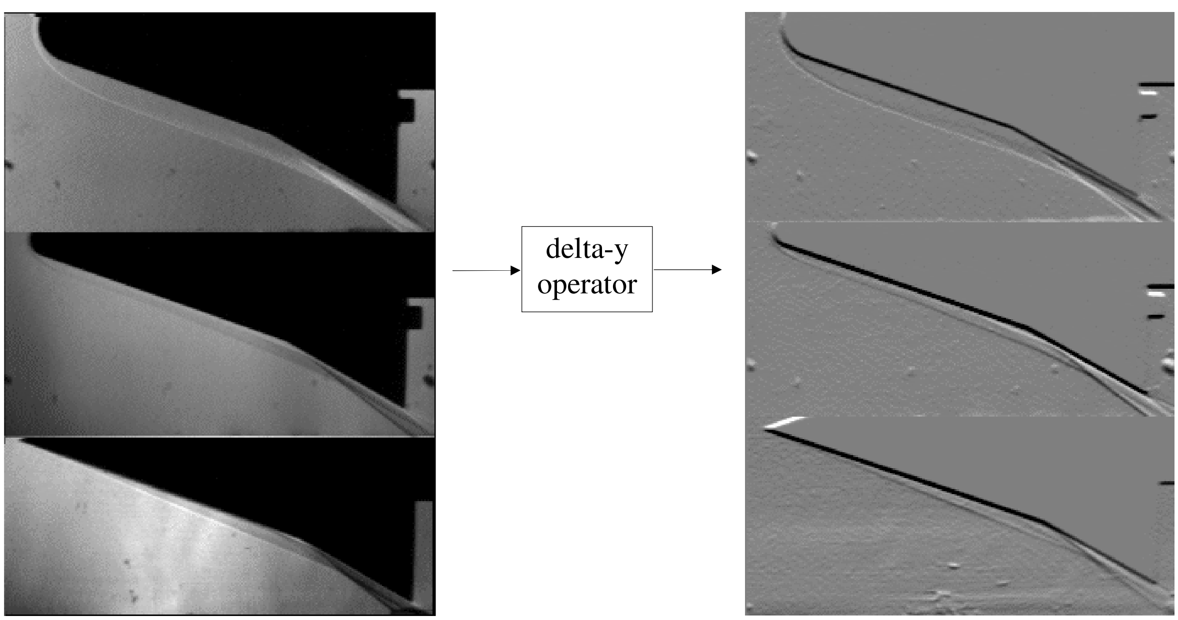

Fig. 9: Double cone model family RXX-2030
(left: original image data, right: processed data by using the delta-y operator)

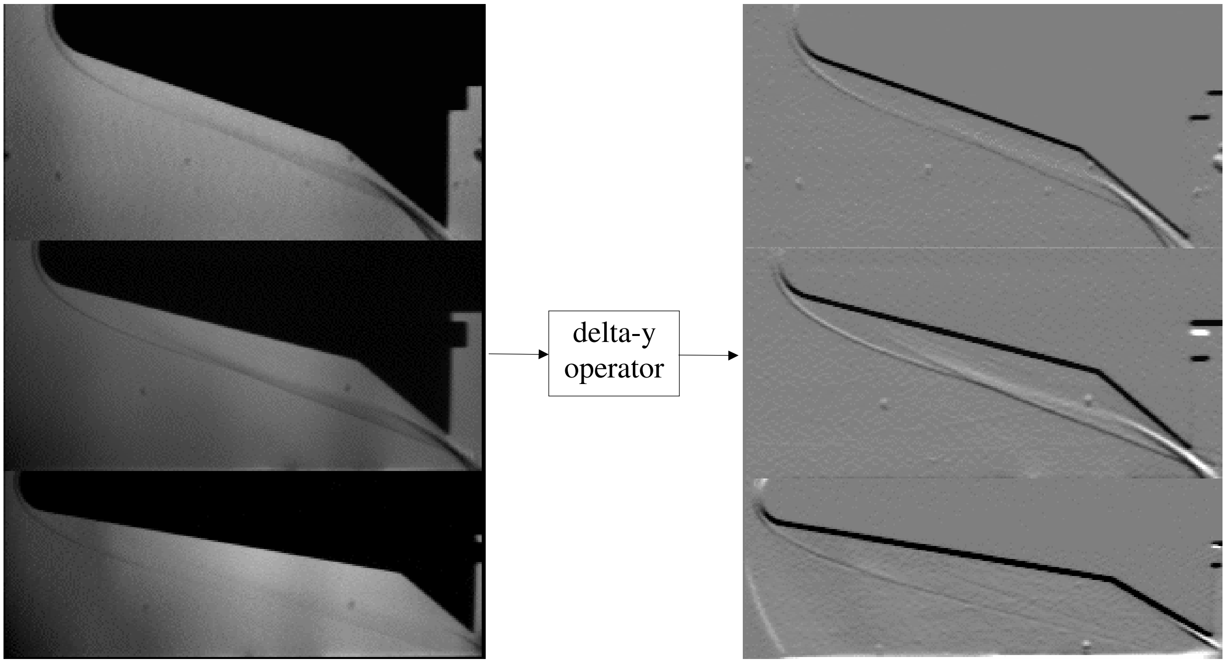

Fig. 10: Double cone model family R10-XX40
(left: original image data, right: processed data by using the delta-y operator)

The second example shows the double cone model family R10-XX40. The first angle of opening ϑ_1 varies (ϑ_1 = 10°, 15° and 20°) and the parameter R_N and ϑ_2 are constant (R_N = 10 mm, ϑ_2 = 40°). Because of the geometry of the model there is only a weak compression shock to see at ϑ_1 = 20° (image to the bottom).

8. CONCLUSION

We implemented a flexible, universal and open designed image capturing and image processing system consisting of a high speed camera (or ordinary video if useful or all other cameras up to 43 MHz pixel clock), an image storage system and a variety of image processing programs for different personal computer based operating systems. It is easy to adapt the system to new scientific or technical requirements and to implemented new software tools on user request. At the moment the system is used by the working groups *aerodynamic* and *combustion* at ZARM to investigate very different scientific questions. Some pictures with hypersonic phenomena were presented and processed to show features of the image processing software *DIGHISPEED*. This Windows 32-Bit program is capable to capture and process sequences of single images or complete image sequences in one program.

Further work is the implementation of additional tools for automatical measurements of density gradients or the geometry of the test body as an example.

9. ACKNOWLEDGEMENT

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