Let There be Shadow

Laser diffraction system for diameter, geometry and edge detection

An evergreen of laser based metrology is the evaluation of one or multiple shadow edges, generated by an object under test. With this technique a collimated laser beam illuminates a CCD-line scan sensor. An object introduced into the laser beam shadows parts of the beam. Directly and without intermediate imaging one or more shadow edges with superposed Fresnel diffraction pattern form on the line-scan sensor.

Chart (a) of fig. 1 shows the diffraction pattern generated on the line scan sensor by the object under test. The complete signal of the line scan camera and a zoomed fraction of a single edge Fresnel pattern are shown on the monitor display in fig. 2.

In the Fresnel diffraction oscillations the wave nature of the light becomes manifest. The plane wavefront of the collimated beam is deflected at the object and light sneaks into the geometrical shadow area. In the illuminated area outside the shadow bars of interference emerge due to interference of the undisturbed wavefront with parts of the deflected beam.

Without an object under test the nearly uniform distributed center of the elliptically, collimated beam illuminates the CCD-line scan sensor. For good agreement with theory wavefronts close to the ideal 'plane' at the position of the object under test are required. A line shaping optics to focus the beam onto the sensor is not necessary, it would only be disturbing the diffraction pattern. To suppress stray background light a wavelength matched narrowband optical filter can be benificial.

To determinate the exact position of the object edge, depending on repetition rates and accuracy requirements, two alternative methods can be used:

The **thresholding** restricts the evaluation to the edge of the diffraction pattern. The edge position is determined by one intensity level below the oscillations (see chart (b) in fig. 1). The line scan camera system of **Schäfter+Kirchhoff** realizes the thresholding onboard on the interface device. As a result of a camera shot the system supplies the numerical pixel positions of the shadow edge in the line scan signal. Thus, measurement frequencies of more than 30 kHz and a spatial resolution of less than 7 µm is reached.

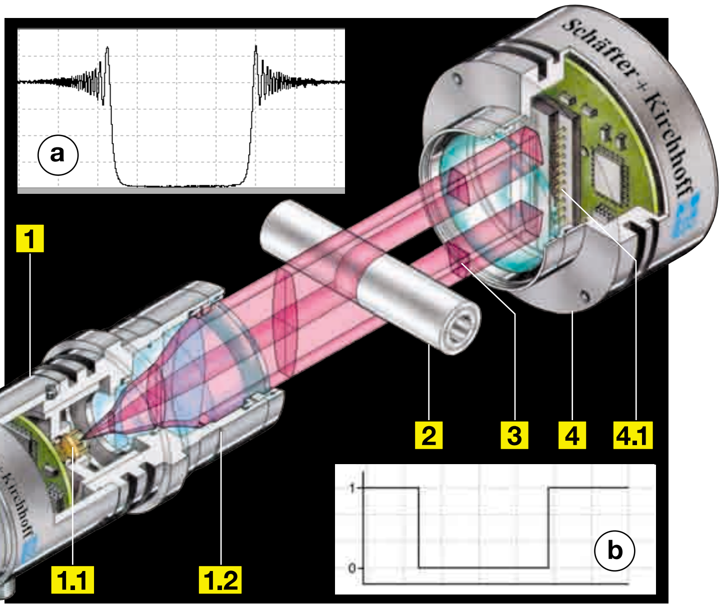


Fig. 1: Schematical measurement configuration and beam propagation with laser diffraction. 1. laser diode collimator, 1.1 laser diode, 1.2 lens for collimating the divergend laser diode radiation, 2. object under test, 3. partial obscured laser radiation, 4. CCD-line scan camera, 4.1 CCD-line scan sensor. The collimated beam is elliptical (vertical beam size 32mm).

The method using **laser diffraction** includes additionally the oscillating fraction of the Fresnel diffraction pattern. Evaluating the positions and intensities of the minima and maxima the spatial resolution is enhanced to < 1 µm. Due to the increase of necessary computing time the possible repetition rate using laser diffraction is decreased to less than 3 kHz, a factor of 10 lower as using the thresholding.

The mathematical formulation of the diffraction patterns developing at edges is traced back to Augustine Fresnel (1788 to 1827). Fresnels theoretical and experimental work helped to leverage the suspected theory about the wave nature of the light.

The diffraction pattern are described mathematically by the Fresnel-sine- and the Fresnel-cosine-functions. Before complex numerical calculations were accessible, the function values were kept tabellized or determined with a graphically method, the so called Cornu's-spiral.

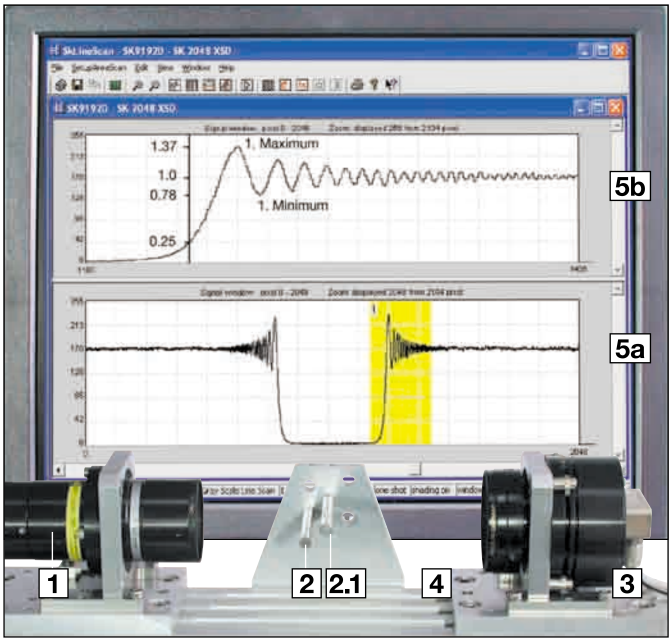


***Fig. 2:** Measuring station laser diffraction*

Measuring station for the evaluation of Fresnel- and other diffraction patterns of an object under test. The displayed arrangement is used, e.g., in practrical trainings at the First Institute for Physics of the RWTH Aachen University, and at the Chair of Quality Management and Manufacturing Metrology of the University of Erlangen-Nürnberg.

1.laser diode collimator, 2. object under test, 2.1 second object under test, not displayed in the signal. It is itroduced for the simulation of a narrow slit (see Fig. 3), 3. CCD-line scan cameras, 4. optical bench, 5. monitor with display of the Fresnel diffraction pattern. 5a: CCD-line scan signal with diffraction pattern of an object of 6mm diameter. 5b: diffraction pattern of a single edge, zoomed.

Edge position and distance derived from the Fresnel diffraction pattern

Given the wavelength λ, the diffraction pattern contains information about the exact position of the edge as well as about the distance z between the object under test and the CCD line scan sensor. The distances of the intensity ma-xima and minima from the geometric position of the edge are increasing with the factor of $1/\sqrt{z\lambda/2}$. Given a smooth, straight and sharp edge, Table 1 includes the intensities of the first 5 minima and maxima and their normalized, with the factor of $1/\sqrt{z\lambda/2}$ multiplicated, distances from the edge. Additionally, an example with the distance of z = 80 mm and a wavelength λ = 630 nm is listed. The intensity at the exact position of the edge is reduced by the factor of 0.25 compared to the undisturbed illuminated signal level. The relative intensity of the first maximum is 1.37.

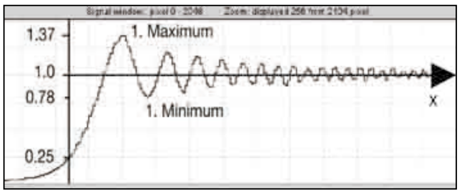


Fig. 5: Display of the intensity distribution orthogonal to the diffracting edge.

Table 1	nomalized intensity	norm. distance $x/\sqrt{z\lambda/2}$	x (µm) at z = 80 mm
schadow edge	0.25	0.00	0
1. Maximum	1.370	1.22	193
1. Minimum	0.778	1.87	297
2. Maximum	1.199	2.34	372
2. Minimum	0.843	2.74	435
3. Maximum	1.151	3.08	489
3. Minimum	0.872	3.39	538
4. Maximum	1.126	3.67	583
4. Minimum	0.889	3.94	625
5. Maximum	1.110	4.18	664
5. Minimum	0.901	4.42	701

Tab. 1: *Intensities of the maxima, minima and their distances from the smooth, straight and sharp diffracting edge. With the normalizing factor $1/\sqrt{z\lambda/2}$ universally valid values for the positions of the extrema can be listed. The right column shows a certain example for the wavelength 630nm and a distance between diffracting edge of the object under test and the CCD line sensor.*

Calibration with a reference object

A calibration is necessary with both methods, the thresholding and the laser-diffraction. The theoretical formulation of the intensity distribution implies an ideal plane incoming wave and an smooth, straight and sharp edge. Disturbances due to imperfect surface finishing, surface defilement like oil film, stray light or further diffraction due to air turbulence from heat convection always occur in reality. They influence particularly the evaluation of the diffraction pattern but also degrade the thresholding measurement precision.
For calibration an object of known size and preferably same edge properties as the object under test is measured in different sensor regions. The results are accounted for as a reference in following measurements.

Applications

On the basis of the achieved measurement repetition rates in the kHz-range, the described measurement technique is qualified to the evaluation of dynamic processes like the control of hydraulic pipes, micropositioning of SMDs or the true running characteristics of rotor turbines (see 'applications' at page bottom).
A further application is the analysis of physical diffraction phenomenons in physical high universities practical training.
In fig. 3 the measured diffraction pattern of two rods is displayed. Due to the small distance of the rods of 1mm a measurement of a slit is simulated. The superelevated signal in the narrow spacing between the two rods is generated by interference of the diffraction at the adjacent edges. Fig. 4a shows the two dimensional illustration of a vibrating rod. The x-dimension corresponds to the line sensor length. The single line signals are stored in the computer memory and stacked to the second dimension of the display. The number of lines displayed determine the vertical extent of the display and represent the time axis. A fundamental oscillation and a second harmonic can be seen. Signals due to diffraction pattern exited by particles moving through the beam are illustrated in fig. 4b. The spatial resolution in x-dimension corresponds to the sensor. The line frequency of the camera determines the vertical resolution of the image.

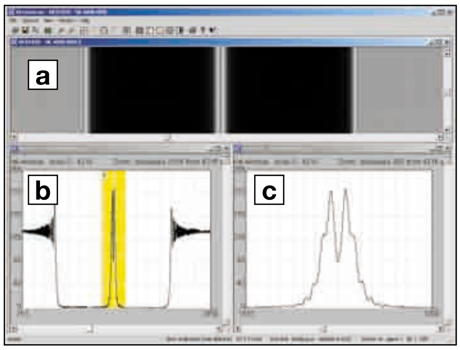


Fig. 3: Diffraction by two round rods in a distance of 1mm. (Measurement setup see Fig. 2, Objects 2, 2.1)
Between the rods the Fresnel diffraction patterns of the two edges superimpose. This leads to an increase of the signal amplitude.
[a] 2D-display of a number of line scans.
[b] Complete image of the diffraction structure,
[c] Zoomed display of the yellow highlighted signal section.

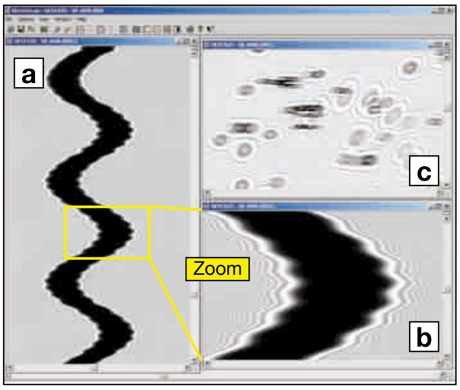
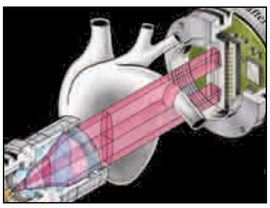


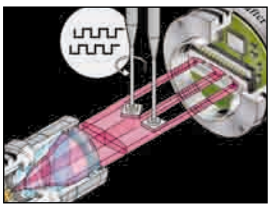
Bild 4*: Recording dynamic activities.*
[a] 2D-display of 1000 subsequently recorded line scans showing diffractive structures of a vibrating rod with a diameter of 0.8 mm. (line frequency 9.47 kHz).
[b] Zoomed display of the highlighted section in [a]
[c] Diffraction patterns of particles moving through the beam (line frequency 9.47 kHz).

Applications



Diameter and contraction

Dynamic diameter measurement of hydraulic conduits under alternating loads. Mesurements of response time and latency. Measurement frequency up to 36 kHz, resolution < 7 µm



Micro positioning

SMDs require an exact positioning on the designated carrier. Tweezers rotate the components. The required rotational position is determined with the CCD signal of the deflecting edge.

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Laser diode collimator

For the laser diffraction measuring system displayed in fig. 1 the collimator 90CM-M90-635-2-H01-02 is deployed. The collimator emits a parallel, 32mm high laser beam onto the line scan sensor. The wavelength is 635nm, the divergence (deviation from parallelism) is typically 0.014 mrad. Integrated electronics supply a feedback laser power control, the output power can be selected by an extern potentiometer in a range of 1 - 100% of the maximum laser power.

Beam shaping

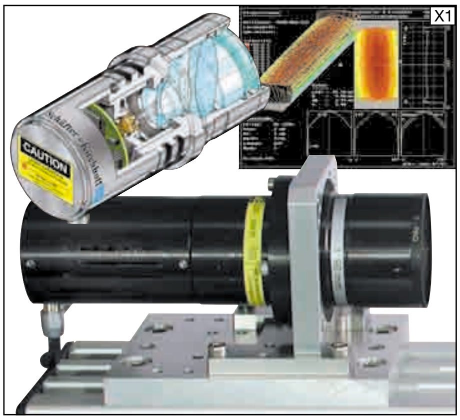


Fig. 6: *The laser diode collimator flatbeam@ 90CM-M90-635-2-H01-02 emits a telecentric (parallel) laser beam (beam profile X1) onto the line scan camera (vertical beam size 32mm).*

Due to the microscopically small cross section of the laser diode active surface (typically 0.1 x 3 µm) the emitted laser diode radiation is diffracted and the divergent beam cone with elliptical cross section and Gaussian intensity distribution, tyical for laser diode emission, is formed (see fig. 7a).
Collimation lenses transform the divergent laser diode radiation to a parallel beam. This beam is characterized by the aperture and focal length of the lens and the emitted divergences $\theta_\perp$ and $\theta_\|$ of the laser diode (see fig. 7b). If laser diode radiation is not obstructed by the lens, an elliptically Gaussian distributed beam emerges with diameters $Ø_\perp = 2 \cdot f \cdot \sin(0{,}85 \cdot \theta_\perp)$ und $Ø_\| = 2 \cdot f \cdot \sin(0{,}85 \cdot \theta_\|)$. The factor 0.85 converts between the divergences, given at 50%-level, and the beam diameters, given at 13.5% ($1/e^2$) levels. The used laser diode has typically divergencies of 8°x31°. With a collimation lens of 90 mm focal length the Gaussian beam diameters result in 21x80 mm. The free aperture of the lens restricts the beam to a maximum of 32 mm. Figure 6 shows the resulting beam profile X1. Because of the obscuration of beam parts by the finite aperture, Fresnel diffraction occurs and only the undisturbed central part of the beam can be used for laser diffraction measurements (the sensor length is 28.7 mm).

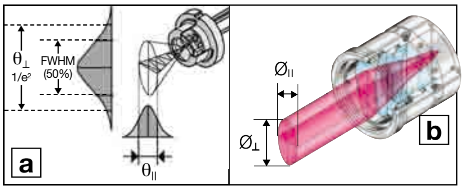


Fig. 7A: *Laser diodes emit a divergent elliptical beam profile with Gaussian intensity distribution. The beam divergence θ is given in FWHM (Full Width Half Maximum).*

Fig. 7B: *The collimation lens generates a parallel elliptical beam. The beam diameter are measured on the 13.5%-level (1/e²).*

CCD-line scan sensor

CCD-line scan sensors are semi conductor cameras with an only one dimensional light sensitive array. It can contain up to 10680 separate addressable pixel elements of 4 - 14 µm width, depending on type. The light incident on the sensor is transformed into analog voltage values, transported by shift register following the bucket chain principle, and digitized by a camera integrated A/D-converter. The advantages of high optical resolution and free synchronizing of each individual line enable numerous applications in the technology fields of optosensors and measuring systems. Evaluating diffraction patterns the dynamic range of the line scan sensor should exceed 500:1. For thresholding a dynamic range of 100:1 is sufficient.
Schäfter+Kirchhoff CCD-line scan sensors with high line frequency are connected to a PC mounted interface board using the LVDS standard. For mobile applications cameras with USB 2.0-interface are avalible (further information on line scan cameras see last page of this article).

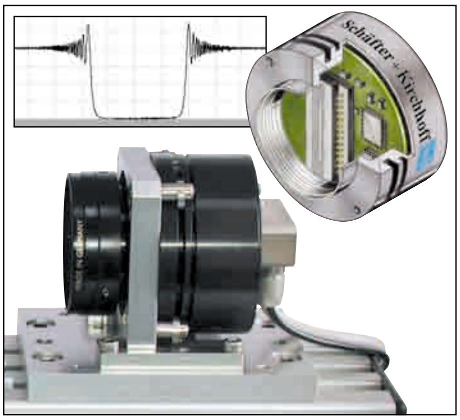


Fig. 8: *CCD-line scan cameras SK2048 UJR has a pixelsize of 14 µm and 28.7 mm sensor length. An optical edge filter placed befor the sensor suppresses stray ligth. An imaging optics is not necessary with the described application.*

Shading correction

Ideal diffraction structures require a homogeneous intensity distribution of the laser radiation on the CCD line scan sensor. Due to interference effects on optical surfaces and intensity decrease of the collimated laser beam at the sensor edges the intensity distribution on the sensor is not uniform (fig. 9a). The shading correction compensates for this and generates a uniform intensity distribution. An average line scan is recorded with full illumination, i.e. without object in the beam path. An individual gain factor, calculated from the measured intensity distribution, is assigned for every single pixel in an allocated memory. With activated shading correction all pixels of a line scan are corrected with the corresponding gain factor. Thus, unobscured illumination on the line scan sensor result in a line scan signal with a homogenious intensity distribution (fig. 9b).

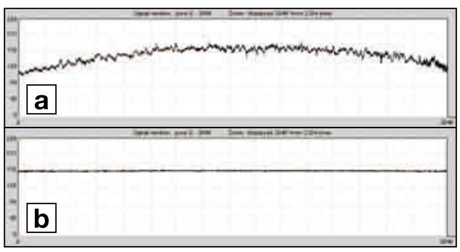
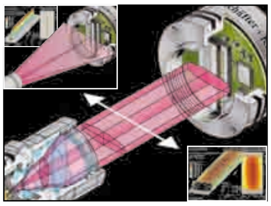
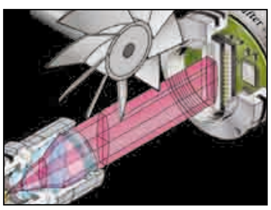


Fig. 9: *Shading correction for compensation of non-uniform illumination of the CCD-sensor.* **a** *without,* **b** *with shading correction.*



Laser beam analysis

The laser radiation propagates straight to the CCD sensor without intermediate imaging or filter absorption. A 2D image of the beam profile as shown in fig. 6, X1, is generated when the laser collimator is moved lateral to the line sensor.



True running characteristics

Inserting an engine shaft into the beam, variances of big diameter probes can be examined. The distance between laser diode collimator and CCD line scan sensor can amount to several meters.

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CCD-line scan camera systems

The laser diffraction system is offered with two different CCD line scan camera systems. The System I is the version with USB 2.0-line scan camera. The System II is the traditional alternative with digital CCD line scan camera, PCI-bus-interface and LVDS standard.
Using the universal serial bus (USB) in the version 2.0 data transmission rates of of up to 480Mbit/s can be realized. With the increasing distribution of USB 2.0 connections in modern PCs, particularly in notebooks, and the hot-plug abilities the CCD-line scan camera system with USB 2.0 interface is perfectly applicable for the deployment with alternating measuring stations.
Using the installation CD by **Schäfter + Kirchhoff** the software and driver installation is automated. The software package SK91 USB-WIN contains the executable operation program SkLineScan for promt start-up of the system as well as all necessary DLLs and class libraries for the development of proprietary software.
The operation program SkLineScan provides a concise user interface and is handled intuitively. The oscilloscopic signal display shows changes in the optical system and the camera parameters immediately.

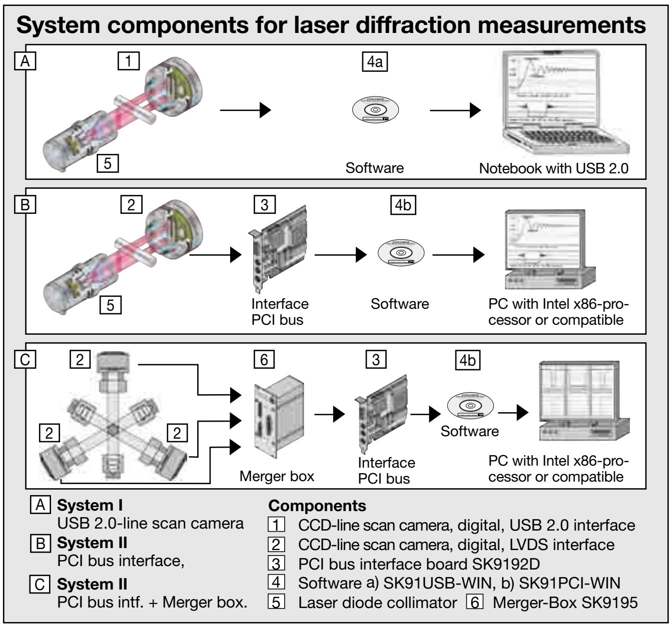
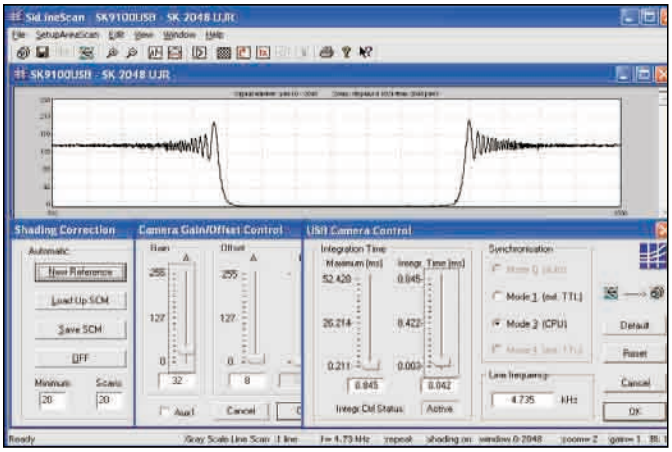


Fig. 11: *System components of the laser diffraction measuring system*



Using the dialog window for the shading correction individual reference signals for each measurement system to correct intensity variations can be grabbed, recorded and and reactivated if required .	The USB 2.0 cameras provide a programmable gain and offset control. The values are set through the slides, memorized by the EEPROM of the camera and will be preserved also by changing the computer.	The integration time of the USB 2.0 camera is conveniently adjustable over wide ranges. With the maximum slide the top level of the adjustment range is set. For very short integration times the slide unit will automatically activate the integration control function of the camera (shutter).

Fig. 10:
User interface of the SkLineScan software with dialog for the shading correction, gain and offset programming and camera control.

Table 2	System I	System II
data transfer:	USB 2.0	PCI bus
line frequency max.:	27.1 kHz	70 kHz
hot plug:	yes	-
extern sync.:	yes	yes
shading correction:	software	On-Board
cabel length:	1.8 m	up to 20 m
multi camera operation:	-	up to 5 cameras
additional hardware:	-	PCI bus interface SK9192D,
		Merger box SK9195
software:	SK91USB-WIN	SK91PCI-WIN

Tab. 2: *CCD-line scan camera systems with USB 2.0 and PCI bus systems*

For both system versions **Schäfter+Kirchhoff** offers several types of CCD-line scan cameras with different sensor lengths and pixel sizes. Subsequently an assortment is listed.

camera type	interface	pixels	pixel size	measur. size	line frequ.
SK512DPD	LVDS	512	10 x 10 µm	5.12 mm	70 kHz
SK2048JRI	LVDS	2048	14 x 14 µm	28.67 mm	4.7 kHz
SK4096DPD	LVDS	4096	10 x 10 µm	40.96 mm	9 kHz
SK2048UJR	USB 2.0	2048	14 x 14 µm	28.67 mm	4.7 kHz
SK2048USD	USB 2.0	2048	10 x 10 µm	20.48 mm	7.1 kHz

After installing the software once the operating system recognizes the CCD-line scan camera with every afresh connection to the system automatically. The system is immediately ready for operation without reboot of the computer.
The System II requires the istallation of a PCI-bus interface board SK9192D (grabber). The interface board is a further expense factor. On the other hand the digital CCD line scan cameras using LVDS standard has even higher line frequencies as the USB 2.0-cameras. The shading correction is realized on-board of the interface board SK9192D. Thus, the workload of the CPU during signal evaluation is reduced in comparison to the USB 2.0-cameras. In the thresholding measurement frequencies of more than 30kHz are possible.
Using the Merger box SK9195 up to 5 CCD line scan cameras can be deployed parallel and pixel synchronized with one interface board (e.g. for roundness measurements of threaded materials).

Summary:

The laser diffraction system of **Schäfter+Kirchhoff** is perfectly assigned for measurements of diameters, geometries and edge detection with high precision and speed. Due to the modularity and the variety of the components the system is applicable in many domains of science and industry.
Caution: Particularly with the evaluation of diffraction, disturbing influences like imperfect surface finishing, surface defilement like oil film, stray light or further diffraction due to air turbulence from heat convection are to avoid.

Information:

CCD-line scan cameras, flyer made by **Schäfter+Kirchhoff**

Presentation:

AUTOMATICA, 1. international trade fair for Robotic + Automation june, 15th - 18th, 2004, in Munich
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