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HYBRID OPTIMUM SIGNAL PROCESSING FOR A STRAIN SENSOR

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Abstract: Recently there has been a shift in material sciences towards the use of non contacting laser optical methods to characterize material behaviour. This development has been driven by the need to test specimens at relatively high temperatures. We present a hybrid system for tracking laser speckles consisting of a Fourier-optical preprocessor followed by a digital signal processing unit that is able to determine engineering strain within specimen at viewing distances of several hundred millimeters. We will show in this paper that advanced digital signal processing using a polarity coincidence correlation method allows for an increase of the processing speed without undue degrading of system performance. We will further show that an optimum analog to digital conversion characteristic exists which if applied results in displacement estimates with almost ideal variances.

Keywords: optical and digital signal processing, optimum analog to digital converter, laser speckle, strain sensor.

1 INTRODUCTION

Standard material testing procedures of modern high temperature materials like ceramic matrix compounds which operate at temperatures beyond 1000°C demand for non contacting displacement, displacement gradient and strain measurement methods. Several optical methods are discussed in the literature [1, 2] most of which try to track imaged parts of the specimen's surface during mechanical testing. Engineering strain can be easily determined by tracking two separated parts of the specimen's surface, calculating the change in separation and dividing by the initial value. Subjective laser speckle patterns [3] being characteristic for particular surface elements [4] allow for high resolution tracking even under the influence of high levels of thermal background radiation [5]. This tracking has to be performed at least in two dimensions (2D) in space even if only displacement components in the strain direction are of interest because of imperfections in the bearings and grips of commercial stress testing equipment. The tracking can be done by digital signal processing (e.g. by estimating the cross-correlation function of surface elements before and after the deformation process [1]). Because the numerical load of two dimensional signal processing algorithms is very high the tracking rate attainable is too slow for some standard material testing procedures. Rates of only about a few per second can be achieved even if numerically very efficient algorithms and high power PCs or dedicated signal processors are used. Real-time applications like load dynamic material testing or cyclic testing are not feasible and so all available methods are not able to cope with the relatively high strain rate necessary for high temperatures materials to avoid creep effects.

In recent publications [6, 7, 8] we demonstrated that extremely fast operating Fourier-optical signal processing [9, 10, 11] within so called optical 4f-arrangements can be utilized to perform at least some parts of the necessary processing by particular manipulations of the laser speckles optical power spectra. We will point out in this paper how for the 2D problem at hand the (electrical) data acquisition and the subsequent digital signal processing can be performed one-dimensionally (section 2). As a result of the 1D processing we are able to speed up the processing substantially. In section 3 we will show a particular unbiased cross-covariance estimator to further increase the measuring rate and compare this estimator's variance to that of the most often used standard cross-correlation estimator. Furthermore we will prove in sections 4 and 5 that by implementing an appropriately designed optimum analog-to-digital converter the variance as a measure of random error of the suggested estimator can be kept nearly as low as for the standard estimator. This way both real high speed and high quality measurements become feasible for the first time.

2 FOURIER-OPTICAL SIGNAL PROCESSING OF LASER SPECKLES

Fourier transforming properties of lenses [9] offer a very smart way to perform coherent optical signal processing by (spatial) Fourier-filtering. It is shown [8] in great detail how appropriate spatial filtering of laser speckles produced by reflective coherent wave-scattering from objects with optical rough surfaces within well designed optical 4f-arrangments can be carried out and how desired power spectra and as a result particular laser speckle patterns can be shaped using Fourier-plane filter masks. It is well known [3] that the power spectral density (psd) for subjective (but also in a slightly modified way for objective) laser speckle patterns consists of a δ-function component at zero spatial frequency plus an extended component that takes the shape of the autocorrelation function of the intensity transmittance of the lens pupil if no spatial filter mask is present in the optical signal processing system. For a circular lens pupil of diameter D the psd of the speckle pattern in the image plane (e.g. see Fig. 1, right side) is given by Eqn. (1):

$$\mathrm{psd}\left(f_x,f_y\right)=E[I]^2\cdot\left\{\delta\left(f_x,f_y\right)+\left(\frac{\lambda z}{D}\right)^2\cdot\frac{4}{\pi}\left[\arccos\left(\frac{\lambda z}{D}f\right)-\frac{\lambda z}{D}f\sqrt{1-\left(\frac{\lambda z}{D}f\right)^2}\right]\right\} \tag{1}$$

for $f < (D/\lambda z)$ and zero otherwise, with

E[...]	denotes expectation or mean value
f_x , f_y	spatial frequencies in *x*- and *y*-direction respectively
$f = (f_x^2 + f_y^2)^{1/2}$	spatial frequency magnitude
λ	wavelength of the illuminating laser light
z	distance between the lens pupil and the image plane.

We had shown in recent papers [6, 7] that well dimensioned, inexpensive binary amplitude filter masks are best suited to be applied in practical set-ups when commercial stress testers are performing the loading process. Intensity patterns like the one shown in Fig. 1 (left) which are basically sensitive only to displacement- and strain components in loading direction (here the horizontal direction) can be produced in the image plane of an optical signal processing system optimized for the measurement of 1D displacements and strains.

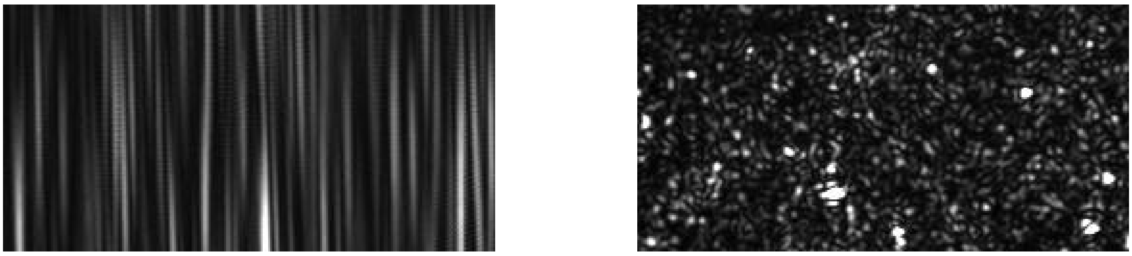

Figure 1. Image plane intensity patterns of an appropriately designed optical signal processing system with (left) and without (right) a suitable Fourier-plane filtering mask

This kind of elongated speckle pattern lends itself to 1D signal acquisition with a properly oriented line scan camera followed by only 1D digital signal processing. It can easily be seen that unwanted displacements in the system's non-sensitive vertical direction will cause on the spatially stable line scan camera only small signal decorrelations compared with the signal taken at the reference position whereas displacements in the horizontal direction can be measured with high sensitivity. It is proven [8] in great detail that the properties of this measurement system are excellent when sought after in-plane displacements in horizontal direction have to be determined even if bothersome displacements in vertical in-plane direction and out-of-plane direction are present at the same time.

If no spatial filtering is applied, more familiar speckle patterns similar to that depicted in Fig. 1 (right) are formed in the image plane. In this case the line scan camera signals will strongly decorrelate [4] even if the specimen under test experiences only small displacement components in vertical direction which result in erroneous measurement values.

3 DIGITAL SIGNAL PROCESSING

One of the principal applications of correlation in digital signal and image processing is the area of template matching. The closest match between signals can be found by selecting those signals that yield the correlation function with the largest value. Correlation is also widely used for the determination of linear displacements. Accepting more complicated mathematics robust algorithms can be designed even if rotation and scaling during the displacement cause problems. Because these effects normally do not provoke undesired side effects in standard material testing procedures we are allowed to keep the mathematics easy and focus on the basic new concept without loss of generality. The method shown in the following can be adapted to all robustness maintaining algorithms.

Correlation functions as a second order statistical property of speckle signals are defined over an ensemble-average of rough surfaces. Even if ergodicity can be assumed only estimates of the true correlation function can be calculated because the captured signals have to be restricted to finite extents in all practical cases. Therefore a finite set N of data is assumed to be used in estimating the correlation functions.

3.1 Polarity Coincidence Correlation Function Estimator

Because appropriate, extremely fast operating, optical signal processing reduces the 2D feature tracking problem to a 1D one, all further digital processing can be performed much faster in 1D. Although the data which are fed into a conventional optimum linear, nonparametric cross-correlation estimator [10] is only 1D the computational load remains still high. It should be mentioned that using the convolution theorem and implementing it through the fast Fourier transform (FFT, [12]) can offer a numerically more effective calculation possibility. Measuring rates up to 100 per second are achievable for this 1D digital correlation method.

Moreover we are able to further decrease the computation time by implemention of dedicated correlation function estimators. The simplification of the classical or conventional cross-correlation estimator yields an estimate which is called polarity coincidence correlator PCC (Eqn. 2):

$$R_{PCC}(i) = \sin \cdot \left\{ \frac{p}{2} \cdot \frac{1}{N-|i|} \cdot \sum_{n=i+1}^{N} \mathrm{sign}\big(I_1(n) - E[I_1]\big) \cdot \mathrm{sign}\big(I_2(n-i) - E[I_2]\big) \right\}, \qquad (2)$$

with:

i	space lag argument, -(N-1) i (N-1)
N	total number of samples (pixels of the CCD camera)
$I_1(n)$	recorded intensity signal before the specimen's loading process
$I_2(n)$	recorded intensity signal after the specimen's loading process
E[...]	denotes expectation or mean value

This kind of correlation function is determined by the signals' zero crossings and does only use the signum (sign) of the signals. It is obvious that the computational complexity have to be substantially reduced compared to the conventional correlator. Therefore the measuring rates can be greatly increased up to several hundreds or even thousands per second depending on the type of the calculating hardware.

The displacement Δ of the specimen in the system's sensitive direction can be derived from the location of the peak of $R_{PCC}(i)$ by taking the optical magnification m (=image size/object size) of the signal processing system and the pixel pitch p of the utilized CCD line-scan camera into account:

$$\Delta = \frac{p}{m} \cdot \arg \left\{ \max_{\forall i} [R_{PCC}(i)] \right\} \qquad (3)$$

Engineering strain ε within the specimen can be calculated with the difference of the displacements Δ_1 and Δ_2 of two tracked object regions separated by the base length l_0:

$$e = \frac{\ddot{A}_1 - \ddot{A}_2}{l_0} \qquad (4)$$

3.2 Variances of Correlation Function Estimators

The variances - as a measure of quality and performance - of the two estimators mentioned and defined in section 3.1 are shown in Fig. 1, where N is again the length of the digital signal sequences. Specifications of the somewhat unhandy and complicated mathematical expressions of the approximated estimators' variances [13, 14] shall not be given here, instead we decided to show the variances in a much more explaining graphical way.

Because the sought after displacement is derived from the position of the peak of the correlation function as explained in section 3.1 and only small signal decorrelations occur when the specimen is displaced, the region in which the (normalized) true correlation function approaches 1 is of greatest interest: It can be seen that the lower computational cost of the polarity coincidence correlator is paid for by a larger variance which is still small, however, in this region. To decrease the variance of the estimates the total number N of pixels must be as high as possible. If similar variance magnitudes for both estimators are required the signal sequence lengths N have to be somewhat increased when using the PCC method.

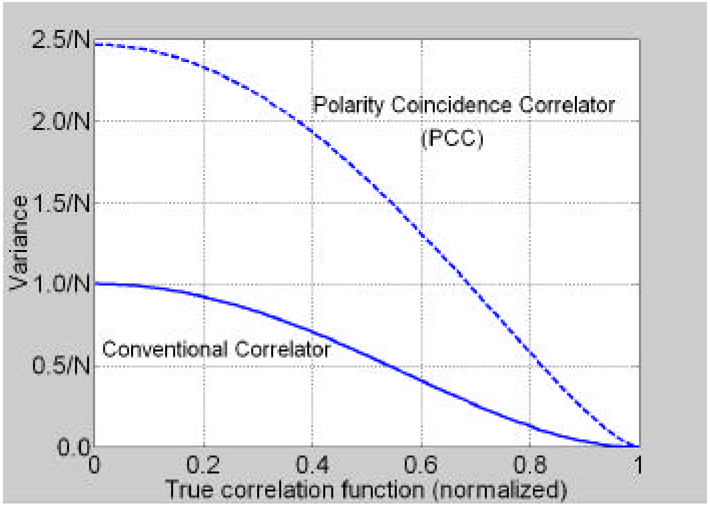

Figure 2. Variances of estimators as a function of the normalized true correlation function for large (uncorrelated) signal sequence lengths N

4 OPTIMUM ANALOG TO DIGITAL CONVERTERS (ADC)

Analog to digital conversions of 1D intensity signals as in our case and of images in general consist of both (spatial) sampling and gray level quantization. Whereas the sampling is defined by the pixel geometry of the CCD-sensor the quantization of image intensities is determined by the utilized ADC. Each quantizer maps a continuous variable I into a discrete one $\hat{I}$, which takes values from a finite set $\{r_1,...r_L\}$ of numbers. This mapping is a staircase function and the quantization rule determines a set of increasing transition levels $\{t_k, k=1,... L+1\}$ with t_1 and t_{k+1} as the minimum and the maximum values of I respectively. I is considered to be mapped to r_k if it lies in the half-open interval $[t_k,t_{k+1})$. The quantizer design problem is to select the best t_i and r_i for a particular optimization criterion and a given continuous probability density function $p_I(I)$ of the scalar random variable I. Each quantization process is irreversible, the input values cannot be determined uniquely from the output values and so the quantizer introduces distortion which should be attempted to be minimized. The optimization criterion used here is the minimization of the mean-square quantization error (MSE). Furthermore a realizable estimator $\hat{I}$ can be obtained by minimizing the MSE because $\hat{I}$ is an unbiased estimate of I:

$$MSE = E[(I-\hat{I})^2] = \int_{t_1}^{t_{L+1}} \left(I-\hat{I}\right)^2 \cdot p_I(I)\,dI = \sum_{i=1}^{L} \int_{t_i}^{t_{i+1}} (I-r_i)^2 \cdot p_I(I)\,dI \qquad (5)$$

The conditions necessary for the minimization are obtained by differentiating the MSE given in Eqn. (5) with respect to t_k and r_k and equating the results to zero (note that I corresponds to t_k and $\hat{I}$ to r_k). After a few mathematical steps the results are obtained and can be interpreted as follows: The optimum reconstruction levels lie at the center of mass of the probability density function over the specified transition levels, which in turn are halfway between the optimum reconstruction levels. The expressions for t_k and r_k are combined so that they have to be solved simultaneously by any kind of iterative scheme. An approximate solution for the transition levels given in Eqn. (6) can be obtained by modelling *p(I)* as a piecewise constant function [15]:

$$t_{k+1} \cong \frac{(t_{L+1}-t_1)\cdot \int_{t_1}^{\frac{k}{L}\cdot(t_{L+1}-t_1)+t_1} [p_I(I)]^{-\frac{1}{3}} dI}{\int_{t_1}^{t_{L+1}} [p_I(I)]^{-\frac{1}{3}} dI} + t_1 \qquad (6)$$

with $k = 1, ..., L$. This method requires that the dynamic range which is defined by the quantities t_1 and t_{L+1} is finite and has to be known before determining the optimum transition levels t_k. The optimum reconstruction levels r_k can be determined easily by averaging t_k and t_{k+1}. The corresponding quantizer is often called a Lloyd-Max quantizer [16]. To put in the ideal probability density function $p_I(I)$ of laser speckle intensity patterns [3]

$$p_I(I) = \frac{1}{E[I]} \cdot \exp\left(-\frac{I}{E[I]}\right) \qquad (7)$$

in Eqn. (6) yields the optimum quantization function which is shown in Fig. 2 for an ADC with 5 bit gray level resolution. It can be seen clearly that the transition and reconstruction intervals, respectively are much smaller at small intensities than at larger ones which is caused by the negative exponential statistics defined in Eqn. (7).

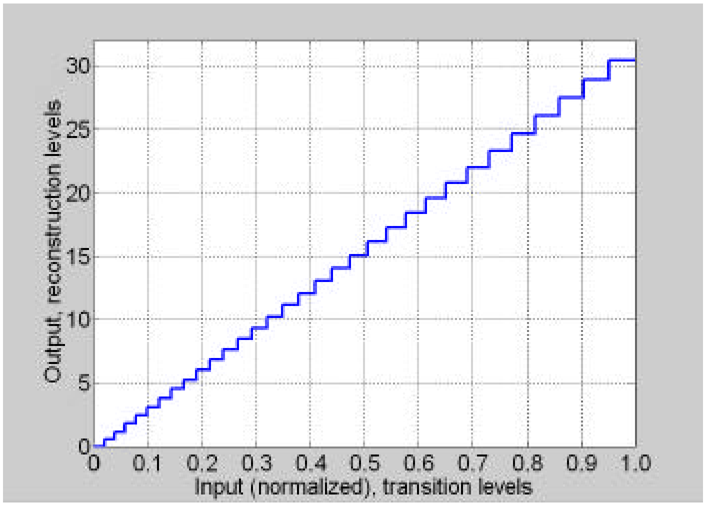

Figure 3. Optimum quantization function (5 bit gray level resolution) if laser speckle signals are to be analog to digital converted

For uniform distributions the equations governing the quantizer become linear, giving equal intervals between the transition and reconstruction levels. Quantizers of this kind, called linear quantizers, are implemented in most commercially available ADCs. One way to produce the desired optimum quantizer function with a standard linear quantizer is to implement code conversion from a high resolution code (e.g. 8 bit) to a lower one (e.g. 5 bit or lower). This was done for the investigations in this paper by appropriate designed look-up-tables (LUTs). LUTs were also used to produce linear quantizers with different gray level resolutions.

5 EXPERIMENTAL AND MEASUREMENT RESULTS

Our aim is to investigate the performance of different quantizers within the entire strain measurement system specified so far which yields optical preprocessed images shown in Fig. 1 on the left side. Because speckle signals from which the "displacement of the specimen" is estimated are random variables, the quality of different estimators and quantizers, respectively can only be expressed in a statistical way. Therefore the following results are drawn from 128 signal realizations each taken exactly at the same horizontal displacement Δx. The specimen is displaced in the system's sensitive horizontal direction by using a hysteresis compensated piezo actor having an absolute positioning accuracy of 30 nm. At several different positions the actually grabbed line signals are correlated with the corresponding reference signals and the displacements are determined. The resolution of the digital signal processing technique was enhanced by theoretical ideal interpolations of the correlation functions by a factor of 16 where 1/16 pixel corresponds to 0.425 µm on the specimen's surface.

Investigations were made for gray level resolutions of the utilized linear quantizers and optimum Lloyd-Max quantizers from 8 bit down to 1 bit. The results show that only minor differences occur if resolutions from 8 bit down to 4 bit for either quantizer types are implemented. Lower gray level resolutions than 4 bit cause different results of measurement which are discussed in the following:

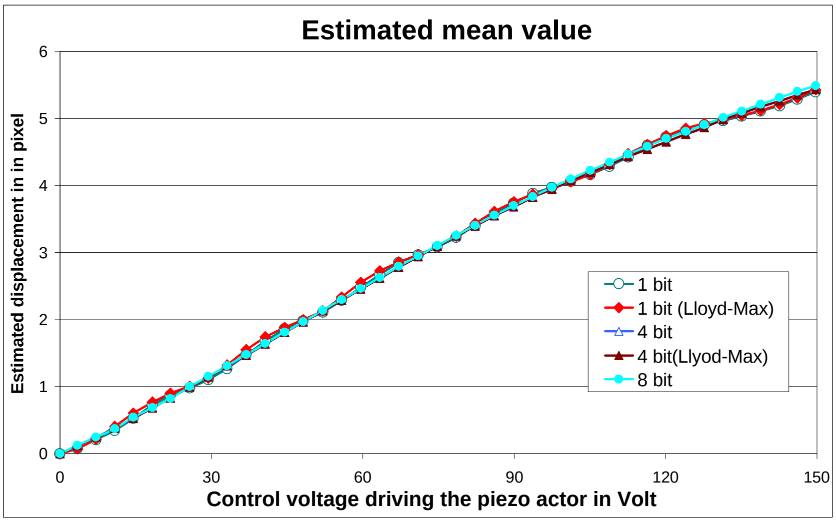

Figure 4. Mean value of estimated displacements when using different types of quantizers (linear, Lloyd-Max) and different gray level resolutions

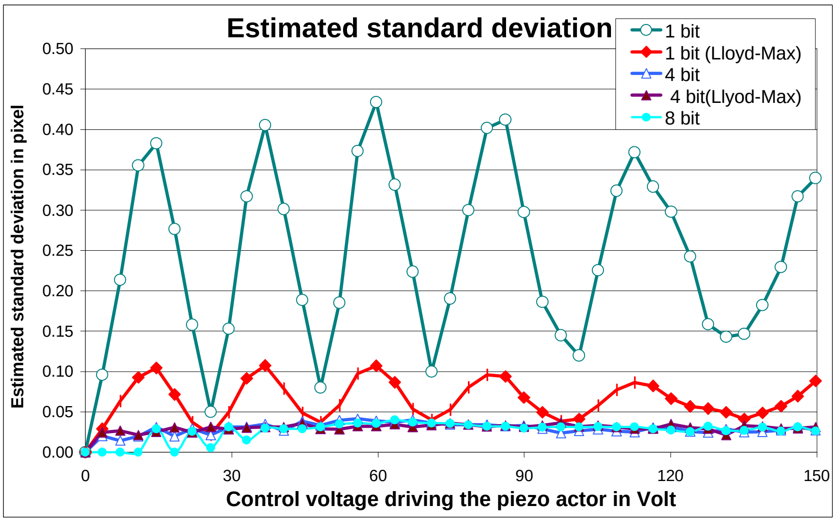

Figure 5. Standard deviation of estimated displacements when using different types of quantizers (linear, Lloyd-Max) and different gray level resolutions

Fig. 4 shows estimates of the displacements' mean values which do not differ significantly when different gray level quantizers (linear, Lloyd-Max) are implemented. It can also be seen that the relationship between the control voltage driving the piezo actor and the displacement of the specimen is not highly linear. This fact does not influence the results of the investigations in any way because relative comparisons are of interest. Fig. 5 depicts unbiased estimates of the standard deviations $\sigma_{\Delta x}$ as a measure of random errors and uncertainty of measurement. Each individual data point shown in the diagrams is estimated as mentioned before from 128 samples taken under constant conditions exactly at the same horizontal position. Periodical deviations of $\sigma_{\Delta x}$ at very low gray level resolutions of the ADC are caused by the pixel fill factor of the utilized CCD camera which is around 50 %. Maximum values of $\sigma_{\Delta x}$ occur at displacements which are odd-numbered multiples of half of the pixel pitch (see curves for 1 bit linear and 1 bit Lloyd-Max quantizers in Fig. 5). The optimum quantizer in an ADC with 1 bit gray level resolution reduces $\sigma_{\Delta x}$ by a factor of approximately 4 compared with the 1 bit linear quantizer. Under worst case conditions, that is at distinct displacements, $\sigma_{\Delta x}$ can be at maximum twice as large as for high gray level resolutions. If the geometrical properties of the utilized camera are properly chosen, $\sigma_{\Delta x}$ will not show periodical deviations and will reach values as in the high resolution (8 bit or even higher) case. Therefore the polarity coincidence correlation estimator defined in Eqn. (2) can be implemented without increase of $\sigma_{\Delta x}$ if the 1 bit optimum quantizer derived in this paper is used.

6 CONCLUSIONS

Material testing procedures for elevated temperatures demand very high processing speed of the measurement equipment. In this paper we showed that an increase in the measurement rate over conventional laser speckle extensiometers can easily be achieved if besides using Fourier-optical means to preprocess speckle images the image acquisition process as well as the image processing itself can be performed on optimally quantized data without greatly degrading system performance.
Future work will be devoted into incorporating the reported research into programmable logic devices.

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