THE COMBINATION OF SPECKLE CORRELATION AND FRINGE PROJECTION FOR THE MEASUREMENT OF DYNAMIC 3-D DEFORMATIONS OF AIRBAG COVERS

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1 Introduction

The explosion of an airbag causes fracture of the covers (Fig. 1) at certain predefined sites. The task of the engineers constructing the airbag systems is to optimize the process of deformation and subsequent fracture of the airbag covers. Usually this is done by FE calculations. The accuracy of the numerical simulations, however, strongly depends on the exact knowledge of the loading conditions, i.e. the local dependence of the pressure on time, and on the material behavior which is given by a set of rate and temperature dependent material parameters. Both the time sequence of the pressure as well as the material parameters are difficult to determine. Therefore the numerical results for the transient 3-D deformation of the airbag covers have to be compared with results of experiments in which the time dependent deformations are measured. As for a correct evaluation of the deformations many measurement points are needed in small time intervalls, only optical and fullframe measurement methods are suitable.

2 Experimental procedure

2.1 Measuring methods

The out-of-plane deformations are expected to be large compared to the in-plane deformation. Besides this the deformation rate is high and the surface of the test object exhibits poor reflectivity. Therefore some of the well established 3-D measuring methods like electronic speckle pattern interferometry (ESPI) for instance cannot be applied. It turned out that the best way to solve the problem is to measure the in-plane deformations and out-of-plane deformations by separate methods [Wolf, 1996]. For the determination of the in-plane deformations a white light speckle correlation method seemed to be most suitable. This method yields the in-plane displacements. For the out-of-plane deformation fringe projection is used. With this method the contour of the airbag cover can be determined. From the contour map of the deformed cover and from an additional contour map of a reference state the out-of-plane displacement field can be calculated.

2.2 Measuring setup

The setup for the measurement of all three components of the displacement vector field of the dynamically deformed air bag covers consists of a speckle correlation system with a white light source of 250 W and a CCD camera (camera 1) and of a fringe projection system with a fringe projector and an additional CCD camera (camera 2). The optical axis of the two systems lie in the same plane (Fig. 2). The cameras are high speed KODAK CCD cameras with frame rates of 4500 per second and an image size of 256x256 pixels. For synchroneous recording of the speckle pattern the cameras must be synchronized electronically. A spectral separation of the two systems is necessary, to supply the corresponding measurement information to each system. This is performed by application of spectral filters, respectively, and by matching of the spectral sensitivity of the cameras to the frequency of the filters. For the speckle system blue filters are used and red ones for the fringe projection system.

Figure 1: Steering wheel with airbag cover.

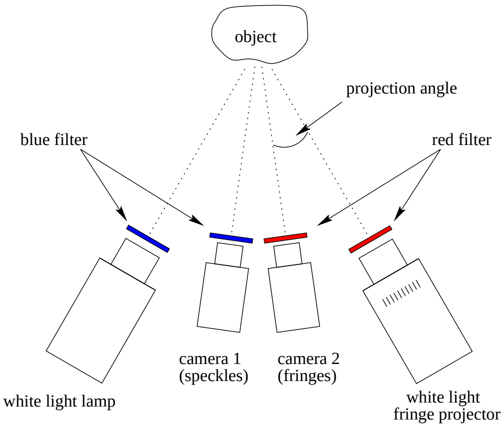


Figure 2: Measuring setup.

2.3 Object surface preparation

In order to receive sufficiently high fringe modulation the reflectivity of the originally black surface of the covers is increased by a thin coating of white paint. The speckles, however, are artifically created by air brushing the surface of the airbag with red paint. Because the reflectivity of the red light from the fringe projector is the same for the white background of the speckle pattern and for the red speckles the speckles cannot be “seen” by the fringe camera. On the other hand the speckles appear black in the speckle camera because they do not reflect the blue light.

2.4 Speckle correlation

The determination of an in-plane displacement vector field by speckle correlation is a problem of pattern recognition. The image of the surface is divided into correlation subsets of e.g. 32x32 pixels. The pattern of one subset in the undeformed state is then searched in the surface of the deformed state by direct digital cross correlation. In contrast to methods which are based on variational principles [Sutton et al, 1986] this method needs no interpolation of the discrete pixel data. Mathematical operations are restricted to multiplication of the discrete Fourier transforms of the subsets of the deformed and undeformed states and to a back transformation of their product. The maximum of the correlation function of a subset is identified as the correlation peak. It provides the position of the pattern in the deformed state.

If the grey level of the reference subset at pixel position m,n is given by $f(m,n)$ and the grey level of the deformed subset by $g(m,n)$ then the Fourier transform of f and g are

$$F(u,v) = \mathcal{F}\{f(m,n)\} \tag{1}$$

$$G(u,v) = \mathcal{F}\{g(m,n)\}. \tag{2}$$

The correlation function follows from

$$K_{gf}(m,n) = \mathcal{F}^{-1}[F(u,v) \cdot G^*(u,v)] \tag{3}$$

with G^* being the conjugate complex of the function G. In pattern recognition G^* is called a matched filter. It is known that for patterns which have nearly uniform distribution of amplitudes in the frequency space the relevant information is contained in the phase φ of the Fourier transform of the pattern. Therefore filters which primarily are sensitive to phase information seem to be of great benefit for solving pattern recognition problems. One of these filters is the phase-only filter (POF) [Hoerner and Gianino, 1984]. It is defined by

$$G^*_{POF}(u,v) = e^{-i\varphi(u,v)} = \frac{G^*(u,v)}{|G(u,v)|}. \tag{4}$$

With this filter the correlation function follows from

$$K_{POF}(m,n) = \mathcal{F}^{-1}\left\{\frac{G^*(u,v)}{|G(u,v)|} \cdot F(u,v)\right\}. \tag{5}$$

This filter we used sucessfully for the evaluation of speckle patterns [Gutmann, 1994]. Therefore we also applied it in this investigation.

2.5 Fringe projection

The intensity distribution of a sinusoidal modulated fringe pattern recorded by the fringe camera is given by

$$I(m,n) = b(m,n) + a(m,n) \cdot sin\varphi(m,n) \tag{6}$$

as a function of the pixel position (m,n), containing the background intensity b and the fringe amplitude a. The phase difference $\Delta\varphi(m,n)$ between the phase value $\varphi_{obj}(m,n)$

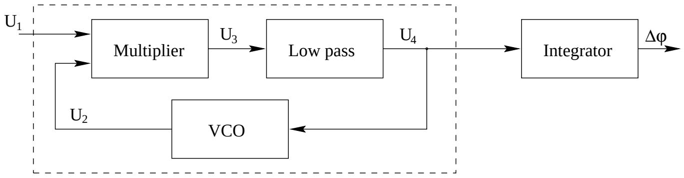


Figure 3: Block diagramm of the PLL.

of an object point and the corresponding phase value φ_{ref} at the same position m on a reference plane yields the height or contour $h(m,n)$ of the object by the relation

$$h(m,n) = s(m,n) \cdot \Delta\varphi(m,n) \tag{7}$$

with s being the scaling function which is determined by geometric calibration of the fringe projection system.

From the contour map of the deformed cover and from an additional contour map of a reference state the out-of-plane displacement field is calculated.

The most accurate method to determine the phase distributions is based on temporal phase shifting with subsequent phase unwrapping. In the highly dynamic measuring task under consideration, however only one fringe pattern for each time instant is available. Therefore the phase calculation must be performed by one-image techniques. Instead of using Fourier transform method [Takeda, 1982] which is recommended in literature we used a new method. It is based on a phase locked loop (PLL) [Rodriguez and Servin, 1993]. By this method the phase unwrapping process can be avoided completely. The only condition is that there are no discontinuities or steps in the contour of the object.

2.6 Phase locked loop and its digital simulation

Fig. 3 shows the block diagramm of the phase locked loop circuit for real time fringe evaluation. It consists of four main parts: Multiplier, voltage controlled oscillator (VCO), low pass filter and integrator. The signal $U_1(t)$ is generated by the fringe camera when scanning the fringe pattern with an intensity distribution given by eqn. (6). After cutting off the time independent part of the signal and normalising its amplitude to 1 U_1 reads as follows

$$U_1(t) = sin\left(\omega_0 \cdot t + \varphi_1(t)\right). \tag{8}$$

The signal $U_2(t)$ is chosen to be equivalent to the intensity distribution of the fringe pattern on the reference plane, i.e.

$$U_2(t) = cos\left(\omega_0 \cdot t + \varphi_2(t)\right). \tag{9}$$

U_1 and U_2 are multiplied in the multiplier and low pass filtered. For small phase differences $\Delta\varphi = \varphi_1 - \varphi_2$ this yields the signal

$$U_4(t) = \frac{1}{2}\Delta\varphi(t). \tag{10}$$

For each row which has to be scanned the process starts at the reference plane (locking period) so that $\varphi_1 \equiv \varphi_2$ or $\Delta\varphi = 0$. When the scanning process reaches the contour of the object φ_1 begins to differ from φ_2, i.e. $\Delta\varphi$ is no longer zero. During a small time interval δt a change $\delta(\Delta\varphi)$ of the phase difference is produced. This causes the control procedure of the PLL circuit to start by changing the frequency of the PLL circuit to start by changing the frequency of the signal U_2 in the VCO according to

$$\omega_{VCO}(t) = \omega_0 + 2\kappa \cdot U_4(t) = \omega_0 + \kappa \cdot \delta(\Delta\varphi). \tag{11}$$

in order to compensate $\delta(\Delta\varphi)$. In this equation κ is a feedback parameter which has to be properly selected [Wolf, 1996].

As we are interested in $\Delta\varphi(t)$ we have to integrate the output $U_4(t)$.

The contour of the airbag covers need not to be determined on-line. Therefore it is not necessary to use the analogue version of the PLL [Lichtenberger, 1998]. The electronic circuit can be simulated digitally [Rodriguez and Servin, 1993]. As $\omega_{VCO}(t)$ is changing according to $\Delta\varphi(t)$, i.e. $\omega_{VCO}(t) = \frac{d(\Delta\varphi)}{dt}$, it follows from eqn. (11)

$$\frac{d(\Delta\varphi)}{dt} = 2\kappa \cdot U_4(t). \tag{12}$$

Neglecting the low pass filter in the PLL circuit, $U_4(t)$ can be replaced by $U_3(t) = U_1(t) \cdot U_2(t)$. From eqn. (8) and (9) we receive the differential equation 13 aftre setting $\varphi_1(0) = 0$ and replacing t by x and $U_1(t)$ by $I(x)$ according to equation (6)

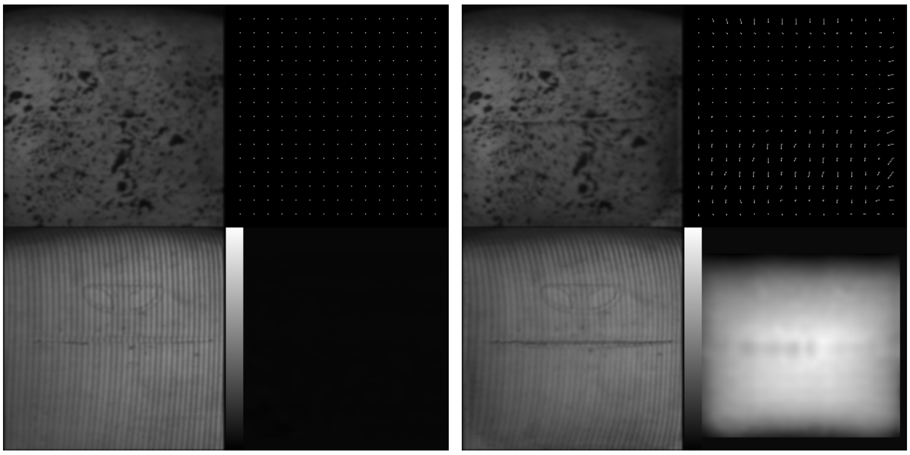
$$\frac{d(\Delta\varphi)}{dx} = 2\kappa \cdot I(x) \cdot cos(\omega_0 x + \Delta\varphi). \tag{13}$$

However, the constant backgound intensity b of I yields an offset in $\Delta\varphi$. Therefore instead of $I(x)$ the derivative $dI(x)/dx$ is used in eqn. (13). For numerical evaluation of (13) the differentials are replaced by finite differences with a step width $\Delta x = 1$. The equation for the calculation of the phase difference $\Delta\varphi$ at the pixel positions m,n then reads

$$\Delta\varphi(m+1,n) = \Delta\varphi(m,n) + \kappa \cdot [I(m+1,n) - I(m,n)] \cdot cos\,[\omega_0 m + \Delta\varphi(m,n)]\,. \qquad (14)$$

The numerical integration procedure has the same effect as the low pass filter in the electronic circuit (Fig. 3).

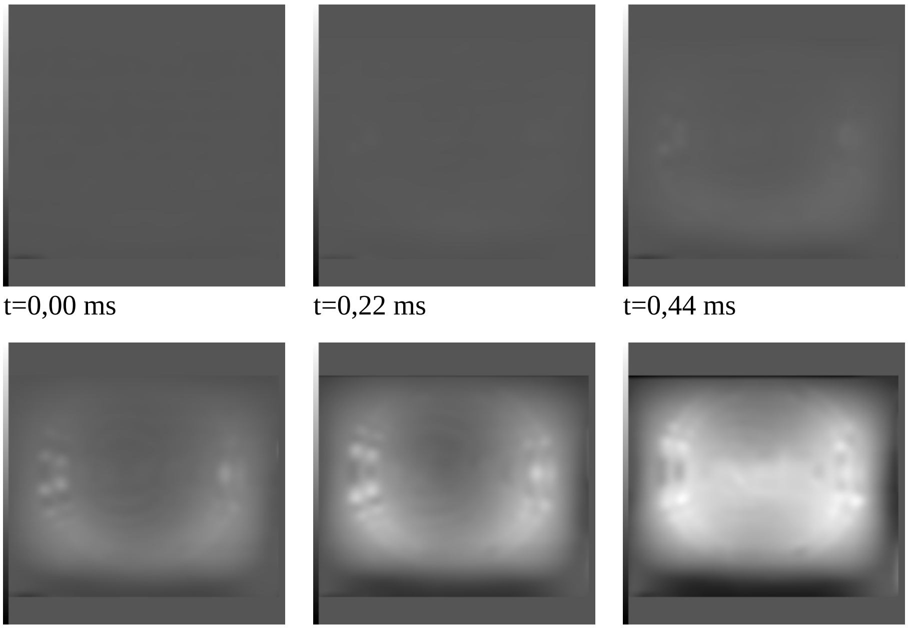
3 Results


reference state
t=0,00 ms

deformed state
t=1,33 ms

Figure 4: Reference state and deformed state. Shown on the left side are the speckle and fringe images and on the right side the in-plane vectors and grey level coded out-of-plane deformation.

Fig. 4 shows an example for the 3-D deformation of an airbag cover which is gained by the combination of digital speckle correlation and fringe projection as described in the preceding chapters. The in-plane component of the deformation is much smaller than the out-of-plane component. The grey level coded out-of-plane component is scaled to the maximum value of 13,2 mm reached just before the fracture. Figure 5 shows a time series of the grey level coded out-of-plane displacement. Each image in Figure 5 is scaled



t=0,00 ms t=0,22 ms t=0,44 ms

t=0,66 ms t=0,88 ms t=1,11 ms

Figure 5: Time sequence of the grey level coded out-of-plane-displacement of an airbag cover.

to the minimum and maximum displacement values in the image. It can be seen that the deformation of the airbag cover starts in the four corners and not in the center of the cover.

4 Conclusion

Digital speckle coorelation and fringe projection can be combined to measure dynamic 3-D deformations in cases where the ranges of in-plane and out-of-plane displacements differ remarkably. This methods have been successfully applied to study the highly dynamic deformations of air bag covers directly after the ignition of the inflator. It was necessary to use a single-image procedure to determine the phase distributions of the fringe patterns from fringe projection. The digital simulation of a PLL circuit proved to be an alternative to Fourier transform methods because no phase unwrapping has to be performed.

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