Computer-Aided Evaluation of Chromatic Interferograms

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Abstract: A computer-aided system for the reconstruction of a thin fluid film shape from chromatic interference colours is presented conceptually and the parts of the system are demonstrated. The interference colour evaluation technique is based on the idea of replacing human eye by a simple differential colorimeter realised by computer program. Three-dimensional visualisations of the film shape are generated using techniques of image processing and computer graphics.

1. Introduction

Interference fringe patterns produced by various types of interferometry and moiré techniques are widely used in the measurement of shapes, surface roughness, displacements, strains, deformations, optical characteristics, fluid properties, and so on. In simple cases, the fringe patterns analysis is carried out manually. But when the fringe patterns are of a high degree of complexity, such an analysis can be very tedious and in many cases ambiguous. This can be found for example in some cases when the reconstruction of the surface shape or surface topography of an object from optically generated interference fringes is required. It is needed in the areas of microscopy, inspection, quality control and computer-aided design. That is why a large number of techniques for analysing monochromatic interference fringe patterns have been developed [R86, S90, MD92] that have been implemented into various computer-aided systems for surface reconstruction [CHL82, PRP83]. These systems usually perform a three-step process which includes: (1) an image digitization; (2) fringe recognition and contours extraction; and (3) visualisation of the surface. It usually results in a three-dimensional surface model that is suitable for the whole variety of geometric transformations to aid in the interpretation of the physical specimen.

The use of chromatic interferograms instead of monochromatic ones is useful if the number of monochromatic fringes in a pattern is very small and there is not enough information for an accurate evaluation of the phase distribution. Its another advantage is that the interference order need not be known as each optical thickness is represented by the unique colour. That is given by the superposition of fringe systems produced for each wavelength and interference pattern consists of continuously changing colours instead of the dark and bright fringes of the monochromatic pattern. Algorithms for the fringe recognition and contours extraction are based on colour vision models and they are quite different from those developed for the processing of monochromatic interferograms.

For a few years ago our Laboratory has been developing computer-aided optical interference technique [HKL96] for the study of lubricated contacts taking place between highly loaded, non-conform curved bodies in relative motion. In such cases the elastic deformation plays significant role during creating a thin coherent lubricant film of thicknesses up to few hundreds nanometers that carries the entire load excerted on the surfaces. This phenomenon is called as an elastohydrodynamic lubrication which is an abbreviation expressing an elastic deformation of the surfaces and hydrodynamic pressure generated in the fluid. The determination of the lubricant film thickness distribution is of a key-importance for the understanding of many physical and chemical processes occurred in such contacts. Nowadays, the most widely used experimental technique, developed by Professor A. Cameron [GC67] from Imperial College of Science and Technology in London, is based on the evaluation of the interference colours produced by lubricant films. Despite of undoubted advantages of this technique (1) the relatively simple experimental equipment used; (2) possibility to study film shape in whole contact; and (3) ability to study dynamic phenomena, its main weak point is the limited resolution and accuracy. It is mainly caused by the inability of human beings to perceive colours precisely and accurately during the visual evaluation of interference colours. In addition to it very complicated calibration and time-consuming colour comparing are required if it is necessary to obtain the film profile or three-dimensional representation of the film thickness. That is why our work has been concentrated on removing subjective influences and manual work out of the process of interference colour recording and evaluating. It resulted in developing the computer-aided system performing an image synthesis to reconstruct lubricant film thickness distribution from chromatic interferograms.

2. Technique Principle

Interference colour evaluation technique is based on the idea of replacing human eye by a simple differential colorimeter realised by computer program executing colour-difference measurements between "standard" and "sample". As a standard, a digital colour chart is used. It contains of colour coordinates of all interference colours produced by the film in dependence on its thickness and is obtained by the observing of an interference system with known geometry. Such a system can be represented e.g. by Newton interferometer - any arrangement of two surfaces in contact illuminated by a source of light producing Newton fringes [M92]. The sample is each digitized interferogram recording an interference colour distribution in measured layer. Physical aspects of colours are taking into account so that only information about the phase of the interference colour and its position is important. From this point of view it is not crucial how these colours are interpreted by human brain.

The whole technique substance can be summarised into three following steps:

1) Both the standard and the sample are obtained with the use of the same light source - an uniform stabilised white light source with colour temperature conversion filters for proper chromatic adaptation of the detector. Both of them are recorded in succession and the standard is retained in computer memory in the form of the table.

2) Both the standard and the sample are obtained with the same detector - RGB CCD camera or colour film in a photographic camera or high speed camera. The video signal processing is relatively easy and can be done in real time that is particularly suitable for the study of transient and quasistatic phenomena. However, the spatial resolution of RGB CCD camera is usually much lower than that of the colour reversal film, where it is up to 100 lines per millimeter. When the colour film is used, images must be recorded on the same film-strip that is digitized by Kodak Photo CD System. The results presented in this paper were obtained with the use of 35 mm reversal colour film Kodak Ektachrome 160 Professional digitized into Kodak Photo CD Master file format.

3) Colour differences between L^* a^* b^* triple in each sample pixel and all L^* a^* b^* triples of the standard are evaluated with the help of CIELAB colour difference equation and two colours with corresponding film thicknesses with the least colour differences are chosen from the standard. The final film thickness is determined by their interpolation.

3. Image Digitization

The idea of Kodak Photo CD System is to offer an inexpensive platform-independent storage and retrieval of images captured by film and digitized by a film scanner. There are several forms of the Kodak Photo CD image file format intended for different application.

The baseline format called Kodak Photo CD Master is intended to handle full-quality 35 mm colour negative or colour reversal images. The images are at first scanned by Kodak PCD Film Scanner with scanning resolution of 2200 pixels/inch in both dimensions that gives 3072 pixels x 2048 lines per image. Then, a nonlinear transformation is applied to encode RGB data. For positive values of R, G, and B the transformation corresponds to the opto-electronic transfer characteristic defined in CCIR 709. As a result, colours that are outside of the gamut defined by the CCIR 809 primaries are encoded by the negative values [FU94]

$$\begin{aligned} R' &= 1.099R^{0.45} - 0.099, \\ G' &= 1.099G^{0.45} - 0.099, \\ B' &= 1.099B^{0.45} - 0.099, \end{aligned} \tag{1}$$

for R, G, B > 0.018 and for R, G, B values ≤ 0.018

$$\begin{aligned} R' &= 4.5R, \\ G' &= 4.5G, \\ B' &= 4.5B. \end{aligned} \tag{2}$$

The R', G' and B' values are converted to one luma Y and two chroma components C1 and C2. The encoding equations [FU94] correspond to CCIR Recommendation 601-1

$$\begin{aligned} Y &= \ \ 0.299R' + 0.587G' + 0.114B', \\ C1 &= -0.299R' - 0.587G' + 0.886B', \\ C1 &= \ \ 0.701R' - 0.587G' - 0.114B'. \end{aligned} \tag{3}$$

Finally, these data are stored in three 8-bit channels

$$\begin{aligned} Y(8bit) &= (255/1.402)Y, \\ C1(8bit) &= 111.40C1 + 156, \\ C2(8bit) &= 135.64C2 + 137. \end{aligned} \tag{4}$$

The scale factors and offsets for the C1 and C2 channels result from the distribution of real world colours.

The data for each image are decomposed into hierarchy of images which are related to the spatial resolution of the original image (Base x 16) by the factor of 1/2 (Base x 4), 1/4 (Base), 1/8 (Base/4), and 1/16 (Base/16). The Base, Base/4, and Base/16 images are stored uncompressed in the Kodak Photo CD Image PAC File together with Huffman-coded difference images that record the differences among the Base, Base x 4, and Base x 16 image. Kodak Digital Science Photo CD Master Disc enables to store one hundred such files.

Equations for converting PhotoYCC data to RGB 24 bit data for displaying by computers with CCIR 709 reference primaries are [FU94]:

$$\begin{aligned} Y &= 1.3584Y(8bit), \\ C1 &= 2.2179(C1(8bit)-156), \\ C2 &= 1.8215(C2(8bit)-137), \\ \\ R &= (Y+C2)/353.2, \\ G &= (Y-0.194C1-0.509C2)/353.2, \\ B &= (Y+C1)/353.2. \end{aligned} \tag{5}$$

Obtained R, G, and B values are in the range from 0 to 346 that are converted with the help of look-up table to 8-bit data.

The conversion from the Kodak Photo CD Image PAC File into RGB 24-bit Window's bitmaps (BMP) is performed by widely accessible Dynamic Link Libraries (DLL) from Kodak Inc..

4. Colour-Difference Evaluation

There is a number of colour models available [SCB87] but only CIELAB and CIELUV uniform colour spaces are recommended for comparing colour differences by CIE. Both of them are opponent-type colour spaces and they are non-linear transformations of the 1931 CIE XYZ system. Colour information is referred to the reference white and non-linear relation for L* is intended to mimic the logarithmic response of the eye.

For the evaluation of colour-differences between the standard and the sample the CIE 1976 L*a*b* colour-difference equation is used [BS81b]

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2},$$

where (6)

$$\Delta L^* = L^*_i - L^*_{jk},\ \Delta a^* = a^*_i - a^*_{jk},\ \Delta b^* = b^*_i - b^*_{jk},$$

which represents the Euclidan distance in CIELAB colour space between coordinates of i^{th} colour of the standard and the colour of $(j,k)^{th}$ pixel of the sample (Fig. 1). For each pixel of the sample two adjacent colours (A, B), whose value of colour-difference is the least, with corresponding film thicknesses are found in the standard. The resulting film thickness is determined by the interpolation and corresponds to the point in CIELAB colour space (D) which lies on the connecting line of two earlier obtained points and whose distance from the colour of the pixel of the sample (C) is minimal.

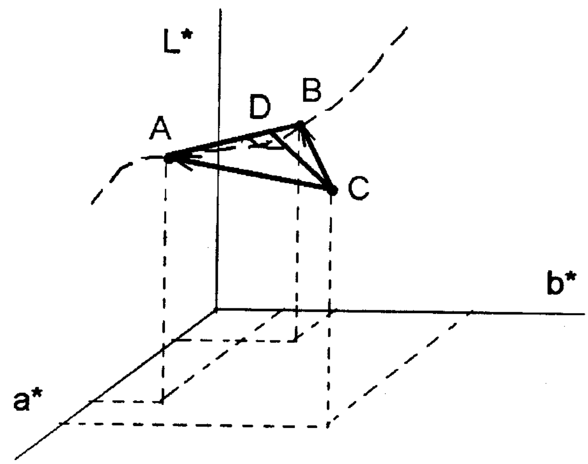

Fig. 1 Interpolation in CIELAB colour space.

XYZ tristimulus values are used for transformation between YCC and L*a*b* data [BS81a]

$$L^* = q\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16, \quad a^* = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right], \quad b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right],$$

where (8)

$$q = 116 \qquad for \frac{Y}{Y_n} > 0.008856,$$

$$q = 903.29 \quad for \frac{Y}{Y_n} \leq 0.008856,$$

where L* is a psychometric lightness coordinate, a* is a redness-greenness coordinate, and b* is a yellowness-blueness coordinate. X_n, Y_n, and Z_n are tristimulus values of the reference white. All calculations have been done with tristimulus values for the CIE standard illuminant D_{65} having a correlated colour temperature of 6500 K.

5. Computer Software

Above described process is realised by the software developed in 32-bit professional developers system Borland Delphi 2.0 for the Microsoft Windows 95 operating system and a true-colour display adapter. Six bookmark windows are associated with procedures accessible from a menu bar containing five drop-down sub-menus that are used to control an image data handling and enhancement, colour chart creating, film thickness evaluation and image synthesis (Fig. 2).

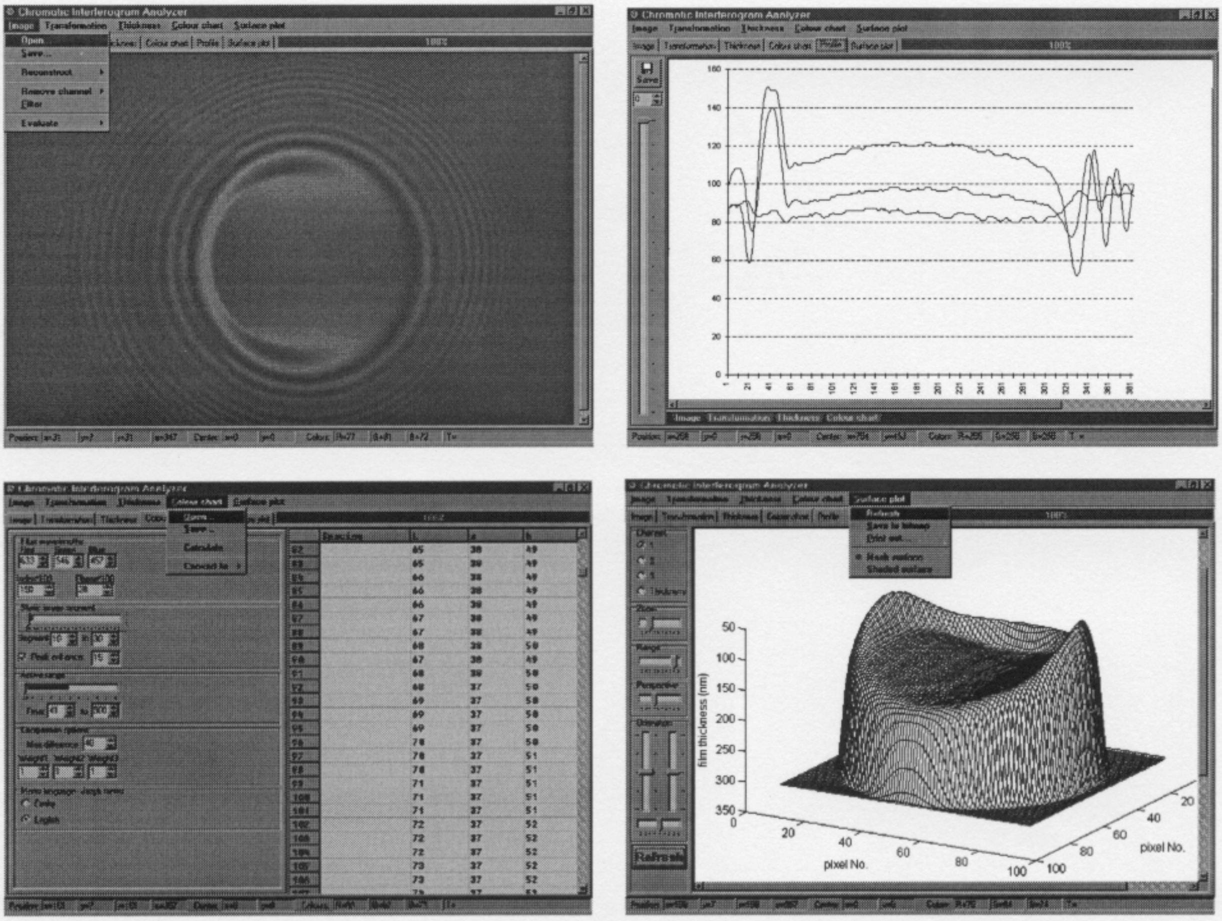

Fig. 2 Arrangement of main bookmark windows.

The image data handling and enhancement involves reading and saving the desired images, specifying the boundary of the image to be analysed, image filtering, converting image between the RGB, HSI, HSV, XYZ, YCC, Luv or Lab colour spaces, and image profile displaying.

The colour chart creating procedure enables to create calibration curves of the film thickness and corresponding colours from Newton rings produced by the interference system illuminated consequently by the monochromatic and white light source. The monochromatic interferogram is processed through fitting curves to the intensity data with a view to interpolating between fringe centers, finding fringes maxima and minima, finding the centre of curvature of the fringes, transforming from polar to Cartesian coordinate system and determining the film thickness values by the third degree spline function from maxima and minima fringe locations. Colours of the chromatic interferogram are adjoined to the values of thicknesses obtained by above mentioned procedure.

The film thickness evaluation procedure evaluates film thickness from the interferogram by CIELAB colour difference equation.

The image synthesis procedure consists of the reconstruction of the lubricant film thickness distribution and its visualisation with mesh or shaded surface.

6. Application for Elastohydrodynamic Film Thickness Measurement

Quasistatic elastohydrodynamic films were generated in an experimental equipment working as a two-layer Fizeau interfeometer described in detail elsewhere [HKL96]. Chromatic interferograms produced by Tolansky method were photographed and digitized by the above described process. The digital colour chart was obtained from Newton rings observed in a thin oil film between the steel ball and the glass disc coated with a sputtered chromium semireflecting layer. This colour chart plotted in the CIE xyY and L*a*b* colour spaces is displayed on Fig. 3, where figures are optical thicknesses in nanometers.

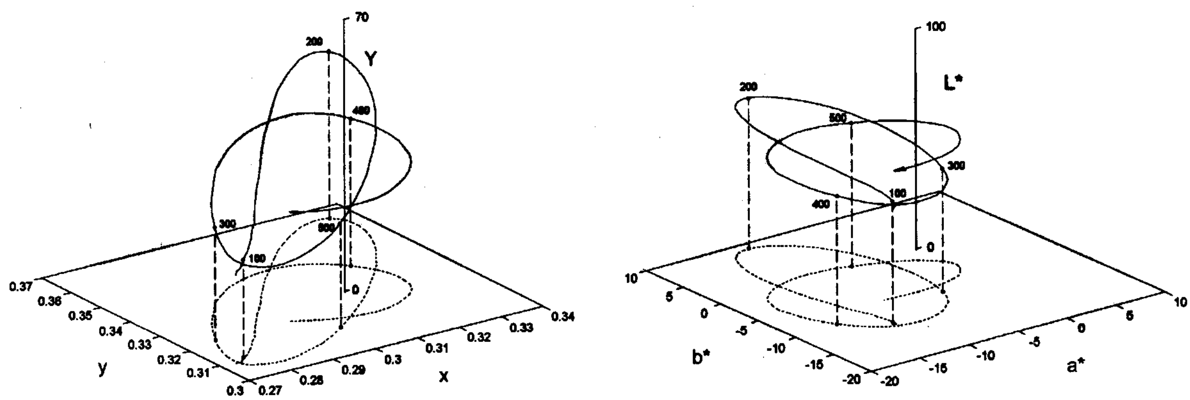

Fig. 3 Interference colours in CIE x, y, Y and L*, a*, b* colour spaces (figures are optical thicknesses in nanometers).

Fig. 4 shows mesh surfaces giving a perspective view of the film thickness shape for rolling velocities of 0.0382, 0.0541, 0.0646, and 0.0725 m/s and load of contact bodies of 29 N. Each mesh surface is obtained from interferogram of 87 pixels x 81 lines with one pixel corresponding to 4.5 μm. For the presentation purpose the vertical scale shows the distance from the glass disc (not shown). From this figure it can be seen the characteristic elastohydrodynamic film shape having the plateau region bounded by the horseshoe shaped constriction. This shape is caused by lubricant viscosity changes across the contact region with pressure. Increasing rolling velocity causes the increasing of the lubricant film thickness.

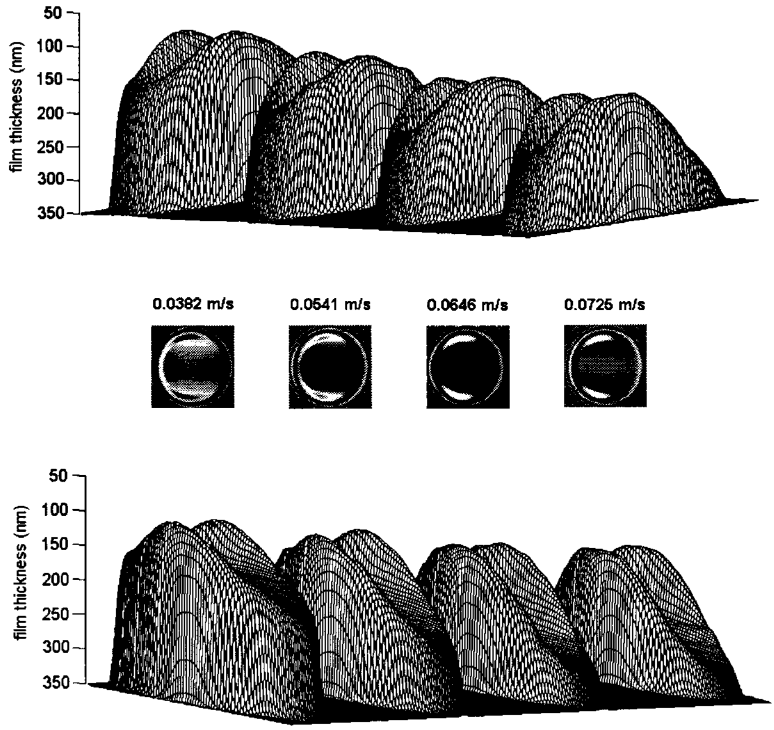

Fig. 4 Film thickness shape visualisation with corresponding gray scale interferograms (figures are rolling velocities).

To validate this technique its accuracy has been checked and a comparison with conventional monochromatic interferometry has been done. The technique has been successfully used for the study of elastohydrodynamic lubrication of point contacts that is described elsewhere [HKL96].

7. Conclusion

We have demonstrated that it is feasible to produce a new technique by combining a computer graphics and an interference microscopy to calculate and visualise thin film thickness distribution. The main advantages of this technique are its relatively simplicity and accuracy. It is especially suitable for visualisation of quasistatic and dynamic phenomena taking place in thin film lubrication. Nevertheless, there are some limitations connected with proposed technique. First, the spatial resolution of processed images is limited by the optical resolution of the optical instrument used that is about 900 nm. Another limitation is imposed by the information content of the images and time needed for the image processing.

8. Acknowledgement

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9. Literature

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