DIMENSIONAL METROLOGY OF CYLINDERS BASED ON DIGITAL IMAGE PROCESSING:APPLICATION TO LHC CORRECTOR MAGNETS*

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Abstract

This paper presents the development of a method to measure relative deformations of bodies (basically cylinders) based on the analysis of images taken with a digital camera. The main application is the measurement of the deformation of the shrinking tubes of superconducting corrector magnets, which allows the calculation of the final pre-stress exerted to the coils.

1 INTRODUCTION

One of the main concerns when manufacturing superconducting magnets is to achieve the required pre-compression in the coil to avoid tensile stresses in the conductors and hence potential quench development.

For the particular case of LHC corrector magnets, the cylindrical external geometry allows a simple way to deduce the pre-stress by measuring the elongation of the outer shrinking tube [1]. In order to do a fast and inexpensive measurement of this magnitude (for instance for a quality control process), we have developed a procedure based on the analysis of digital images of the contour of the magnet which are taken by a camera placed inside an special device for this purpose.

2 MEASURING PRINCIPLE

The basis of the method is very simple: to measure the number of pixels inside a closed contour, which automatically gives the equivalent diameter for the case of a circumference.

The one-dimensional version of the method is simple and the evaluation of the accuracy is also easy to analyse. If we want to measure the length of a segment with a "ruler" of pixels each of them with a length *p* (see figure 1.a), we count the number of pixels enclosed by the segment, establishing a certain criteria for the edges (if the segment covers more than 50% of the edge pixel, this pixel is included, otherwise it is excluded). The length of the segment will be the number of covered pixels and the absolute error will vary periodically from –*p* to + *p* as the length of the object grows.

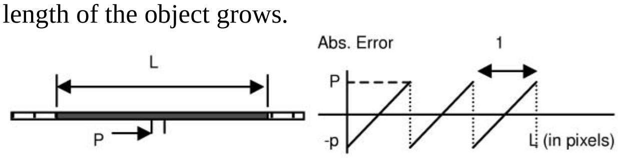

Figure 1: a) Measuring principle b) Error distribution.

For the two-dimensional case, the measuring principle is the same: there is a "grid" of pixels where the object is placed (see figure 2); if one pixel is covered by the object then it is included in the area, if not, it is excluded, and for the edge pixels, only if the area covered by the object is higher than 50%, the pixel is included.

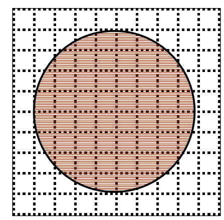

Figure 2: 2-D Measuring method principle.

The first interesting difference between both cases is that for the 1-D one, the resolution of the method (smallest length increment of the object that the method is able to detect) is the length of the pixel, while for the 2-D is much smaller because if the diameter varies in a small amount, a fraction of edge pixels close to the changing limit, will "switch" and contribute to modify the area.

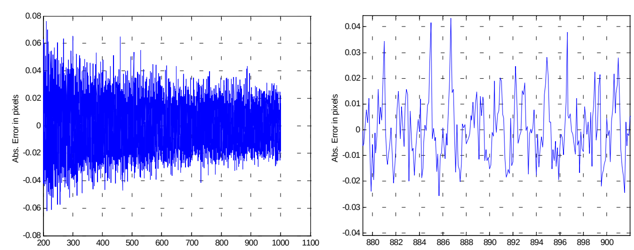

Figure 3: Absolute error distribution for the 2-D case

To evaluate the absolute error, a simulation was performed for a circumference whose diameter was varying from 200 to 1000 pixels. Error distribution shows a random pattern. In any case its maximum value is limited to about 0.04 pixels for a diameter of 1000 pixels (a typical value for a 1.5 Mpixel camera) which is a factor of 25 lower than the 1-D case. Figure 3 shows the absolute error in pixels as the diameter increases. The right figure shows a zoom of the left one where the random variation of the error is depicted.

Digitalisation of closed contours also allows to measure the perimeter of the curve. For a perfect circumference of radius R, the following statements are valid [2]:

- The "digital area" tends to πR^2 when the number of pixels tends to infinite.
- The "square digital perimeter" always measures 8R, no matter the number of pixels (this perimeter only considers sides of each square pixel).
- The "diagonal digital perimeter" always measures $16\cdot\tan(\pi/8)\cdot R$, no matter the number of pixels (this perimeter considers also diagonals of each square pixel).

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This set of statements allows a verification of the digitalisation accuracy. If the "diagonal digital perimeter" is available from the image processing software, then if the number of pixels is high enough, the ratio of the second power of the perimeter to the area, χ, (which in an "analogical" circumference should be 4π) is 13.981.

Another verification, if available, of the digitalisation quality is the fractal dimension of the contour. For a perfect digital circumference, its fractal dimension is one.

3 DESCRIPTION OF APPLICATION

The main application of the method is to measure the deformation of an aluminium cylinder which shrinks a corrector superconducting magnet for the LHC. Figure 4.a depicts the basic scheme of the application. The magnet coils are pre-compressed by an outer cylinder with a certain interference. Two images are taken: first, one of the outer tube and then a second picture of the whole magnet already assembled. In both cases the measuring contour is the outer cylinder circumference at the lower end of the tube.

Figure 4.b shows the so-called "edge error" calculated using a F.E.M simulation. It represents in % the error in the determination of the real deformation in the outer diameter by measuring the deformation at the lower end, if the shrinking cylinder is longer than the coil in a magnitude 2d. Once both images are taken, the next step is to determine the difference in diameter through the computation of the areas. This deformation can be easily related to the stresses inside the coil.

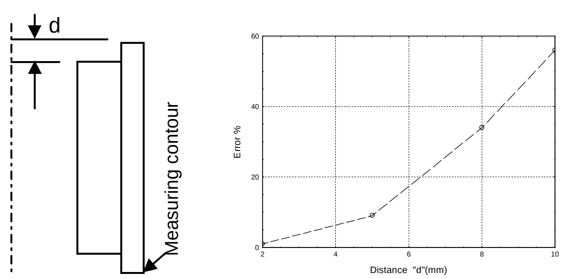

Figure 4: a) Scheme of the application b) Edge error

4 DESCRIPTION OF THE DEVICE: THE HARDWARE

The general arrangement of the device is depicted in figure 5. It consists of a supporting structure where all the main components are placed. At the bottom, the digital camera (7), which is connected to a TV monitor (8) to allow an easy continuous monitoring of the image. At a distance of 240 mm from the camera objective, there is a tray (5) where the magnet to be measured (4) is placed. It is water-tight to allow measuring under liquid immersion as it will be described later on.

One of the most critical issues to achieve a high precision in the measurements is to guarantee optimal illumination conditions, which are summarised in two parameters: stability and diffusivity. The first condition is achieved by using halogen lights (2). The second condition requires the use of two screens. One is a reflective screen (1) placed at the top, which avoids direct illumination from the light. The second one is a diffusing screen, made of an special glass, which increases the spatial homogeneity of the light reaching the magnet.

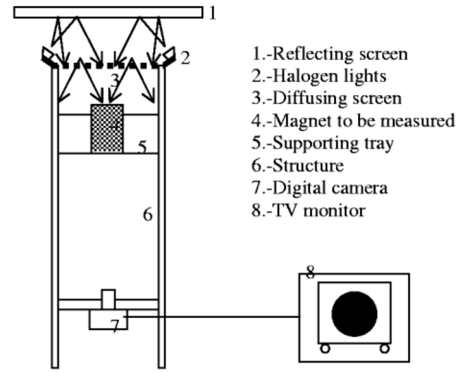

Figure 5: General arrangement of the device

Temperature control is also extremely important, since the camera is very sensitive to that parameter. A permanent reference pattern is being analysed to overcome this problem.

To achieve a clear contour, high contrast images should be used. This type of images have been obtained by two different methods:

- Immersion in a contrast liquid
- Backlight illumination

In the first one, a very dark liquid is poured in the tray with the object so that only its contour is seen by the camera. A drawback of this method is that the viscosity of the liquid varies with the temperature and the "wet" contour changes as the liquid penetrates more or less in the edges of the object.

In the second one the high contrast is produced by the fact that all the light sources are placed behind the object as described in previous paragraphs. Two main advantages are that it is a "dry" method and no time degradation is produced. Figure 6.a shows an image using the Immersion method, while figure 6.b shows an image of the same object using the Backlight method.

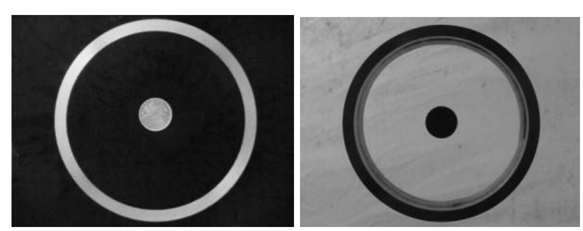

Figure 6: a) Immersion method b) Backlight method

5 DESCRIPTION OF THE DEVICE: THE SOFTWARE

To analyse the images acquired with the camera, a general image processing freeware has been used, selected from different available options. It is called ImageJ [3], a software developed in Java, which main applications are in the medical sector, although many of its capabilities can be applied to our case.

The general procedure to analyse an image is:

1) Conversion of the image to grey scale
2) Contour detection
3) Area and perimeter measurement

If required, a circular fit can also be performed to analyse the quality of the perimeter, using an specific Matlab code developed for this purpose [4].

We started measuring a real object (a stainless steel cylinder) analysing different parameters of the image. The main goal was to compare several measuring techniques in order to select one for further measurements. Differences arise, mainly, on the contour definition. Figure 7.a shows an image of the cylinder, while figure 7.b represents the grey-level histogram of the full image.

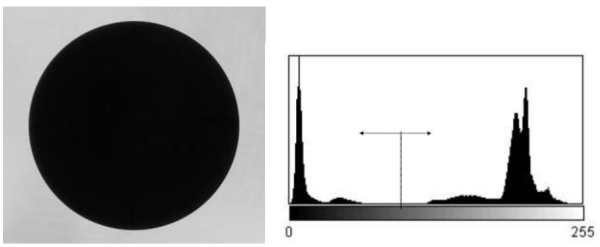

Figure 7: a) Image of a stainless steel cylinder. b) Image histogram

There are a significant number of border pixels with a grey value placed between two peaks. Obviously, the selection of the thresholding value to define the border will influence the contour dimensions. For this reason it is important to define a systematic criteria for every image analysis. To evaluate the importance of the thresholding value, we performed a sensitivity analysis (see figure 8). It is interesting to see how while the area is continuously increasing, perimeter fluctuates with a first reduction and a further increase. The ratio χ, as defined in I, was taken as a quality factor. Relative fractal dimension of the contour is also shown.

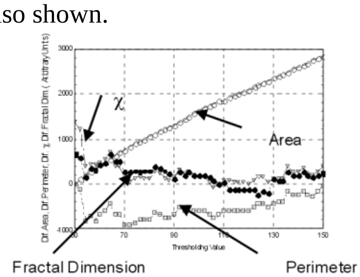

Figure 8: Threshold Sensitivity Analysis

Obviously, to perform a manual threshold analysis of every image becomes tedious so that we relay on the automatic thresholding, which provides a difference for the equivalent diameter of the cylinder of about 4 microns with regard to the value provided by the manual method.

A second and crucial verification, is the repetitivity of the measurements for different images of the same object under the same conditions. Biggest differences between two equivalent diameters were 2 μm and the value of σ for each set of measurements was 0.8 μm, typically.

6 CALIBRATING APPLICATION

Finally, we present the application of the method to a case which is a simulation of the end use. It consists of an aluminium cylinder that shrink fits a stainless steel bar with a certain interference as it appears in figure 9, where the dimensions of both pieces (all in mm.) are also shown.

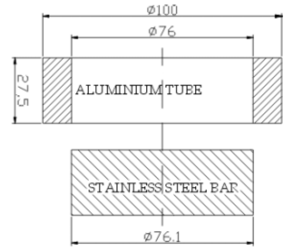

Figure 9: Application case of the method

Prior to the experiment, the outer diameter of the shrink fit cylinder was measured on a 3-D table, and after the experiment, measured again in the same manner. F.E.M. calculations were also performed to compare measured results to theoretical predictions. Table 2 shows the comparison between the results for the three methods for the diameter increase of the outer cylinder after it was shrunk, measured or calculated in every case at the lower plane of that cylinder.

Table 2: Diameter increase comparison.

FEM	3-D Table	Image Processing
89 μm	90μm	93μm

Agreement between the three values confirms that the method is able to measure with a relative error of about 3%, or in terms of absolute error of about 3 μm. This means that for the case of a magnet where expected deformations in diameter are about 40μm, errors from this method can be limited to about 8%.

7 CONCLUSIONS

We have developed a procedure to measure stresses in superconducting correction magnets for LHC, based on digital image processing. The method consists of analysing images before and after the shrink fit of the coils with an outer aluminium cylinder. These images are then processed, calculating the area of the contour corresponding to this cylinder and the diameter increment is deduced from this area value.

The images are taken with a digital camera placed inside an special device where the magnet and the lights to guarantee the illumination conditions are also included. The method has been calibrated with an experiment where the same type of measurements could be carried out very precisely, in a 3-D table. Agreement between both types of results confirms that the method can be valid for magnet measurement with an estimated accuracy of about 8%.

8 REFERENCES

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