COMPUTED TOMOGRAPHY IN THE AUTOMOTIVE FIELD. DEVELOPMENT OF A NEW ENGINE HEAD CASE STUDY

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ABSTRACT

Industrial computed tomography has the potential to become one of the most versatile and powerful nondestructive evaluation techniques. The high number of advantages and benefits which characterize it may promote its use not only for inspecting the interior of components, but also as an excellent means for research of new materials and processes and development of new products.

This work is aimed at identifying inspection applications in the automotive industry for which CT can provide an effective evaluation means to improve the product quality and to reduce its time to market. As major case study the CT analysis of aluminum engine heads is discussed. Due to the large shape complexity of the part and the following resulting process difficulties, CT technique is a unique tool to locate defects, check internal geometry and thus provide a better understanding of actions to be undertaken to obtain the required quality of the part. In this way the time consuming trials and error process, currently in use, is avoided.

The economic potential and added value of CT over other traditional inspection techniques is finally addressed.

INTRODUCTION

Computed tomography, whose mathematical principle was developed early in this century by Radon, had its first commercial application in the late 1960s and early 1970s, when Hounsfield developed the first CAT scanner. However, these early efforts were mainly directed towards medical diagnostic imaging.

Since the end of the 1970s specific efforts were made towards the application of computed tomography in the industrial environment (petroleum and aerospace industry), so that industrial CT systems are now designed and manufactured to address inspection objectives that extend beyond the capabilities of medical CT scanners.

Compared to conventional film radiography, CT differs not only because of the apparatus set up, as the radiation beam and the detector array in CT systems lie in the same plane as the surface being imaged, but also in the quality of the resulting image, achieved without the confusion of superposition of features, often found with conventional radiography.
CT provides better flaw depth and flaw distribution information than conventional film radiography, which are useful in identifying defects and evaluating whether they are in a critical or non-critical location.

Another important and innovative feature of CT is that it results in digital data sets, which can be readily processed by image processing software for display and enhancement, or converted into a format (such as CAD, STL, IGES file) suitable for other purposes, available to any users and compatible to the most commonly used engineering design software applications.

Therefore, CT can play an important role in the field of Reverse Engineering, as a powerful tool for relating the CAD model of a component to the real component itself, when modifications applied onto the real object must be updated into its CAD model.

Opposite to the large advantages of the CT technique, the high cost of the equipment and installation, X ray hazard, the need of very specialised personnel and consequently the high cost of the CT analysis are just some of the main drawbacks of this method. This is why until now the use of CT has been limited to few applications where safety or reliability concerns are of so large importance to justify the expenditure.

The last decade have seen an increasing attention being paid to the product development cycle. It has been clearly stated in conferences, articles and several books that care given to the prototyping phase can lead to a sizeable decrease of costs and quality improvement of the final product. This is where CT finds its best industrial field of application because of its unique capacity to deal with interior structures and its easy integration with three dimensional electronic models. In fact CAD is the core of the product prototyping phase as it links design, product performance analysis and process simulation, dimensional control and rapid prototyping manufacturing techniques.

To demonstrate the impact of the CT method on the product development cycle, a new aluminum alloy engine head was chosen as a reference case study. While the design methodologies are rather well established, the development of this component rises large difficulties at the stage of the first metal prototypes realisation, where final production processes cannot be afforded because of the large investments and long machining time required by the final tooling. The general rule is to fabricate the first small batch of parts by sand casting. Excellence foundry companies are recently introducing the new Rapid Prototyping techniques, like Selective Laser Sintering of sand, to further shorten the fabrication time of sand cores and moulds. However the need to optimise the sand casting process, especially because of the introduction of not completely assessed new technologies as rapid prototyping, hinders the achievement of a sound component at the first shot. In order to avoid performing mechanical machining operations or, even worse, carrying out a complete test bench on a fault engine head, CT can be chosen as a valuable tool in checking for defects in critical locations and testing the correspondence between CAD model and real internal geometry of cavities.

System description

The industrial CT scanner installed at FIAT Research Centre, supplied by Scientific Measurement Systems, Inc. (Austin, Texas), is composed of four subsystems:
• the *X-ray source subsystem*, represented by a Philips MCN 451 X-ray tube, with 450 kV maximum voltage, 10 mA maximum current and dual beam spot size (1.0 and 4.5 mm);

• the *radiation detector subsystem*, consisting of a linear array detector (63 CdWO$_4$ scintillators);

• the *object positioning unit* (4 degrees of freedom), which mechanically handles the inspected component, once it is placed on the rotary table; allowing for the inspection of objects with 100 kg maximum weight, 880 mm maximum height and 720 mm maximum diameter.

• the *computer subsystem*, which controls the acquisition, processing and analysis of the experimental information collected; it is comprised of a Pentium personal computer, for data acquisition, and a Sun-Ultra workstation, for computation-intensive reconstruction.

**System capabilities**

According to ASTM standards (reff. [1], [2]), preliminary tests on standard phantoms were performed, in order to evaluate the capabilities of the system. Methodology and results are described in the Appendix.

**ACTIVITIES AND RESULTS**

During the past year CRF inspected a wide range of materials and components, in order to test CT system’s capabilities and performances, as well as to optimise the scanning parameters set according to the size and composition of the object to be inspected.

Acquiring experience with different types of components also helped get acquainted with common artifacts that generally affect CT reconstructed images. Artifacts are errors or false structures occurring in an image, which have no counterpart in the original object. The ability of recognising them is essential for a correct evaluation of the test-piece.

As far as aluminium castings are concerned, non-destructive evaluation was performed on a number of engine head prototypes and qualitative analyses of flaw distribution and characterisation were carried out.

The ability of the CT system to precisely locate flaws in three dimensions allows to determine their severity levels, so that predictions can be made about the component’s behaviour during subsequent tests.

Moreover, the kind of information provided by CT inspection can be essential in evaluating and optimising the quality of the casting process to avoid defects. This aspect of CT makes it very useful and effective when applied to the research and development of new casting processes, because it helps reduce the prototype fabrication time.

The most common defect found in all inspections was porosity, both isolated and diffuse (figg. 1, 2).

Some of the reconstructed images show aluminum sprouts on the edge of internal cavities, due to improperly positioned cores. The size, location and composition of
such defects, which are obviously made out of aluminum as the casting itself, make them undetectable with conventional non-destructive techniques, such as film radiography.

Non destructive testing was performed according to ASTM standards (reff. [3], [4]).

Fig. 1 Example of relevant porosity found in an aluminum casting. The sharp definition of the internal cavities is due to the accuracy of sand cores produced by SLS (Selective Laser Sintering) rapid prototyping technology (EOSintS system by EOS GmbH)

Fig. 2 Example of diffuse porosity found in an aluminum casting

**Search for porosity**

An engine head prototype sample was non-destructively inspected with the aid of X-ray computed tomography, in order to evaluate the casting quality before performing life tests. The inspection was mainly addressed to image cross-sectional planes of the engine head’s injection tube and inlet and exhaust ports, where the water circuit is sophisticated in order to ensure precise cooling, and the sand cores could have some problems. It provided the identification and location of a variety of defects
originated during the casting process. Information on defect severity level and defect spatial distribution help better evaluate the state of the component at the end of life tests.

The overall examination demonstrated a better casting quality in the flame plate area, whereas the oil housing surroundings are characterised by a distributed and homogeneous porosity, mainly located near pivot elements housings and valve guides (figg. 3, 4, 5, 6).

Fig. 3 Example of a tomogram of an aluminum engine head (1st cylinder)

Fig. 4 Cluster of pores (0.4 to 1 mm in diameter) in the 1st cylinder’s cross section
Fig. 5  Diffuse porosity in the 1st cylinder’s cross section

Fig. 6  Cluster of pores (1 mm in diameter) in the 1st cylinder's cross section
**Check for subsequent mechanical machining operation**

A truck engine head prototype was non-destructively tested with the aid of computed tomography, in order to image internal geometry and evaluate if any negative allowance with a cavity would result by drilling of the glow plug housings (fig. 7).

![Fig. 7 Superposition of 3 adjacent image contours of a truck engine head. Glow plug housings are visible at the bottom of the image.](image)

**Check for CAD correspondence**

The iges file of the section contour can be extracted from the tomogram. The operation is very simple, depending only on the correct choice of a threshold for the grey shadow. Iges files may be imported in any CAD and automatic verification of the proper cavities positioning is done. The large tolerance level (0.1mm) typical of foundry process is the same order as CT one: there is no need to take special care in the choice of the grey shadow threshold.

**CONCLUSIONS**

The above described analyses, performed on new aluminum engine head prototypes, clearly demonstrated the ability of CT to inspect components characterized by complex shape and large size (up to 230 mm in thickness).

It precisely provided the size and location of flaws, lying in the inspected cross sectional plane, with a spatial resolution of a few tenths and in a relatively fast way, as the typical scanning time for each slice does not exceed 10 minutes.

Consequently, thanks to CT’s exhaustive information, it was possible to avoid performing a complete test bench on a flawed engine head, which means saving time and reducing expenses.
Besides, as tomograms are in digitized formats, it is possible to manipulate them in order to carry out further analyses and check, if necessary, the correspondence with the CAD model of the component, without any other inspection being needed on the component itself.

By introducing CT in the product development cycle, the prototype fabrication time can decrease even of a month in some specific situations. This represents an important achievement in such a rapidly changing market as the one where the automotive industry operates.

Therefore, preliminary high cost investments on the CT system can be justified by CT's economical potential and added value over traditional testing practices, especially when CT is applied for very specific purposes as the ones described in this paper. Traditional inspection techniques of course may be less expensive than CT in terms of equipment, personnel and maintenance, but the kind of information they are able to provide in this particular field cannot be as exhaustive and effective as CT's.

REFERENCES
APPENDIX

System capabilities

1) Contrast sensitivity

It is commonly referred to as the ability of the system to detect the presence or absence of features in an image. Contrast sensitivity is quantified as the minimum contrast required to detect a compact uniform feature of a given size against a uniform background.

The test was performed on a uniform aluminum disk standard (125 mm diameter), placed at the centre of the rotary table.

The measurement of contrast sensitivity is obtained by determining the average and standard deviation for all CT numbers in a region taken at the centre of the reconstructed image. The inverse of the ratio of the average to the standard deviation (referred to as «signal-to-noise ratio») is a measure of contrast sensitivity.

Results: 0.563 %

2) Spatial resolution

It is commonly referred to as the ability of the system to image fine structural details whose contrast is substantially greater than the image noise.

The test was performed on a steel line pair standard, placed at the centre of the rotary table.

The measurement of spatial resolution is obtained by analysing the reconstructed image and measuring the modulation of the CT numbers resulting from a trace across the lines pairs.

Results: 4 line pairs/mm (0.125 mm), 55 % modulation

3) Dimensional accuracy

Dimensional measurement accuracy of the CT system depends on both spatial resolution and contrast sensitivity.

A purpose-built aluminum dimension phantom (40 mm diameter), containing gaps of 3, 1, 0.5, 0.250, 0.125 mm, was tested twice. The first time it was placed at the centre of the rotary table, the second time it was placed at a 60 mm distance from the centre of the rotary table.

The aim of this test is to evaluate how the location of a feature, in the component being inspected, can affect dimensional measurement accuracy.

Results are listed in the table below:

<table>
<thead>
<tr>
<th>Standard-to-rotation centre distance (mm)</th>
<th>Absolute deviations (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 mm gap</td>
</tr>
<tr>
<td>0</td>
<td>0.011</td>
</tr>
<tr>
<td>60</td>
<td>0.229</td>
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</tbody>
</table>

As expected, dimensional measurement accuracy decreases as the distance of the feature from the centre of rotation increases. In fact, in the first test an accuracy of a few hundredths is achieved, whereas in the second one it decreases to a few tenths. However, a better dimensional accuracy is not required within the aim of the work described in the present paper. In fact, typical foundry components do not need better dimensional measurement accuracy than a few tenths.