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The Remote Photogrammetric Survey and Engineering Analysis of the Divertor Structure during JET's Remote Tile Exchange

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1. INTRODUCTION

The main components of the divertor support structure are an inner and outer ring mounted on a baseplate (fig.1). The outer diameter of the assembly is 6.2m and the inner diameter 4.5m. The divertor structure was manufactured as twenty four sub assemblies which were assembled together once inside the vacuum vessel. JET's CAT (Computer Aided Theodolite) system was used extensively throughout the manufacture and assembly of the structure, and was also used in-vessel to ensure the accurate installation and positioning of the structure with respect to the magnetic centre of the machine. It was decided to evaluate the structure integrity during the Remote Tile Exchange (RTE) [4], when the MKIIA tile carriers were replaced by the MKIIGB carriers, by surveying to allow a size and shape assessment to be made [1]. A survey to metrology standards was required i.e. with sub-millimetre accuracy. Due to the lack of manned access to the vacuum vessel, the survey would have to be carried out remotely. As difficulty was expected with fitting conventional targets to the structure remotely, a survey system with targetless capability was required. There were two aspects to the survey, one concerned the preparation of the appropriate measuring procedures, while the second was to carry out an engineering analysis of the divertor structure based on the survey results. Consequently the structure was assessed to identify all possible failure scenarios, quantified in terms of deflections or shape changes on the structure. The 'allowable deviations' established here determined how a reasoned assessment of the structure could be made, based on survey results.

Fig. 1 The divertor structure

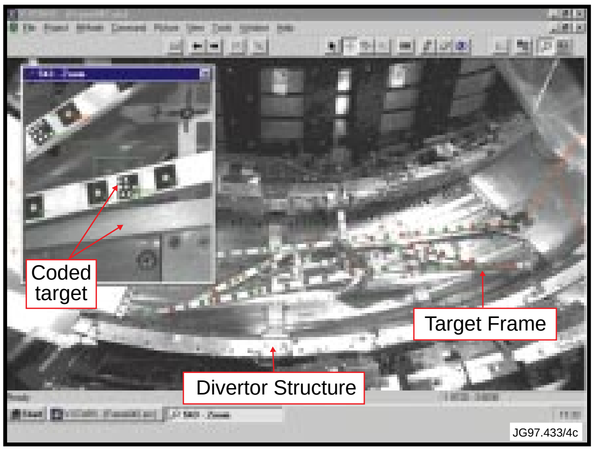

Fig. 2 Typical image used for targetless analysis

2. ENGINEERING ASSESSMENT OF DIVERTOR STRUCTURE

Among the criteria for the successful operation of the divertor are its alignment to the magnetic centre of the Torus, the concentricity, roundness and radii of the three rings of the structure, together with the flatness and height of the baseplate. Measuring accuracy of about ±0.1mm was achieved during installation. The objective for the remote survey was to achieve similar measuring accuracy. The assessment of the structure determined the acceptable deviations of size, shape and position from nominal (fig. 3), considering the tolerances achieved during manufacture and installation. These deviations were derived by considering the likely effects of failure or yielding of the most highly stressed areas of the structure.

Fig. 3 Table of allowable deviations.

Feature	Base (A) RB=2628	Inner Ring RI=2302	Outer Ring RO=3000
Radius of Best Fit Circle	±0.2	±0.4	±0.4
Deviation from Best Fit Circle	±1.0	±2.0	±2.0
Offset of centre of Best Fit Circle	0.5	±0.8	±0.8
Toroidal offset	+0.1 -2.0@R_B	+0.7 -2.0	+0.7 -2.0
Deviation from Best Fit Plane	±0.7		
Height of Best Fit Plane	-1763.4±0.4		

3. SURVEY CONCEPT

Digital photogrammetry using the V-STARS system [2,5], in conjunction with 'targetless' software was selected on the basis of being commercially available, suitable for remote deployment and the natural evolution of the survey techniques already developed for use at JET. Based on trials carried out, measurement accuracy for untargeted features of ± 0.3mm was anticipated.

To determine the co-ordinates of untargeted features using digital photogrammetry, it is essential that the camera positions are known as accurately as possible. This requires the use of many retro-reflective targets, as accuracy is directly influenced by the number of photographs and targets. Clearly, it was not practical to install several hundred targets remotely. Instead, a three dimensional frame fitted with targets was used. The complete frame could then be installed in-vessel using JET's 10m remote articulated boom[4]. Eight frames were needed to provide a network of targets which allowed accurate (±0.06mm) determination of the camera positions. The frame was exploited further by designing it to reference the baseplate for height and the outer ring for radial position. No toroidal location of the frame was employed. Having determined frame positions from the target co-ordinates, the shape of the outer ring and the shape and level of the baseplate could be established relatively quickly.

For the remote survey at JET, use of newly developed software, which supported coded targets, reduced the processing time from about forty hours to eight hours. The coded target technology provided another significant advantage in allowing the survey circle to be closed in the first iteration of the calculation. This is instead of processing on a photograph by photograph basis which can result in divergence of the iterative solution process (bundling) for a large and complex survey. This problem is not specific to photogrammetry, but is a symptom of the 'bundling' process. It was encountered at JET previously when similar surveys were carried out using theodolite systems.

4. DEVELOPMENT OF ANALYSIS PROCEDURE

A major part of the survey task was analysis of the results. The survey was scheduled to take place after the removal of the MKIIA tile carriers and before the installation of the MKIIGB carriers. This allowed a period of twenty four hours after the survey in which to carry out the preliminary analysis and identify any additional inspection that might be necessary, before removal of survey equipment from the vacuum vessel. Less than a week was available for the full analysis. Clearly, detailed preparation was necessary to ensure that the conclusions of the analysis be determined without delaying the shutdown programme. An inspection schedule for the structure was prepared, which defined the specific elements of the structure to be analysed. This was extremely important in order to ensure that the analysis work proceeded quickly and efficiently. Personnel involved were prepared and practised, so that the maximum amount of information was extracted from each picture in a single visit. Using a suite of software which included Microsoft Excel, Leica ECDS3 and V-STARS, templates were prepared to semi-automate the data analysis process.

For the purposes of assessing the status of the divertor structure from the survey results, the analysis was split into several steps. For example, the roundness and radius of the outer ring and the level of the base-plate were examined first, using the information from the position of the target frames obtained from the most accurate, ‘targeted’ stage of the survey. Subsequently, the radius and roundness of both inner and outer rings were determined using targetless analysis. This also allowed a comparison to be made between targeted and untargeted results as the outer ring was measured using both techniques. This verified the accuracy of the targetless analysis. The next stage was to assess the radius of the base-plate. At this stage the concentricity of the three rings was also examined. Finally the position of the complete structure was related to the magnetic centre of the Torus via the in-vessel datum system which had previously been fitted with prototype plasma compatible targets. Initially, this indicated an apparent lowering of the structure in-vessel by 1.4mm. Further investigation of the structure position relative to other components confirmed that the structure had not changed. In fact the lower saddle coils supports on which some of the datum system targets were mounted appear to have undergone a rotational deflection.

5. SURVEY RESULTS AND STATUS OF STRUCTURE

The survey was completed in one day. One hundred and twenty photographs were taken with the assistance of ‘teach and repeat’ files to guide the remote articulated boom to the required camera positions. Extra photographs were necessary because of excessive shadow cast by the boom in some positions. During the survey, time was allowed for the boom to stabilise before taking photographs for optimum quality. Each picture was reviewed before saving. Photographs were backed-up to a second PC connected to the main PC in a local network configuration.

Additional photographs were taken to survey the antenna waveguide for the KG6 diagnostic, damaged during the operational campaign. It was not clear whether the waveguide was so misaligned as to render the installation of the new gasbox divertor antenna fruitless. Timely survey results indicated that the damage was minimal in terms of the misalignment caused and that installation of a new antenna would be worthwhile. Survey results were used to provide data for the design of a new antenna profile. This was manufactured in time to be installed just before the end of the shutdown.

Initial processing of the survey was carried out automatically thanks to the use of coded targets. The final result for this survey was achieved with a mathematical area of uncertainty or RMS (Root Mean Square) error of 0.03mm for targets and an RMS of 0.06mm for camera positions leading to an average RMS for the survey of 0.1mm. A summary of results is presented below (figs. 4 & 5)

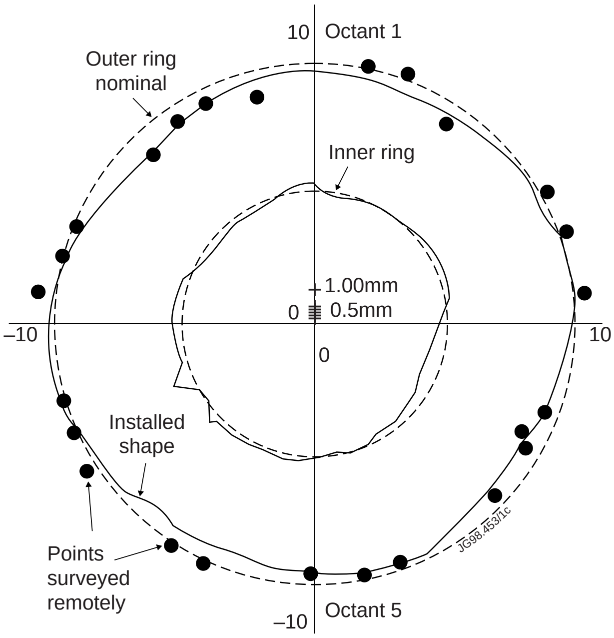

Fig. 4 Comparison of structure shape

Best Fit Circles	Dev. from Nominal	RMS of measurement
Outer Ring (targeted)	-0.11	0.1
Outer Ring (untargeted)	-0.22	0.29
Inner Ring (untargeted)	-0.22	0.19
Base Plate (untargeted)	-0.08	0.14
Best-Fit Plane Height	0.11	0.11

Fig. 5 Summary of structure deviations

6. CONCLUSIONS

The remote application of photogrammetry developed at JET proved that there has been no unacceptable change in shape or position of the divertor structure, therefore confirming its integrity. The flexibility of this technique was demonstrated when it was used for an unplanned, high accuracy, remotely targeted survey of the damaged KG6 outer waveguide. The ability to carry out an engineering analysis of large structures, using data captured remotely, is essential for the construction, operation and maintenance of fusion machines [3]. This ability, using commercially available survey equipment, has been successfully demonstrated at JET.

7. REFERENCES

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