Introduction [1]

The Wendelstein 7-X stellarator is a superconducting fusion experiment, presently under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik. This paper gives an overview of the reverse engineering processes applied on cryostat components of the W7-X superconducting magnet system.

1. Device description [1]

Wendelstein 7-X has a superconducting magnet system with five-fold symmetry to confine the plasma and allow steady-state operation. This system consists of 50 non-planar and 20 planar coils of all together 7 different types. Coils of the same type are connected in series and can as a group be operated independently. The coils are attached to a central support structure. (see Fig. 1).

Fig. 1. Overview of W7-X magnet system

The close packing of the components within the cryostat, e.g. the coils, the support structure and their close neighbourhood to the plasma and outer vessel walls as well as the ports make the device very complex. Standard reverse engineering process is applied on all coils, hybrid reverse engineering process is applied on the plasma vessel, outer vessel and ports.

2. Need for Reverse Engineering

The sum of the tolerances that need to be taken into account for all components and the deformation of the components during operation lead to overlapping tolerance regimes. Thus detailed studies based on real geometry are desirable. The risk of collisions during installation or operation can be reduced, for example, by using CAD models that as accurately as possible describe the components after fabrication rather than the nominal models. Reverse engineering (RE) is the process that generates these CAD models, so called “as-built” models, on the basis of outer shape measurements of the fabricated components. These models can then be used in collision studies of the various device configurations during operation, e.g. at assembly, after cool down, or during the various magnetic configurations that W7-X is able to run.

Fig. 2 shows two neighbouring non-planar coils (diameter > 3 m) at their nominal positions. In the marked constriction area the minimum distance is only about 8 mm according to the nominal CAD models. Using as-built models of the coils one is able to perform detailed collision studies and, if required, to selectively define areas where some machining is still necessary.

Fig. 2. Example of adjacent components

3. Reverse Engineering

Two different processes for creating as-built models were developed: One for cases where the measurement points densely cover the surface of the component (standard), and one for cases where the measurement data are sparse (hybrid).

a. Standard

In the first case the source of the data is typically provided from 3D laser scan (see process in Fig. 3). The whole surface of each coil is scanned with Faro arm and scanner. The latter throws out a laser line which reflects back from the coil surface to the sensor of the scanner. The result of the data processing inside the device including the attached computer is stored as measurement stripes that contain lines and points. The surface area of a non-planar coil of about 10 m^2 is represented by a point cloud of about one million data points, each taken with an accuracy of 0.1 mm.

Fig. 3. Laser scan procedure of a non-planar coil

Such a large amount of point data is not suitable for direct use in a CAD system. Therefore, the cloud is merged to a polygonal model in Polyworks, thereby reducing the overlap areas. Finally the polygonal mesh is compressed to allow creation of a CAD model in CADDS5 or CATIA V5. Handling this amount of data and the conversion processes requires sufficiently fast processors.

The goal of a standard RE process is surface-model creation that will be explained by a part of the header area of a non-planar-coil (Fig.4). The whole polygonal mesh is replaced by a curve-network by defining control points and curves on the mesh. Each point has to be defined “by hand” and then the software fits and optimizes the curves on the mesh including the defined points. Surfaces are created automatically from this curve-network by fitting them to the original mesh. Getting the result is very time consuming and requires three weeks of handwork because of the curve-network definition.

Fig. 4. Polygonal mesh, curve network and the final surface

The final surface-model is easy to be handled in any CAD system because it is simplified. The surface differs from the polygonal mesh. This difference must be smaller than the specified value of 0.5 mm.

b. Hybrid

In the second case only a sparse data set is available. It could be measurement points taken with a laser tracker system. This technique is based on laser beam emission (Fig. 5). The tracker emits a laser line which hits a prismatic target element, the so-called corner cube. Wherever this target element moves, the tracker follows it (tracking) and gets the three coordinates of the touched point.

Fig. 5. The principle of laser tracking

As an example, the data set of a plasma vessel sector consists of typically ten thousand points with an accuracy of 0.1 mm, taken on the outer surface on top of the water cooling pipes. Since the measurement data by themselves are not sufficient to create a standard as-built model, one can use the CAD model of the component and adopt it to match the measurement data. This is done as follows (shown schematically in Fig. 6).

Fig. 6. Data preparation for Morphing function

Each measured point (black crosses) is normally projected onto the nominal geometry (red crosses). These two points are defined to be the end and start points, resp., of a deformation vector. The nominal geometry is then deformed along these vectors using the function Morphing within CATIA. The nominal shape is transformed into a new one given by the displacement vectors. In doing so, the function estimates the complete surface either with interpolation or extrapolation. Fig. 7 shows how the function works in 3 dimensional environment with the Hybrid model as result.

Fig. 7. Morphing function in 3D

In the case of a plasma vessel half-module the hybrid model was compared to the as-built model created from laser-scan data that was additionally available for one sector. In the regions with measurement data the differences were only fractions of mm, in regions with few data (closest data point about 200 mm away) the difference was about 10 mm.

Fig. 8. Hybrid-model with texture

The above mentioned differences tell us how accurate the model is, depending on the available measurements. In Fig. 8 a tricolour texture indicates this accuracy. The green areas are exactly calculated – transformed by displacement vectors and well approximated between two closely adjacent vectors. Far away from any measurement the program extrapolates, the result which can be unrealistic is shown in red colour.

4. Conclusions

The available measurement data determine the reverse engineering process that we apply on the component. Very precise models can be built up from laser scan measurements. Without having them, it is still possible to get an as-built model with less accuracy but still acceptable regarding our tolerance-chain system.

Fig. 9. Non-conformity report

Visual control and measurement in CAD systems give us the possibility to create non-conformity reports that clearly show the differences between the nominal and as-built model. Fig. 9 shows an example for this in a colour scale of +10mm to -10mm represented by the header area of a non-planar coil. Based on this, re-machining of components can be specified, if necessary. With the help of these procedures the risks of collisions during operation are greatly reduced.

References

[1] F. Schauer, Status of Wendelstein 7-X construction, presented at 24th SOFT Conference, Warsaw, Sept. 2006