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Including measures of assembly complexity in proactive geometry assurance, a case study

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Abstract

Geometry assurance is an important part of quality assurance in the manufacturing industry. Typically virtual geometry assurance is done in Computer Aided Tolerancing (CAT) tools. Earlier research shows that assembly complexity influences the product quality but is not considered in CAT simulations. Recently a new robustness value in CAT has been introduced that not only considers sensitivity to variation but also the complexity of the assembly. This study tests this in two industrial case studies. The case studies show good conformance between actual results and simulated results verifying that assembly complexity influences geometrical quality and the benefits of including it in early geometry assurance activities.

Peer-review under responsibility of the organizing committee of the 6th CIRP Conference on Assembly Technologies and Systems (CATS)

Keywords: Complexity; Assembly; Robust Design

1. Introduction

1.1. Introduction to subject

Geometry assurance is an important part of quality assurance in the manufacturing industry, especially the automotive industry. The geometry assurance work is done both with respect to the esthetics [1, 2, 3, and 4] and functions [5].

In the automotive industry whole organizations and departments are usually built up to ensure the geometrical quality of the vehicle. Responsibilities for such departments include creating the geometry system solutions; defining locators, balancing tolerances, doing stack up analysis in 3D, measuring and verifying geometrical demands, matching and trimming etc. Today this is a task that has been heavily virtualized, different computer tools are used for the work, so called CAT-tools (Computer Aided Tolerancing) [6, 7, and 8].

It is however not easy to create a virtual model of a complex manual assembly operation, one study [9] shows that assembly factors, such as assembly complexity are not included in the virtual models and another study shows that the correlation between virtual CAT simulations and actual outcome in a pace assembly line is low [10]. Further previous research has shown that manual assembly complexity has a major impact on product quality [9, 10 and 12].

An assessment model for evaluating manual assembly complexity has been developed [12]. This has been implemented in a CAT-tool in conjunction with geometrical stability analysis [13] forming a new robustness value for the geometrical system solution. Further a new geometry assurance process that incorporates the use of the assessment model in CAT has been proposed [14] including virtual geometry assurance activities that are proactive instead of today's more usual, reactive activities.

This paper aims at testing the new research findings and tools in two industrial cases, exploring the strengths and weaknesses of them and suggesting improvements.

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1.2. Nomenclature

Nomenclature

Geometry Assurance: a set of activities with the purpose to ensure that all geometrical requirements on the product are fulfilled.
CAT: Computer Aided Tolerancing, 3D tolerance chain stack up analysis
Variation analysis: analyses variation in critical dimensions (measures) of the design
Contribution analysis: presents a ranked list of points and tolerances, contributing to measurement variation
Geometry system solution: Locating scheme, tolerances, fasteners etc. for a part
Geometry assurance process: A sub-part of the product development process, a description of how the geometry assurance work is integrated in the product/production development processes

1.3. Related work

The ideas and principles behind geometry assurance were introduced by Taguchi [15] defining the concept of robust design and insensitivity to variation which is the basic principle for all quality work within geometry assurance.

These ideas have then been used widely and are implemented into the CAT-tool RD&T [16, 17] that is used in this study. Other CAT tools can be seen in [18, 19, and 20].

The area of robust design in geometry assurance has since then been thoroughly expanded by numerous scientific contributions such as:

- Optimization of locator position to achieve maximum robustness in critical measures [8]
- Non-rigid sheet metal simulations aiming to decrease the need for physical prototype builds [21]
- Visual robustness [4]
- Forming simulations as input to CAT [22]
- Overall robustness optimization [23,24]
- Robustness for plastic components [25]
- Etc.

All of these have expanded the use of design in geometry assurance by adding more parameters and/or applications to geometry assurance to improve accuracy. Recently the need to take manual assembly complexity into consideration and the need to include process tolerances for the operator in the CAT simulations have been introduced. [9, 10, 11, 12, 13, 14, and 15]. This paper continues this work testing the current research in two industrial test cases.

1.4. Scope of the paper

The paper describes two industrial test cases using the manual assembly complexity method in CAT. The intention is to validate if this method is feasible to use in real industrial settings. The results of the two test cases and improvement suggestions to the method will be presented.

In section 2 geometry assurance in general is described. In section 3 objectives and methods are presented. In section 4 the results from the test cases are described and these are then being discussed in section 5 and concluded in section 6.

2. Geometry Assurance

2.1. Geometry assurance process

All types of assembly processes are subject to variation, it could be the repeatability of a robot in an automated process or the ability of an operator to perform an assembly task. Adding variation to an assembly process affects the final product in many ways, for example esthetics, functions and life span.

To enable a stable geometrical quality at the desired level several geometry assurance activities have to be performed during the product development process. Recently an updated geometry assurance process [14] was proposed that includes assessment of manual assembly complexity [13]. This geometry assurance process is a sub process of the generic product development process introduced by Ulrich and Eppinger [26].

The industrial test cases in this study will focus on the work done in phases 1 - 3.

2.2. Locating schemes

Fundamentally, only 2 parameters regulate the geometrical quality; locating schemes and tolerances. These two form the final result and both can be optimized to achieve the desired results. In this study optimization of the locating schemes will be explored.

Locating schemes are used to control the propagation of variation in the assembled product and to lock all six degrees of freedom for each part or assembly. By locking all six degrees of freedom the part is physically located in the coordinate system. Figure 1 shows a common type called 3-2-1.

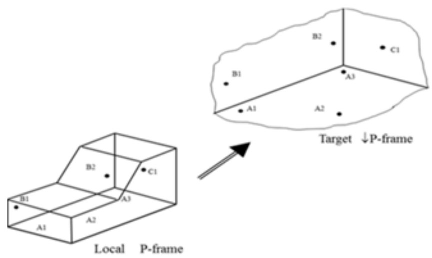

Fig. 1. 3-2-1 locating Scheme.

Point A1-A3 form the primary plane that locks two rotations and one translation, point B1-B2 form the secondary line that locks one rotation and one translation and the tertiary point C1 locks the last translation [16].

The locating schemes are set and fixed in early phases of the product development process and also form the base of the assembly operation, fasteners and process equipment. Therefore, it is very important that assembly factors are considered when the locating schemes are developed. However it is more common that the assembly process is developed much later creating unnecessary issues.

2.3. CAT software RD&T

RD&T is a CAT simulation software based on Monte Carlo principles. It consists of several simulation functions that support geometry assurance activities throughout the entire product development process [17]. All CAT simulations in this study are done in RD&T.

Here the newly developed function for assembly complexity is used. It uses two simulations described below:

- Stability analysis:
  This analysis evaluates locator sensitivity by varying each locator in the locating scheme a small increment, one at a time. The result is a color coded robustness value for all points on the geometry. In the assembly complexity function this value has been normalized between 0 and 1.
- Manual assembly complexity assessment:
  The user judges 16 high complexity criteria with yes or no to determine the level of assembly complexity. The analysis returns a normalized value between 0 and 1 that represents the complexity level.

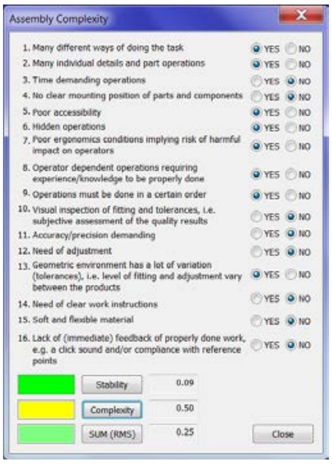

Fig. 2. Assembly complexity analysis in RD&T.

The two values, Stability and Complexity, are then summarized with a RMS operation to form a robustness value that not only considers sensitivity to variation but also how complex the product will be to assemble. Figure 2 shows an example of an assembly complexity analysis in RD&T. For more information about the analysis see [13, 14].

3. Methods

3.1. Objectives

The objective of this study was to test previously developed research results in an actual industrial environment using two test cases.

The study aims at validating the use of manual assembly complexity in geometry assurance carried out using a CAT tool.

The purpose is to find out if the method works and what conclusions can be drawn from using it. Further improvements and missing functions will be identified.

3.2. Limitations

The study was done reactively, not proactively due to the fact that several years elapse from a design being created until the production is up and running at stable full speed. Therefore, the chosen cases are from current production. However, the validation will still be possible since the steps and criteria are the same, regardless of which phase in the project they are made.

3.3. Industrial test cases

The test cases were done at two European heavy truck manufacturers.

- Case 1:
  Pre-assembly of the front module: It consists of an aluminum carrier onto which the bumpers, front lights, plastic and sheet metal panels are assembled.
  Assembly operations are performed in 5 different stations on a small assembly line parallel to the main assembly line. The front module is lifted into the main line after it is finished and docked to the truck chassis.
  In this case the gap relations between the 3 bumper pieces have been analyzed.
- Case 2:
  Pre-assembly of the front module: It consists of a steel carrier onto which front lights, plastic and sheet metal panels are assembled.
  Assembly operations are performed in 4 different stations on a small assembly line parallel to the main assembly line. The front module is then lifted into the main line after it is finished and docked to the truck chassis.
  In this case the gap relations between the headlight and the surrounding plastic panel have been analyzed.

The two cases are very different:

- Case 1 is a new truck model and case 2 an old truck model
- They are very different in design, both in looks and mechanical design.

In each case the following data was used:

- Collection and evaluation of engineering data, CAD, tolerance calculations, requirements etc.
- Collection and evaluation of assembly data, assembly instructions, quality data from production, ergonomics assessments etc.
- Visit to the factory observing each assembly operation live, including filming all operations and

tools used. This was done together with the manufacturers own experts.

- Interviews with the operators, managers, ergonomics specialists, quality engineers, engineering departments etc. about the assembly.

4. Results

4.1. Observations

Case 1:

The assembly line had long station times, 7.42 minutes and low assembly pace, 60 units per day. The operators had high levels of experience with on average 13.8 years as operator. Several different variants were not assembled in the same way. However, in this study only the variant with painted plastic bumpers has been studied. 4 of the stations are assembly stations and the 5th station is a quality control station that only inspects and corrects the assembly operations made previously. The quality control is performed on all produced units. This fifth station was added due to quality problems that were propagated to later sections of the production. Despite the quality control this is one of the assemblies that has the most quality remarks of the completed truck. Two different problems occur that are related to the gap relation that is studied:

1. The gap relation is out of specification (too small, too large, bad symmetry) and the operator in the quality control station adjusts the position of one or several parts to correct this. See Figure 3. This is done on approximately 25% of the trucks, even though some of the assembly operators discover this and adjust it in previous assembly stations.
2. The clips, that are also locators, have not been correctly mounted and are partially loose. The operator refits these with high force. See Figure 4. This is done on almost all trucks.

The 3 different bumper parts have a defined locating scheme on the drawing that requires the locators to be fixed in a certain order to work correctly but different operators use different orders.

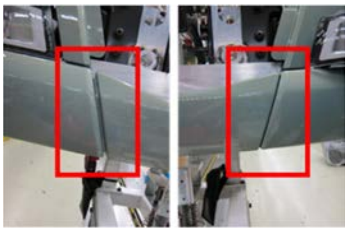

Fig. 3. Incorrect Gap relation on truck, too large on the left and too small on the right.

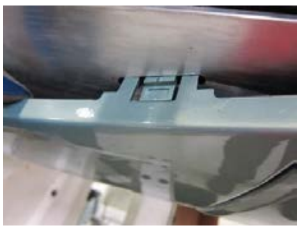

Fig. 4. Clip that is loose.

Case 2:

The assembly line had long station times, 7.29 minutes and low assembly pace, 50 units per day (for the automotive industry). The operators had different levels of experience ranging from just a few months to 18 years. Several different variants were not assembled in the same way. However, the parts that affect the gap relation investigated in this study all have the same type of assembly regardless of variant. All 4 of the stations were assembly stations and quality control was performed later in the assembly line.

The main problem that occurs is that the gap relation between the headlight and the plastic panel is too small or too big with bad parallelism. See Figure 5.

Fig. 5. Incorrect gap on truck, too big on the left and too small on the right.

The headlight and plastic panel have defined locating schemes on the drawing that requires the locators to be fixed in a certain order to work correctly but different operators use different orders. In some cases, the locators don't even determine the position in space because other screws are fastened first. The actual amount of trucks that have quality issues here are unfortunately not monitored, but during the study all trucks showed a similar type of error.

4.2. Quality data

Each of the assembly stations in the paced line was assessed using the manual assembly complexity method (CXB) and all quality errors for each station were collected from the factory's quality monitoring system. The results are presented in Table 1 and 2. Note that the companies do not log and classify errors in the same way so the quality errors number is not comparable. To save space only the relevant assemblies are included in the tables but the entire paced line was included in the analysis and the conclusions are based on all data. Y = yes and n = no.

Table 1. Quality data for case 1, Position 1 is the plastic bumper.

CXB criteria	Position 1	Position 2	Position 3	Position 4
1	y	y	n	n
2	n	y	y	y
3	n	y	y	y
4	n	n	n	n
5	n	n	n	n
6	y	y	n	n
7	y	y	n	n
8	y	n	n	n
9	y	y	y	y
10	y	y	n	n
11	y	y	n	n
12	y	n	n	n
13	y	y	n	n
14	y	y	n	n
15	n	n	n	n
16	y	n	n	n
Fulfilled criteria:	11	10	3	3
Errors:	8	9	5	6

Table 2. Quality data for case 2, Position 3 is the headlamp.

CXB criteria	Position 1	Position 2	Position 3	Position 4
1	y	y	y	n
2	n	y	y	n
3	n	y	n	n
4	y	n	n	n
5	n	n	n	y
6	n	n	y	y
7	y	n	n	y
8	n	y	y	n
9	y	y	y	y
10	n	y	y	n
11	y	n	n	y
12	y	n	y	n
13	y	n	y	y
14	n	y	y	n
15	n	y	y	y
16	n	n	n	n
Fulfilled criteria:	7	8	10	7
Errors:	46	20	37	NA

4.3. CAT simulations

Each of the cases was modeled in the CAT software RD&T building a simulation model replicating the process in the factory. The assembly was analyzed both with regards to geometrical stability (robustness) in a traditional way and the combination of geometrical stability and assembly complexity to evaluate the conformance with the physical process.

Case 1:

The stability analysis returns a normalized value of 0.13 which is very good, a very robust geometry system using traditional geometry assurance assessment. The assembly complexity assessment from chapter 4.2 has 11 high complexity criteria fulfilled which returns a value of 0.63 which is average. Combined these two values form a robustness value of 0.32.

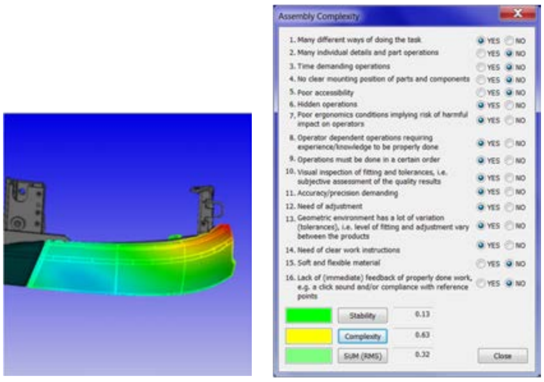

Fig. 6. CAT analysis of Case 1

The analysis shows that this geometry system is very robust in theory but is rather difficult to assemble in practice, resulting in a geometry system where the operator will add variation to the system. To simulate the variation of this system process tolerances need to be included in the simulation model but this was not done when the product was developed. The CAT simulations performed during product development predicted the variation for the gap to be within specification but when measured in production it is out of specification [27]. See Figure 6.

Case 2:

The stability analysis returns a normalized value of 0.08 which is very good, reflecting a very robust geometry system using traditional geometry assurance assessment. The assembly complexity assessment from chapter 4.2 has 10 high complexity criteria fulfilled which returns a value of 0.63 which is average. Combined these two values form a robustness value of 0.31.

The analysis shows that this geometry system is very robust in theory but is rather difficult to assemble in practice, resulting in a geometry system where the operator will add variation to the system. To simulate the variation of this system process tolerances need to be included in the simulation model but this was not done when the product was developed. See Figure 7.

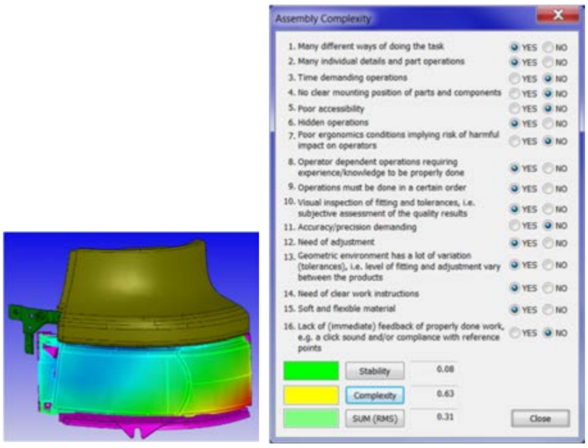

Fig. 7. CAT analysis of Case 2

5. Discussion

The two industrial cases highlight a common problem, making accurate virtual models of the real world is difficult. Although both cases have geometry systems that are robust from a traditional geometrical perspective they are not robust in actual running production. A standard 3D stack up tolerance simulation in CAT would give the answer that this should work, but it doesn't. The study shows that one reason for this is that the manual assembly operations have high complexity. By using the newly added research results and method this could have been detected early in the product development process instead of in running production. Both cases show that high manual assembly complexity gives more errors and problems with the geometrical quality. This has only been validated for this type of parts and assembly, but combined with previous research and studies it is presumably valid for most types of manual assembly operations on a paced line.

Some improvements to the developed method in CAT should be implemented before it is used in an industrial setting:

- To assess the 16 High Complexity Criteria is difficult without any aids. Each of the criteria should have assessment instructions included in the method.
- Only assembly operations with one assembly step are supported. The method should therefore be expanded to support several parts assemblies.

The study verifies the need for early proactive work with geometry assurance that not only includes tolerances and locators but also considers the assembly process and human factors. It is suggested that the method is implemented and tested as working procedure in the geometry assurance process in the participating companies which, they are positive to. If this is done, further research cases can be performed to validate the method more generally.

6. Conclusions

The two industrial cases show good conformance between actual results and simulated results in CAT (with the assembly complexity method) verifying that assembly complexity influences geometrical quality and the benefits of including it in early geometry assurance activities. Quality data from running production also verifies a connection between number of errors, geometrical quality and the level of manual assembly complexity.

Some improvements are suggested to the method and it is suggested that the method is implemented in an industrial setting to test and verify it generally.

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