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Integrated geometrical and dimensional tolerances stack-up analysis for the design of mechanical assemblies: an application on marine engineering

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ABSTRACT
This paper presents a knowledge based engineering environment methodology to support the designer in the correct setting of geometrical and dimensional tolerances in assemblies of mechanical components. The procedure is based on the definition of the functional requirements needed to allow the proper working of the assembly; in the further, a software tool is used to do a statistical analysis of the assembly relations, providing an estimation of the components waste due to poor compliance to the tolerances. A case study given by the design of a marine power transmission is presented: the methodology leads to the change of some tolerances to improve the design by reducing the number of waste components. The strength of the methodology is represented by the fact it can help unskilled designers in the correct setting of tolerances in drawings.

KEYWORDS
CAD; GD&T; CAT; design; power transmission

1. Introduction

In the product design process, several alternative tasks structures might be available, which make it difficult to define general rules ([25]). To this aim, in the literature, several decisional methods, optimization strategies and CAX-based procedures have been proposed to satisfy strict requirements typical of specific industrial fields (e.g. [5], [30], [31]). Some tasks are directly defined by means of a transfer process of the designer experience from the senior designer or the industrial know-how. This process is also known as Knowledge Based Engineering, (KBE). After, the necessary knowledge about design of products, processes and manufacturing resources has to be captured and structured, a model is defined with problem solving capabilities, helping or automating the design choices. Finally, the model is implemented in a design tool in order to reuse the knowledge in future projects ([25]).

A KBE interpretation of GD&T have been proposed in literature before (e.g.[11]), to take into account the allowable variations in dimensions and shape with respect to the ideal geometry conceived by the designer and improve the inspection process. The correct setting of these variations is a challenging problem in the manufacturing and assembly process. Geometric and dimensional tolerances have been introduced in Standards, to support the designer in the definition of dimensional and shape feature ranges assuring the functionality of a component and its suitability to be assembled in mechanical assemblies. Dimensional and geometrical tolerances are widely described, as well as symbols to be used in drawings in the ASME Y14.41-2003 ([2]) (as its expansion ASME Y14.5-2009,[3]) and ISO 16792:2006 ([19]). Standards provide rules on the application of GD&T in the 3D axonometric representation of components and of their dimensional and geometric variations, to provide a complete and clear representation in the Computer Aided Design (CAD), Coordinate Measuring Machine (CMM), and Numerical Control (NC). Strategies for testing conformance to GD&T standards have been proposed ([13]) for enhancing applicability to industrial cases and reducing data exchange/interpretation errors.

The acronym GD&T, Geometric Dimensioning and Tolerancing, is used to describe all the rules, symbols, prescriptions, suggestions related to the definition of the geometry and shape of a component. When dealing with the development of a mechanical assembly, a correct GD&T implementation is a strategic issue for ensuring functional requirements, increasing perceived quality, reducing redesign activities and time to market, and avoiding the waste of time where machining processes are required to respect unnecessary tolerances. On the one hand, too much strict tolerances increase the manufacturing times and requires machining time, usually on complex and expensive CNC tool machines. On the other, too weak tolerances (or their absence) can lead to

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problems in assembly of components where pin and holes do not match, where the contact of parts happen in a wrong way, or where unwanted clearance or blocking are noticed. The modern manufacturing globalization has highlighted the criticality of GD&T even more: in several industrial fields, for political or economic reasons, components are produced all around the world, with a final assembly line requiring a perfect logistical chain to respect the scheduled delivery times. Due to the key-role played by logistic and mass-production problems in the modern industry, a bulk of literature deals with GD&T and assemblies (e.g.[32]). For what concerns rigid assemblies, the tolerance stack up analysis has been tackled by means of several approaches. One-dimensional tolerance charts, based on the Worst Case method, and the statistical models, based on the Root Sum Square (RSS) criterion, have been largely used ([4]). Even if these methods are useful for managing dimensional tolerances, they are still imprecise in the implementation of geometrical tolerances. Moreover, they often do not include neither ISO nor ASME regulations. Regarding the tolerance stacks up, several methods have been proposed, that are at the basis of the Computer-Aided Tolerancing (CAT), namely: the Variational Analysis ([17]), the Vector Loop (e.g.[16]), the matrix ([10]), the Jacobian ([20]), the Torsor ([6]), the unified Jacobian-Torsor ([9]), and the T-Map® (e.g. [8], [22], [35]).

Several reviews on tolerance design are present in the literature. In [34], CAT software basics are described, enlightening the main theoretical features of each method. The same can be said for [27], in which previous reviews have been classified, in terms of tolerance representation, tolerance specification, and tolerance processing/synthesis/analysis. As reported in [18], these reviews cannot be exhaustive as they depict the current status of 3D CAT software and methods which are currently in evolution.

1.1. CAT tools in companies

Computer Aided Tolerancing (CAT) tools have been introduced on the market to support the GD&T within companies. CAT tools are mainly used within a Model Based Design (MBD) approach, as reported in [12], proposing a “Closed Loop Product and Manufacturing Information (PMI)” approach, for enhancing quality from design to manufacturing operations. The approach involves the Model Based Design (MBD) technique, for defining a complete 3D GD&T model. This is used as the only source of data for building a 3D model of tolerance stack up to drive GD&T Design and Validation. Hence, operations of inspection and validations are performed on the model and the results are reported on the GD&T model back to close the loop. Once the 3D assembly is produced, in which GD&T information are set, the CAT tool usually requires for defining tolerances, assembly sequence and inspection specifications. Simulation of the tolerances providing optimal tolerance set for each component closes the loop. Focusing the attention on software tools used in companies, some commercial CAT software packages use variational models. Nevertheless, as reported in [36], Commercial CATs use point-based analyses which are not compliant to true 3D tolerance zones nor geometric variations of the GD&T standards.

All software for handling tolerance analysis are aimed at predicting the amplitude and the cause of deviations from theoretical models. A digital prototype is used to create a complete representation of geometry, taking into account tolerances due to manufacturing operations and variations due to the assembling process. Hence, the assembly sequence, the definition of restraints, the measurements estimation are required. In this way, possible assembly problems are predicted, long before that the components are built or carried out by tooling.

The variation analysis is aimed to reduce possible negative impact of the product’s dimensional variation, thereby ensuring quality and reducing costs and time-to-market. Here follow some examples of dedicated software for handling chain tolerances.

Dimensional Control Systems’3-DCS®([1]), carries out the variation analysis, by means of the Variation Analyst tool, allowing to input a planned assembling sequence, assign tolerances to parts and fixture system, simulate several possible assemblies using the Monte-Carlo method, define the key product characteristics (KC), determine the influence of tolerances on KC.

Sigmetrix’ CETOL 6σ Tolerance Analysis Software ([38]) implements the second-order tolerance analysis (SOTA) method based on the vector loop method, for evaluating possible assembly assets. This method has been showed to overcome the Monte-Carlo method in terms of speed, tolerance allocation, and capability to handle closed loop constraints ([16]).

Siemens’ Tecnomatix® Variation Analysis software ([37]) carries out variation analysis within the Teamcenter® software. Since Tecnomatix® uses the lightweight JT™ data format for handling 3D data. This helps reducing the memory requirements of the 70%, speeding up the response of the entire system. this is appreciated in case several data have to be managed, as for example in a complete vehicle assembly. From a literature point of view, few applications of 3D CAT analyses involve industrial cases studies ([24]). Most literature is dedicated to proposing methods for simplifying the 3D CAT analysis or providing comparisons between methods. In [7] the 3D CAT is integrated for considering working conditions and operating windows (as also in [6]). In [33], a graphical method for easy up the tolerance stack up analysis is proposed, for only analysing dimensional and parallelism tolerances in a thermal camera assembly. In [26], an approach for dealing with dimensional and geometric tolerances applied to free-form surfaces have been proposed.

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1.2. Motivation of this paper

Looking at the design/manufacturing process, the management of geometric variations must be handled during the entire design process, since the beginning of the early design phases. In particular, dimensional and geometric requirements defined in the conceptual/preliminarily design phases, have to be fulfilled in terms of GD&T in the embodiment phase, as the assembly is defined, and controlled in the quality inspection phase, after the production phase. As it can be understood from the above literature analysis, the lack of a unique environment for integrating CAD and CAT in an industrial environment is noticed. Hence, this paper aims to provide a KBE based procedure for optimal tolerance analysis in 3D assemblies, as a guide for practitioners. It is worth to note that the use of GD&T is quite complex. On the one hand, large companies own design division specialized in GD&T: on the other, Small Medium Enterprises are not able to afford the cost of internal designers specialized in GD&T. The need for tools to help general-purpose mechanical designers in a correct tolerancing motivates this study. This paper is structured as follows: the next second section presents a description of the methodology, which can be applied to achieve a correct GD&T. The fourth section presents a case study in the design of an assembly of interest for the marine engineering where several problems have to be solved for satisfying functional assembly requirements by the SME in charge of the system development. Moreover, results are provided, related to application of CAT simulation, providing the main contributors to tolerance chain for a specific measure. A following section of discussions reports the description of the advantages and drawbacks of the proposed method. Conclusions end the paper.

2. Method

This work aims to guide practitioners in the achievement of a robust design method for production. The method aims at including the 3D CAT analysis in a knowledge based engineering (KBE) environment, in which all data referred to the design and production requirements are gathered in a single digital document.

The method integrates the functional aspects of the product, the know-how of the industry, in terms of production, material, manufacturing process, quality inspection. Moreover, it includes a 3D tolerance stack up analysis and simulation of mechanical assemblies.

The application of the tolerance stack up analysis in the early design phases is aimed to reduce redesign activities in later design stages. Hence, the main phases of the early design are integrated with steps for tolerance analysis.

The method consists of the following steps: gathering information on the product, within a the Functional Analysis, the Assembly Sequence Modelling, the application of GD&T on components, according to the international standards, the *Tolerance optimization* by means of a Monte Carlo optimization method (as in Fig. 1). The post processing actions regard the *Identification of the contributors* to the tolerance chain for the specified measures, as well as the probability distribution of the analysis target and the sensitivity analysis result of the main contributors.

(1) Functional analysis. On the 3D CAD assembly, the functional analysis is carried out, to determine which measurements have to be controlled within the tolerance chain. To this aim, assembly requirements are listed, as gaps between the edges, or distances between contact faces
(2) Assembly sequence modelling. The assembly is built by means of the CAT software features, by input components moved in the actual assembly sequence. This is aimed to replicate the effective asset of contacts and DOF in the assembly.

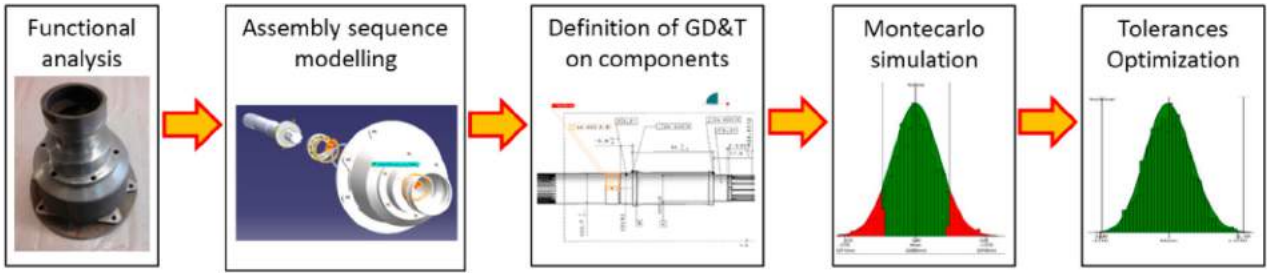


Figure 1. Methodology Flow Chart in a KBE environment.

(3) Definition of GD&T on components. A first attempt allocation of geometrical and dimensional tolerances is carried out on the components, according to international standards and knowledge retrieved from company knowhow. The nominal CAD dimensions are required to vary following a normal distribution.

(4) Monte Carlo simulation and Tolerances Optimization. The simulation starts from a set of constraints that contains all possible dimensional and shape variations for all the components, providing a simulation of all assembly combinations. After the simulation has been run, a histogram is displayed with the statistical data related to the measurement, which is associated to the assembly model. For each measurement, a histogram is produced. In particular, statistical data regard the number of simulated samples n to be run with the Monte Carlo algorithm, the nominal and mean values of the measurement, the standard deviation σ. In particular, the latter is defined as in equation (2.1), ([28]), in which x_i is the value of the simulated sample, μ is the mean value of the simulated samples.

$$\sigma = \sqrt{\sum_{i=1}^{n} (x_i - \mu)^2/(n-1)} \tag{2.1}$$

The tolerance stack simulation of the assembly can be described by means of a normal distribution, according to the 6σ design criterion ([28]), for which 6 times the Standard Deviation value is equivalent to 99.73% of all variation and represents the width of the normal curve. Extreme values of the normal curve, are the Upper Specification Limit USL $= \mu+3\sigma$, and the Lower Specification Limit LSL $= \mu-3\sigma$ which are input data for each measurement. The performance of the process is measured by means of indices as the process performance P_p which compares the variation of the process to the allowable variation that is set by the specification limits (USL and LSL), as in Eqn 2.2. Another index is the P_{pk} index (Eqn. (2.3)) which indicates how far the process is from the mean μ, in relation to the specification limits (USL, LSL).

$$P_p = (\text{USL - LSL})/6\sigma \tag{2.2}$$

$$P_{pk} = \min((\mu \text{ - LSL})/3\sigma, (\text{USL - } \mu)/3\sigma) \tag{2.3}$$

The Monte Carlo simulation provides the response of the product to the quality requirements, defined as the percentage of the assembled products, which will be unable to fulfill the critical quality characteristics ([1]). The High-Low-Median analysis evaluates the contribution based on the total range of a tolerance. A combination of these results provides the information for tolerance and process optimization.

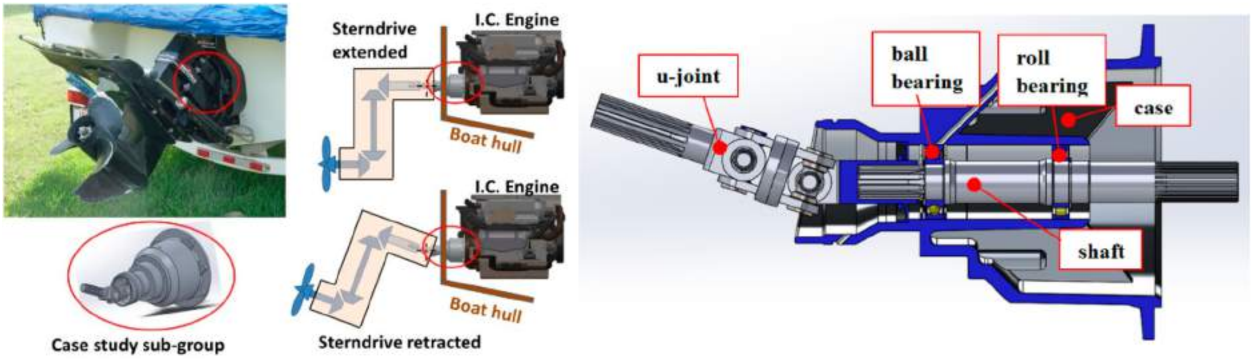


Figure 2. Sterndrive Unit (left) and sub-group to design nomenclature (right).

Results of the simulation phase deliver the expected standard deviations and mean value of the controlled measures, as identified in the functional analysis. The optimization phase is aimed at adjusting the set of tolerance ranges that minimize the assembly cost. The tolerance ranges resulting from the CAT analysis are introduced into a cost function to be minimized. The tolerance ranges are iteratively relaxed or tightened to reduce the cost function while still delivering the assembly functions. The values of dimensional and geometrical tolerances to be applied on the parts depend on the specific manufacturing method adopted. The resulting optimal set of tolerance ranges is provided to the product detail design phase.

According to [27] the future CAT software should be able to satisfy the following requisites:

(1) to suggest geometric and dimensional tolerances once the manufacturing process has been assigned
(2) to suggest the manufacturing process once the tolerances have been assigned to the parts
(3) to suggest the tolerances on the parts according to the part functionality.

In the proposed method, the functional analysis is the first step for the CAT analysis.

3. Case study

The case study proposed in this work deals with marine engineering. In particular, the design of a sub-system of the transmission line of a boat is considered, in which the internal combustion engine (inside the boat) is connected to a sterndrive unit, as Fig. 2 shows.

The sterndrive system is widely used in marine engineering. The propeller drive is outside the boat and connected to the engine through a u-joint, pivoting around a horizontal axis. In this way, the propeller is horizontal, working with a higher efficiency, than traditional inclined shafts. Moreover, the propeller drive can be extended and retracted, easing up the handling of the boat while on the ground. Moreover, there is no need for a rudder since the sterndrive allows a rotation around the vertical axis, so that the boat can be steered by acting on it. From a mechanical point of view, the core of the drive is provided by two 90 degree-angle conical gearboxes. The first one takes the mechanical power from the u-joint aligned with the engine shaft and conveys it to a vertical shaft, and the second one connects the vertical shaft with the propeller shaft. The flywheel of the engine is connected to the sterndrive through a housing, where a shaft links the female spline at the entre of the flywheel, to the u-joint. This is required to allow vertical and horizontal pivoting of the sterndrive: the design of this part of the transmission line will be discussed as a case study, in the following of the paper. The assembly is made by a flywheel housing, a shaft connecting the motor flywheel to a u-joint allowing to extend and retract the sterndrive (which includes a case, a set of

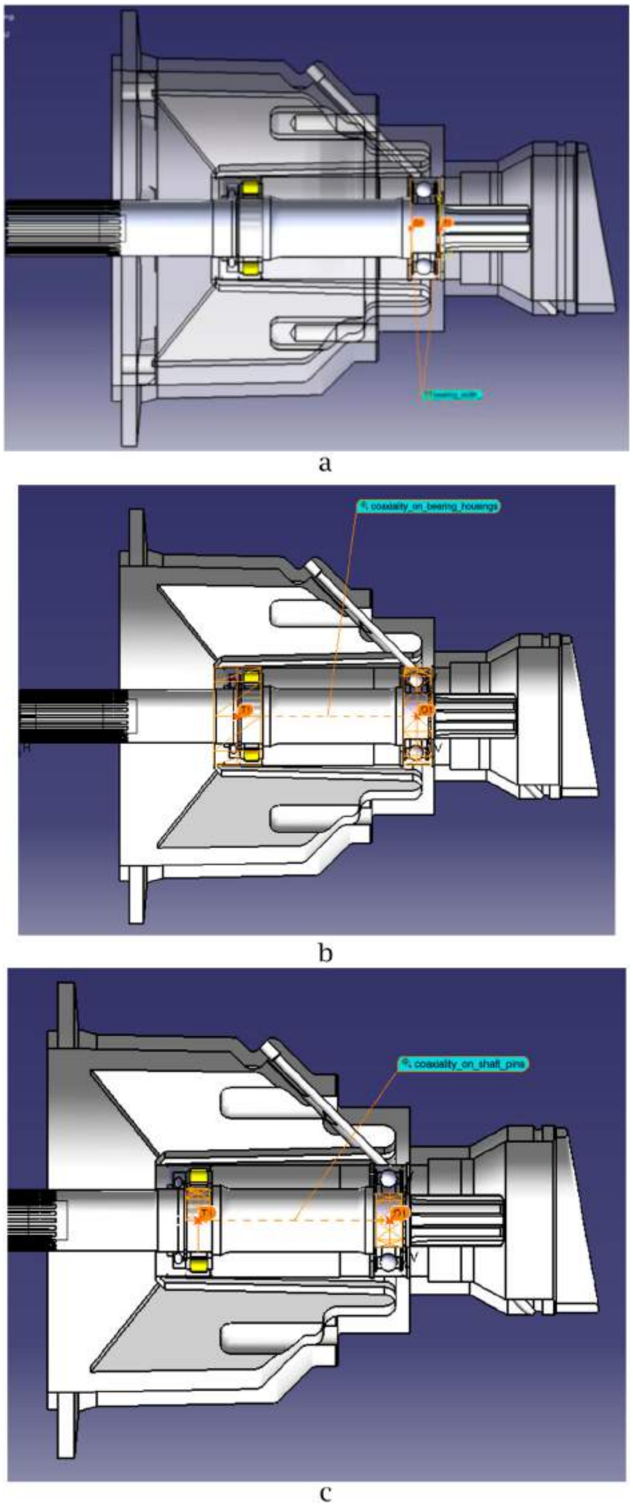


Figure 3. (a) Measure 1, (b) Measure 2, and (c) Measure 3.

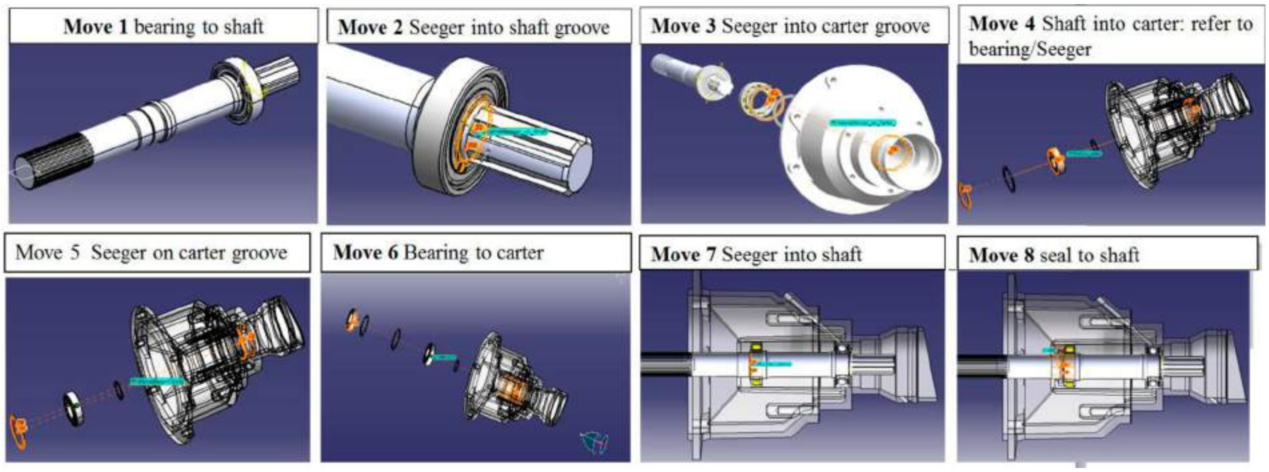


Figure 4. Assembly sequence: move1 to move 8 to complete the assembly asset.

conical gears and the propeller), together with bearings and seals. The application is quite critical since marine engineering needs close tolerances to reduce heating of moving parts, waterproof zones requires effective sealing often between moving parts, the salt water environment is corrosive, a reduced maintenance is required to avoid the expensive lifting of the ship from water and finally safety requires a high reliability of the propulsive system. Moreover, marine engines can run for several hours without interruptions owing to large quantities of heat do dissipate. Vibrations and bumps must be controlled to reduce structural stresses and increase the comfort. These problems suggest the need for a tolerance stack up analysis in the 3D assembly of the transmission mechanism. The design of this part of transmission has been proposed in the past to a small Italian SME. The power transmission unit, object of the tolerance analysis, is made by a carter containing the assembly of shaft and bearings, blocked by retaining rings, and a single u-joint, coupled to the shaft, by means of a SAE spline, universally used for power transmission purposes, as Fig. 2 shows.

3.1. The measures

In order to control eccentricity owing to vibrations, displacements due to temperature changes, and bumps, several tolerances have to be checked. These will be the “measures” to be analyzed within the KBE based 3D CAT simulation. Among them, the following “measures” will be controlled (Fig. 3,a,b,c) to ensure functionality of the assembly during the duty service:

Measure 1: clearance check on the width for the ball bearing retaining ring groove, in order to avoid blocking due to non-controlled thermal dilatation of the shaft.

Measure 2: coaxiality between bearing housings on shaft, to ensure the correct position of the bearings on the shaft, and reduce eccentricity that could cause vibrations.

Measure 3: coaxiality between bearing housings on the case, to ensure the correct position of the bearings on the case, and the correct mounting with the rest of the power transmission components by the flange.

3.2. Assembly sequence modelling

The “moves” defining the actual sequence for assembling the transmission can be described in 8 steps, namely (Fig. 4):

(1) The first bearing is mounted on the shaft, to the shaft housing.
(2) The retaining bearing blocks the bearing on the shaft.
(3) The retaining ring is mounted inside the grooved carter, as a shoulder for the bearing external ring.
(4) Shaft is mounted inside the carter until the ring housing shoulder is reached.
(5) Retaining ring is mounted on the grooved carter
(6) Roll bearing is mounted on the shaft
(7) Retaining ring is mounted on the grooved shaft.
(8) Seal is mounted on the shaft.

3.3. Tolerances on the components

Concerning the shaft, the following tolerances have been considered, as showed in the 2D draft of the shaft (Fig. 5), as well as in the MBD of the shaft, reported in Fig. 6.

Shaft. Tolerances on the shaft follow the ISO 16792:2006 standards ([19]). Dimensional tolerances involved in the tolerance chain are mainly set on the pin diameters (bearing housing). Geometrical tolerance are the *cilindricity* of the pins related to bearing housings,

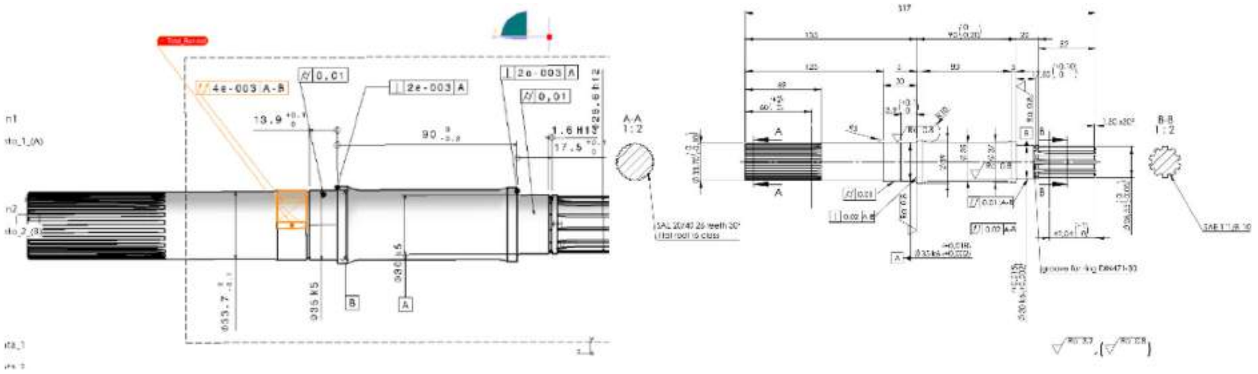


Figure 5. Runout of shaft in relation to the flange (left) and 2D drawing (right).

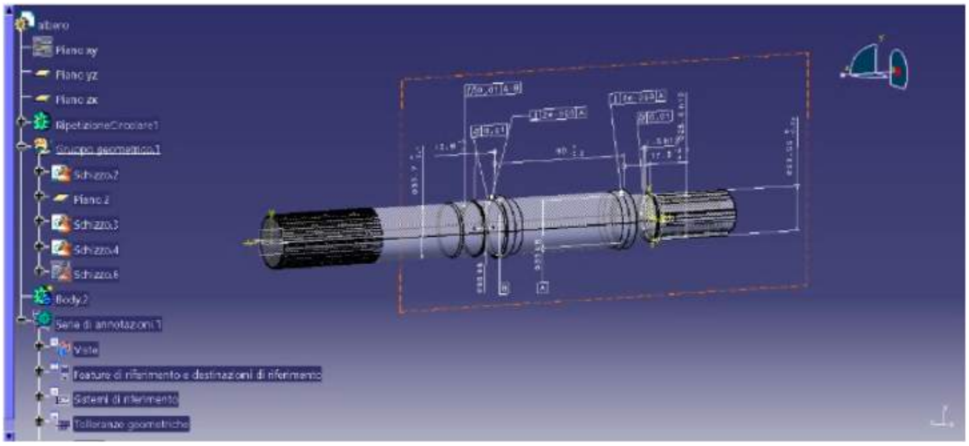


Figure 6. Dimensional and Geometric tolerances on shaft in the MBD.

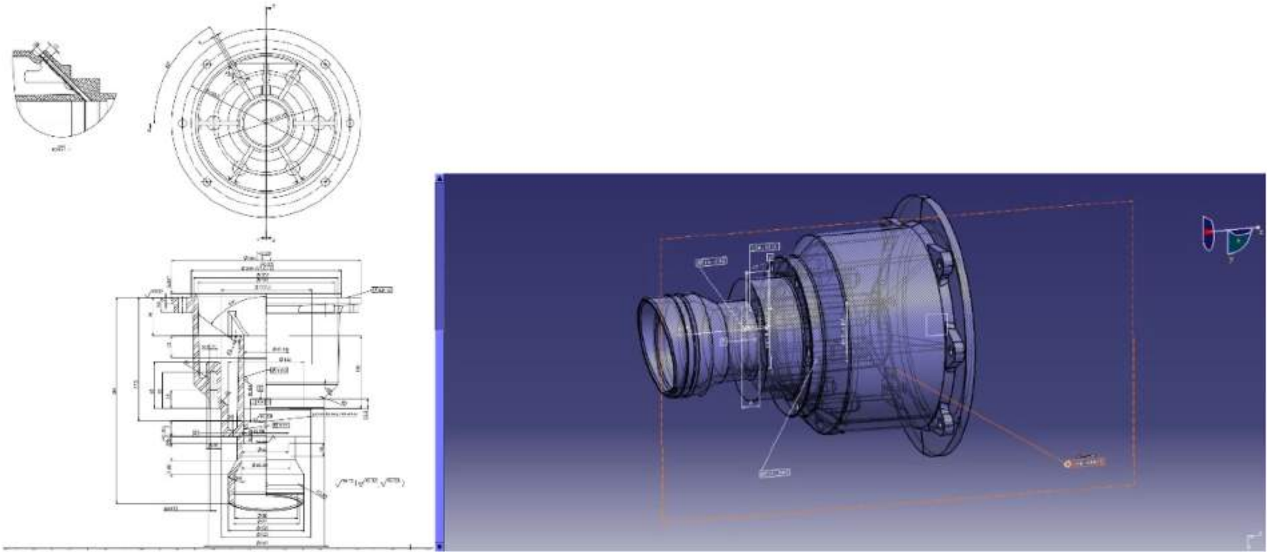


Figure 7. 2D drawing of the case and 3D tolerance asset in the MBD of the case.

and the *perpendicularity* of the housing shoulder to the shaft axis. Another geometric tolerance of the shaft is the runout on the surface mounting the seal, to avoid eccentricity causing wearing problems during shaft rotation.

Case. Tolerances on the case have been defined as in the following, replicating the 2D draft (Fig. 7, left), as defined in the following MBD model (Fig. 7, right). Dimensional tolerances related to the tolerance

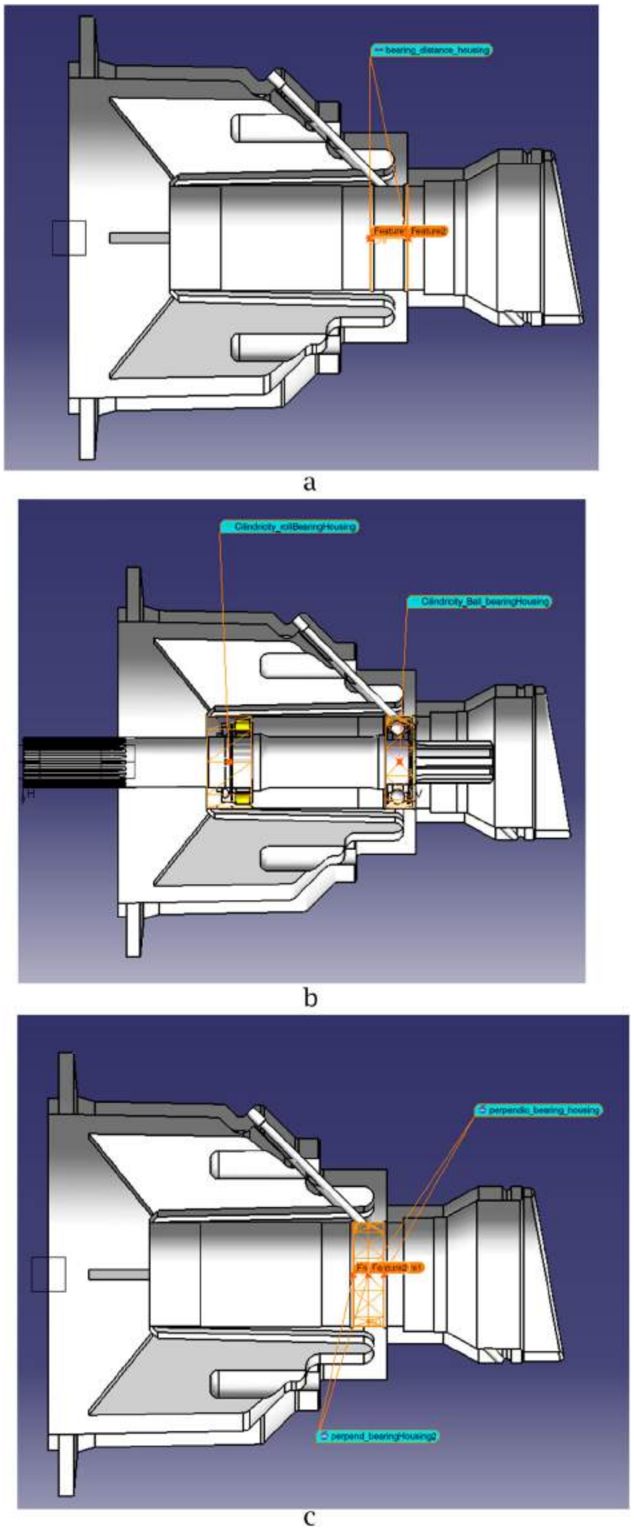


Figure 8. (a) Dimensional tolerances on the case. (b) Cilindricity of bearing housings on the case. (c) Perpendicularity of shoulder housings.

chain mainly control the functional distance between grooves.

Geometric tolerances on the case, which are correlated to the tolerance chain, control the shape of the bearing houses in terms of cilindricity and perpendicularity of the shoulder housings with respect to the shaft axis (Fig. 7 and Fig. 8a,b,c).

3.4. *Results of the tolerance simulations*

The 3DCS environment is perfectly integrated in CATIA V5, by means of a dedicated module, which can be opened from the main CATIA V5 menu. Commands allow the user to provide an assembly sequence, to set the tolerances on the components, as well as to define the measurements, remaining in a user-friendly interface, which is the one of the CAD software.

The Monte Carlo simulation runs in the 3DCS environment and provides the following results, according to each measurement. The parameter n of eq. 2.1 was set equal to 2000.

Measurement 1. The first measure that has been performed is the check on the clearance between the ball bearing and the retaining ring. As in Fig. 9 (left), the main contributor to the distance between the flange and the groove is the groove distance on the case, for more than the 99%. The perpendicularity of the bearing housing shoulder on the case and the cilindricity of the bearing housing represents other minor contributors.

Measurement 2. The second measure is the coaxiality on bearing housing on case (Fig. 9, centre). Results show that dimensional tolerances on the bearing pins are the main contributors, for almost the 50 percent each one. A minor contributor is the cilindricity on the same surfaces.

Measurement 3. The main contributors on the coaxiality of the bearing pin (Fig. 9, right) are the dimensional tolerances of the pins, for the 45% on the ball bearing, and the 35% on the roll bearing. A minor contributor is the cilindricity of the ball bearing pin for the 22%.

4. Discussion

Almost all the measures provide acceptable results in the sense that the nominal value is nearby the mean of the Gaussian curve. This is an index of best practice in terms of production, since it means that the most of the samples will be produced within the 6-sigma requisites if the chosen tolerances will be reproduced. Concerning measure 2, related to the coaxiality of the bearing housings in the case, the red bars of the histogram show the number of samples that are out of the LSL and the USL, in case contributor tolerances will be used. A solution is to increase the area between LSL and USL, with respect to the one predefined. In this case the measure range can be increased from 0.01 to 0.02 mm. Results reported in Fig. 10 show a reduced number of wasted samples, as well as an increased value of process performance index (P_p).

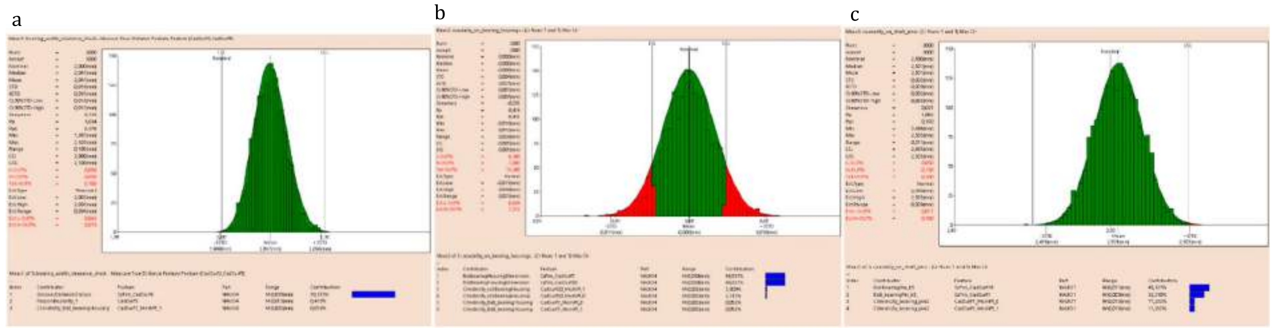


Figure 9. (a) Results related to measure 1. (b) Results related to measure 2. (c) Results related to measure 3.

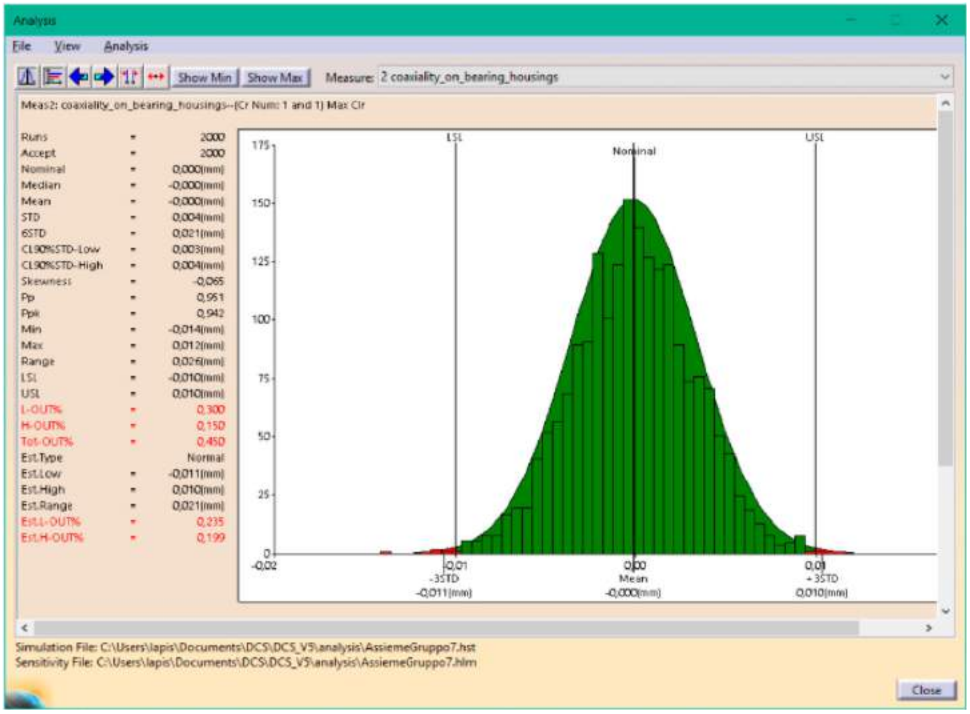
The following Table 1 summarizes the results obtained before and after the change of the tolerance of cilindricity on the bearing houses from 0.01 to 0.02, with increased values of P_p and P_{pk}.

This case study shows that the methodology described in this paper can help the designer of complex mechanical assemblies to set tolerances trying to solve functional problems and reducing waste of parts. This approach presents advantages respect to what currently carried out in SME companies where often tolerances are set by the most experienced and respected member of the technical staff who bases his/her decisions on the company past experience and personal background. Just to provide an idea of the economic impact of the methodology application, the following Table 2 shows the average manufacturing costs of the assembly parts while produced in a SME with CNC machines, the percentage and cost of waste parts both before and after applying the proper tolerances setting.

Table 1. Process performance index for measurements.

Measure	Std dev σ	P_p	P_{pk}
1	0.016	1.034	0.978
2 (before)	0.004	0.476	0.467
3	0.002	1.082	0.970
2 (after)	0.004	0.951	0.942

As suggested by Table 2, the application of an optimal tolerances setting leads to a sparing of 42€ per group produced, which is the 7.63% of the assembly manufacturing cost in the zero waste scenario (550€). The approach we developed can be useful in SME since also a young designer can propose a tolerance stacking by



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Meas2: coaxiality_on_bearing_housings--(Cr Num: 1 and 1) Max Clr

Runs             =        2000
Accept           =        2000
Nominal          =    0,000(mm)
Median           =   -0,000(mm)
Mean             =   -0,000(mm)
STD              =    0,004(mm)
6STD             =    0,021(mm)
CL90%STD-Low     =    0,003(mm)
CL90%STD-High    =    0,004(mm)
Skewness         =       -0,065
Pp               =        0,951
Ppk              =        0,942
Min              =   -0,014(mm)
Max              =    0,012(mm)
Range            =    0,026(mm)
LSL              =   -0,010(mm)
USL              =    0,010(mm)
L-OUT%           =        0,300
H-OUT%           =        0,150
Tot-OUT%         =        0,450
Est.Type                 Normal
Est.Low          =   -0,011(mm)
Est.High         =    0,010(mm)
Est.Range        =    0,021(mm)
Est.L-OUT%       =        0,235
Est.H-OUT%       =        0,199

Simulation File: C:\Users\lapis\Documents\DCS\DCS_V5\analysis\AssiemeGruppo7.hst
Sensitivity File: C:\Users\lapis\Documents\DCS\DCS_V5\analysis\AssiemeGruppo7.hlm
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Figure 10. Results related to measure 2 with increased measure range.

Table 2. Economic impact of the methodology application.

Component	Manufacturing cost of the single part (€)	% of parts out of the 6σ (before)	Cost per single part produced including waste parts (before) (€)	% of parts out of the 6σ (after)	Cost per single part produced including waste parts (after) (€)
Case (aluminum casting, thermal treatment, lathe machining)	282	15.2	324.9	0.45	283.3
Shaft (raw steel bar, lathe, splines machining and temper)	68	0.2	68.136	0.2	68.136
Roll Bearings (off-the-shelf)	18	18	18	18	18
u-joint (off-the-shelf)	147	147	147	147	147
Seeger rings (off-the-shelf)	9	9	9	9	9
Manual **Assembly** and dimensional **checking**	26	26	26	26	26
TOTAL	550		593		551

simply detecting the critical working conditions of an assembly. Moreover, this approach can be also updated based on the maintenance records showing where the criticalities of an assembly lie, so that future designs can benefit of the past experience. The main limit of the approach is that it requires some time to provide simulations and to tune the tolerances in order to reduce the waste of parts. These drawbacks could be solved by driving the tolerances changes with an optimization algorithm whose fitness function related the reduction of parts waste.

Even if CAT design approaches are widespread, few examples in the analysed literature show the use of CAT software in industrial applications. A systematic approach in the use of the CAT software would provide a huge cost reduction, due to the reduction of redesign activities, as well as design errors, as remarked in the discussion section. This is fundamental in the SME due to several factors.

In SME the presence of design procedures for helping to find out

Moreover, the proposed case study has been chosen as basic as possible, to show the economic efficiency of the CAT design application. Besides, this paper has the main aim of providing a method for guiding the designers through the phases for achieving an enhanced and efficient design of components in industrial contexts, starting from the early design phases.

5. Conclusion

Geometric Dimensioning and Tolerancing is a critical issue in modern mechanical design and industry to allow the assembly of parts assuring functional requirements. Despite a huge literature and standards on GD&T there are no procedures to support the designer in the setting of tolerances. In this paper, a KBE based environment to set tolerances based on the functional requirements of an assembly is presented; a strategy based on a Monte Carlo simulation of waste part useful to suggest the change of tolerances in critical points has been implemented as well.

The methodology has been applied to the design of a group required in a marine transmission, connecting an internal combustion engine to a retractable sterndrive unit. Results show that the KBE based environment can be useful to drive the tolerances change toward values assuring the optimal functionality of the assembly and reduction of waste parts.

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