Advanced Characterization of Free-form Surfaces in High Precision Machining

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Abstract

Precision free-form components are functionally complex objects with very accurate surfaces. In the manufacturing of these parts the complete and correct characterization of geometrical errors is an important aspect since it allows the adoption of preventive actions to control errors causes such as the thermo-mechanic behaviour of the machine tool, the removal mechanism of the cutting operation, the wear of the tool, the lubricant action, etc. In this work an advanced method of geometry characterization has been adopted to investigate the various contributions of the geometric error, resulting from the machining of any free-form geometry. The method allows the effective estimation of the size contribution error as well as form, orientation and position deviation. The method consists in an iterative process that minimize the distance of the cloud of points measured to an optimized offset of the nominal model of the component. At the end of minimization process, optimal parameters are used for the complete shape characterization of the part.

1. Introduction

Every manufacturing process is characterized by an intrinsic variability that can be found in the geometric characteristics of the finished product. The identification of geometrical deviations can be used to adjust the manufacturing process, as suggested in ISO 17450 [1]. For regular geometries, geometric characterization, based on ISO 14660 [1] and ISO 17450 concepts, consist in the determination of an "associated feature" that has the same shape of the nominal model and differs from it for size, orientation and position. The relevant standard for measuring procedures is ISO/TR 5460 [2], which is not adequate for the evaluation of profile tolerances by using coordinate measuring machines and the nominal CAD model: conventionally the characterization of an actual free-form profile is implemented by fitting algorithms that align a cloud of measured points to the nominal CAD model. This approach is becoming a critical issue due to the increasing complexity of surfaces and the need to obtain very precise surfaces [3][4][5][6][7][8][9]. Its formulation regards minimizing the distance between the measured points and the nominal curve. A review of the main free-form surface inspection techniques is given by Li and Gu [5]. The disadvantage of this approach is that only form, orientation and position errors can be determined. Some works propose algorithms for exact best fit of parametric surfaces and separately calculate orientation/position, dimension and form deviation [10][11], using a vector which contains the “dimensional” parameters. The disadvantage of this procedure is that, at the end of the best-fit, the associated feature doesn’t preserve the nominal shape of the element, in particular for complex geometries, described by many dimensional parameters. Therefore the consistency of these approaches to standards and traceability requirements is lost.

In the present work a method for separately determining size, form, orientation and position errors of a real profile is proposed. The approach has been verified by computer simulation experiments whose results are discussed in the following.

2. Problem formulation and proposed approach

An actual profile can be described, using a parametric form, as:

$$p(u) = [T(t)](p^*(u) + h \cdot n(u) + \varepsilon(u))$$

where u is the parameter that define the position of the point on the curve, p(u) is the actual profile, T(t) is the transformation matrix that define the position and the orientation of the actual profile compared to the nominal p*(u), h is the size error, n(u) the normal vector to the curve, and e(u) the local deviation.

Consequently, local deviation of the i-th point can be calculated as:

$$\varepsilon(u_i) = [T(t)]^{-1} P_i - (p^*(u_i) + h \cdot n(u_i))$$

where $p^*(u_i)$ is the nearest point to P_i on the nominal curve p*(u) and $n(u_i)$ is the local normal vector. The approach needs to minimize the objective function:

$$F(t, h) = \Sigma(\varepsilon(u_i))^2$$

The problem is addressed computing the best rigid transformation that aligns the measured points to an offset of the nominal profile: the minimization process consists on the determination of two translation components **tx**, **ty** (position error), a rotation component **θ** (orientation error) and the offset parameter h (size error). The form error **e** is calculated at the end of the process.

3. Implementation and results

The method is implemented in MATLAB®. Nominal models are described in parametric form using the Bezièr curve definition.

The application has been verified with tests on several ideal geometries; measured points have been obtained imposing an offset and a rigid transformation to a nominal profile. Some results are presented in Figure 1 and Table 1, where both nominal values and deviation calculated from the nominal value are presented.

It can be highlighted that the proposed approach gives results more consistent with simulated errors than conventional fitting methods. Moreover, results make evidence of the effect of the conventional fitting method in the repartition of the size error contribution in the position, orientation and form errors: the form error is considerably overestimated and thus the rejection of the part due to general tolerances specification is expected.

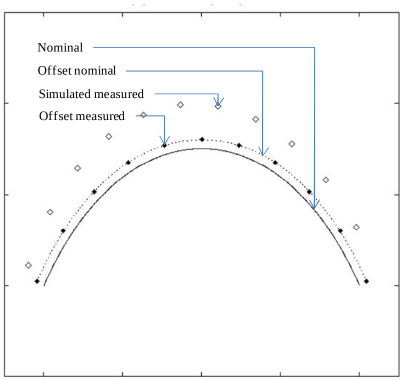

Figure 1. Example of fitting results with the proposed method.

Table 1. Conventional least square versus the proposed fitting method on simulated data without form error contributions [mm].

Errors	tx	ty	θ	h	e
Simulated	0.1	0.1	0.1	0.1	-
Proposed approach	0.10000054	0.09999922	0.10000035	0.09999981	0.00000026
Conventional least square	0.08813972	0.21820584	0.09999993	-	0.06354289

Further simulations have been performed introducing gaussian distribution or sinusoidal distribution of local deviations, with the aim of simulating actual manufacturing errors. Results are shown in Table 2.

Table 2. Results obtained with the proposed fitting method on simulated data with form error contributions [mm].

Errors	tx	ty	θ	h	e
Nominal	0.1	0.1	0.1	0.1	0.02
Random deviations	0,01214	0,00554	0,00994	0,01487	0,01887
Sinusoidal deviations	0,00991	0,01087	0,00994	0,00999	0,02116

4. Conclusion

This paper proposes a new approach for freeform profile characterization. The problem of identifying and separating dimensional, form, position and orientation contributions, comparing a cloud of measured points with a nominal model of the profile is formulated as a minimization problem. Differently from the conventional methods that fit data points on the reference profile, the proposed solution consists in an iterative process of minimization, where at every iterative cycle the calculated parameters are used to resize the nominal profile and reposition the measured points. The method is useful in all the cases where the compensation of size errors can be used to control the manufacturing process by effectively differentiate size from form errors contributions , thus increasing the possibility of identifying good parts.

References:

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