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Post-machining distortion mitigation via bending straightening, a multiparametric ROM study

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Abstract. Large and thick aeronautical structural parts frequently exhibit significant distortions after machining because of the residual stresses generated along the manufacturing process. A post-machining shape correction phase, called *reshaping*, has to be applied to each part before proceeding to the assembly stage. At the moment this process relies entirely on the know-how and experience of a specialized operator. As a consequence, the process is expensive and time-consuming. Therefore, there is a need at an industrial level to solve this problem with the support of numerical simulation tools. However, to reach this target, it is required to explore beforehand the input space to construct a solution dictionary in order to provide real-time response. Both requirements oblige to launch a multi-parametric analysis under a Model Order Reduction (MOR) framework. A complete reshaping process consists of a sequence of elementary operations, among which bending straightening is selected in its three-point bending configuration and it is simulated by applying the Sparse Subspace Learning method (SSL). By using the MOR approach, new insights for the distortion mitigation via plastic bending can be explored that will help to understand the open problem of reshaping.

INTRODUCTION

Large and thick aeronautical structural parts are made of aluminum forgings in order to produce a lightweight construction [1]. However, they frequently exhibit significant distortions after machining because of the residual stresses generated during the sequential manufacturing steps, especially after the heat treatment of quenching [2, 3]. Such distortions are variable in nature, but the industrial process incorporates a robust reshaping stage: skilled boilermakers operate series of mechanical loadings on the non-conforming part and re-establish its nominal geometry while obeying guidelines imposed by stress offices – which guarantees the produced part has still mechanical characteristics compatible with its operational role –. Nonetheless, numerical simulations may offer here huge margins for improvements: operational assistance to boilermakers and related gains in time-cycle (optimized reshaping sequence, optimized parameters for each elementary reshaping operation), improved knowledge of actual part and related gains in safety (monitoring of actual plastic strains) [4, 5]. An example of the structural parts subjected to reshaping are the cruciform beams that form the wing-box in an aircraft.

Reshaping can be considered as the sum of four local operations where the part is plastically deformed. These operations are: bending straightening, torsion straightening, roller burnishing, and ultrasonic needle peening. The main idea in this process is to produce a local deformation in the opposite direction of the deformed shape in order to counteract the mismatch between the real and the theoretical geometry.

This corrective stage is an iterative operation and its work-flow diagram is represented in Figure 1. Starting from the initial geometry, a measurement and control step is performed in order to determine the level of distortion. Based on the result, one of the four reshaping operations described before is selected. To perform one single plastic deformation step, the selected reshaping operation needs to be configured, it means, the technological parameters μ_i (e.g position, imposed displacement, length of the application) need to be defined. This process is repeated until the part is repaired and fits into the design tolerance.

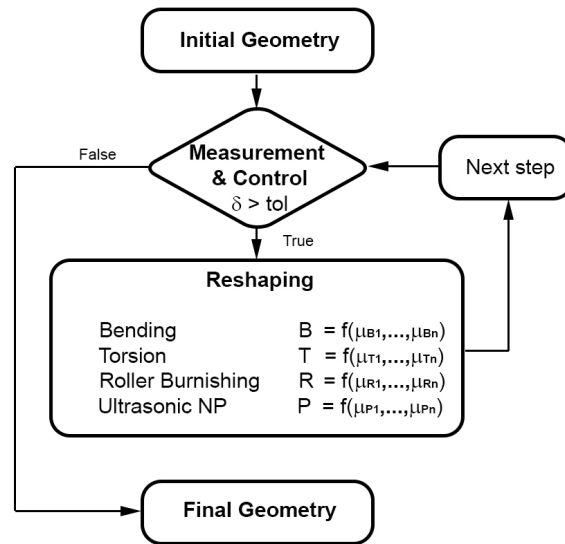


FIGURE 1. Reshaping work-flow.

As stated before, nowadays, reshaping relies on the experience of a well-trained operator. The goal to introduce numerical simulation in this process is to assist the operators and provide support during the decision-making step in order to reduce the number of operations needed to repair a part. However, from the technical point of view, reshaping simulation presents three main challenges:

- the initial distortion after machining is unknown and, with the available state-of-the-art simulation techniques, there is a mismatch between the numerical and the real distortion [6].
- distortions vary from one part to the other (non reproducibility), that is why reshaping cannot be standardized. As a consequence, reshaping simulation needs to provide multiple possible initial distortion scenarios.
- each time a new reshaping operation is performed, distortion changes and with it, the technological parameters associated with the next reshaping operation. Hence, reshaping simulation must be able to handle multiple parameters in real-time.

Under the described scenarios, the requirement of multiple reshaping simulations together with a real-time response obliges to launch a multiparametric analysis under a MOR framework [7]. For the different MOR available techniques, the Sparse Subspace Learning (SSL) is the selected method to study reshaping thanks its non-intrusiveness and the capability to handle the nonlinearities present during the process (e.g geometrical non-linearity and plasticity). For a detailed description of the method, the interested reader can be referred to [8, 9].

This document is organized as follows: first, the SSL formulation applied to reshaping is explained. Then, the problem setup used for a T shaped beam geometry is described. Next, the results of the multi-parametric ROM study are analysed and finally, the obtained conclusions are addressed.

RESHAPING UNDER THE SSL FORMULATION

Sparse Subspace Learning (SSL) is a non-intrusive Model Order Reduction technique, suitable for multiparametric studies and nonlinear analysis. The method exploits the sparsity of the solution with respect to the parameters in order to build a parametric solution from the computation of only few wisely chosen snapshots [8]. From the four available reshaping techniques, the bending straightening operation is selected in its three-point bending configuration to be studied with the SSL method, due to this operation is the most used to repair the structural parts in the industry [10].

For bending straightening, we are interested in determining the final shape of a part after performing a cycle of loading and unloading. Therefore, the displacement field $\mathbf{u}(\mathbf{x})$ for a given set of parameters $\boldsymbol{\mu}$ is our objective function and, by using the separated variable representation under the SSL formulation, it can be written as:

$$\mathbf{u}(\mathbf{x}; \boldsymbol{\mu}) = \sum_{i=0}^k \alpha_i(\mathbf{x}) \psi_i(\boldsymbol{\mu}) \quad (1)$$

where $\alpha(\mathbf{x})$ and $\psi(\boldsymbol{\mu})$ are defined as the *surpluses* and *parametric functions*, respectively. The parametric functions $\psi(\boldsymbol{\mu})$ act as the shape function. They are known, define the hierarchical basis and correspond to the Lagrangian polynomials, while the surpluses functions $\alpha(\mathbf{x})$ need to be determined. They are calculated as a linear combination of sampling or measurements evaluated at the *collocation points* $\mathcal{P}_n = \{\mu_0, \mu_1, \dots, \mu_n\}$.

For a unidimensional parametric problem, the collocation points are the extreme of the n -th Chebyshev polynomials of the first kind, $T_n(\mu)$ and are referred as Gauss-Chebyshev-Lobatto points (GCL) too.

In order to handle a multidimensional parametric problem, first, each parameter is treated as the unidimensional case described before and then, the *Smolyak rule* is introduced with the aim of constructing the sparse grid to be used during sampling. To put into perspective the advantage of the sparse sampling respect to the full sampling based on the tensor product, for a 2 parameters problem and a selected hierarchy level $k = 5$, the full sampling requires $33^2 = 1089$ points, while the sparse sampling only needs 177 points, providing a reduction of 83.7% in terms of computational cost.

Once the sampling points are defined, the simulations are launched in a commercial FEM software (e.g ABAQUS, PamCrash). The displacement field $\mathbf{u}(\mathbf{x}; \mu_i)$ is known at each collocation point and for our case, it is considered as the reference solution. With this available information, the corresponding surplus functions are determined as the difference between the exact and the approximated solution at the hierarchy level $(k - 1)$, as expressed in the following expression:

$$\alpha_i(\mathbf{x}) = \mathbf{u}(\mathbf{x}; \mu_i) - \mathbf{u}^{k-1}(\mathbf{x}; \mu_i) \quad (2)$$

Coming back to the reshaping problem, for the three-point bending straightening operation, the set of parameters $\boldsymbol{\mu}$ is composed by the initial distortion δ_0 , the position of the bottom roller r_b and the imposed vertical displacement y_s . For our problem, each parameter is considered as a dimension.

$$\boldsymbol{\mu} = (\delta_0, r_b, y_s) \quad (3)$$

When the solution $\mathbf{u}(\mathbf{x}; \boldsymbol{\mu})$ is reconstructed for all the parametric domain, the remaining distortion δ can be found as a post-processing operation and it is defined as:

$$\delta(\boldsymbol{\mu}) = \max_{\mathbf{x}} [\mathbf{u}(\mathbf{x}; \boldsymbol{\mu})] - \min_{\mathbf{x}} [\mathbf{u}(\mathbf{x}; \boldsymbol{\mu})] \quad (4)$$

However, for all the possible reshaping configurations, we are mainly interested to know the optimum stroke y_s^{opt} that, for a fixed set of parameters (δ_0, r_b) will minimize the remaining distortion δ in the structural part.

$$y_s^{opt} = \arg \min_{y_s} [\delta(\delta_0, r_b, y_s)] \quad (5)$$

PROBLEM SETUP

To study the three-point bending operation, a T shaped beam is defined, as shown in Figure 2. This geometry corresponds to a simplified version of a cruciform part, which exhibits critical distortions when machined and is a primary structure of main importance for aircraft manufacturers. The parameters to be explored are available in Table 1 with its minimum and maximum values μ_{min} and μ_{max} , respectively.

The selected material is an aluminum AA7010 previously characterized by Airbus Group Innovations. The elastic material properties are summarized in Table 2. To run the reshaping simulations, a Chaboche's isotropic/nonlinear kinematic hardening model was used. However, as the material parameters are under a nondisclosure agreement, they are not included in this document.

Finally, a Python script in combination with ABAQUS was used to run the 123 required simulations to explore the parametric input space under the SSL method for a hierarchy level $k=3$.

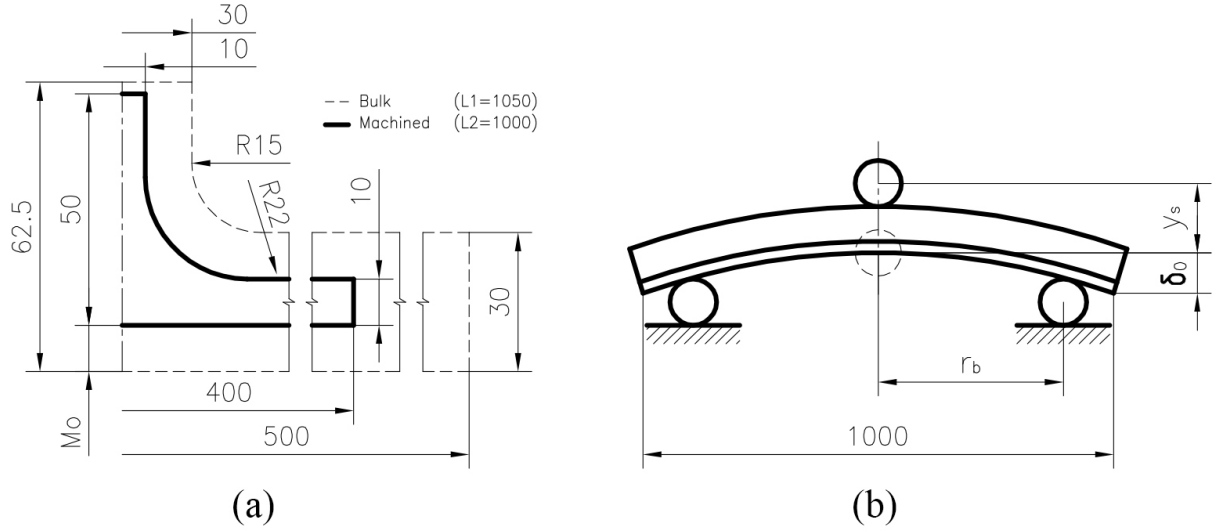


FIGURE 2. T shaped beam. a) Geometry definition and b) Parameters representation for three-point bending straightening.

TABLE 1. Parameters values for the three-point bending operation

Parameter ID	Description	μ_{min}	μ_{max}
1	Initial distortion δ_0 (mm)	-15	0
2	Bottom roller position r_b (mm)	100	485
3	Imposed vertical displacement y_s (mm)	5	30

TABLE 2. Elastic properties for Aluminum AA7010

Young's Modulus E (MPa)	Poisson's ratio ν (-)	Yield stress σ_y (MPa)
73000	0,3	390

RESULTS AND DISCUSSION

Before proceeding to explain the effect of each parameter in the bending straightening operation, it is required to introduce the evolution of the remaining distortion δ along the process. An example of the different zones present during reshaping is represented in Figure 3. In the beginning, if a small value of y_s is applied, the warped geometry will remain inside of the elastic region and there is no modification of δ_0 . We define this region as zone A and it is characterized by the relation $\delta \approx \delta_0$. A reduction of the initial distortion is only performed when plasticity takes place along the part. We call zone B at the region where $\delta < \delta_0$. Inside this zone, the optimum configuration ($\delta = \delta_{min}$) is located in a narrow space. To find properly this configuration is one of the challenges of reshaping. On the other hand, an excessive value of y_s can be counter-productive and invert the shape of the initial distortion from concave to convex (or vice-versa), giving as a result the operation zone C, where $\delta > \delta_{min}$, and which should be avoided.

The reshaping diagram described before is the result of a particularized solution where δ_0 and r_b were previously defined and y_s was set free. In order to generalize the problem, the next step is to set free a pair of parameters (e.g δ_0 and y_s), giving, as a result, a response surface. With the aim to explore the obtained multi-parametric solution, instead of using a 3D representation, a 2D plot together with level curves are used to describe if the remaining distortion δ will decrease or increase for a fixed bottom roller position r_b , as can be appreciated in Figure 4.

Effect of the initial distortion δ_0 : In a previous work, it has been proved that reshaping can be studied by using as a main input δ_0 under a Residual Stress Free hypothesis (RSF) [5]. This approach was used in order to generate numerically the warped geometry. By including δ_0 as a parameter, the problem of not knowing its magnitude beforehand is overcome. In that way, the reshaping problem is solved numerically for all the interval of initial distortions and

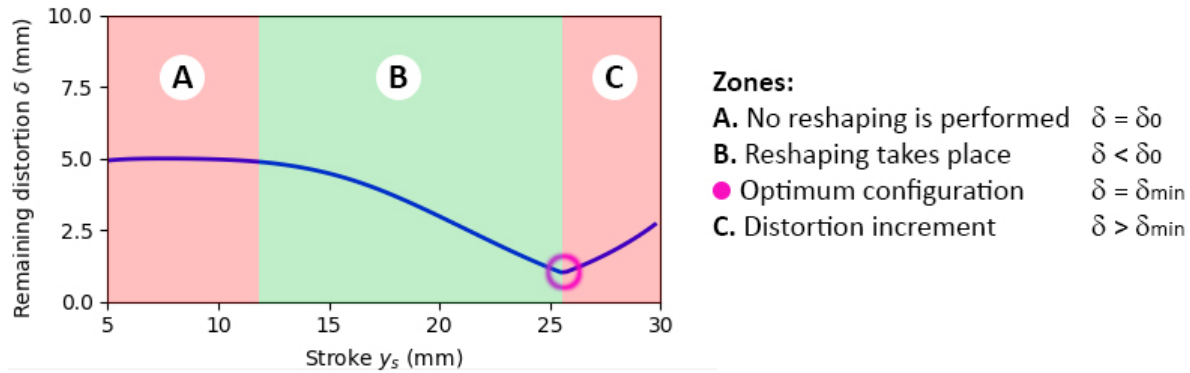


FIGURE 3. Zones present during reshaping as a function of the stroke y_s .

once the part is machined, the operator only needs to access to the solution dictionary and select a distorted geometry closer to the experimental result.

Effect of the bottom roller position r_b : Once the initial distortion δ_0 is known, the next step is to select the reshaping operation. For the three-point bending operation, the internal roller (top) is fixed and located at the middle of the beam while the external rollers (bottom) need to be placed. The position of the bottom roller is defined by the parameter r_b and it defines the slope of the response surface that relates the remaining distortion δ with δ_0 and y_s .

A value of r_b closer to the top roller produces a difficult reshaping operation to control, as it is expected to have a quick change of the remaining distortion δ during bending. On the other hand, a value of r_b away from the top roller generates the opposite behavior with a progressive variation of δ . In the performed parametric study, the selected value of r_b particularizes a page of the solution dictionary.

Effect of the imposed vertical displacement y_s : For a fixed initial distortion and a selected bottom roller position, the three-point bending operation is completed when a vertical displacement y_s is imposed at the internal roller. The magnitude of y_s needs to be defined in order to minimize the remaining distortion δ . The response surface obtained for a fixed r_b shows that reshaping is more difficult to be performed for smaller values of δ_0 as the required stroke y_s only to induce plasticity in the cross section is bigger than δ_0 . On the other hand, for a bigger magnitude of δ_0 , it is expected to have more margin to find the stroke that minimizes δ .

CONCLUSIONS

The industry is willing to have new tools to solve problems that nowadays are treated in an empirical way. Reshaping of large thick structural parts is an example of how MOR can be applied to an open problem, especially the SSL, allows to perform a multi-parametric study to test different *what-if* scenarios in a cost-effective way and, thanks to its non-intrusiveness, acts as a bridge to join MOR with the available third-party FEM solutions.

For the case of bending straightening, the initial distortion δ_0 is the starting point for reshaping and it determines the setup for the technological parameters r_b and y_s . Additionally, the problem of not knowing beforehand the value of δ_0 is overcome by including it as a parameter. Then, thanks to the SSL, this reshaping operation can be studied in a virtual environment before launching the real process.

Future work will focus on how to chain multiple reshaping operations and to include material properties as extra parameters. As expected, the computational cost for the numerical analysis will increase. Again, here it resides the importance of studying reshaping with MOR techniques.

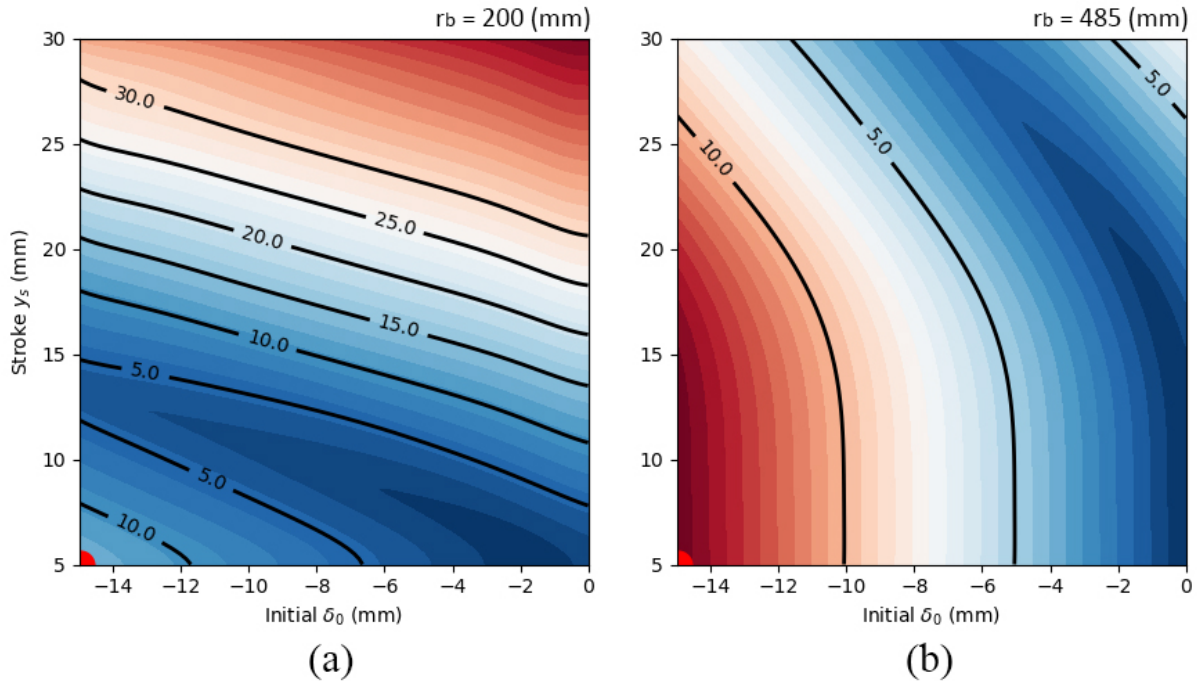


FIGURE 4. Response surface: Remaining distortion δ . Solution selection as a function of r_b . a) $r_b = 200(\text{mm})$ and b) $r_b = 485(\text{mm})$.

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