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Integration of gradient based and response surface methods to develop a cascade optimisation strategy for Y-shaped tube hydroforming process design

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ABSTRACT

In the last years a strong research effort was produced in order to develop and design new forming technologies able to overcome the typical drawbacks of traditional forming operations. Among such new technologies, hydroforming proved to be one of the most promising. The design of tube hydroforming operations is mainly aimed to prevent bursting or buckling occurrence and such issues can be pursued only if a proper control of both material feeding history and internal pressure path during the process is performed.

In this paper, a proper optimisation strategy was developed on Y-shaped tube hydroforming process which is characterized by a quite complex process mechanics with respect to axi-symmetric tube hydroforming operations. The design procedure was aimed to properly calibrate the internal pressure histories. The basic idea, in this paper, is to integrate a steepest descent method with a moving least squares approach in order to reach the optimal internal pressure curve in the hydroforming of an Y-shaped steel tube. Thus, a cascade optimisation procedure was implemented which consisted of two optimisation steps: the former is focused on the application of a steepest descent method, the latter is based on a response surface approach utilising a moving least squares approximation. The cascade procedure was driven by the will to reduce the total number of numerical simulations necessary to reach the optimum with respect to other optimisation methods.

1. Introduction

In the last years a strong research effort was produced in order to develop and design new forming technologies able to overcome the typical drawbacks of traditional forming operations. Among such new technologies, hydroforming proved to be one of the most promising. On the other hand, also a great interest in optimisation algorithms aimed to design forming processes was demonstrated by many researches.

Actually, in metal forming problems optimisation, several approaches were developed [1]: some approaches are characterized by a certain number of iterations of an iterative algorithm (usually gradient based) which are stopped when convergence is reached. Generally, such algorithms are interfaced with numerical simulation aimed to solve a certain number of direct problems necessary to calculate objective function gradients. Such algorithms may lead to local minima instead of global ones even if many of these algorithms are very efficient since few iterations are necessary to reach technologically satisfying results [2–8].

A totally different approach is based on intelligent techniques, for instance, genetic algorithms found a lot of applications [9–14] even if they generally require a high number of objective function evaluations. Some authors presented also some approaches which are based on the possibility to adapt the finite element analysis by some proper adaptive algorithms aimed to optimise some time dependent variables of a given process along the numerical simulations. Of course such approaches imply the possibility to manage the source code of a finite element software [15–17].

Maybe, one of the most effective approaches presented in the recent years in the technical literature is founded on response surface methodology [18]. Response surface methods (RSM) are based on approximation of a given objective function to be optimised through a set of points belonging to the domain of variation of the independent variables the function itself depends on.

Some works are focused on the application of RSM in sheet metal forming aimed to reduce the number of numerical simulations [19–23]: some authors used surrogate models and response surfaces in order to optimise a stamping operation for an automotive component [20] while other authors focused on springback effects control through RSM based approaches [21,22]. Another interesting approach concerns the sheet metal flanging process [23]. Actually, the main drawback of such method is the number of direct

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problem to be solved in order to reach good function approximations. A very interesting aspect in RSM application regards the possibility to build response surfaces basing on moving least squares approximations (MLS) by utilising a moving region of interest [19,24]. MLS are commonly used in mesh free methods as well as in many computational mechanics applications [25–29]. The MLS approach was also utilised in metal forming problems such as in optimising complex stamping operation even for industrial automotive cases: in particular the authors investigated the possibility to exploit MLS peculiarities in order to reach a high quality stamping part [19].

As tube hydroforming optimisation is concerned it has to be underlined that the basic idea in hydroforming is to replace costly dies with the action of a pressurised fluid on sheets or tubes [30]. The main result in the application of such technology is the reduction of tooling costs, nevertheless, also an improvement in process flexibility is gained with respect to traditional processes; in fact, a lower number of deformation stages are usually necessary to reach even complex formed shapes. Maybe, tube hydroforming is the principal example of hydroforming technologies advantages. Actually, tube hydroforming avoids the sequence of stamping and welding operations which characterizes the traditional tube production. In tube hydroforming processes the simultaneous actions of a fluid under pressure and a mechanical tool providing material feeding can lead to complex shape components characterized by good mechanical properties. The design of tube hydroforming operations is mainly aimed to prevent bursting or buckling occurrence and such issues can be pursued only if a proper control of both material feeding history and internal pressure path during the process is performed.

What is more, the production of T or Y-shaped tubes generally requires also the control of a counterpunch action with the aim to reduce thinning in tube bulged zones. In operations aimed to obtain Y-shaped tubes material feeding action is provided by two punches whose strokes have to be generally regulated in different ways.

The optimisation of tube hydroforming processes can be generally formulated as an optimisation problem in which some design variables have to be optimised in order to minimise a fixed objective function.

In this field, many studies were presented: some papers present integrations between numerical simulations and analytical or statistical procedures [17,31]; other researches investigated three dimensional processes with the aim to improve final part quality [32]. Many approaches concern the design of loading paths by numerical methods [33], while others utilised artificial intelligence to this aim [34,35]. The authors developed a wide research project on tube hydroforming optimisation even concerning three dimensional T-shaped tube hydroforming operations [36]; as Y-shaped tube hydroforming processes are concerned, some authors analysed their calibration with an integrated numerical–experimental approach [6].

The authors experienced the effectiveness of gradient based optimisation procedures, namely of steepest descent method, in designing the typical process parameters in tube hydroforming and the experimental validations supported such effectiveness [37]. Nevertheless, such procedure could lead to local optima instead of global ones. Moreover, a certain difficulty can arise in dealing with constraints to be taken into account during optimisation iterations.

In Y-shaped tube hydroforming design field, some authors presented the results of the application of Augmented Lagrangian and response surface methods for loading paths optimisation [38]. Such results prove that a significant number of numerical simulations are necessary to reach good results in terms of final product shape; namely the application of ALM led to a total number of numerical simulations which was higher than 150.

Other applications of optimisation strategies, such as the utilisation of Sequential Approximate Optimization (SAO) algorithm, to tube hydroforming optimisation cases were presented but even in this cases more than 100 simulations were developed [1].

Moreover, the possibility to exploit the capabilities of different optimisation methods in an integrated methodology was investigated in recent years [39]. The authors have recently applied a decomposition approach, based on gradient techniques, in order to analyse a Y-shaped tube hydroforming operation as the one here studied [40].

Following the above considerations and the analysis of the technical literature, the authors propose an optimisation strategy focused on the utilisation of few design variables to be optimised to reach good performances on the chosen objective function. More in details, the proposed approach is based on the considerations discussed in the following.

- There is no one single robust and “correct” technique to solve a given optimisation problem; on the contrary the exploitation of the main advantages of different methods may be a promising approach.
- Gradient techniques, such as steepest descent method, are simple to be implemented and they work very well in identifying a sort of “optimum region” i.e. a region in the neighbourhoods of the real optimum.
- Gradient techniques allow a strong objective function reduction towards minimisation even starting from initial design variables values which are very far from real optimum.
- Gradient techniques are affected by some drawbacks such as a difficulty to converge in close proximity of the optimum (they risk to remain trapped into local optima) and a strong sensitivity to finite element code approximation in solving the necessary direct problems.
- Response surface methods work quite well in the neighbourhoods of the real optimum and the can be easily implemented if a reduced number of variables is taken into account.
- Moving least square approximations provides more accurate response surfaces when irregular grids of data have to be managed. This advantage allows, for instance, the reuse of points already available within the design variables domain thus reducing the required computational effort.

In particular, in this paper, an optimisation strategy was developed on Y-shaped tube hydroforming process which is characterized by a quite complex process mechanics with respect to axisymmetric tube hydroforming operations and even with respect to T-shaped tube ones. The design procedure was aimed to properly calibrate the internal pressure histories. Such aim was pursued by implementing a cascade optimisation procedure which consisted of two optimisation steps [41,42]: the former is focused on the application of a steepest descent method to reach an optimal solution which is in the neighbourhood of the actual optimum. The latter step of the optimisation process is based on a RSM utilising moving least squares approximation. Such final step is aimed to fine-tune the results in order to reach an optimal solution which is more satisfactory and in close proximity to the real optimum.

The basic idea, in this paper, is to integrate a steepest descent method with a MLS approach in order to associate and to exploit the advantages of both the utilised techniques. Moreover, the proposed approach also aims to minimise the number of numerical simulations necessary to accomplish the optimisation goals.

In the following sections the investigated problem will be presented as well as the optimisation procedure. Moreover, the results of the proposed optimisation strategy will be discussed and validated. Such validation was performed both by carrying out a sensitivity analysis at the varying of the starting solution and by