Shape Optimization of Devices Taking into Account Production Tolerances

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***Abstract*---A technique of shape optimization of devices is proposed that takes into account acceptable tolerances of their dimensions. The technique is based on combination of classic optimization procedures and sensitivity analysis carried out in several steps in the course of the optimization process. This analysis is able to decide whether the given variant is worth further optimizing or the changes in the objective functions are unacceptably high even with small variations of parameters (such a variant is immediately rejected). The power of the methodology is illustrated on an example of induction brazing, whose results are discussed.**

***Index Terms*—Shape optimization, sensitivity analysis, production tolerances, numerical analysis.**

I. INTRODUCTION

DIMENSIONS of many devices and their structural parts must be optimized prior to the process of their production in order to satisfy necessary technological or functional requirements. In many real cases, for various reasons these parts cannot be manufactured quite accurately and some of their dimensions are characterized by uncertainties that, however, must not exceed prescribed tolerances. Optimization then means that the extreme is reached for the ideal dimensions, but within their tolerance zones the changes of objective functions must be as low as possible. Thus, the aim is not to find an absolute extreme (optimum) that might be highly sensitive to the change of some dimensions [1], but rather a sub-optimum that exhibits the lowest possible changes in the tolerance zones of the corresponding parameter [2, 3, 4].

Solution to this problem by purely optimization algorithms would be extremely expensive. After obtaining a seemingly good solution (for example, selected from the Pareto front), it could prove to be unacceptably sensitive to the change of some dimensions. That is why the authors propose a combination of the optimization process and techniques of sensitivity analysis. In this way, the variants showing excessive sensitivity to small changes of dimensions are rejected already in the starting phases of the optimization process and further optimization steps are applied only to variants with lower sensitivities.

II. FORMULATION OF THE PROBLEM

Consider a general multiparametric and multicriteria shape optimization problem with n parameters $x_1, x_2, \ldots, x_n$. Let the first k parameters ($k \le n$) may exhibit uncertainties, i.e. their values may range in intervals $\langle x_i - t_i, x_i + t_i \rangle$, $i = 1, 2, \ldots, k$, where t_i denotes the allowed tolerance of the i th parameter.

Let $h_j(x_1, x_2, \ldots, x_n)$, $j = 1, 2, \ldots, m$ are particular objective functions. Their values are usually determined by solution of the forward task, in technical domains mostly by the finite element analysis. After optimization, they should reach such sub-optimal extremes where a change of any parameter x_j, $j = 1, 2, \ldots, k$ would not cause any significant variations of the considered objective functions. In other words, in the vicinity of the calculated sub-optimum their shapes must be sufficiently “flat”. Mathematically expressed, there must hold $\left| h_j(x_1, x_2, \ldots, x_k, \ldots x_n) - h_j(x_1^*, x_2^*, \ldots, x_n^*, \ldots x_n) \right| < d_j$ together with $x_i - t_i \le x_i^* \le x_i + t_i$, $i = 1, 2, \ldots, k$, for $j = 1, 2, \ldots, m$. Here, d_j denotes the acceptable difference from the flatness.

In case of coupled problems however, it cannot generally ever be predicted whether a solution with such properties for the given tolerances exists. Nevertheless, for several technical problems that we solved, this methodology, provided satisfactory results.

After its wide testing, we decided for the implementation that consists of the following steps:

1. The first part of the process is realized using an appropriate genetic algorithm (NSGA 2, NSGA 3 etc.). The selection of the first population is carried out using the Latin Hypercube technique. Then, several optimization steps are performed followed by the sensitivity analysis that rejects all unsuitable individuals. This part may repeat several times.
2. The remaining individuals are further optimized by a deterministic technique based on simplex or conjugate gradient methods.
3. After finishing the process, the optimized individuals are again subjected to the sensitivity analysis that provides the best possible result.

III. ILLUSTRATIVE EXAMPLE

One of practical problems where the methodology was successfully applied was the design of an inductor for brazing pipes into sleeves of evaporator of an air conditioner for automotive industry. The pipes are made of aluminum (melting point 660.3 °C) and solder is an alloy of zinc and aluminum (melting point 580 °C). Heating of the pipe and sleeve should be as uniform as possible in order to avoid a cold connection between them at the moment of melting the solder. Nonuniform distribution of temperatures may cause faults such as

- insufficient amount of solder between the pipe and sleeve,
- material of the pipe is replaced by solder,
- melting or evaporating of material of the pipe or solder.

The basic arrangement of the whole system (evaporator with sleeve, pipe and inductor) is depicted in Fig. 1.

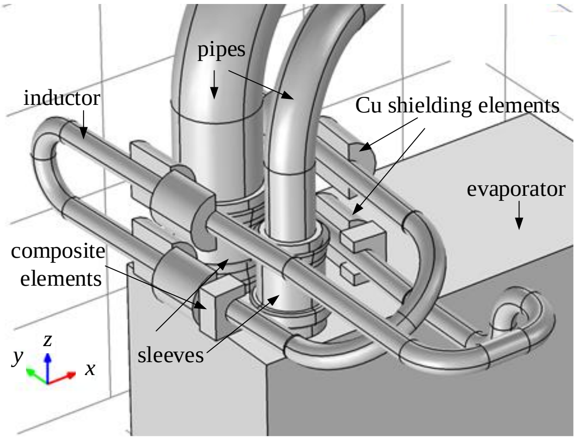

Fig. 1. Arrangement with inductor to be optimized

The inductor is represented by a hollow copper pipe cooled by water. Its dimensions are not accurate and may exhibit certain variances.

The requirement is to heat both pipes and sleeves as uniformly as possible even when the dimensions of the inductor and its position with respect to the brazed parts can change in the range of several tenths of mm.

Three optimization approaches were used for the solution of the problem. First, a mono-criterion optimization was used, where the objective function was defined as the difference between the minimum and maximum temperatures in the exposed domain if the lowest temperature exceeded the melting point of solder.

Also a two-criterion optimization was tested. The second objective function was the brazing time that should be minimized.

The third way of optimization was aimed at minimizing the variance and sensitivity.

The forward problem was solved by the classical way [5], using the professional code COMSOL Multiphysics 5.2. 3D electromagnetic field generated by the inductor produces Joule losses that heat the processed parts. Reaching the prescribed uniformity of temperature in the exposed spots requires not only the shape optimization of the inductor, but also the presence of shielding and composite (Fluxtrol 50) elements.

Figure 2 shows the non-optimized arrangement after 80 s of heating. From the map of the temperature field, it can clearly be seen that the distribution of temperature along both pipes is non-uniform and the difference between the hottest and coldest spots is about 50 °C, which is quite unacceptable.

Then the dimensions of the inductor were optimized using all three above algorithms. Generally, the fastest one was the first of them; on the other hand, the two-criterion procedure provided the best results. These are depicted in Fig. 3 that contains the distribution of temperature along the perimeters of both pipes. Now the difference does not exceed 15 °C.

IV. CONCLUSION

The presented algorithms are robust and provide results that could be even verified experimentally. The full version will contain all details concerning the algorithms and complete mathematical model of the problem.

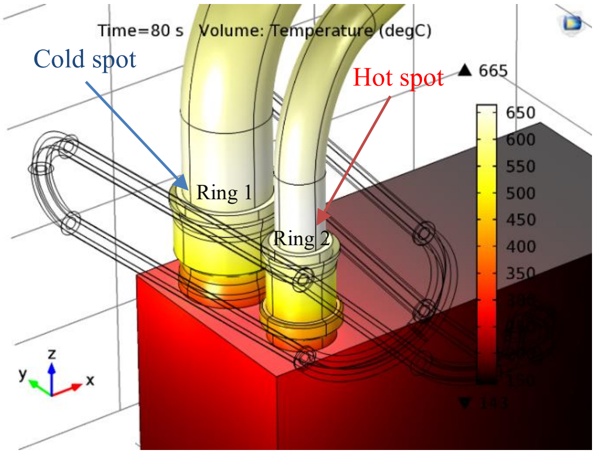

Fig. 2. Temperature field distribution for non-optimal inductor. The temperatures of cold spot and hot spot differ by about 50 °C.

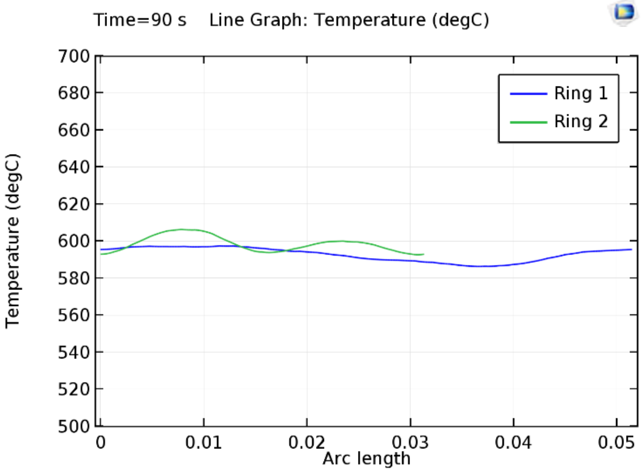

Fig. 3. Temperature along soldered ring for optimized variant. Difference between hottest and coldest places is less than 15 °C. Blue line is longer as corresponding perimeter of ring 1 which is larger.

V. ACKNOWLEDGMENT

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