Optimization of fastener distribution during airframe assembly

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1 Concept

The ASRP software tool is designed for simulation and optimization of the assembly process for large scale airframe parts. In particular it provides fast and accurate solutions of contact problems arising during the simulation of riveting process.

These problems have specific features that are taken into account during development of problem solving technique:

- Tangential displacements in the junction area are negligibly small regarding the normal ones that justifies the use of node-to-node contact approach;
- The junction area is relatively small in comparison with the whole model;
- External loads are applied in the junction area or can be transferred there;
- Friction is not taken into account;
- Stress state of each part in the assembly obeys the linear theory of elasticity;

Due to these assumptions dimensionality of problem is reduced. The problem is reformulated in a variational form corresponding to minimization of deformation energy with regard to linear non-penetration conditions. The only considered degrees of freedom are normal displacements in the junction area.

A very important feature of ASRP is the wide range of options for setting the initial gap between riveted parts. The gap in certain points can be imported from measurement devices in the automatic or manual mode. Then using interpolation and extrapolation techniques, it can be calculated all over the junction area. Alternatively, the gap can be generated as a random function with given parameters. Usually this technique is used to generate the so-called cloud of gap fields (the set of different gap fields with given properties) for subsequent statistical analysis. Usually a cloud of gaps contains up to thousands of gaps. Both approaches can be combined if given gap is modulated by random component.

The mentioned options make it possible to use ASRP for elaboration and analysis of assembly technology for given types of junctions.

2 Statement of optimization problem

During the airframe assembly process it is important to reduce the number of installed temporary fasteners. At the same time the gap between parts has to be inside a given range (e.g., smaller than 0.2 mm) in order to provide sufficient quality of drilling and sealing, and to reduce stresses caused by assembly. Theoretically, the gap has to be within a given range everywhere in the junction, but in practice it is impossible to fulfill this condition for the whole cloud of initial gaps. Thus, it is reasonable to formulate the optimization problem in probabilistic terms.

Problem 1:

For a given number N of fastening elements find the disposition of fasteners that gives the minimal probability of the gap G exceeding given level G_{max}.

$$P\{G(x_1, ..., x_n) > G_{max}\} \to \min, \tag{1}$$

$$cstr: \sum_i x_i = N, \tag{2}$$

$$w.r.t.: \{x_i\}_{i=1,...n}, \quad x_i \in \{0, 1\}, \tag{3}$$

where n is the total number of holes, and x_i is one/zero if a fastener is installed/not-installed into the i-th hole.

As calculations in ASRP are made only in computational nodes, and a cloud of initial gaps is generated beforehand, the following simplified formulation is used instead of the previous one.

Problem 1':

For a given cloud of initial gaps and given number of fastening elements find the disposition of fasteners providing minimal number of nodes with computed gap exceeding given level.

Also it is possible to consider another optimization problem that is connected with the previous one.

Problem 2:

Find the minimal number of fastening elements and corresponding disposition of fasteners under condition that the gap G exceeds a given level G_{max} with fixed probability ε.

$$\sum_i x_i \to \min, \tag{4}$$

$$cstr: P\{G(x_1, ..., x_N) > G_{max}\} < \varepsilon, \tag{5}$$

$$w.r.t.: \{x_i\}_{i=1,...N}, \quad x_i \in \{0, 1\}. \tag{6}$$

3 Possible ways to solve

All above-posed problems are large-scale nonlinear combinatorial problems with discrete variables. The direct solution of such problems is difficult and resource-intensive task. The following approaches may be applicable to the problem: heuristic algorithms (already partly implemented in ASRP software), simulated annealing method (or other Monte-Carlo methods), genetic and other evolutionary algorithms, greedy algorithms. Also three variants of relaxation for Problem 2 were discussed.

3.1 Spatial relaxation

Instead of fixing holes positions, we can consider them being distributed arbitrarily within the junction area. In this case, we need to minimize the number of fasteners, provided that the gap exceeds a given level with given probability. Then, we use the penalty function in order to attract the optimal hole positions to the locations of real holes.

3.2 Force relaxation

Instead of fixing fastener force values, we consider variable force and minimize the sum of fastener force values in all holes, provided that the gap exceeds a given level with given probability. Then, we use a penalty function in order to reduce the optimal force distribution to a binary form (fastener installed/not installed in a given hole).

$$\sum_i (F_i + \theta\Pi(F_i)) \to \min, \quad (7)$$

$$cstr1 : P\{G(F_1, ..., F_N) > G_{max}\} < \varepsilon, \quad (8)$$

$$cstr2 : F_i \in [0, F_{max}], \quad (9)$$

$$w.r.t. : \{F_i\}, \quad i = 1, \ldots, N. \quad (10)$$

3.3 Combined relaxation

Instead of fasteners in holes, we can consider compressive pressure distributed along the junction area. We search for distribution of pressure providing minimal pressure force (that is, the integral of pressure over the junction area) under constraint that the gap exceeds a given level with given probability. Then we use penalty function approach in order to transform the optimal pressure distribution to the binary form (fastener installed/not installed in a given hole).