On the Application of N-2-1 Locating Principle to the Non-rigid Workpiece with Freeform Geometry

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Abstract. Fixture design for non-rigid workpieces is performed based on the N-2-1 locating principle (with N > 3 base locators). Determination of the position and orientation of the application points of the locators are among the most challenging processes that fixture designers are encountered with, especially in case of the freeform workpiece without specific datum features. In this paper, the N-2-1 locating principle has been applied to a non-rigid freeform workpiece which is chosen from the aerospace industry. In this regard, four distinctive locating plans have been designed by alternating of two parameters: the quantity of the base locators (N) and the position of the locating points on the base locating surface. Numerical analyses have been conducted using finite element software in order to investigate the effects of the mentioned parameters on the fixturing characteristics under the application of the clamping forces. The output parameters can be elaborated as workpiece deformation, displacements of the locating points, stress values and the reaction forces generated on the locating agents. The best locating plan has been chosen by the application of the suggested decision-making model by incorporation of the calculated fixturing characteristics. Based on the results, reductions of almost 41.6% and 66% were observed respectively on the workpiece maximum deflection and cumulative locating points' displacements by switching from the 3-2-1 to the N-2-1 (with N = 6) locating system without sensible change in the stress values.

Keywords: Fixture design · Fixturing layout · Finite element analysis
N-2-1 locating principle · Sheet metal part

1 Introduction

The traditional 3-2-1 principle is widely used to design the locating systems for the rigid workpieces. For the non-rigid workpieces, however, the N-2-1 locating principle has been suggested which incorporates N (N > 3) base locators on the workpiece base surface. Towards the determination of the position and orientation of the locating and clamping points on the non-rigid workpieces, several types of research have been published by incorporating different meta-heuristic optimization methods (such as GA,

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PSO, ACO, etc.) with various objective functions. In the real world application, however, several technical limitations usually emerge during the design of fixture for this kind of workpieces, which can't be mathematically modeled and considered, especially in cases of workpieces with freeform geometry. Some of these limitations can be named as the lack of appropriate datum feature on the workpiece geometry, the unavailability of application of the point-contact locators on the workpiece, the lack of appropriate base locating surface, etc. Based on the mentioned limitations, the fixture designer usually considers several heuristic models to design the locating and clamping systems and chooses the best solution by taking into account the most critical parameters of both workpiece and fixture systems. From the viewpoint of workpiece, these parameters can be named as the accuracy of the fabricated workpiece to be within both dimensional and geometrical requirements, the surface quality of workpiece, residual stress of workpiece, etc. Hence, finite element software is one of the indispensable tools that the fixture designer utilizes in order to determine the required parameters and select the best solution between several alternatives. Based on the above-mentioned challenges in the real world application of fixture design process, in the present study, the design of locating system is considered for the workpiece selected from aerospace industry by taking into account the N-2-1 locating principle. For this purpose, four distinctive layouts have been suggested as a locating system of the workpiece and using the numerical analysis, the best solution has been chosen based on the suggested decision-making model.

2 Literature Review

Among the most recently published research works in the field of application of FEM at investigation of the fixture-workpiece system, Ivanov et al. [1] employed numerical analysis to design an innovative fixture for the lever machining in single set up considering the tool access problems that emerge at the multi-axis machining and ensuring of the manufactured part tolerances that meet the required values through the application of several FE analyses: workpiece-fixture deformation analysis, fixture-workpiece modal analysis, and harmonic analysis under the effect of oscillatory machining forces. Integration of the FEM application in the modeling of fixture-workpiece system with the heuristic and evolutionary optimization techniques have been recently focused on by several researchers. Sundararaman et al. [2] combined FEM, RSM and evolutionary optimization models of GA, PSO and their combinations for optimization of the locating layout of fixture aimed at machining of a hollow shaped workpiece. The presented model employed response surface methodology and developed a quadratic model to enable the suggested methodology to search for the optimized locating layout on the continuous spaces of the workpiece surfaces. Integration of the PSO with RSM was concluded to generate more realistic results at optimization process. Literature of the locating system design can be surveyed based on the workpiece geometry and rigidity. Hurtado and Melkote [3] optimized the quantity, dimension, and position of the pins with the clamping force intensity at the pin-array configuration method by considering the objective function as the maximum conformation of pins to the workpiece with freeform surfaces. Three heuristic ideas were suggested in [4] for fixturing of the freeform workpiece: fixturing with the magnetorheological fluid, moving arms with the pneumatics powered bladder strips and a motor driven pin-array like configuration. Parvaz and Nategh [5, 6] suggested a mathematical analysis to design the locating and clamping systems for the workpiece with the freeform surfaces. The fixture design activities are going to be more challenging by adding flexibility to the workpiece. Having suggested the N-2-1 locating plan for these kinds of workpieces by Cai et al. [7], a combined GA and FE model was developed by Xiong et al. [8] for the optimization of locating positions in non-rigid aerospace workpieces aimed at minimization of the total and partial workpiece elastic deformation near the active machining regions. In [9], the optimization of the N-2-1 locating system for non-ideal sheet metal part was conducted by considering the variations of workpieces in the production batch. Li et al. [10] proposed a non-rigid fixture based on the controlled motor-driven modular elements for non-rigid workpieces with introducing the follow-up support idea. Yang et al. [11] proposed an efficient concept for optimization of locating plan by application of cuckoo search algorithm. Sample sets were were generated from few FE calls based on the N-2-1 scheme. More recently, Calabrese et al. [12] suggested the optimization of the fixture topology into the mixture of solid-lattice topology with the objective function of maximizing fixture stiffness.

At the real-world application of the fixture design, lots of limitations occur and constrain the incorporation of the mathematical analysis such as optimization methods reviewed above in the design of locating system for the workpiece. These limitations make the designer use finite element packages to obtain the necessary information for choosing the best solution as the locating plan between the alternatives. The main contribution of this paper is to investigate the effective fixturing parameters in selecting the best solutions between the alternatives and how these parameters should be manipulated when selecting the best solution. Specifically, the aim of the paper is to study the applicability of the N-2-1 locating principle to design the fixture aimed at riveting a freeform non-rigid workpiece through determining the best quantity, layout and configuration of the N base, twoside and single stop locators by taking into account effective fixturing parameters. For this purpose, a sheet metal model was chosen from the aerospace industry. Four locating plans were designed as alternatives using the N-2-1 locating principle with varying quantity and pose of the base-locating agents. The effective parameters in the selection of the best alternative were chosen to be the workpiece elastic deformation, displacements of the workpiece locating points, stress values and the reaction force values generated on the locating agents. Numerical analyses were conducted using FE software and the best solution was chosen based on a decision-making algorithm.

3 Research Methodology

Abaqus software was utilized for numerical analysis and determination of the output parameters for the chosen model represented in Fig. 1. The workpiece is selected as one of the parts used in aerospace industry, which is made of AL7075-t6 material with the thickness of 2 mm. The CAD model of the workpiece was prepared and imported for the software using the neutral file format as a deformable body. Locators were chosen to be tip-sphered due to the freeform nature of the workpiece geometry and made up of steel material. Rigid body constraint was applied to all of the locators to ensure that no deflection occurs on them during the workpiece fixturing. Since plastic deformation is not allowed in the fixturing phenomenon, the elastic data of the materials were just submitted as Young's modulus, Poisson's ration and density equal to 200 GPa, 0.29 and 7800 kg/m^3 for Steel and 71.7 GPa, 0.33 and 2810 kg/m^3 for the aluminum, respectively. By applying the locators at the mentioned positions of Table 1, friction was defined between the mating surfaces of the locators and the workpiece with Coulomb's friction coefficient equal to 0.6 [13]. The suggested four locating plans have been graphed in Fig. 1 and the corresponding data have been elaborated in Table 1. Since the analysis includes frictional multi-contacts between the freeform surfaces, the dynamic explicit solver was chosen with time period of 0.1. Full DOF constraint was applied to the locators to ensure that the locators remained fixed during the fixturing application. Total of four clamping forces were applied at the mentioned positions and orientation of Table 1 with equal intensity of 500 N. The parts were meshed by explicit element of C3D10M type with a quadratic geometric order using the second order accuracy. This element type is capable of modeling frictional contact between the mating surfaces, especially of the non-ideal geometries. Following the selection of the mentioned element type, the tetrahedron shaped meshes were applied to the workpiece using a free algorithm with the general size of 5 which was refined to 2 mm in the vicinities of the contact regions.

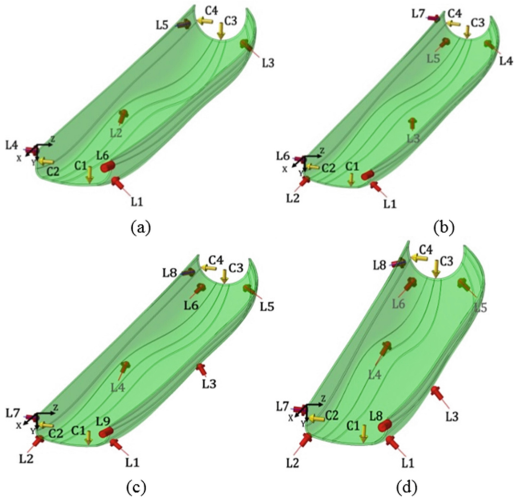


Fig. 1. The model of case study and the suggested (a) first locating plan (3-2-1 system) (b) second locating plan (5-2-1 system) (c) third locating plan (6-2-1 system in three rows) and (d) fourth locating plan (6-2-1 in four rows).

Table 1. The position of the locators at the suggested locating plans.

Locating plan no.	Locating points (mm)	
	Base locators	Side and stop locators
1	(0.43, 29.82, 94.44), (−350, 28.30, 9.72), (−685, 10.9, 55.81)	(−15.37, 10.969, −0.990), (−685, −3.43, −6.6), (16.06, 11.87, 97.03)
2	(0.43, 29.82, 94.44), (−14.604, 38.877, 3.625), (−350, 34.842, 52.358), (−685, 10.9, 55.814), (−685, 15.212, 5.682)	
3	(0.43, 29.82, 94.44), (−14.604, 38.877, 3.625), (−350, 20.934, 99.404), (−350, 28.298, 9.723), (−685, 10.9, 55.814), (−685, 15.212, 5.682)	
4	(0.43, 29.82, 94.44), (−14.604, 38.877, 3.625), (−234, 24.791, 105.555), (−467, 35.571, 15.602), (−685, 10.9, 55.814), (−685, 15.212, 5.682)	

The locators were meshed with the size of 1 mm to ensure the appropriate contact control between the mating surfaces. The model was then solved by requesting the displacements, stress values and reaction forces at the locating agents. It should be mentioned that the clamping points were remained fixed for all of the locating plans as (11.49, 37.05, 69.44), (0.17, 18.78, 1), (−700, 16.12, 26.86) and (−700, −4.02, −4.15).

4 Results

The mentioned output parameters were calculated for all of the locating plans. Typically, Fig. 2 represents the contours of deformation, stress distribution on workpiece, the displacement and reaction forces which are created on the sixth locators and plotted at the local coordinate system ($n - t_1 - t_2$ system) for the third locating plan.

The calculated output parameters for all of the locating plans are demonstrated in Table 2. By referring to the results, the alternatives for the locating plans can be compared from the point of view of each output parameter. The minimum of the maximum deformations calculated on the workpiece is 0.21 mm for the third locating plan which is occurred at the application point of the first clamping unit.

The experimental test has to be performed for verification of the results to the exact real-world data. However, several checks can be performed in order to ensure the results of simulations and confirm the adequacy of the results of FEM analyses. Figure 2(e) represents the typical curves of internal and kinetic energy for the simulation performed on the third locating plan. The kinetic energy is well below the 5–10% of the internal energy which confirms the quasi-static nature of the simulations.

To verify the order of magnitude of the deflection occurred at the free end of the workpiece represented in Fig. 2(a), this part of the workpiece can be roughly modeled by a cantilever beam with a rectangular section with the dimensions of 92.5 mm × 2 mm and the length of 15 mm. It should be noted that the straight distance between the locator No. 1 and 2 at the third locating plan is 92.5 mm. When applying the formula, the deflection occurs at the free end of the cantilever beam to the configured problem,

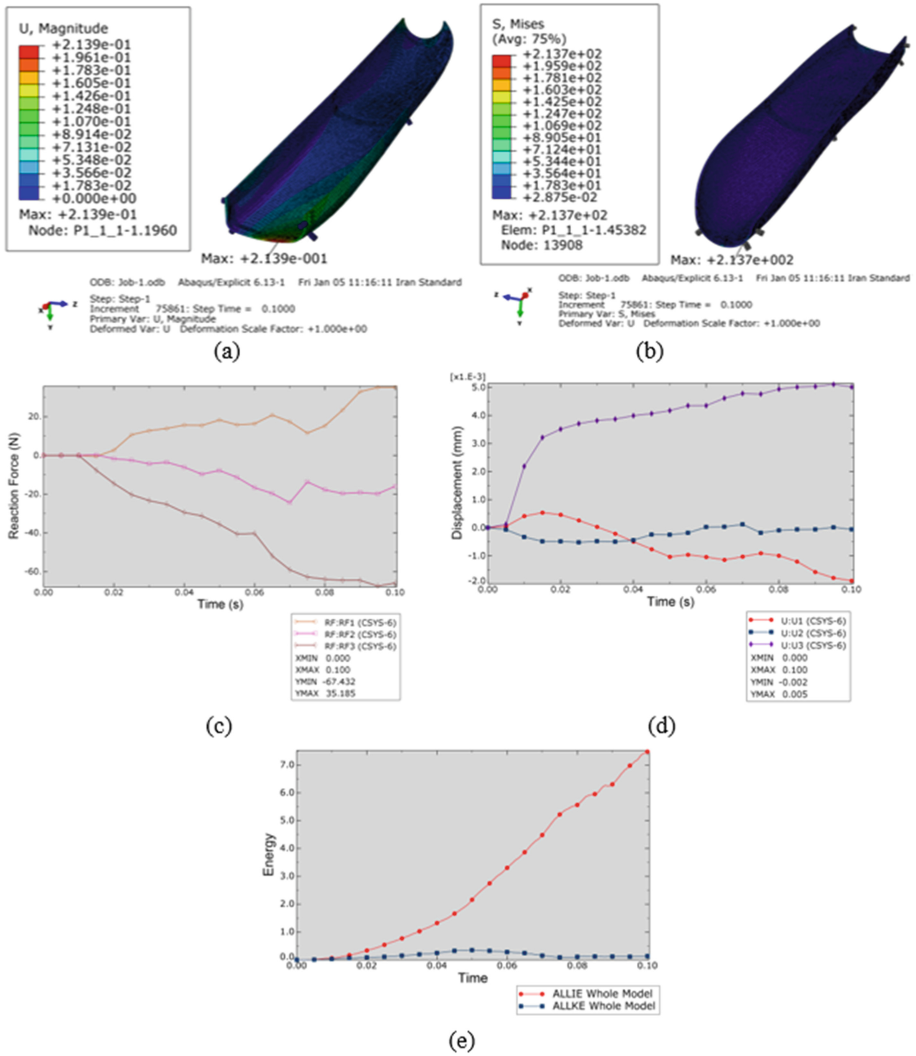


Fig. 2. The output parameters of fixturing the workpiece with the third locating plan (a) contour of deformation (b) contour of Mises stress (c) reaction forces created on locator No. 6 in the normal, first and second tangential directions and (d) the displacement of the third locating point (e) the internal vs. kinetic energy curves (with COF = 0.6 and clamping force intensity of 500 N).

assuming that only the clamping force of 500 N is applied at the free end of this beam at +Y direction, the deflection can be calculated as 1.272×10^{-1} mm.

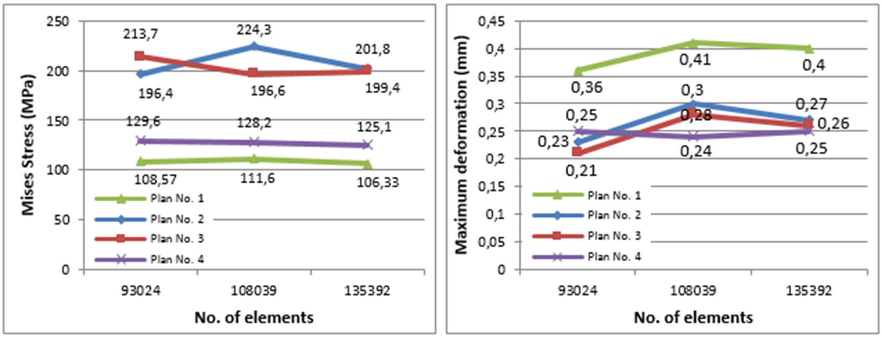
The calculated deflection shows that the order of magnitude of the displacement obtained from FEM analysis is quite reasonable. The difference between the FEM result and the calculated value from the modeled equivalent beam can be justified by assumptions admitted during the beam modeling process: considering only one of the

Table 2. The calculated fixturing output parameters for the locating plans.

Plan no.	Max. deformation (mm)	Max. Mises stress (MPa)	Locating point displacement (mm) $(U_{L1}, U_{L2}, U_{L3}, U_{L4}, U_{L5}, U_{L6})$	Reaction force values (N) $(U_{L1}, U_{L2}, U_{L3}, U_{L4}, U_{L5}, U_{L6})$
1	0.36	133.7	(0.23, 0.07, 0.25, 0.11, 0.09, 0.25)	(20.12, 75.72, 6.12, 26.7, 45.14, 114.23)
2	0.22	196.4	(0.09, 0.01, 0.05, 0.03, 0.00, 0.02, 0.05, 0.10)	(27.08, 28.19, 0.00, 10.95, 77.47, 20.61, 7.00, 141.70)
3	0.21	213.7	(0.09, 0.01, 0.03, 0.02, 0.03, 0.00, 0.01, 0.05, 0.10)	(27.62, 27.31, 17.93, 17.15, 11.97, 78.64, 19.88, 7.49, 97.22)
4	0.247	129.6	(0.13, 0.02, 0.1, 0.07, 0.08, 0.03, 0.04, 0.03, 0.15)	(57.08, 36.84, 0.00, 0.00, 18.55, 76.92, 20.67, 24.61, 84.92)

clamping force with the intensity of 500 N and neglecting the other clamping forces, assuming the boundary conditions as cantilever beam and changing of the geometry of workpiece from U-section to simple rectangular one. Since these parameters had been considered by the FEM analysis, the results were altered in the same order of magnitude.

To investigate the adequacy of the FEM results and its relationship to the mesh size, simulations were repeated three times each with a different number of elements. 12 simulations were conducted for the mesh independence investigation. The results are elaborated in Fig. 3.

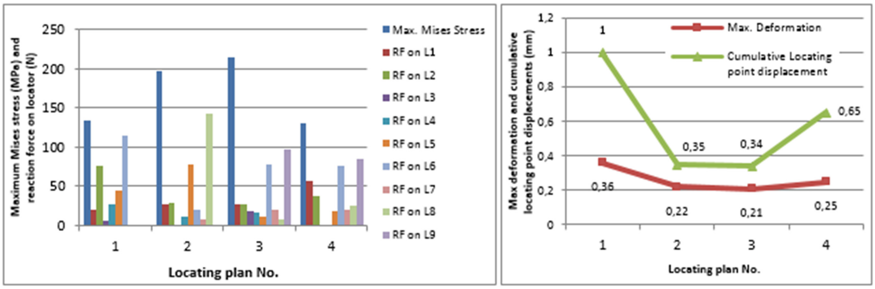


(a) (b)

Fig. 3. The results of mesh independence analyses on (a) maximum Mises stress and (b) maximum deformation of the workpiece.

Curves in Fig. 3 indicate that the results of simulations are almost independent of the mesh size within an acceptable range. Since, the position of maximum Mises stress changes with different element sizes for the first locating plan, stress was measured at the position of the contact between locator No. 5 (Fig. 1c) and the workpiece for this plan. The standard deviations of the results of maximum Mises stress were calculated as 2.16, 12.08, 7.49 and 1.88 from the first to the fourth locating plans, respectively. In addition, standard deviations for the maximum deformations of the workpiece were calculated as 0.02, 0.03, 0.03 and 0.005 from the first to the fourth locating plans, respectively. Based on these results, it can be concluded that the simulations and results were mesh-independent, approximately. It should be noted that the element quantity numbers (horizontal axis in Fig. 3) correspond the mesh sizes of 5, 4 and 3 mm, respectively.

The minimum of maximum Mises stress was obtained as 129.6 MPa in the fourth plan at the contact point of locator No. 6 and the workpiece surface. According to the diagrams of Fig. 4, it can be seen that the minimum cumulative displacement of locating points occurred at the third locating plan which was equal to 0.34 mm. The reduction of almost 41.6% in w/p maximum deformation and 66% in the cumulative locating point displacement can be observed in Fig. 4(b) by switching from 3-2-1 locating system to the third plan (N-2-1 with N = 6).



(a) (b)

Fig. 4. The diagrams of the output parameters regarding the locating plan No.

From the point of view of the reaction forces on the locating agents, it should be considered that the reaction force should be created on all of the locators to ensure that no separation occurs between either of the locators and the workpiece surfaces at the contact points. Considering this principle, it can be observed that zero reaction forces were calculated at the second and fourth locating plans for some of the locators. From the diagram in Fig. 4b, the minimum of the maximum deformations was calculated for the third locating plan which was equal to 0.21 mm.

A decision-making procedure should be performed to select the best solution for the locating system between the four alternatives based on the output parameters. Between the four output parameters, the parameter corresponding the reaction forces on the locating agents is a prerequisite rule which should be satisfied by all of the alternatives. An alternative would be removed from the list if the reaction force was zero in (at least) one of the locators. A scoring and weighting method based on Eq. (1) is incorporated for the decision-making model.

$$S_i = \sum\nolimits_{j=1}^{3} w_j \times (s_i)_j;\ i = 1,2,3,4;\ j = 1,2,3;\ \sum\nolimits_{j=1}^{3} w_j = 1,\ 0<(s_i)_j<1 \tag{1}$$

Where, S_i is the score of the *i*th locating plan, w_j is the weight of the output parameter, $(s_i)_j$ is the score obtained by the *i*th locating plan from the *j*-th output parameter, *i* and *j* stands for the number of locating plans and the output parameters. Between the four output parameters, the fixturing accuracy mostly depends on the two parameters of displacements of the locating points and the workpiece maximum deflection. So, weights w_j were increased for these two output parameters according to Table 3. It should be mentioned that $(s_i)_j$ is calculated based on the linear relationship between the obtained best and worst conditions of the *j*th parameter and normalized between the 0 and 1. Also, the scores of the alternatives from the third rule were calculated based on the yield stress of the workpiece material which was equal to 530 MPa for the case study [14]. Table 3 demonstrates the details of the scores and results.

Since zero reaction forces were observed at some locators of the second and fourth alternatives, they were removed from the list of candidates. According to the results in Table 3, it was concluded that the third locating system should be chosen as the best solution with score of 0.94. So, the 6-2-1 system in the ordered array layout is the best solution for locating the represented non-rigid freeform workpiece.

Table 3. The score of locating plans from the decision-making model.

Plan no. (i)	Score $(s_i)_j$ from the *j*th output parameter				
	Reaction force values	$j = 1$ Locating point displacement ($w_1 = 0.5$)	$j = 2$ Maximum deformation ($w_2 = 0.4$)	$j = 3$ Maximum Mises stress ($w_3 = 0.1$)	S_i
1	Passed!	0.00	0.00	0.75	0.07
2	Not passed!	0.98	0.93	0.63	N. A.
3	Passed!	1.00	1.00	0.40	0.94
4	Not passed!	0.53	0.75	0.75	N. A.

5 Conclusions

In this study, a realistic procedure was suggested for the design of locating system for non-rigid freeform workpieces. A case study was chosen from the aerospace industry and four locating systems were designed as alternatives. Numerical analyses were conducted for the calculation of four main fixturing parameters including displacement of the locating points, workpiece maximum deformation, reaction force values on the locators and maximum stress value generated on the workpiece. A decision-making model was suggested based on the scoring and weighting method and the third alternative was chosen with the score of 0.94 as the best solution for the specific case study. Also, the results showed the reductions of 41.6% and 66% at the N-2-1 locating system (with N = 6) in comparison with the 3-2-1 system in the workpiece maximum deformation and cumulative locating point displacement, respectively. It can be concluded that the suggested generic combined FE and decision-making algorithm can be utilized for design of locating/clamping systems for the workpieces regardless of its geometry and level of rigidity. For the further studies, the experimental verification of the calculated parameters is suggested for the validation of the results and the selected locating system.

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