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Design Methodology for Mechatronic Active Fixtures with Movable Clamps

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Abstract

A new fixture layout design methodology for a novel concept of adaptive machining fixtures, with both actively controlled clamping forces and a dynamically adjustable layout, is proposed. The methodology aims at minimising the deflection of the workpiece due to the dynamic machining forces. The methodology is based on a finite element model of the workpiece, coupled with closed-loop controlled actuators, acting as adaptive clamps of the fixture. The methodology is applied on a theoretical test case of a thin plate workpiece. Results show a reduction by 84.2% of the maximum deflection of the workpiece compared to a traditional fixturing approach.

Keywords: Active fixtures; Mechatronics; Adaptive fixtures; Clamps; Dynamic loading

1. Introduction

Modern manufacturing environments impose a continuous technological pull towards more flexible and efficient equipment. The field of tooling and fixturing could not constitute an exemption of this trend. Fixtures are devices designed to repeatedly and accurately locate a workpiece in a desired position and orientation relative to a global reference frame (e.g. machine tool), and securely hold it in that location throughout the manufacturing process.

In the field of active fixturing, research has focused so far on either flexibility/reconfigurability [1],[2] enhanced fixturing performance [3]-[8], or modelling the workpiece-fixturing system [6],[9]-[11]. Active fixtures have been studied for their ability to reduce deflections of the processed workpiece through maintaining optimal clamping forces [3],[6], enhancing surface finish by suppressing vibration [8], or ensuring repeatable positioning of the workpiece relative to the machine-tool's reference frame [1]. Research work on reconfigurable fixtures on the other hand, has focused on the ability to cater for various workpieces [1],[2]. By combining these two aspects a new fixturing paradigm emerges: fully-active fixtures. These can adapt clamping forces and fixturing element (fixel) positions during the manufacturing process, thus reducing dynamic and static workpiece deflection by increasing local stiffness and decreasing the required clamping forces, significantly improving form accuracy and surface finish. This holds especially true in the case of low-rigidity workpieces. At the same time, such a fixture has the inherent capability to automatically change its layout reducing the time to reconfigure.

In order to explore the capabilities and benefits of fully-active fixtures, it is important to look into the new fixturing strategies that such systems could render possible. A design and planning methodology that takes into account the capabilities of these fixtures is necessary to achieve this. However, such a methodology has not been developed so far. For this reason, this article focuses on the development and description of a fixture design/planning methodology, which takes into account the capabilities of fully-active fixturing systems and outputs the parameters of the fixturing strategy that should be implemented to obtain the desired results. A

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simple test case of a thin-plate workpiece is adopted, intending to facilitate understanding and highlight the potential benefits of fully-active fixturing strategies.

2. Fixture Design Methodology

The fixture design methodology intends to capture the dynamic behaviour of a fixture-workpiece system under moving and dynamic loads exerted by the manufacturing process. Its outputs are the fixturing strategy that should be followed together with its parameters, in order to reduce the displacement of the workpiece below a user-defined limit. The methodology can be split into three distinct phases.

2.1. Workpiece Discretisation

In this phase a Computer Aided Design (CAD) model of the workpiece is first inputted and split down into a grid of nodes using commercial FE packages. In this work the FE package Abaqus™ is used. This phase of the methodology further accepts material properties, type and number of finite elements and modal damping ratios.

The outputs are the system matrices and a nodes file (map of nodes), which contains the information about the coordinates and the identifying number of each finite element node. No boundary conditions should be applied on the workpiece model in the first phase. Boundary conditions are applied in the second phase of the methodology.

Using the resulting system matrices the workpiece model can be expressed by a system of second-order ordinary differential equations (ODEs) [12],[13].

2.2. Model Formulation in Matlab

The system matrices extracted in the previous methodology phase are introduced into Matlab™ in the second phase. This phase consists of three steps.

In the first step the fixturing elements are introduced. Two types of elements are considered: passive and active. Passive elements, i.e. elements that do not change their properties during the manufacturing process, are simulated via mass, spring and damper elements with constant coefficients. Such elements can be coupled to the model as described in [14].

Active fixturing elements, i.e. elements that can change their position and the forces they exert on the workpiece are modelled using first principles. In this work Direct Current (DC) electromechanical actuators are assumed to play the role of the active elements. The modelling of the DC-actuator active elements is described in detail in [12] and [13] and is, therefore, not presented here. For the purposes of this article it will suffice to mention that the active elements can also be described via a system of 2nd order ODEs. This allows the coupling of the workpiece-passive fixture elements model and the active elements model using the impedance coupling method [14].

The second step of this phase of the methodology deals with the application of boundary conditions. For this, the methodology described by [15] is adopted. For the case where boundary conditions mean constraining the motion of certain degrees of freedom, the system matrix rows and columns that correspond to the degrees of freedom which are being constrained are completely removed.

The third step is the generation of the force vector. If the points of application of the external and fixturing forces do not change over time, then a single-force vector with or without time-dependent vector element values is sufficient. If, however, the point of application of these forces moves during the manufacturing process, then a force vector for each time instant needs to be created, resulting in a force matrix.

2.3. Optimisation

With the previous two phases complete, the coupled fixture-workpiece model has been generated. This model is treated as the original solution for the third phase of the methodology: the optimisation phase. The outputs of this phase are:

- Fixturing strategy - number of position changes per tool pass for each fixture element.
- Position coordinates of each contact point between fixture elements and workpiece.
- Time scheduling of position changes.
- Clamping forces for every position of every clamping element.

Before describing the optimisation parameters it is important to highlight the assumptions and limitations under which the methodology operates, as well as establish some useful definitions.

2.3.1. Definitions, Assumptions and Limitations

Working area. Physical limitations, like the travel range of the movable fixels, reduce the working area of each fixel to a fraction of the full workpiece surface. For this reason, each fixel is associated with a surface area on the workpiece within which it can make contact. It is assumed that the working areas of fixels do not overlap. To reflect this, the nodes that belong to the surface of the workpiece that constitutes the working area of a fixel, are grouped into a set of nodes referred to as Fixel Nodes Set (FNS).

Sequential operation. A key limitation of the methodology is that it does not produce the optimal fixturing process parameters for all fixture elements simultaneously. Each fixture element is treated independently. As a result, the optimisation phase is applied to each element sequentially.

Displacement solution area. The target of the fixture design methodology is to improve the form accuracy and the surface quality of the machined area. To achieve this, it is necessary to minimise the displacement of the workpiece at the area that lies directly underneath the cutting tool. Moreover, due to the discrete nature of the problem, it is only possible to obtain displacement solutions at the nodes of the workpiece model. It, therefore, becomes apparent that the machined area needs to be defined as a set of nodes.

Furthermore, it is assumed that the fixel, within whose working area the cutting tool moves, has the potential to impact the result of the process the greatest. Therefore, only the nodes that belong to that area on the machined surface of the workpiece that is the closest to the working area (FNS) of a fixel need to be treated each time. The nodes that are contained within the machined area are grouped into one set of nodes, called the Solution Nodes Set (SNS).

From the above, it can be deduced that the optimisation process targets only one pair of SNS and FNS, at a time. For example, in Fig. 1, assume that the machining process takes place on the surface that lies over the locators L2 and L3. The optimisation process needs to be repeated twice. The machining area is split in two solution nodes sets (SNS_{L2} and SNS_{L3}). First, the optimisation process targets the pair FNS_{L3} and SNS_{L3}. The pair FNS_{L2} and SNS_{L2} is treated second.

Sequencing of the application of the methodology. The sequence with which the pairs of SNSs and FNSs are treated depends on the motion path of the cutting tool. In the example of Fig. 1, assuming that the cutter moves anticlockwise, the optimisation process is first applied to identify the optimal fixturing parameters for clamp C1, then locator L3 and so forth.

Displacements and rotations. It is assumed that the rotations that the workpiece experiences during the machining process are small and can be ignored.

2.3.2. Objective Function

The purpose of the optimisation phase is the minimisation of the elastic deformation of the workpiece. In other words, the goal is to find the contact point between the fixture and the workpiece for which the maximum deformation of the machined workpiece surface is minimised, or mathematically:

$$\min\{\max\{\Delta x_i(t), \Delta y_i(t), \Delta z_i(t)\}\} \tag{1}$$

where Δx, Δy and Δz signify the elastic deformation of a point on the workpiece in the three Cartesian coordinates, at time t when the tool is directly over that point. The indicator i denotes the identifying number of a node.

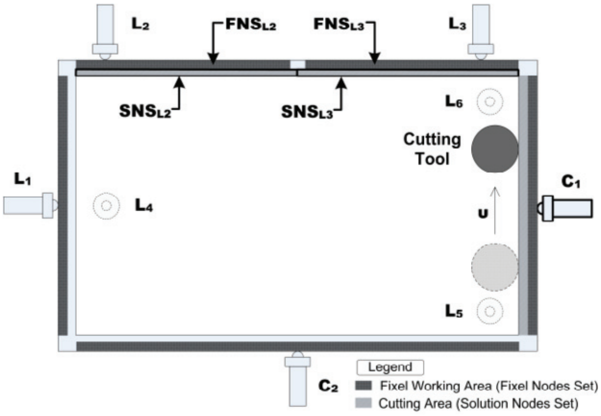

Fig. 1: Illustrative representation of a thin-walled workpiece held by a 3-2-1 fixture with point contacts. The machined and fixel working areas are designated as light and dark shades of grey, respectively. Locators are marked as L and clamps as C.

2.3.3. Nodal Solution Constraints

The optimisation process is applied each time to a pair of SNS and FNS. The process seeks to identify nodes within the FNS that satisfy the optimisation function for the nodes within the corresponding SNS. Most available optimisation algorithms search for the optimal contact points in physical coordinates. Also, by using Cartesian coordinates, the solution becomes independent of the nodes' numbering scheme. Therefore, it is necessary to ensure that the algorithm accepts as feasible solutions only those points on the workpiece that coincide with a node that belongs to a certain FNS. Assuming that a FNS contains M nodes, and that each node is marked by a number n, the previously described constraint is expressed mathematically as:

$$\prod_{n=1}^{M}(x - x_n) = 0, \;\; x \in [x_{b1}, x_{b2}] \tag{2}$$

$$\prod_{n=1}^{M}(y - y_n) = 0, \;\; y \in [y_{b1}, y_{b2}] \tag{3}$$

$$\prod_{n=1}^{M}(z - z_n) = 0, \;\; z \in [z_{b1}, z_{b2}] \tag{4}$$

where the indices $b1$ and $b2$ refer to the physical coordinates of the boundaries of the FNS.

The final constraint that needs to be introduced is that there can be no separation between the workpiece and the fixture elements throughout the machining process. This constraint ensures the workholding stability. This can be expressed as: $F_k(t) - F_{sl} \geq 0$. The lower force limit F_{sl} is optionally used for increased safety. This constraint needs to be satisfied for all fixels simultaneously.

2.3.4. User-Defined Limits

There are three limits that need to be defined in order for the optimisation process to output a solution. These are the maximum allowable displacement limit, denoted as DL, the clamping force limit, and the discrete points limit. The first defines when a solution has been achieved. The second, what the maximum clamping force can be for a solution to be acceptable. The third helps decide between the discretely or continuously moving clamps strategy.

With the objective function and constraints defined, the optimisation problem has been fully formulated and the solution of the problem can commence. The optimisation phase can be represented schematically via a flow chart. The best way to describing this flowchart and the optimisation steps is a walk-through of a test case. This is done in the following section.

3. Thin-Plate Test Case Results

The proposed methodology is applied on a test case involving a thin aluminium plate and a single active fixel. The fixturing element is considered active in the sense that it can change its position. The clamping forces it applies remain constant over the duration of the process. Point contact is considered between the fixture and the workpiece.

The plate is clamped at its both shorter ends. The material and geometric properties of the plate are shown in Table 1 and Fig. 2, respectively. It is considered that the plate is undergoing an end milling operation with a 4 flute tool, and a 25 mm axial depth of cut. The feed rate is c=300 mm/min and the spindle speed is 3000 rpm. Zero damping is assumed at the connecting element (c_c=0), while the spring stiffness is $k_c=10^8$ N/m.

Table 1: Material properties of Aluminium 7075-T6.

Al 7075-T6 Properties	
Density:	2810 kg/m^3
Young's Modulus:	71.7 GPa
Poisson's Ratio:	0.33

The methodology starts by importing the material and geometry characteristics in the FE package Abaqus™. A structured grid of 300 4-node plate elements (S4), namely 341 nodes, is used to discretise the plate. The map of nodes, where the identifying number and coordinates of each node are stored, along with the boundary nodes, mass and stiffness matrices are exported as ASCII files.

The system matrices are then imported into Matlab. In this example, only the mass and stiffness matrices are exported from Abaqus™, so proportional damping needs to be defined using proportional damping with coefficients α=90 s^{-1} and $\beta=7\cdot10^{-7}$ s.

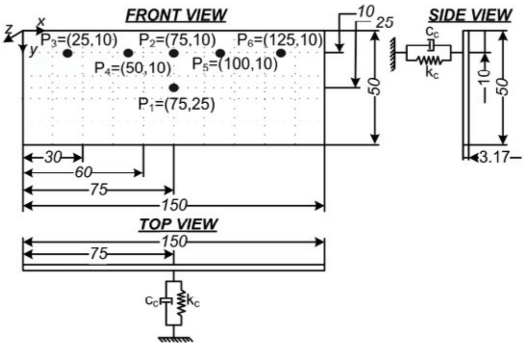

Fig. 2: Schematic representation of the thin-plate workpiece. Key points on the surface of the plate are highlighted. Coordinates in mm.

The machining forces are modelled as a distributed load from y=0 to y=25 and moving from x=15 to x=135 (Fig. 2). The amplitude of the load is $P(t)=3+2.8\cos(\omega t)$ N/mm, where ω=200 Hz, as derived from the spindle speed. Time steps of dt = 757.5 ns are used.

The fixturing element is then coupled to the system matrices via the stiffness of the contact element. As a starting solution, the fixel is coupled at point P_2 (Fig. 2). After the fixture and the workpiece models have been coupled, prescribed displacement boundary conditions are imposed on the 22 nodes that lie on the shorter edges of the plate.

The resulting model is introduced in the optimisation cycle. As previously described, in the first steps of the optimisation phase the objective function, solution constraints and user-defined limits must be set. The solution criteria are the ones defined in Eqs. 2-4. A value of F_{sl}=0 is used. The displacement of the workpiece along the x- and y-axes are considerably smaller than that along the transverse direction. Therefore, the objective function can be simplified to:

$$\min\{\max\{\Delta z_i(t)\}\} \tag{5}$$

Before the optimisation phase can commence the FNS and SNS pair needs to be defined. Based on the previous discussion, all nodes with coordinates $x \in [15,135]$ and $y \in [0,25]$ belong to the SNS. The same set of nodes constitutes the FNS. Finally, the user-defined limits are set. A maximum allowable displacement of DL=13 μm, a clamping force limit of 50 N and a discrete points limit of 5 are set.

The optimisation process starts by attempting to find a solution where no change in the position of the fixture element is necessary, i.e. a traditional fixturing approach. For this, the dynamic response of the initial fixture-workpiece system created in Phase 2 of the methodology is calculated. The results of this are shown in Fig. 3. The maximum transverse (*z*-direction) displacement of different points on the surface of the plate is demonstrated. As it can be seen from Fig. 3, the DL limit is largely exceeded. Therefore, the fixel is moved to a different position on the plate. The nodal solution criterion is checked. Provided that this criterion is satisfied the new fixture workpiece model that is created is solved as described before. The process is repeated until an acceptable solution has been found.

In this test case, and for a static fixture strategy, the minimisation of the maximum transverse displacement of the plate surface is observed when the fixture element is positioned at P_2, namely the initial solution. The value of this displacement is 79.26 μm.

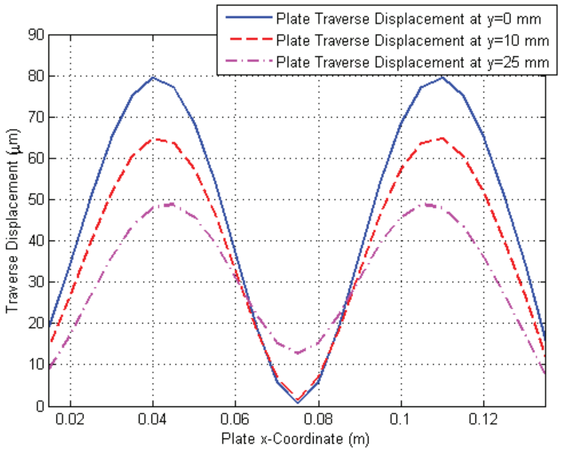

Fig. 3: Workpiece transverse elastic deformation, as the cutting tool traverses the plate. A single clamping element is positioned at point P_2 (Fig. 2).

Since no acceptable solution can be found with a static fixture strategy the methodology attempts to find a solution when the fixture element is changing its position in a discrete fashion. For this the methodology splits the original solution nodes set into two equal or almost equal sub-sets. Then it tries to find a position in the FNS where if the fixel is positioned, the maximum displacement of the nodes within each solution nodes sub-set is minimised and is below the value of DL. If a solution cannot be found for either of the sub-sets, then the original SNS is split into three equal parts, and so forth. If a solution is found for only one of the sub-sets then the methodology stores its solution and focuses solely on the sub-set for which a solution was not reached. When applied in this test case, the methodology cannot find an acceptable solution even when the original SNS is split in 5 sub-sets, reaching the discrete points limit.

Therefore, the methodology searches for a solution assuming a fixturing element that can move continuously. For this, the methodology divides the original solution nodes set to sub-sets, each of which contains nodes with the same *x*-coordinate. Then for each sub-set it searches for the point with the *y*-coordinate where, if the fixturing element is placed, it minimises the maximum deformation. This way the path of the continuously moving element relevant to the moving load can be determined. The time instant at which the minimum maximum deformation occurs is also important to sequence the path of the fixel.

The optimisation phase output for this fixturing strategy indicates that the best results can be obtained when the fixel moves along the *y*=10 line, mirroring the motion of the tool. For this case, the dynamic deformation of the surface of the plate at various points is shown in Fig. 4.

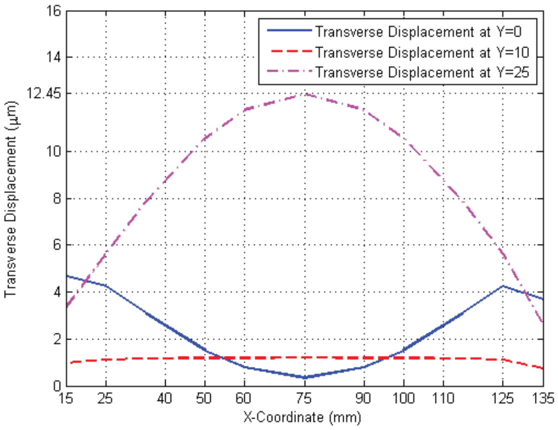

Fig. 4: Workpiece transverse elastic deformation as the cutting tool traverses the plate. The clamping element moves continuously, mirroring the movement, of the tool.

After this solution has been achieved, the methodology checks whether the lift-off criterion is violated. If this is the case the clamping force is increased and the fixture-workpiece model is solved once more with the new clamping force. This process is repeated until a feasible solution has been found or until the clamping force limit is exceeded. In this case a continuously-moving active/adaptive fixel strategy is proposed, or if this is not possible, the optimisation cycle ends by signalling that no feasible solution has been found. In this case the user of the methodology needs to reconsider the entire fixture design and parameters.

For this test case, the continuously moving passive clamp solution shown above satisfies all criteria and is accepted as the final solution.

By applying the proposed fixture design methodology to the thin-plate test case one can note the drastic reduction of elastic dynamic deformation occurring when adopting the fully-active fixturing paradigm. As shown in Table 2, it is possible to reduce the maximum dynamic transverse deformation of the plate by 84.2%, whilst the maximum absolute deformation value can be reduced to 12.45 μm. The percentage reduction is calculated via the following expression:

$$e = \frac{StaticFixe\,l - MovingFixel}{StaticFixe\,l} \cdot 100\% \qquad (6)$$

where *StaticFixel* denote the maximum deformation of the plateworkpiece in the static fixture strategy and *MovingFixel* denote the maximum deformation of the workpiece in the discretely or continuously moving fixel strategies.

The figures in Table 2 translate into smaller vibration amplitudes, ultimately leading to a smoother surface finish of the machined part. They also mean that, during the manufacturing process, the thin-walled workpiece does not experience large deformation, almost maintaining its natural shape. This has a large effect on the form accuracy and the tolerances of the end product.

Table 2: Summary of test-case results.

	Static Fixel	Disc. Mov. Fixel	Cont. Mov. Fixel
Max. Deform. (μm)	79.26	26.45	12.45
Reduction vs. Static fixel (%)	n/a	66.63	84.2

4. Conclusions

This article presented a fixture design/planning methodology tailored to the needs of a new fixturing paradigm, where the fixturing elements are not treated as passive and static but as active and movable. The methodology uses a fixture workpiece model as its basis, which accounts for both passive and active fxturing elements, as well as the dynamic response of the fixture-workpiece system to dynamic and moving loads.

The methodology aims at identifying the optimal fixturing strategy, as well as the positions of the fixturing elements for each strategy that lead to the minimisation of the dynamic deformation of the workpiece.

The methodology was applied on a thin-plate test case. Results showed that a continuously moving passive element fixturing strategy could reduce the dynamic deformation of the thin-walled test workpiece by 84.2% and assist in better adherence to the latter's undeformed shape during the manufacturing process.

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