# Effect of fixture stiffness on the positioning error of the workpiece under machining and clamping forces

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MS Mechanical Engineering

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AUGUST, 2020

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# Copyright Statement

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I am thankful to my Creator Allah ﷻ to have guided me throughout this work at every step and for every new thought which You set up in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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# Abstract

In recent times, the manufacturing industries are struggling to identify ways of minimizing production costs. When a machining force is applied, an error occurs in the machined workpiece due to unavoidable conditions (like vibrations, the surrounding temperature, etc.) because of which tolerance is kept in the desired machining operation. This paper collaborates with this demand in such a way that it presents the simulation and analysis technique of calculating the deformations (which might occur as a result of machining operation) of a workpiece and locators beforehand. CATIA v5 is used for the designing phase of a workpiece, locators, surfaces (to hold the locators in the desired location), and clamps. In past researches, an analytical approach was used to identify the positioning errors of a workpiece. Also, a genetic algorithm approach was used to optimize the position of locators for less deformational error. Now, in this research work, the two placements of locators are taken as case studies and a machining force is applied on each point ($P_1$, $P_2$, $P_3$, and $P_4$) to identify the deformations of these four points on a workpiece, respectively. ANSYS (R19.1) is used for the analysis settings and simulation purposes.



**Key Words:** *Fixtures, Locators, 3-2-1 locators principle, Locators' deformation, CATIA v5, ANSYS R19.1, Workpiece deformation, Clamps, Clamping force.*

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# Chapter 1: Introduction

In this modern era of technological development, strong competition in terms of production exists. Production and manufacturing industries demand to produce parts that meet high-quality standards. Firms focus on mass production with high productivity but less unit cost. It arises the necessity of such devices which can boost the manufacturing process along with quick inspection procedures. The demand of low cost but high-quality products boosted the research activities in the field of fixture designing. To achieve such criteria, industries always heed for such a fixturing system that can produce multiple parts with the proximity of precision.

In general, industries are such organizations that either deal with the production or supplying of goods and services. Classification of such industries is as follows:

- Primary industries – such industries utilize natural resources, such as petroleum, mining, quarries, forestry, agriculture, etc.
- Secondary industries – they perform the manufacturing activities to convert the outputs or products of the primary industries into capital goods or consumer products. They also include power utilities and constructions to do such tasks. Their applications are aerospace, automotive, beverages, construction, electronics, etc.
- Tertiary industries – their job is to offer services to clients or customers, such as banking, educational institutes, hotels and restaurants, transportation, etc.

## 1.1 Context

To deal with the market demand of the current century, (Ryll, Papastathis et al. 2008) introduced the concept of intelligent fixtures which should be able to perform self-configuration, reduce dimensional inaccuracies along with their compensation, and provide stability for the optimum performance. The intelligent fixture should endorse the variety of configurations of a workpiece and be generic. The components included in the intelligent fixturing system are locators, clamps, computer systems as support and micro-actuators. Mechanical elements or a workpiece are repositioned using micro-actuators, while these micro-actuators are controlled by a computer system support. If the workpiece with the geometric variations is placed on the locators, the final product can be a waste. To get rid of such a problem, allowances are included in the workpiece as well as in its supports. By placing every new workpiece precisely in the fixturing system, both the material and a time loss can be avoided, but it requires the mobilized system of a machine.

According to (Wang, Xing et al. 2018), a flexible manufacturing system (FMS) is a manufacturing system being controlled by a computer system. With the availability of limited resources, it can process a variety of parts. Resource sharing and cutting tool path flexibility are usually of higher degrees in such manufacturing systems.

The machine mechanism plays a vital role in the manufacturing setup. The positioning or placement error between the cutting tool and the workpiece may occur. Such a flexible machine should compensate such error by placing the part at an optimum position. If a machine is capable of dense geometric transformations and contains a large number of DOFs, then such error compensation is possible. The setup of a 5-axis machine is not feasible if small displacements are required in the processing operations like an assembly operation or a machining operation. The workpiece can be positioned better on the proposed fixturing system as it does not require machines with high DOF. In addition, it provides low cost product with high quality.

The fixture should be designed to retain high accuracy in workpiece positioning relative to the machining operation, operator convenience, and faster productivity. Generally, jigs and fixtures consist of locating elements, clamping elements, and tool guiding and setting elements. Locating elements locate or hold the workpiece concerning the cutting tool. Clamping elements hold the job securely in the desired position during the machining operation. To guide or set the cutting tool in a correct position with respect to the workpiece, tool guiding and setting elements are used. Clamps and locators are used to achieve such positioning of the workpiece. The quality of the finished product strictly depends upon the fixture's capability to precisely hold and locate the workpiece during the fabrication process.

## 1.2 3-2-1 Locating Principle

There are 12 DOFs for any workpiece which has no boundary conditions i.e. it is free to translate along or rotate around axes (as shown in Figure 1). If a workpiece can translate along with XX, YY, or ZZ-axis, then it is termed as a translational movement. Similarly, if it can rotate around any of these axes, it is called a rotational movement. During the machining operations, it is required to accurately confine the workpiece so that its desired DOFs are restricted.

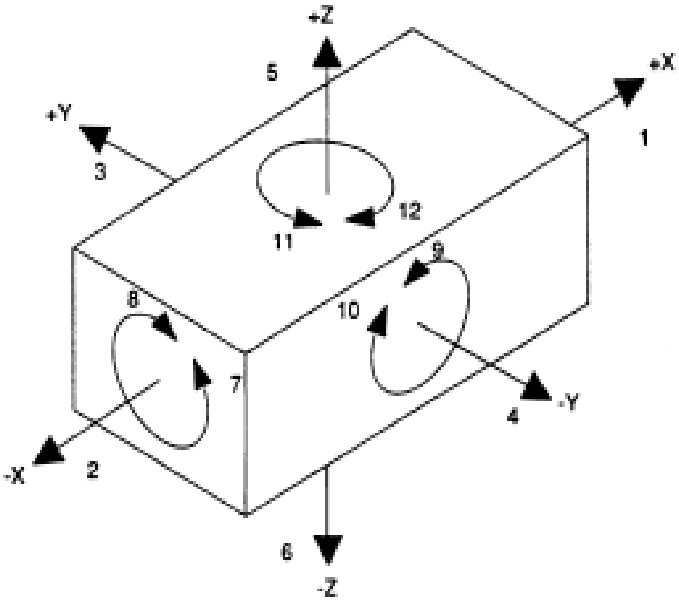


Figure 1: Degrees of freedom of a free body (Butt 2012)

In the 3-2-1 locating principle (Figure 2), there are three planes containing locators. Locators are used to locating the workpiece and to restrict its DOFs. A plane with three locators is called a *primary plane.* Similarly, a plane with two locators and one locator is called *secondary plane* and *tertiary plane* respectively. Three Locators in the primary plane restrict five DOFs of a workpiece. Three more DOFs are restricted using two locators in a secondary plane. Further, a single locator in the tertiary plane limits one more DOF. In such a way, a total of nine DOFs are confined via six locators.

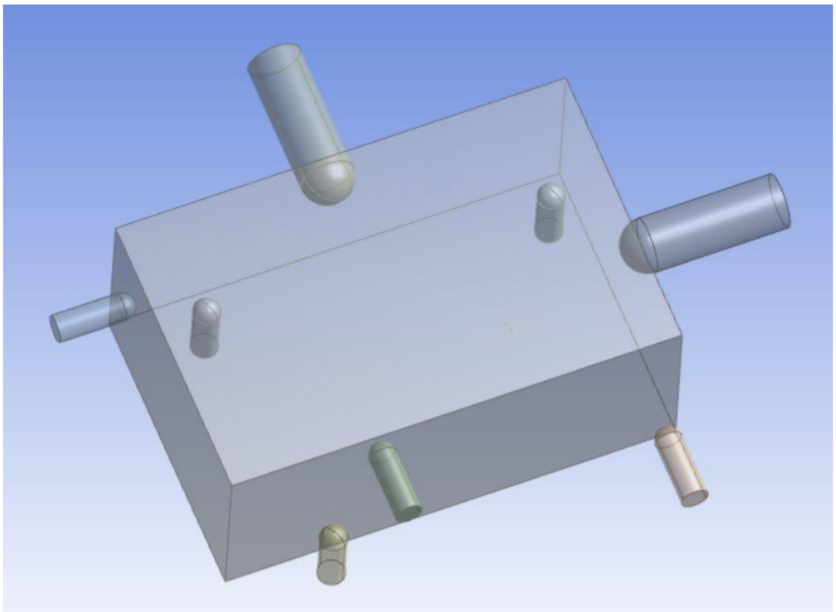


Figure 2: 3-2-1 Locating principle

## 1.3 Proposed Methodology

The fixturing system proposed in this thesis based on which the analysis will be performed contains six locators that can be controlled axially. A workpiece assumed rigid will be resting on these locators. The contact between the workpiece and the locators is assumed to be frictionless. The 3-2-1 locating configuration will be used to design the locators. The locators will only be allowed to move axially. The locators and clamps are assumed to be elastic elements and their material stiffness is known.

When the workpiece is placed in a fixturing system and the machining forces are applied on a workpiece, locators (assumed elastic) undergo deformation. As a result, workpiece deforms from its nominal position. Displacement error in all locators' positions will be determined and catered for in the initial positions. The basic aim of this thesis is to study the effect of fixture stiffness on the positioning error of the workpiece under machining and clamping forces. The goal is solely to identify the displacement of the workpiece under machining and clamping forces.

3-2-1 locators-fixturing system will be used for designing (using CATIA v5) and simulation purposes (using ANSYS 19.1). Later, the application of necessary machining and clamping forces, directional deformation results will be analyzed.

## 1.4 Thesis Disposition

This report consists of six chapters. The first chapter deals with the introduction which includes the global problems and machining problems faced by the manufacturing industries. The fixtures and a 3-2-1 locating principle are also introduced in this chapter. Later, the proposal which contains the aims and objectives to deal with the selected problem is shortly discussed. The second chapter will be about the literature review. In that chapter, the description of locators, their usage along with their types, clamps, and their usage, assumptions, and past research work of other researchers will be discussed.

The third and fourth chapters will contain methodology and analysis of the proposed work, respectively. Different factors used for the designing and analysis purposes will be discussed. The analysis settings which include meshing criteria, forces and moments, and approach to achieve the desired results will also be the part of these sections.

The results and their summary will be part of the discussion in the fifth chapter, while the sixth chapter will be the conclusion of all research studies. The future recommendations and research gaps will also be discussed in the last chapter.

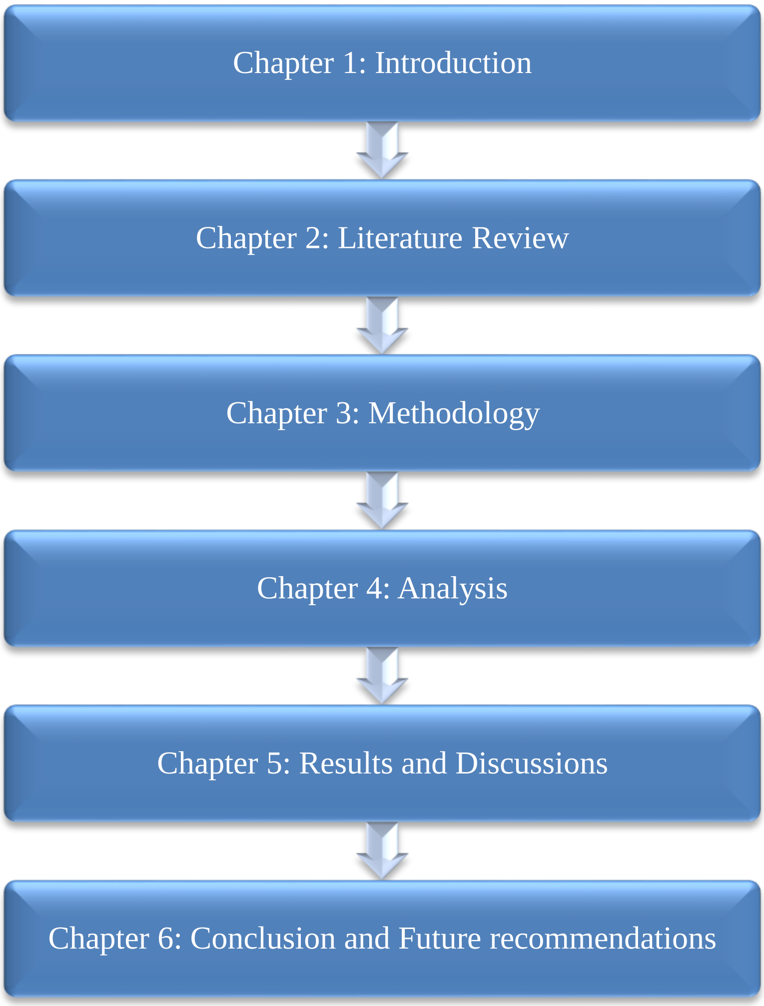



Figure 3: Outline of the thesis

## 1.5 Summary

This chapter gives information about the problems faced by manufacturing industries, objectives and aim, methodology, and organization of the thesis. The upcoming chapter presents a literature review to make a proposal and solution to this study intelligible. The definitions and terminologies which are related to the work have been explained profoundly.

# Chapter 2: Literature Review

In this chapter, a literature review about fixtures, fixture designing, and their positioning error is presented. The key stress in this chapter is to discuss the existing literature regarding locators and their types, clamps, and their possible types. The research work in the related field is described with references. Finally, the research gaps in the relevant work are defined.

The quality of the end product can be affected by different errors like errors in fixturing setup, datum error, or machine tool error. Fixture requirements should be known for fixture planning, whose aim is to place the workpiece precisely w.r.t the reference of machine or cutting tool (Wan, Xiong et al. 2008). If there are machining errors, a workpiece's misalignment may occur. The factors like misplacement of locators, defective geometry or shape of a workpiece, mishandling of clamping or machining forces, or any other kind of mechanical error can induce machining errors.

## 2.1 Fixtures

Fixtures are devices that are used to locate the workpiece and constraint its degrees of freedom during the machining operation. A fixture is usually custom-designed for a specific workpiece. The fixture should be designed to retain high accuracy in workpiece positioning relative to the machining operation, operator convenience, and faster productivity. The discerning characteristic between a jig and a fixture is that the jig guides the tool during the machining operation while a fixture lacks this property (Groover 2007).

Generally, jigs and fixtures consist of locating elements, clamping elements, and tool guiding and setting elements. Locating elements locate or hold the workpiece concerning the cutting tool. Clamping elements hold the job securely in the desired position during the machining operation. To guide or set the cutting tool in a correct position with respect to the workpiece, tool guiding and setting elements are used. Drill bushings and milling cutters are examples of it (Joshi 1998). Clamps and locators are used to achieve such positioning of the workpiece. The quality of the finished product strictly depends upon the fixture's capability to precisely hold and locate the workpiece during the fabrication process.

During a machining process, dimensional inaccuracies may arise due to workpiece deformation. Locators and clamps are utilized to minimize such errors. The optimization of the positioning of clamps and locators in such cases is necessary. The author (Kaya 2006) has suggested the methodology to optimize the fixture layout by using a genetic algorithm (GA) approach. To compute the objective function values for each generation, the finite element (FE) code was utilized. However, clamping force is not optimized and friction is also not considered in this paper. ANSYS was used during this working and it was recommended that the computation time may be decreased by using distributed computation in LAN (Kaya 2006).

### 2.1.1 Flexible Manufacturing System

According to (Wang, Xing et al. 2018), a flexible manufacturing system (FMS) is a manufacturing system being controlled by a computer. With the availability of limited resources, it can process a diversity of parts.

Fixture designing requires engineering skills and expertise, as it is not an automatic process. To automate the fixturing system and its design, a methodology has been proposed in (Roy and Sun 1994). The demand for the flexible fixturing system has increased remarkably with the rise of flexible manufacturing systems (FMSs). The world is rushing towards the "zero part inventory" system where it is required to minimize the physical inventory as much as possible. It assists in controlling the costs. With this advent, the flexible work holding manufacturing system is taking over the less-productive dedicated work holding fixtures. Qualitative and analytical techniques were used in this paper to create an automatic fixture design.

## 2.2 Locators

In the fixturing system, the workpiece needs to sit on something for machining purposes. Locators are such components upon which the workpiece rests and comes in contact. As the workpiece has 12 DOFs before placement in the machining fixture, these locators are used in 3-2-1 configuration to restrict 9 DOFs of a workpiece.

(Kršulja, Barišić et al. 2009) proposed a fixture model relative to the cutting forces. It is intimated that the locators must be able to hold the workpiece against the machining forces, but not the clamps. A method for positioning the locators relative to the machining forces is proposed. Cutting forces' position is planned and discussed and it came up with the best solution. The fixture has a huge impact on tool movements and final workpiece quality is linked to it. A 3D CAD system was used to create a 3D model of a fixturing system and then its flexible solution was selected. Machining simulation and its optimization are left for future work.

When the machining operation starts (which contains machining force and moment), the workpiece transfers this effect to locators. The locators deform in this situation. The deformation of the locator under machining forces is depicted in Figure 4. The contacting plane of the workpiece and the locator is moved from an initial position (i.e. position 1) to a final position (i.e. position 2) (Butt 2012). Under machining forces, the locator deforms axially as well as tangentially. Our main aim is to perform simulation and identify how much deformation (axial and tangential) will occur in the locators under loading.

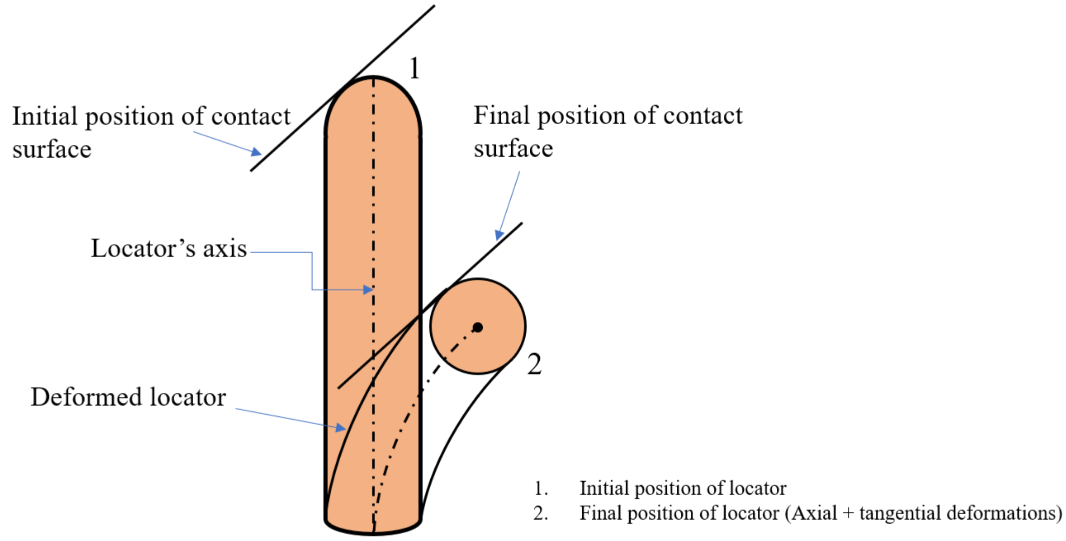



Figure 4: Initial and final position of the locator (Butt, Antoine et al. 2013)

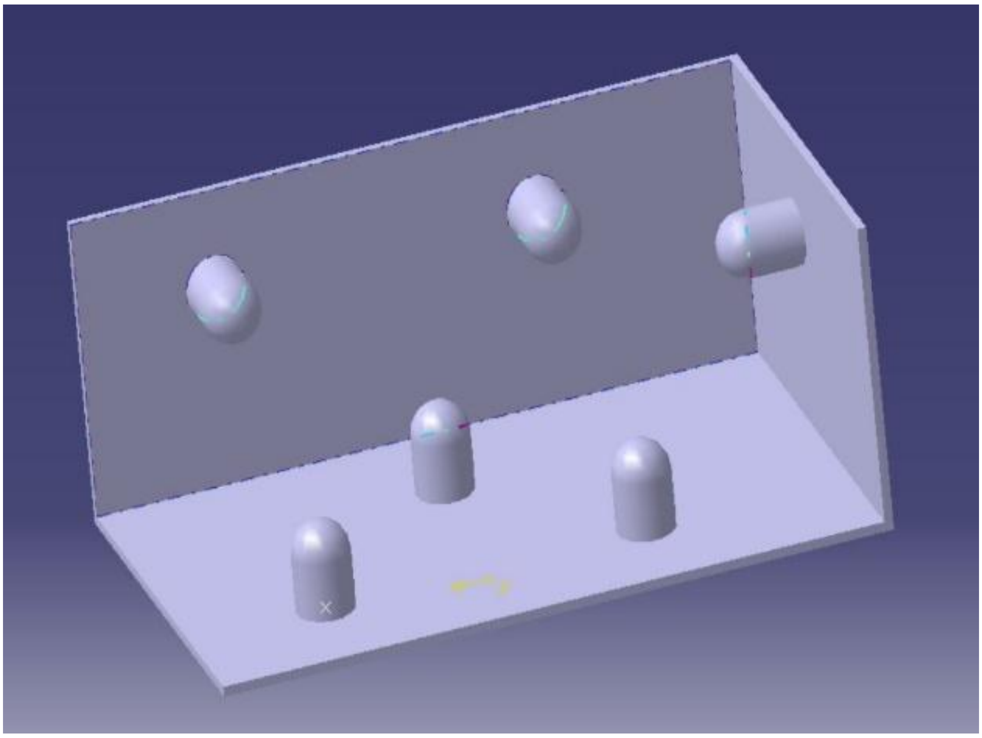


Figure 5: 3-2-1 locators scheme

The locators used in this research study are cylindrical (as shown in Figure 5) because a workpiece can tilt under machining force and come in contact with the locators at any spherical point. If the locators' tips are kept flat, a workpiece cannot tilt upon them and the analysis is not possible.

### 2.2.1 Assumptions

The assumptions used in this research work regarding locators for the simulation purposes are as follows:

- Locators are assumed as an elastic element.
- They are only allowed to displace or move axially
- Their tip is spherical so that the workpiece-locator contact can exist at any point.

## 2.3 Locating Devices

Commonly used locating pins or locating devices are made up of hardened steel (Naman M. Dave). They are feasible in locating a workpiece in jigs or fixtures for necessary machining operations. The locating pins may be classified as:

- Support pins
- Locating pins
- Jack pins

### 2.3.1 Support Pins

Support pins (Figure 6) are used for flat-surfaced workpieces so that it can be supported at an expedient point. They are also termed as rest pins. They are of two types, i.e. fixed and adjustable. In a former type, a locator pin is fixed, and the user is unable to adjust it once it is fixed in the desired location. While in a later type, a locator pin can be adjusted and is user friendly. In this thesis work, we have used support pin locators (fixed type).

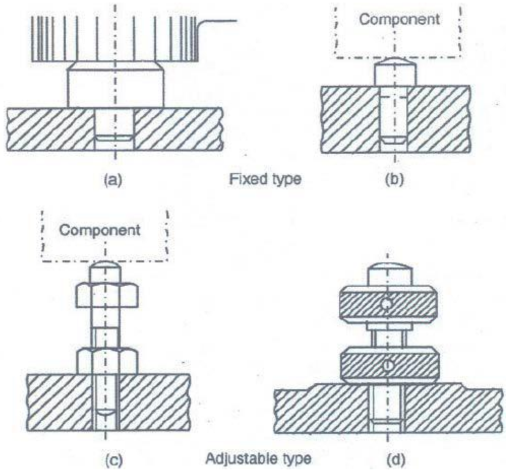



Figure 6: Support pins (Naman M. Dave)

### 2.3.2 Locating Pins

Locating pins are used for such workpieces which have a drilled or reamed hole (Figure 7). Hole in a workpiece is located using this type of pins. They are either conical or cylindrical. Conical pins are used to locate a cylindrical workpiece. The advantage of conical shape is that it can easily accommodate a workpiece having a hole size variation. Cylindrical locating pins are easily push-fit in a workpiece's hole. To facilitate the workpiece load, its top portion is usually chamfered.

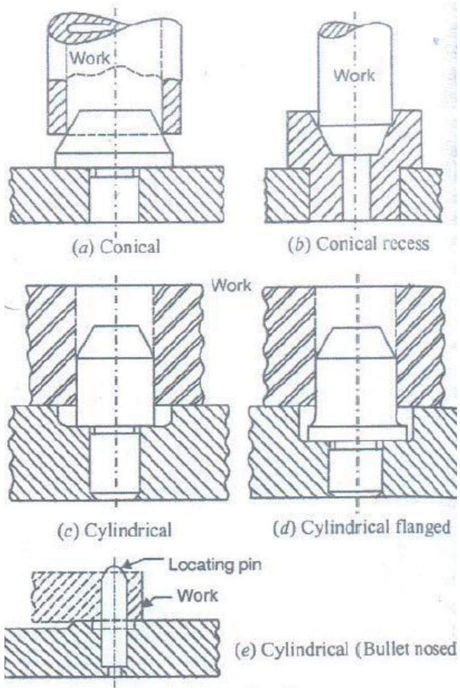



Figure 7: Locating pins (Naman M. Dave)

### 2.3.3 Jack Pins

If the dimensions of a workpiece are variable, then Jack pins (also termed as spring pins) are used. Either, the workpiece presses the jack pin down due to its weight, or this pin uses the spring pressure to lift (Figure 8). Once, the workpiece is located at the desired position, it is securely locked by a locking screw (Joshi 1998).

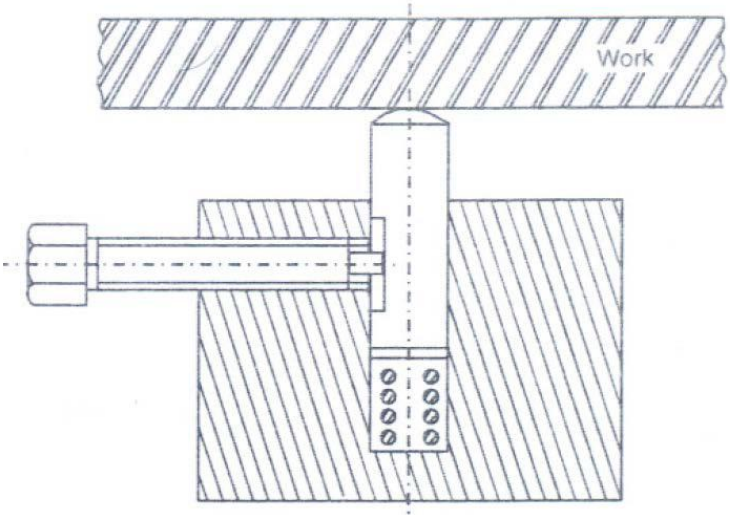



Figure 8: Jack pin (Naman M. Dave)

## 2.4 Locating Principle

In a traditional fixturing system where machining operations are performed, it is necessary to place the locators far from each other to achieve workpiece stability. To deal with this issue, a 6+X locating principle is proposed (Hao, Li et al. 2018), where the workpiece is divided into two regions to facilitate the new locating principle.

1. The first region is called a fixed region.
2. The second region is called a floating region.

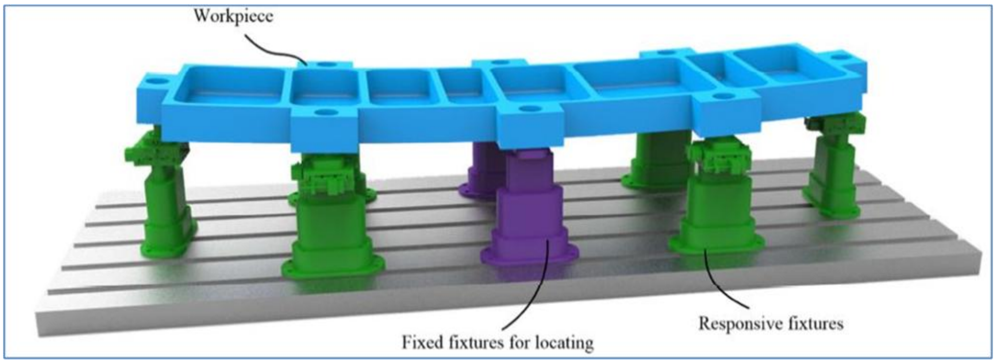



Figure 9: Principle of the adaptive machining with responsive fixture (Hao, Li et al. 2018)

If locators are placed too far from each other, the workpiece can deform. While if locators are placed too close to each other, the workpiece will become unstable (Figure 9). To achieve machining accuracy, the workpiece needs to be in a stable position under the locating and clamping effect and during the machining process. Usually, if the DOFs of a workpiece are constrained in such a way that it is stable and machining accuracy can be achieved, the term locating completeness is used. There are usually two categories of locating principle i.e. for rigid workpieces and low-rigidity workpieces.

### 2.4.1 Locating Principle for Rigid Workpieces

For rigid workpieces, a 3-2-1 locating principle is widely used. Maximum rigidity with less fixturing elements can be achieved by this method (Foster and Geo-Metrics 1994). The rigid workpiece which is free from supports contains six translational and six rotational DOFs. By using a 3-2-1 locating principle, a workpiece rests upon three points which constitute a primary datum plane. The second datum plane perpendicular to the primary plane contains two points to support a workpiece. Similarly, a third datum plane contains one point. In this way, three translational and six rotational DOFs are restricted. Different locators in the machining fixtures are used for such purposes. As an external force (such as machining force) brings disturbance to the fixture system and a workpiece, the stability is quite a principal requirement. The error due to the workpiece surface and fixture setup contains some relevancy which was discussed by the author of paper (Cai, Hu et al. 1997).

### 2.4.2 Locating Principle for Low-Rigidity Workpieces

When the machining operations were applied on workpieces with low-rigidity (like sheet metal etc.), the deformation occurred. Hence, this excess deformation should also be prevented in addition to the basic function of this locating principle. The author of the paper (Cai, Hu et al. 1996) suggested an idea of the N-2-1 locating principle where N>3. It helped restrict additional deformation in cases of low-rigidity parts. However, many researchers used FE analysis and method of nonlinear programming to identify the suitable value for “N”.

The author (Xiong, Molfino et al. 2013) invented the new method of the N-2-1-1 locating principle. In addition to the basic N-2-1 locators, an additional locator was placed on the opposing side of the machining point. It accompanied the cutting tool path by moving on its opposite side as it was the part of the intelligent and self-reconfigurable fixturing system.

In summary, both of the above mentioned locating principles (i.e. 3-2-1 and N-2-1) have been in application. The genetic algorithm approach was used in the paper (Hao, Li et al. 2018) to achieve the desired results. Later, the experiments were performed to support the results achieved in the earlier stage.

## 2.5 Clamps

The clamping devices are used to exert pressure on a workpiece and to hold it against the machining forces. As vibrations in the machines are unavoidable and may cause the workpiece to displace from the desired position, clamps are used to prevent the dislocation. Clamping devices are of many types, e.g clamping screws, hook bolt or lever type clamps, etc.

As the locators are assumed as an elastic body (Figure 10), the external displacement in clamps will compress the locators. Usually, at first, the workpiece is settled on the locators and then the clamp is tightened by bringing it closer to the workpiece.

### 2.5.1 Clamping Forces

There are two ways to deal with clamps as far as a simulation is concerned.

1. Either replace clamps with constant and static point forces (Butt 2012). These forces should be acting at the contacting point of the workpiece and a respective clamp. But in such a case, the clamping force becomes a point force on a workpiece and this point cannot be altered during a simulation.

2. Or design a clamp bigger than locator and create contact between a clamp and a workpiece. By displacing the other end of an axial clamp, it gets tightened on the workpiece. The advantage is that the contacting point of clamps and a workpiece will not remain fixed and external displacement is a known value.

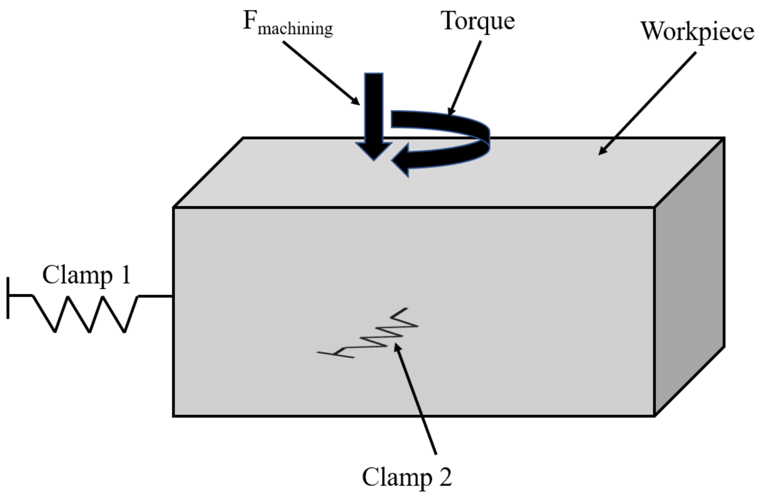



Figure 10: Model of Clamps (assumed elastic) attached with a workpiece

The optimization of the magnitude of the clamping forces along with its position is presented by the author (Cioată, Kiss et al. 2017). But it was done for a particular case i.e. milling of a canal in a prismatic workpiece. ANSYS software was used in this work. The optimization criteria were to minimize both the maximum displacement (total displacement) of the specific edge, as well as the workpiece's maximum equivalent stress. The screening and response surface method was used to achieve this optimization criterion and a real situation (chip removal process) was assumed.

### 2.5.2 Fixture Configuration

Optimum configuration of a fixture was determined in the research work using a drilling operation on a non-rigid workpiece. FEA and FE optimization techniques along with 3-2-1 locating principle were used for such purpose. Due to material removal during drilling, the workpiece stiffness was reduced which was considered in this paper (Rao, Malkapuram et al. 2018). It was concluded that such errors which arise due to machining forces can be minimized or reduced if fixture parameters are optimized. However, the model proposed in this work requires improvement and few dynamic characteristics of drilling operation were also left for future researches.

## 2.6 Positioning Error

The positioning error of a workpiece is the deviation or unsimilarity between nominal and theoretical positions of a workpiece. It may occur if there is any geometrical error between workpiece and locators. Although, the positioning error of locators is minute it may affect the final product. By choosing the fixturing elements wisely, such positioning errors can be reduced.

Workpiece's geometrical errors or deformational error of locators under machining and clamping forces inhibit the positioning error in a workpiece. A model comprising a homogenous transformation matrix (HTM) was proposed by the researcher (Asante 2009). This model was helpful to identify the positioning error of a workpiece which was placed in a 3-2-1 fixturing system containing locators and clamps. He assumed all elements to be rigid and considered the displacements small. Positioning error comprises of geometric error of a workpiece, locators, and clamps.

### 2.6.1 Geometric Error due to Workpiece

This error is caused by surface roughness or dimensional inaccuracies in a workpiece. Machining processes, casting processes, and forging may ensure defects in a workpiece. In such a case, the contact points between a workpiece and the locators are more than one instead of single point contact.

### 2.6.2 Geometric Error due to Locators

According to the 3-2-1 locating principle, all the locators of the 3-2-1 scheme share a reference plane being mutually perpendicular to each other. Any kind of dimensional inaccuracy in the locators results in the misbalancing of those planes. In such a way, a workpiece cannot rest on the plane properly.

### 2.6.3 Geometric Error due to Clamps

Once the workpiece is rested upon the locators and its necessary DOFs are restricted according to a 3-2-1 locating principle, the clamping mechanism is introduced. Under the clamping force, the workpiece shifts from its original or desired position. Such an error is caused by clamps.

### 2.6.4 Deformational Error due to Locators

When the workpiece is located on the locators, either it is clamped via clamping mechanism or a clamping force is applied upon it to keep the workpiece stationary. Later, the machining force is applied. Under machining and clamping forces, the locators deform due to which the original position of the workpiece displaces. The locators' deformation includes a body deformation as well as the local contact deformation. This phenomenon was well explained by the author (Jayaram, El-Khasawneh et al. 2000).

#### 2.6.4.1 Workpiece-Locator Contact Point Invariability

Whenever a workpiece is required to be machined or inspected, a highly efficient and accurate fixturing system is required. Variability in manufactured products is not tolerated in firms, as it results in a loss of material and time and an increase in costs. If contacting points between a workpiece and locators have such variability, then errors can be expected. An algorithm was suggested to compensate for this variability (Chaiprapat and Rujikietgumjorn 2006). The workpiece has geometric variations i.e. translational as well as rotational. First, a rotational error of the workpiece was found and compensated. Then the workpiece was translated to match with its nominal geometry. It should be noted that a workpiece was assumed as a rigid body. Newton-Raphson's method was used to achieve these results. Its statistical results, for future working, can be used in tolerance analysis.

## 2.7 Workpiece Deformation due to External Forces

During the machining operations, the workpiece may deform under the loading and the final product may have inaccuracies. To compensate such positioning or deformation error, a fixturing system was proposed which was able to relocate the workpiece by advancing the six locators (Butt, Antoine et al. 2013). Locators were assumed elastic while the workpiece was assumed as a rigid body. Constant clamping force was applied at a contacting point of the workpiece and a clamp. The analytical calculations were performed to identify the displacement errors of locators. CATIA software was used for modeling purposes. However, the experimental setup and simulation tasks were left as a future recommendation. The simulation work which was left out in paper (Butt 2012) is carried out in this thesis and results are found out.

The author of the research work (Arshad, Butt et al. 2017) used a genetic algorithm approach to minimize the positioning error of a workpiece. The 3-2-1 locating scheme was used in this process. Analytical calculations were used to calculate the workpiece displacement which was lying upon locators. For the calculations of the displacement of a rigid body and deformation of locators, a Langrangian formulation was used. 150 number of iterations were taken as a stopping criterion of optimization.

Under the machining forces, the deflection in the workpiece may occur. To avoid or to minimize it, a methodology of a fixture layout design was proposed. The research study (Papastathis, Bakker et al. 2012) proposed a new concept of controlling clamping forces along with an adjustable fixture layout. This methodology used the FEM model of a thin plate workpiece which was coupled with the actuators. These actuators acted as adaptive clamps. As a result, the large deformations were not faced by the thin-walled workpiece, instead, it maintained its original shape. A work-study (Corrado, Polini et al. 2020) used a flexible component of a composite material as a rigid body and the body was clamped with reduced or fewer constraints.

## 2.8 Objectives/Proposed Work

Based on the literary work of many authors, the calculation of a positioning error is proposed in this paper. The author (Butt 2012) used the theoretical approach to calculate the workpiece's positioning error but its validation through simulation and experimental setup was leftover. The simulation will be used to identify the workpiece's positioning error. The procedure along with the assumptions involved in the analysis is as follows:

- Designing of the models of a workpiece, six locators, and two clamps using CATIA v5
- The workpiece will be assumed as a rigid body and no deflection will take place in it
- The locators will be assumed as elastic elements and they will deform under the action of machining force and moment
- The clamps (instead of the clamping forces) will be used to keep the workpiece in a position

- The clamps will be assumed as elastic elements
- Contact between the tip of locators and a workpiece is taken as "frictionless" in ANSYS
- Contact between the tip of clamps and a workpiece is also taken as "frictionless" in ANSYS
- The aim is to calculate the positioning error of the workpiece as it will displace due to the external displacement of locators under the machining forces and moment

## 2.9 Summary

In this chapter, the theoretical aspects of fixtures, locators, types of locating devices, locating principle, clamps and clamping forces are explained. Also, the literature in the respective field is discussed, and it is summarized in Table 1.

Table 1: A summarized overview of the literature.

| **Author** | **Work** | **Method** | **Assumptions / Considerations** | **Software / Approach** |
|---|---|---|---|---|
| Necmettin Kaya (2005) | Optimization of machining fixture locating and clamping position | GA | Clamping force optimization and friction is not considered | ANSYS |
| Supapan Chaiprapat et al. (2006) | Resultant geometric variation of a fixtured workpiece | Newton-Raphson | Rigid workpiece | Monte-Carlo simulation method |
| V G Cioată et al. (2017) | Optimization of the clamping forces in machining fixtures (a specific case of processing: milling of a canal in a prismatic workpiece) | Screening and response surface method | Real situation (chip removal process) is assumed | ANSYS |
| S.U.Butt et al (2012) | A Kinematic Approach for 6-DOF Part Positioning | Analytical Modeling | Elasticity and rigidity | CATIA, Mathematica |
| Hao, X., et al. (2018) | 6+X locating principle based on dynamic mass centers of structural parts machined by responsive fixtures | GA | Short cylindrical locators are used | MATLAB |
| Roy, U. and P.-L.J.C.I.M.S. Sun (1994) | Selection of preliminary locating and clamping positions on a workpiece for an automatic fixture design system | Geometric reasoning mechanisms | Workpiece oriented automatically | Concept Modeller |
| Kršulja, M., B. Barišić, | Assembly setup for modular fixture machining process | Fixturing methodology | Rigid workpiece | CAD |

| | | | | |
|---|---|---|---|---|
| and J. Kudlaček (2009) | | | | |
| Rao, B.S., et al. (2018) | Force and deformation analysis for determination of optimum fixture configuration | FEM | Deformable workpiece, rigid fixturing elements, friction between contact surfaces | ANSYS |
| Arshad, M., et al. (2017) | Optimization of Locators Placement for Minimum Workpiece Positioning Error | GA | Elastic locators, rigid workpiece, frictionless contact between locators and baseplate | Analytical method |
| Papastathis, T., et al. (2012) | Design methodology for mechatronic active fixtures with movable clamps | FEM, Matrices | Ignored workpiece rotations during machining | Abaqus, Matlab |

These researchers have used several approaches for their concerned problems, but in our thesis, the workpiece is assumed to be a rigid body. The locators and clamps are assumed to be elastic elements. The real clamps instead of clamping forces are used in this research work. FEM approach is used to analyze the resultant deformation, while CATIA v5 and ANSYS are used for such purpose.

In the upcoming chapters, the design parameters, proposed methodology, and case studies along with results will be discussed.

# Chapter 3: Proposed Methodology

In this chapter, a problem statement based on which this thesis work is structured is explained. As explained in earlier sections of this paper, a workpiece displaces from its desired position due to the displacement of locators under the action of machining and clamping forces. A proposed methodology to identify such displacement error and the assumptions used are explained in this section.

## Overview

When the machining forces, moments, and clamping forces are applied on a workpiece, it undergoes displacement. As the workpiece is settled upon 3-2-1 fixture locators and its DOFs are restricted, the locators deform under the effect of machining forces, moments, and clamping forces. By the dislocation of locators, the workpiece displaces from its original position. In such a way, an error is imparted in the machined surface of a workpiece. This error can be calculated beforehand with the help of a simulation process which is the aim of this research.

Workpiece error due to locator displacement under machining operation and clamping forces are identified using the methodology in Figure 11. It was proposed by (Butt 2012), that a simulation can be done to find out the displacement of locators when the workpiece is machined.

The genetic algorithm approach was used to identify the minimum possible error in the locators' displacement by (Arshad, Butt et al. 2017). The GA was used to calculate the optimized position of locators for each machining point separately, and then the deformational error was calculated for each point. Later, the positioning of locators was optimized for all machining points and its deformational error was compared with the previous cases' results. Same approach is being used in this report and two case studies are being taken to support these relative theories.

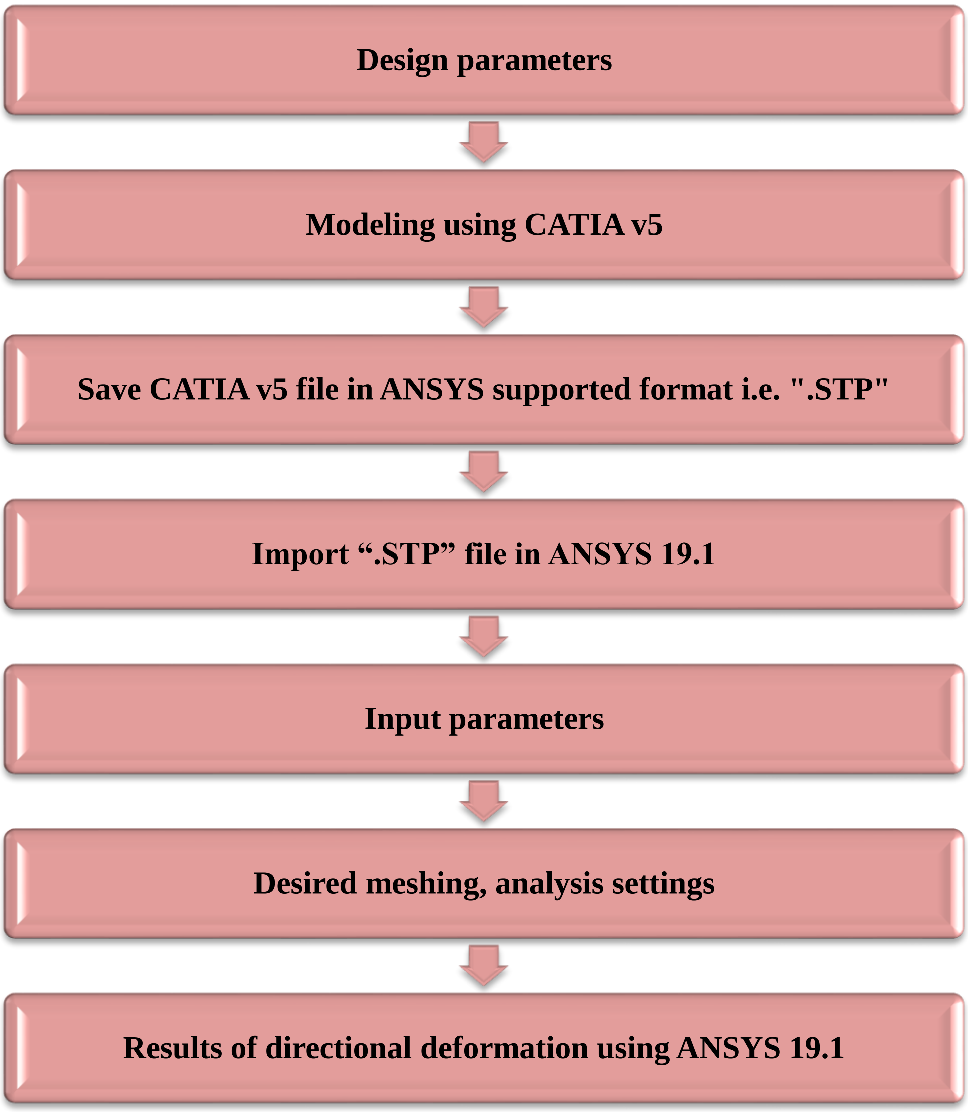



Figure 11: Methodology steps

## 3.2 Design Parameters

CATIA v5 was selected as a designing software and the required models (workpiece, locators, clamps) were designed in it. All assembly processes were also performed using CATIA v5. The shapes and dimensions of all six locators and two clamps were chosen. The particular position of each locator was extracted from the research work performed by (Arshad, Butt et al. 2017). Materials to be used for clamps and locators were selected. Some initial contacts were also given in CATIA v5 so that the complete model can be used in ANSYS for further formalities.

## 3.3 Modeling

Based on the literature review, a 3-2-1 locators principle scheme was selected to restrict the necessary degree of freedom of a workpiece. Two clamps and a rectangular workpiece was designed. A CATIA v5 software was used to design the models of six locators, two clamps, and a workpiece. As depicted in Figure 12, the machining force ($F_{machining}$) and a moment were applied on a workpiece at one point to perform the analysis.

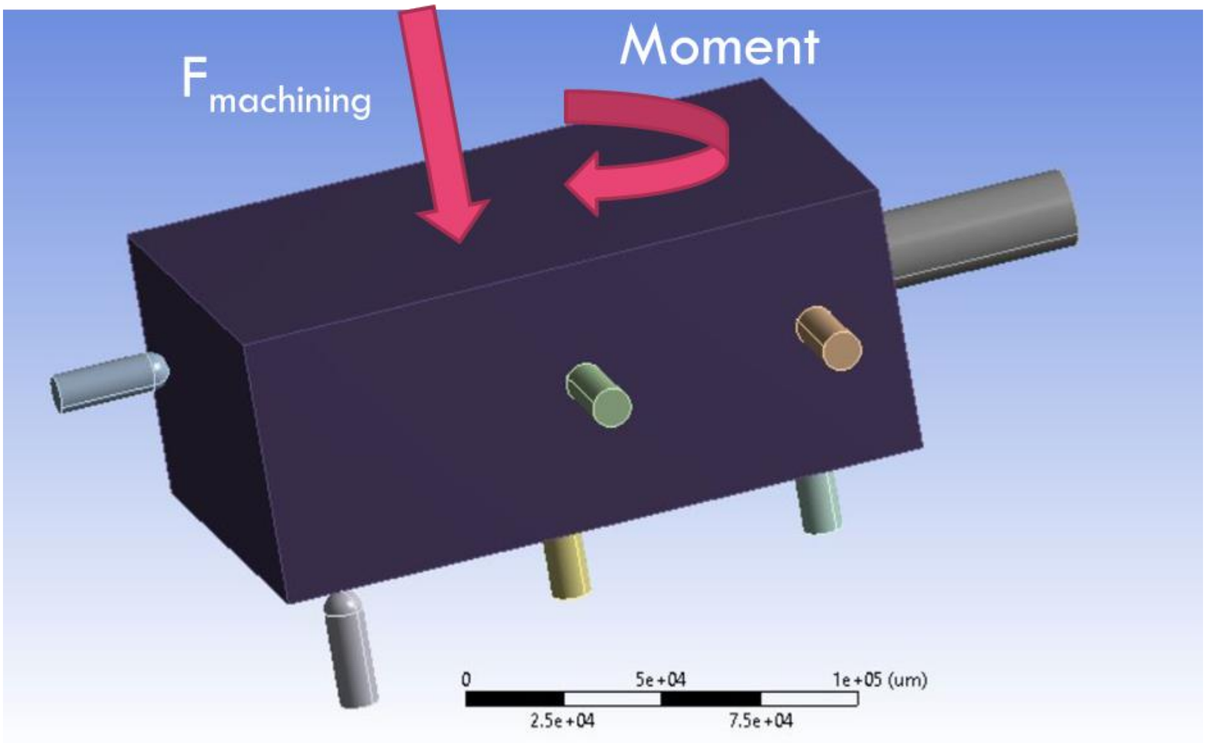



Figure 12: Model containing locators, clamps and a workpiece

### 3.3.1 Modeling of a Workpiece and Walls

The rectangular model of a workpiece was designed in CATIA v5. The machining forces and torque were applied to this workpiece for the analysis. The workpiece was kept stable by using sets of clamps and locators before applying machining operations for the analysis.

The locators and clamps were required to be positioned during the modeling stage. For such a purpose, the supporting walls were designed which kept them in place during whole analysis. Without these supporting walls, clamps and locators couldn't have been placed in the desired location.

### 3.3.2 Modeling of the Locators

The purpose of locators is to keep the workpiece in a firm position and to avoid any disturbances (vibrations, dislocations, etc.) during the machining operation. A 3-2-1 locators principle scheme was used. According to this principle, a primary datum plane contains a set of three locators. These three locators create an imaginary triangular plane upon which the workpiece rests and is balanced. A secondary datum plane perpendicular to a primary plane contains a set of two locators. A tertiary datum plane perpendicular to both primary and secondary planes contains a single locator.

CATIA v5 was used to design the locators. Under the machining force and the machining torque, the workpiece may come in contact at indefinite points with the contact point of locators. It was desired to keep the workpiece-locator contact at a single point, so the tip of each locator is kept cylindrical. The dimensions used in this study are as follows which can be changed as per the requirements:

Diameter (locator's body) = 10mm

Radius (cylindrical tip of locator) = 5mm

Length (locator's body) = 25mm

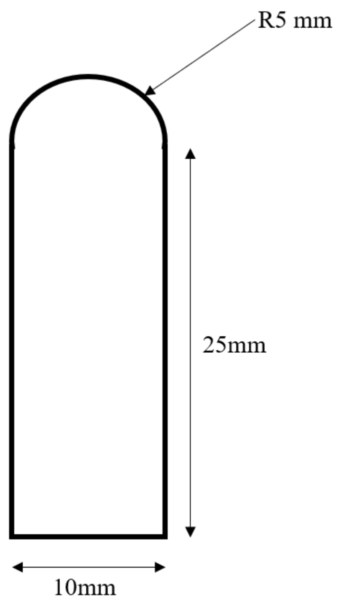



Figure 13: Locator's dimensions

### 3.3.3 Modeling of the Clamps

The clamps are used in the fixturing system in addition to the locators to hold the workpiece in a position. Two options exist in the clamping mechanism for analysis purposes, i.e. either to exert a clamping force on the workpiece or to design the clamps and use them physically in the model. In this thesis, the clamps were designed (just like the locators) and were brought into contact with the workpiece. Their tip is also kept cylindrical for the same reason as of locators. The dimensions of the clamps are as follows which can be changed as per the requirements:

Diameter (clamp's body) = 20mm

Radius (cylindrical tip of clamp) = 10mm

Length (clamp's body) = 50mm

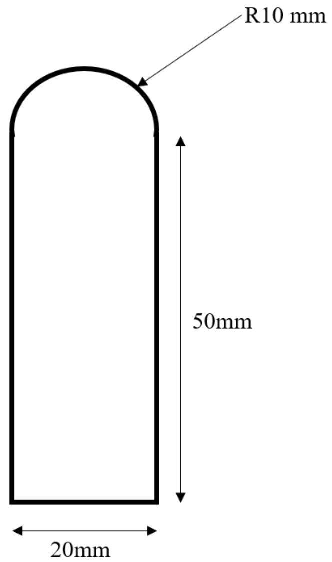



Figure 14: Clamp's dimensions

## 3.4 Assumptions

The workpiece was assumed to be acting as a rigid body and no deflection took place in it. The locators were assumed to be elastic and they deformed under the action of machining force and machining torque (moment). The clamps were assumed to be elastic as well. The clamps (instead of the clamping forces) were used to keep the workpiece in a position. Contact between the tip of locators and a workpiece was taken as "frictionless" using ANSYS. Contact between the tip of clamps and a workpiece was also taken as "frictionless" using ANSYS.

## 3.5 Case Study

The workpiece was placed on 3-2-1 locators fixturing system and its coordinate system is shown in Figure 15. For the case study in this research work, a workpiece is assumed as a rectangular body with dimensions (x, y, z) = (170, 110, 70) mm.

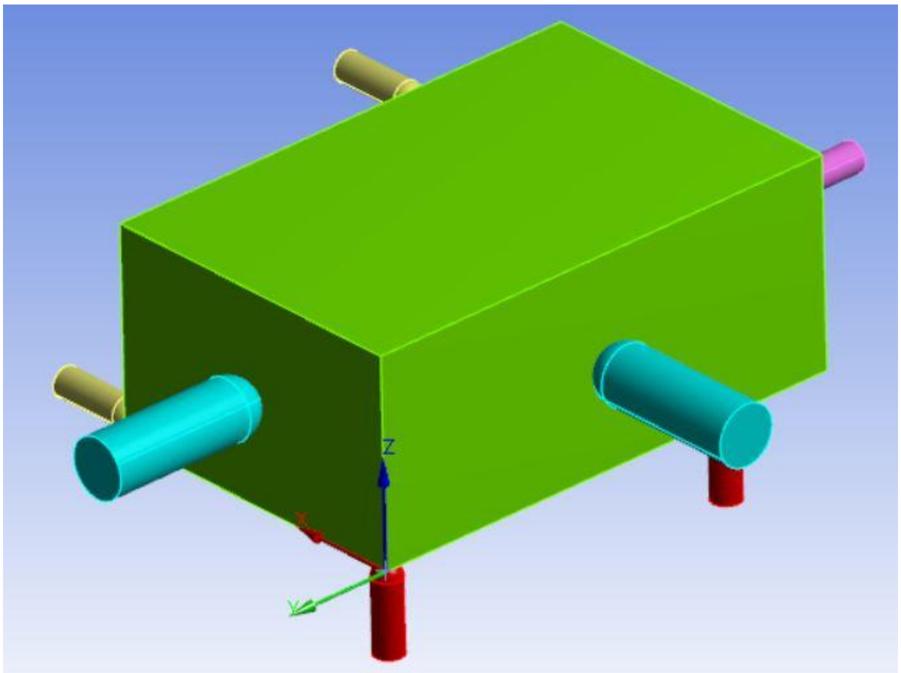



Figure 15: Workpiece coordinate system

Four different points ($P_1$ to $P_4$) were assumed on its top surface to be the cutting tool's contour points (or machining points) as depicted in Figure 16. Point "P" was assumed to be the center of gravity of a workpiece whose ideal position was taken as ($P_x$, $P_y$, $P_z$) = (85, 55, 35) in a WCS (workpiece coordinate system).

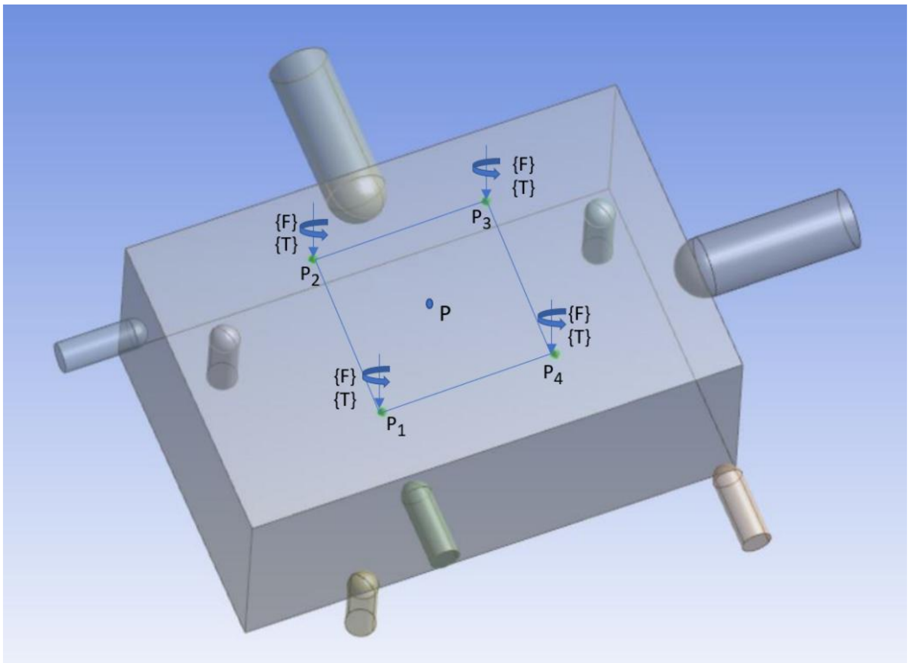



Figure 16: A case study of the fixturing system with cutting tool contours

### 3.5.1 Material Properties

Structural Steel was used for six locators and two clamps, while Titanium Alloy was used for a workpiece. Young's modulus used for Structural Steel and Titanium Alloy was $2x10^{11}$ Pa and $9.6x10^{16}$ Pa, respectively. Poisson's ratio used for Structural Steel and Titanium Alloy was 0.3 and 0.36, respectively.

Table 2: Material properties

| Material | Young's modulus (Pa) |
|---|---|
| Structural Steel | $2x10^{11}$ |
| Titanium Alloy | $9.6x10^{16}$ |

Here, Young's modulus of the workpiece is increased so that the workpiece does not deform and behaves as rigid as possible as compared to the clamps and locators.

## 3.6 Summary

In this chapter, the methodology is proposed for the selective case study which will be discussed in detail in the upcoming chapter. The modeling of locators, clamps, and a workpiece has been discussed. The assumptions used in this study have also been written down. The material properties of the clamps, locators, and a workpiece are also shared in this chapter.

# Chapter 4: Analysis

In this chapter, the fundamentals of the analysis performed in this research work are explained. The contact settings of the workpiece-locator contact point and workpiece-clamp contact point are discussed. The mesh settings used for the analysis are also shared. Further, the case studies, different positions of locators, and their displacement errors are discussed.

## 4.1 Analysis Using Ansys (2019 R1)

All the analysis and simulation processes were performed using ANSYS (2019 R1). After opening ANSYS workbench, materials were selected for a workpiece, locators, and clamps. Contacts were assigned between workpiece-locators and workpiece-clamps. Then, after completing meshing properties, the analysis settings (such as forces, moments, displacements, fixed bodies) were finalized. Later, to calculate the results, necessary solution settings were performed before running the analysis.

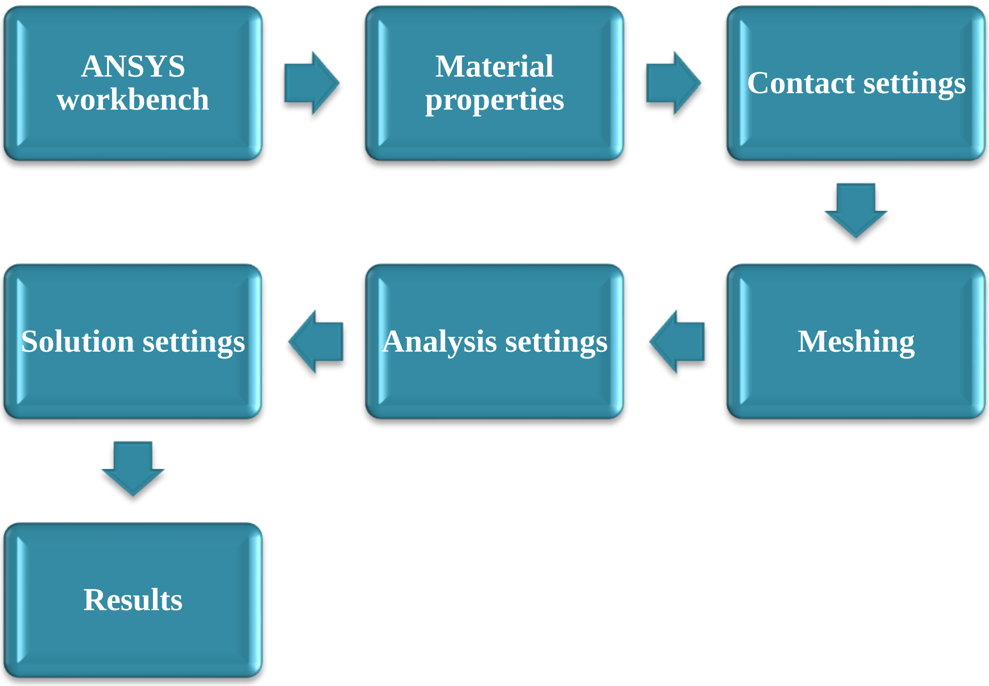



Figure 17: Flowchart for analysis in ANSYS

A model upon which the analysis of the first case study was performed is shown in Figure 18.

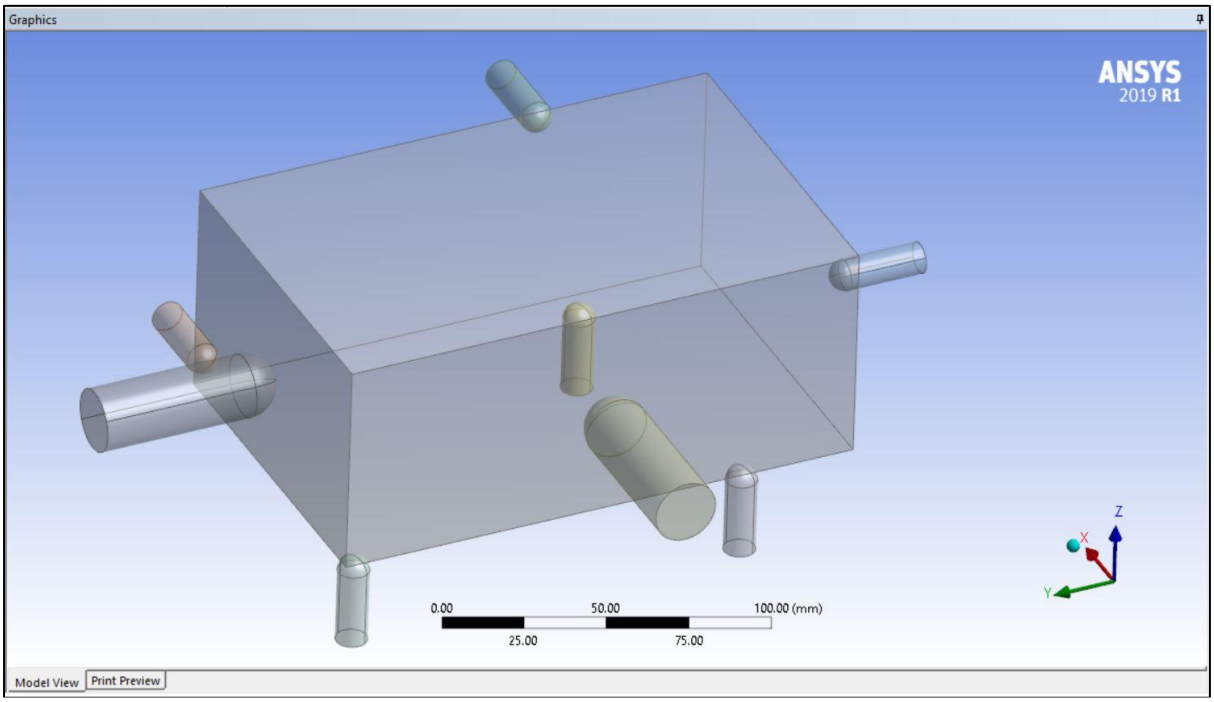


Figure 18: A case study model

## 4.2 Machining Points on a Workpiece

The workpiece was assumed as a rigid body. It was desired that the workpiece should not go under deformation once machining forces are applied. And all the effects were desired to be shifted on locators to achieve the best results. It was not possible to apply a machining force on a rigid body in ANSYS R19.1. To cater to that problem, the workpiece was made non-rigid but young's modulus of its material i.e. Titanium Alloy was increased from $9.6x10^{10}$ Pa to $9.6x10^{16}$ Pa.

$$\boldsymbol{k = \frac{Force}{Displacement} = \frac{F}{x}}$$

From the above equation, we know that;

$$\boldsymbol{k \propto \frac{1}{x}}$$

The more the young's modulus, the less the body displaces or undergoes deformation. By doing so, our workpiece acted as a rigid body and had nearly zero deformation under machining forces.

| Details View | |
|---|---|
| **Details of Point1** | |
| Point | Point1 |
| Type | Point Load |
| Definition | Single |
| Base Faces | 1 |
| Guide Edges | 1, 170 mm |
| FD1, Sigma (>=0) | 115 mm |
| FD2, Edge Offset (>=0) | 85 mm |
| FD7, Face Offset | 0 mm |
| # Points generated | 1 |

Figure 19: Details of Point-1

| Details View | |
|---|---|
| **Details of Point2** | |
| Point | Point2 |
| Type | Point Load |
| Definition | Single |
| Base Faces | 1 |
| Guide Edges | 1, 170 mm |
| FD1, Sigma (>=0) | 115 mm |
| FD2, Edge Offset (>=0) | 25 mm |
| FD7, Face Offset | 0 mm |
| # Points generated | 1 |

Figure 20: Details of Point-2

| Details View | |
|---|---|
| **Details of Point3** | |
| Point | Point3 |
| Type | Point Load |
| Definition | Single |
| Base Faces | 1 |
| Guide Edges | 1, 170 mm |
| FD1, Sigma (>=0) | 55 mm |
| FD2, Edge Offset (>=0) | 25 mm |
| FD7, Face Offset | 0 mm |
| # Points generated | 1 |

Figure 21: Details of Point-3

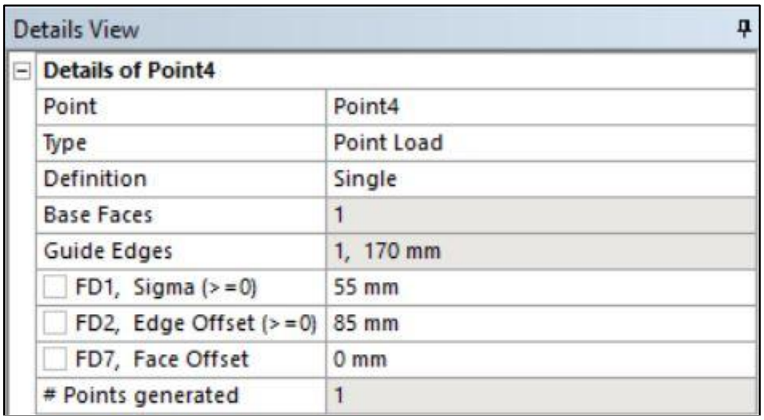



Figure 22: Details of Point-4

When the machining operation takes place, it follows some trajectory or a path. Four different points ($P_1$, $P_2$, $P_3$, $P_4$) were taken into account as contour points (Arshad, Butt et al. 2017). As an input, the machining force and a moment were applied to one of these points. Resultantly, the directional displacement (in X-, Y-, and Z-axis) of each point was identified.

At first step, *point* load was selected as a type of point. Then, as per our requirement, we defined it as a *single* point under the definition. The top face/side was selected as a base face and then a guide edge was selected as shown in Figure 23.

Three terminologies under *guide edges* were used in ANSYS i.e. *sigma, edge offset, and face offset.* To define these terminologies, we require a reference edge as already shown in Figure 23. *Sigma* contains the distance or location of a point upon the reference edge. *Edge offset* contains the location of a point away from the selected reference edge as shown in Figure 19 to Figure 22.

Summary of dimensions of all the points (sigma and edge offset values) are shown in Table 3.

Table 3: Dimension of points (Sigma and Edge offset)

| **Point** | **Sigma (mm)** | **Edge offset (mm)** |
|---|---|---|
| **$P_1$** | 115 | 85 |
| **$P_2$** | 115 | 25 |
| **$P_3$** | 55 | 25 |
| **$P_4$** | 55 | 85 |

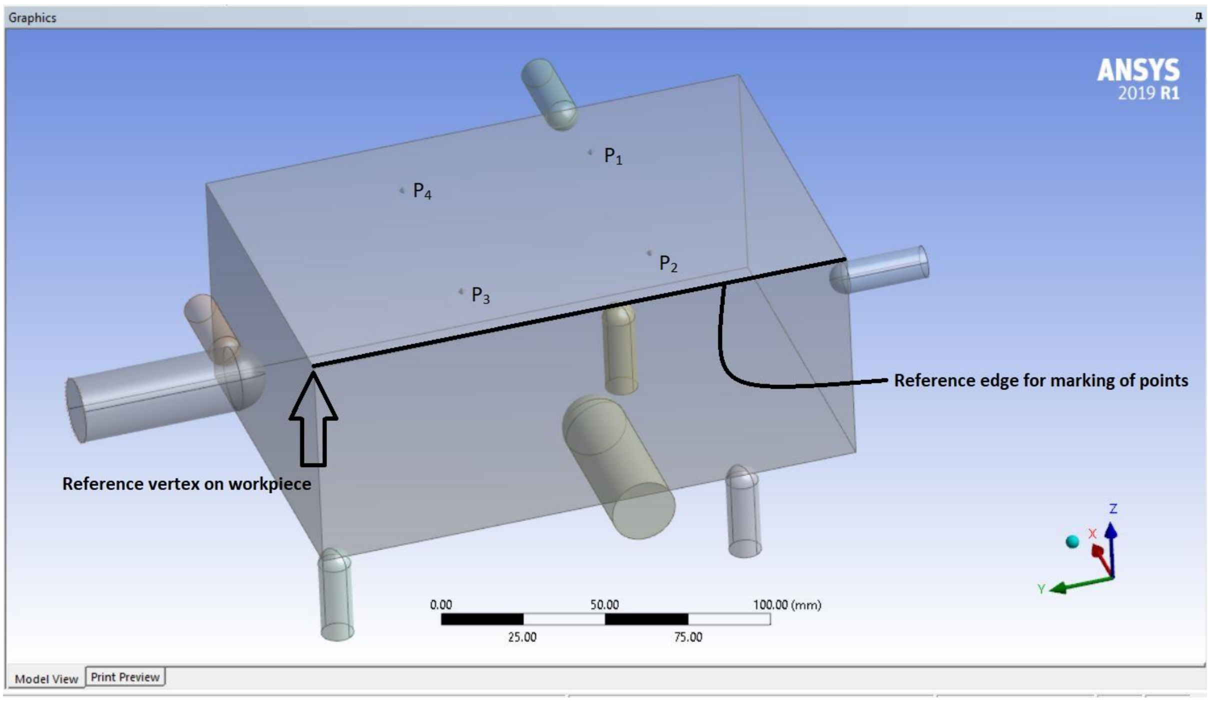



Figure 23: References used for Points

The point P is the center of gravity of a workpiece and its coordinates concerning the workpiece coordinate system were $[85, 55, 35]^T$ mm. But, as a workpiece was resting on the locators, the coordinates of a point "P" changed. The dimensions of the length of each locator were added in "P" to achieve its location in the fixturing system. The coordinates of point P w.r.t the global coordinate system became $[115, 85, 65]^T$ mm.

## 4.3 Meshing

The mesh settings used for the simulation purpose were applied to seven bodies. A workpiece along with six locators is included in those seven bodies. A hex dominant method was used to achieve results. For better results in future studies, these mesh settings can be changed and different geometries can be selected to compare the results with this study.

## 4.4 Contacts

The most important settings during the whole simulation process include contact between geometries. Each locator and each clamp was brought into contact with the workpiece. The settings used for the contacts between each locator-workpiece and clamp-workpiece are depicted in Figure 24. There are four different main sections under a single contact setting. These sections are *scope*, *definition*, *advanced* and *geometric modification.*

1. Under “*scope”*, there are two options that need to be emphasized (i.e. contact and target). Most often, a flat or a planer surface is considered as a **“target”** body. While a surface with less curvature is considered as a **“contact”** body. By keeping in view these tips, a *“contact”* contains the tip of each locator (in the locator-workpiece contact) and the tip of each clamp (in the clamp-workpiece contact). Similarly, a *“target”* contains the respective flat surface of a workpiece (in the locator-workpiece contact as well as in the clamp-workpiece contact).

2. In the *“definition”*, the most important thing is the “**type of contact”**. There are five different types of contact available in the ANSYS which are as follows:

a. Bonded
b. No separation
c. Frictionless
d. Rough
e. Frictional

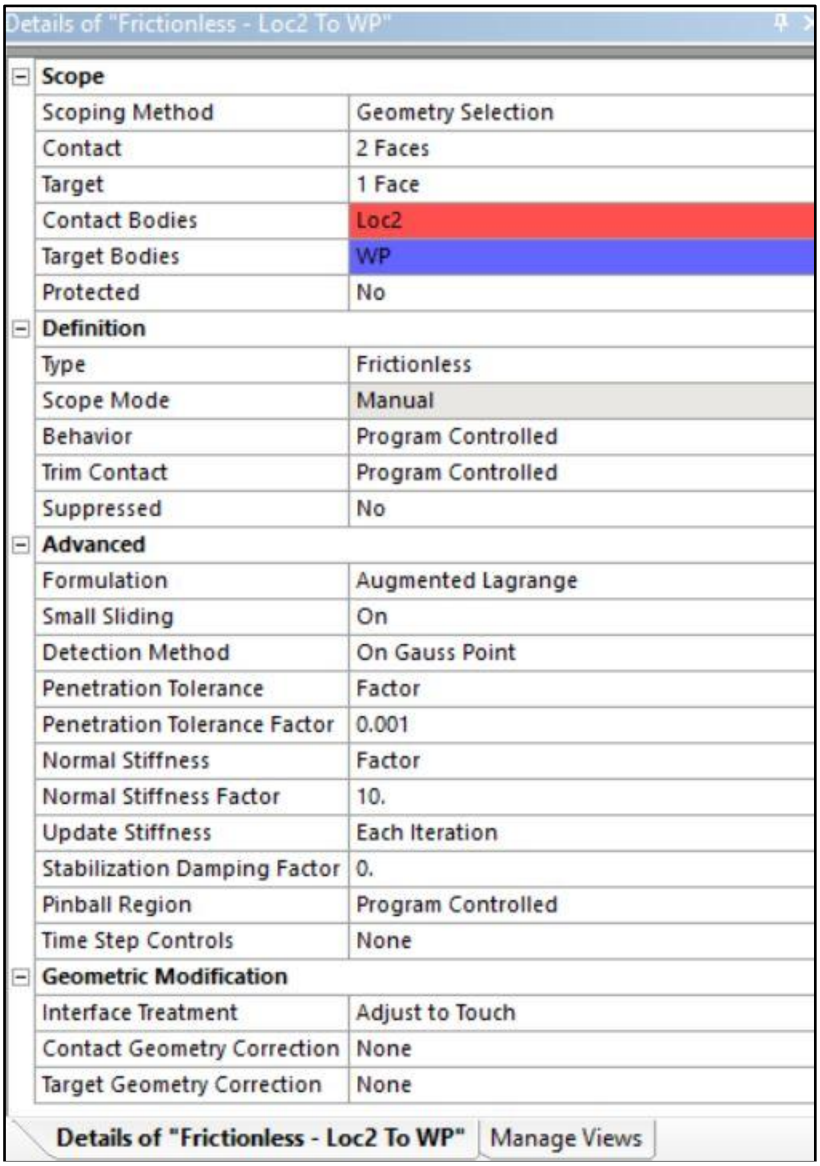
The contact between two bodies means the bodies cannot penetrate each other. Either the bodies in contact can separate in the normal direction or the tangential direction. So, in the bonded contact, the bodies cannot separate in both normal and tangential directions and they are glued together during the simulation process. In the no-separation contact, the contact pair cannot separate in the normal direction, while a pair can slide without resistance. In the frictionless contact, the contact pair can easily separate in the normal direction and can also slide freely in the tangential direction. In the rough contact, the contact pair can separate in the normal direction while cannot slide in the tangential direction because $\mu=\infty$ in this case. In the frictional contact, the contact pair can separate in the normal direction but in the tangential direction, it can slide with resistance. For that purpose, a value of resistance is required as an input. Bonded and no-separation contacts are termed as linear contacts because they are unable to separate in the normal direction. Rough, frictional, and frictionless contacts are termed as nonlinear contacts because they can separate in the normal direction.

In this research working, a frictionless contact was used between locator-workpiece contact settings, as well as between clamp-workpiece contact settings.

3. In the *”advanced”* settings for locators-workpiece contact, a formulation was set to “Augmented Lagrange” and a small sliding was kept “on”. The detection method was “on Gauss-point” and a penetration tolerance factor was kept as “0.001” as shown in Figure 24. It should be noted that these settings can affect the results’ output and may be changed during

future studies. For the clamp-workpiece contact, most of the options were left program-controlled.

4. In the *"geometric modification"*, the interface treatment for locator-workpiece contact was set to "adjust to touch" and this setting affected our results positively. For the clamp-workpiece contact, as the contact type was bonded, so this option was not available.



Details of "Frictionless - Loc2 To WP"

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Contact | 2 Faces |
| Target | 1 Face |
| Contact Bodies | Loc2 |
| Target Bodies | WP |
| Protected | No |
| **Definition** | |
| Type | Frictionless |
| Scope Mode | Manual |
| Behavior | Program Controlled |
| Trim Contact | Program Controlled |
| Suppressed | No |
| **Advanced** | |
| Formulation | Augmented Lagrange |
| Small Sliding | On |
| Detection Method | On Gauss Point |
| Penetration Tolerance | Factor |
| Penetration Tolerance Factor | 0.001 |
| Normal Stiffness | Factor |
| Normal Stiffness Factor | 10. |
| Update Stiffness | Each Iteration |
| Stabilization Damping Factor | 0. |
| Pinball Region | Program Controlled |
| Time Step Controls | None |
| **Geometric Modification** | |
| Interface Treatment | Adjust to Touch |
| Contact Geometry Correction | None |
| Target Geometry Correction | None |

Details of "Frictionless - Loc2 To WP" | Manage Views

Figure 24: Contact settings (contact between locators and a workpiece)

## 4.5 Boundary Conditions

Four points ($P_1$, $P_2$, $P_3$, and $P_4$) were selected on a workpiece as described previously. Initially, $P_1$ was selected as a point of application for a force and a moment. Displacement was also applied to both clamps. Displacement on the clamps instead of a point force was selected because a point force remains constant throughout the simulation process. While displacement is dependent upon the elastic modulus of a material and changes during the simulation. With the help of displacement applied upon the clamps and an elastic modulus of a material of each clamp, the force which is being exerted upon clamps can be identified (if required).

Fixed support was also added in the boundary conditions (in the static structural section). Six faces (base face of each locator) were selected as fixed support, without which the analysis could not run.

### 4.5.1 Application of Force

The force of 500N was applied on point $P_1$ and its components were $[0, 0, -500]^T$ N as shown in Figure 25. It should be noted that the force was applied on a single point and deformation of that particular point was analyzed in the simulation as a first step. The force was also applied on the other points (i.e. $P_2$, $P_3$, $P_4$) for further case studies, and deformations of all four points were calculated one by one.

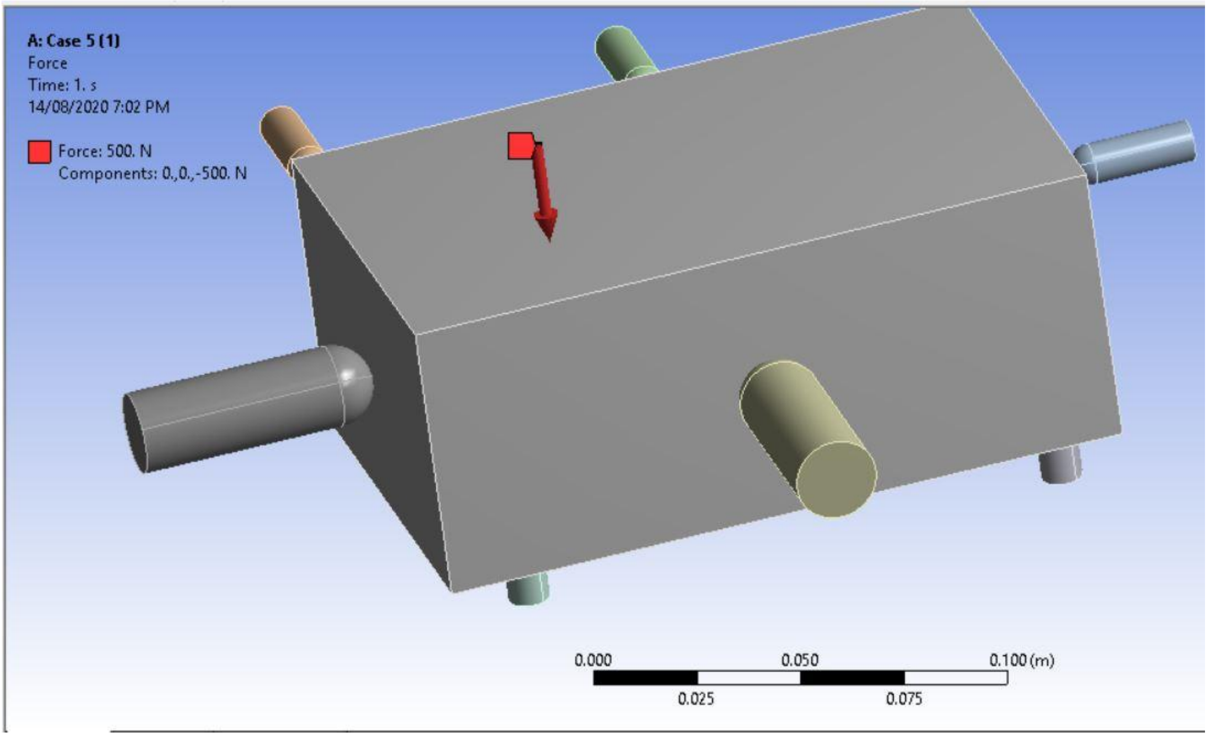



Figure 25: Application of force

### 4.5.2 Application of Moment

The moment of 10N-m was applied on point $P_1$ and its components were $[0, 0, -10]^T$ N-m as shown in Figure 26. Just like the case of forces, the points of application of the moment were changed after getting results of the previous point.

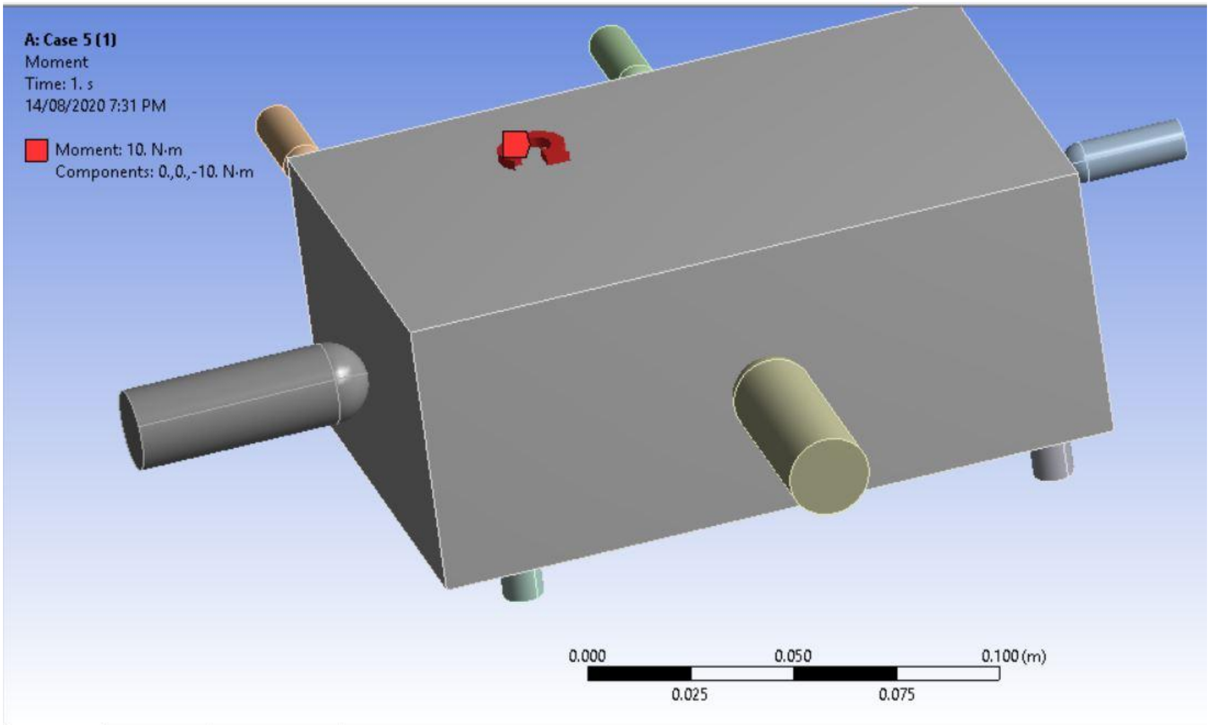



Figure 26: Application of moment

### 4.5.3 External Displacement on Clamps

Displacements were applied on both clamps as shown in Figure 27 and Figure 28. The base face of each clamp was used as a face of application of displacement. Magnitudes of the displacements and their components are as follows:

Displacement on clamp1 = 1µm

Components of displacement on clamp1 = $[0, -1, 0]^T$ µm

Displacement on clamp2 = 1µm

Components of displacement on clamp2 = $[1, 0, 0]^T$ µm

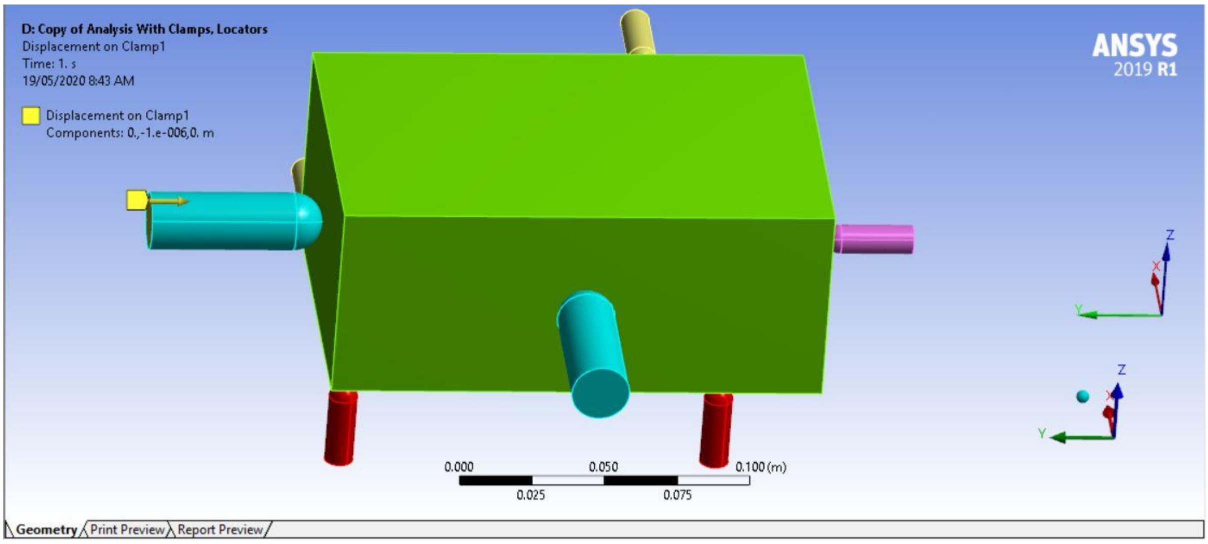



Figure 27: External displacement on clamp1

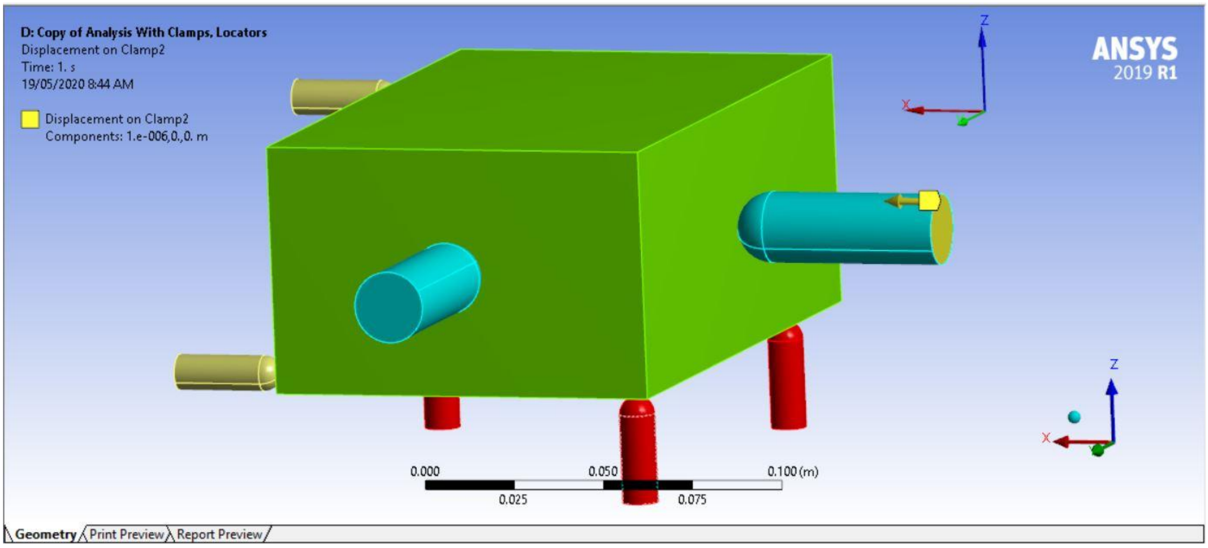



Figure 28: External displacement on clamp2

## 4.6 Locators' Position

In reality, when the machining force is applied on a workpiece, the locators deform under the action of force and moment. The deformational results of locators change and the error increases when the point of application of force changes from $P_1$ to any other point. It is not possible to change the position of locators during the machining operation. The author (Arshad, Butt et al. 2017) has optimized the position of locators for every point (i.e. $P_1$ to $P_4$). We have selected one position (shown inTable 4) as a case study to identify the errors. For our case study, we applied a force on every point and calculated the deformational results of the respective points.

Table 4: Position of locators (Case study-1)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Position of locators** | **X(mm)** | 105.3 | 132.17 | 187.2 | 40 | 129.95 | 0 |
| | **Y(mm)** | 134.94 | 131.85 | 74.55 | 0 | 0 | 93.11 |
| | **Z(mm)** | 0 | 0 | 0 | 82.09 | 90.4 | 73.82 |

The positioning of locators used in Table 4 is the optimized position for the $P_3$. It means that the deformational error of $P_3$ which will be mentioned later should be minimum as compared to other three points.

## 4.7 Clamps' Position

The dimensions of all holes of clamps (position of clamps) are shown in Table 5. Two clamps were used for our case study instead of a clamping force. They were displaced externally as discussed previously.

Table 5: Position of clamps

| Position from origin | X(mm) | Y(mm) | Z(mm) |
|---|---|---|---|
| **Clamp 1 position** | 250 | 85 | 65 |
| **Clamp 2 position** | 115 | 150 | 65 |

## 4.8 Summary

In this chapter, all analysis settings which are used in ANSYS for analysis are discussed. Four machining points are introduced upon which the whole analysis and results are based. Necessary meshing criteria and contact settings are briefed. The boundary conditions such as the application of forces, moments, and displacement on clamps are discussed. Further, the position of all locators and clamps in the fixturing system is also a part of this chapter.

# Chapter 5: Results and Discussions

In this chapter, the results are summarized and discussed. Once all the necessary analysis settings and boundary conditions were applied, the analysis was started to identify the results. As it was described earlier that the deformation was required to be analyzed on all four points, the “solution” option was used for such purpose.

In ANSYS, according to the author of (Lee 2018), directional deformation for only a single axis can be calculated at once. As we had four different points and each point had three axes, so twelve different cases arose. Each point (as a vertex) was selected separately for a directional deformation. Then this step was followed by the selection of a required axis. The workpiece coordinate system was selected as a desired coordinate system but it doesn’t affect the results during the simulation. The analyzed results are discussed below.

## 5.1 Results

### 5.1.1 Case Study-1

At first step, the force was applied on point $P_1$ and the directional deformation results of $P_1$ were calculated after analysis. Then, for the same set of placement of locators (as shown in Table 4), the force was applied on the point $P_2$ and its directional deformation results were identified. Similarly, the results for the points $P_3$ and $P_4$ after applying the forces on the respective points were calculated after analysis using ANSYS. The results of this case study are shown in Table 6.

Table 6: Directional deformation results (Case study-1)

| Point of application of force | Directional deformation results of the respective point | | | Total deformation (μm) |
|---|---|---|---|---|
| | X(μm) | Y(μm) | Z(μm) | |
| $P_1$ | 3.4825 | -8.486 | -22.467 | 24.268 |
| $P_2$ | -0.615 | -4.089 | -5.982 | 7.272 |
| $P_3$ | 1.741 | 4.73 | -0.43 | 5.058 |
| $P_4$ | 4.508 | -4.528 | -6.985 | 9.467 |

The “contact tool” was used in ANSYS to identify any deformational change in contacting points. The models before deformation and after deformation are depicted in Figure 29 and Figure 30, respectively. It should be noted that these views have been exaggerated (“auto scale” in ANSYS) to check the noticeable deformation, which was not possible with “true scale” views.

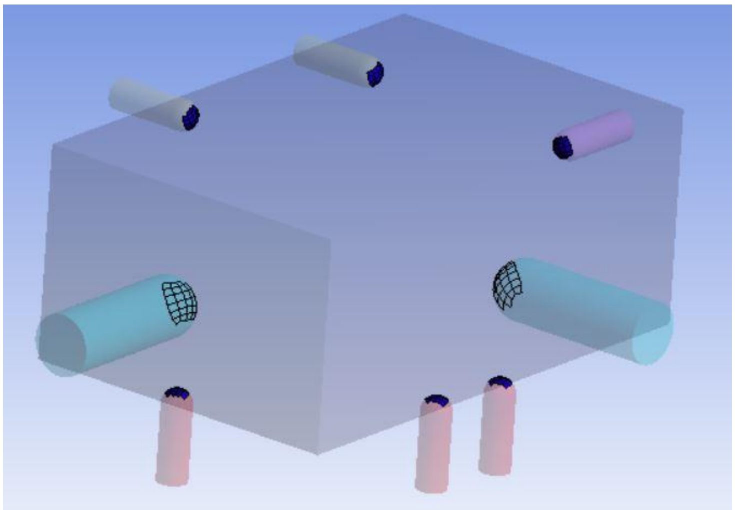


Figure 29: Model before deformation (Case study-1)

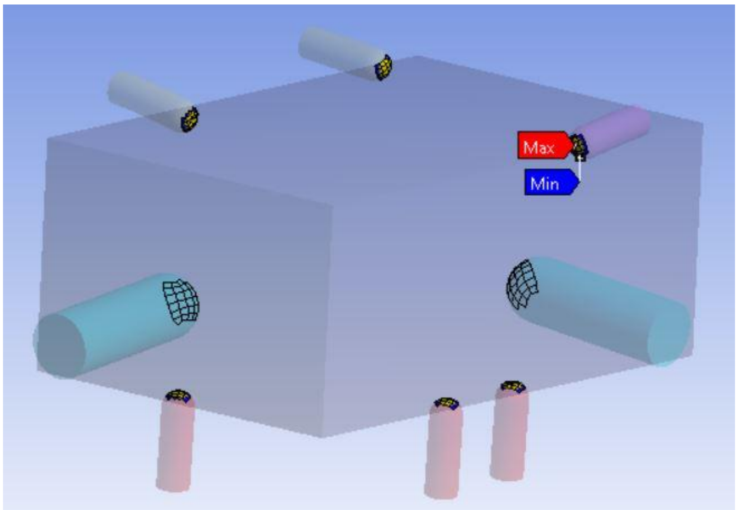



Figure 30: Model after deformation (Case study-1)

### 5.1.2 Case Study-2

For the second case study, the position of locators was changed (as shown in Table 7). Initially, before optimization, the less deformational error (for respective points) was found at a respective optimized location. The error was less for that particular point where the force was applied. But the error increased for the other points for the same point of force. Similarly, when the point of application of force was changed in the paper (Arshad, Butt et al. 2017), the error became less for that particular point and increased for other points.

The author (Arshad, Butt et al. 2017) has optimized the position of locators for all the points using the GA approach. After optimization, when the force was applied on any single point, the error became less for all other points as compared to the previous scenario.

Table 7: Position of locators (Case study-2)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Position of locators** | **X(mm)** | 107.03 | 192.79 | 164.51 | 84.65 | 131.89 | 0 |
| | **Y(mm)** | 120.03 | 114.69 | 44.34 | 0 | 0 | 128.4 |
| | **Z(mm)** | 0 | 0 | 0 | 90.97 | 85.19 | 77.97 |

Table 8:Directional deformation results (Case study-2)

| **Point of application of force** | **Directional deformation results of the respective point** | | | **Total deformation (μm)** |
|---|---|---|---|---|
| | **X(μm)** | **Y(μm)** | **Z(μm)** | |
| **$P_1$** | 0.234 | -8.007 | -9.839 | 12.688 |
| **$P_2$** | -3.886 | -2.67 | -3.587 | 5.924 |
| **$P_3$** | 0.293 | -0.094 | -1.153 | 1.194 |
| **$P_4$** | 2.001 | -2.756 | -1.386 | 3.678 |

The “contact tool” was used for case study-2 too just like case study-1 to identify any deformational change in contacting points. The models before deformation and after deformation are depicted in Figure 31 and Figure 32, respectively.

It should be noted that these views have been exaggerated (“auto scale” in ANSYS) to check the noticeable deformation, which was not possible with “true scale” views.

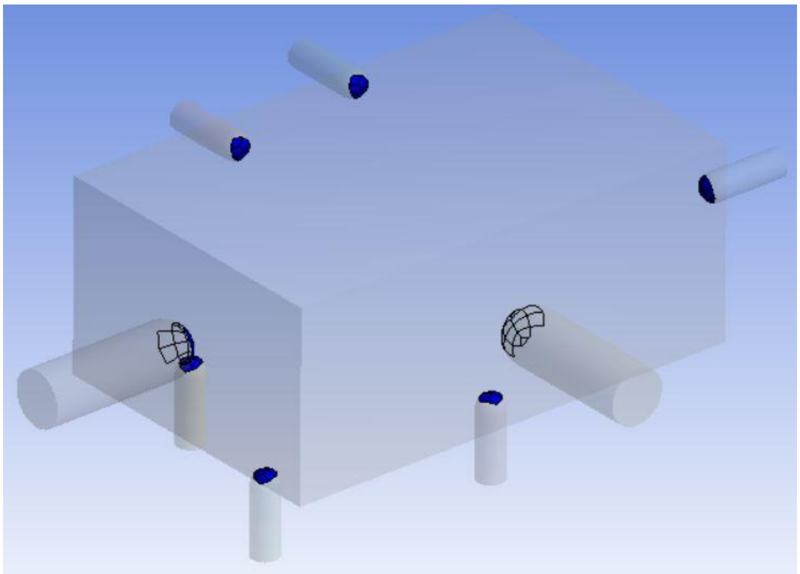


Figure 31: Model before deformation (Case study-2)

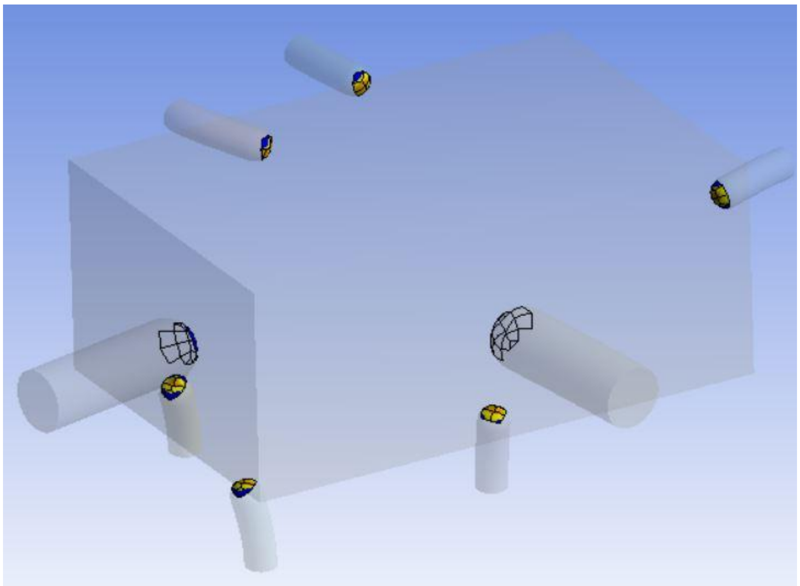


Figure 32: Model after deformation (Case study-2)

## 5.2 Comparison of Deformational Results

According to the case studies described above, in the case study-1, the optimized position of locators for $P_3$ was used to get the minimum deformation at $P_3$ only. In the case study-2, as the position of locators was optimized for all points (i.e. $P_1$ to $P_4$) and when the force was applied upon all points separately, the total deformation minimized for all points respectively (as shown in Table 9).

Table 9: Comparison of total deformational results

| **Point of application of force** | **Total deformation (µm)** | |
|---|---|---|
| | **Case study-1** | **Case study-2** |
| **$P_1$** | 24.268 | 12.688 |
| **$P_2$** | 7.272 | 5.924 |
| **$P_3$** | 5.058 | 1.194 |
| **$P_4$** | 9.467 | 3.678 |

## 5.3 Contribution

Many theories exist about the optimization of positions of locators as well as for clamps using a genetic algorithmic approach. Few researchers have used analytical methods to calculate positioning errors. It was already described in previous researches that the positioning error becomes a minimum for the respective optimized position of locators. In this report, the two case studies were taken to calculate the total deformational errors which supported the theories (regarding positioning for minimum error) already presented.

In the analysis performed in this research work, the real clamps were used and displaced externally instead of clamping forces. The difference between both these cases is that when the elastic clamps are displaced externally, the programming/analyzing environment automatically generates the force according to the geometric materials and reaction forces involved. Such force may vary throughout the analysis and is not constant. But if the clamping force is applied instead of using real clamps, that force will remain constant throughout the analysis which disturbs the system along with the output results. The results are quite satisfactory as far as the two case studies taken are concerned. As some of the data was assumed (e.g. materials, Young's modulus of materials, dimensions of the workpiece, clamps, and locators, the magnitude of external displacement, etc.), these results can only be used to support the theory of previous researches but cannot be compared with any other study due to lack of required input data for analysis.

## 5.4 Advantages

When the machining operators are required to perform the machining operation on a workpiece, they are unaware of the expected errors which may arise during machining. This research work was aimed to design such an environment so that the positioning errors can be calculated using such simulation and analysis techniques. In real life, the engineers can mockup the real setup using all required data input into the designing software for analysis beforehand. Then different techniques (e.g. use of actuators, sensors for clamps, and locators) can be discovered to compensate those errors or the tolerances can be applied in the workpiece before applying any machining operation. By doing so, the material handling cost reduces and material wastage can be decreased.

## 5.5 Summary

In this chapter, the results of the performed analysis for both case studies (case study-1 and case study-2) were discussed in detail. The results of both cases were compared in a tabular form. The contribution of this research work was also discussed along with the satisfaction of the results. Few deficiencies faced while using the input data were also discussed. The advantages of this study and its usage in the real world were also a part of the discussion in this chapter.

# Chapter 6: Conclusion and Future Recommendations

The domain of this research work is the designing and analysis of a reconfigurable fixture. The research work contains the designing of a workpiece using CATIA v5. 3-2-1 fixture locator principle was used and the workpiece was rested upon these locators. 3-2-1 locators' positioning restricted the nine DOFs of a workpiece. Further, the designing and positioning of two clamps restrained the workpiece's two more DOFs. The initial assembly process was completed using CATIA v5. Later, ANSYS R19 was used to create contacts between locators and a workpiece, to apply mesh settings, to create a vertex point for application of machining force and moment. Material properties were also assigned in ANSYS R19 and the young's modulus (default value) of a workpiece's material was increased to make the workpiece rigid. By doing so, the workpiece showed presumably zero or minute deflection. Directional deformation results of four points were analyzed and calculated. The results of case-1 showed that if the position of locators is optimized for certain locators, its deformational error comes out to be less than other points. Similarly, in case-3, the deformational error was reduced for all four points as locators were placed on the optimized location of all four points.

If we have different placement options of the workpiece, before assembling the system, the possible positioning error of the workpiece can be calculated and based on the results, the best position of the locators can be selected. This proposed methodology allows us to correctly place the locators to achieve a high-quality product.

In this research study, the machining force was applied on eight points (four points for each case) due to certain limitations like high computation time. In the future, a machining force can be applied on a complete contour boundary/path of a cutting tool, and its results can be analyzed and compared with the results of a genetic algorithm approach. Also, the meshing can be refined for more precise results using the facility of supercomputers. The optimized location for clamps can also be used (just like locators in this study) for further research studies.

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# CERTIFICATE OF COMPLETENESS

It is hereby certified that the dissertation submitted by **NS Hashir Ali Safdar**, Reg. No. **00000170952**, Titled: **Effect of fixture stiffness on the positioning error of the workpiece under machining and clamping forces** has been checked/reviewed and its contents are complete in all respects.

Supervisor's Name: **Dr. Sajid Ullah Butt**

Signature: ________________
Date: ________________