



Development and validation of a machining fixture for complex-shaped components based on Plückerian matrix approach and SDT concept

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Abstract

In the manufacturing industry, there are several types of parts of complex shapes owning various functions. The turbine blades (buckets and vanes) are one of the most important components in gas turbines. However, these blades have complex shapes and irregular surface curvature which make them difficult to machine. Production of such kind of parts is so complicated and requires a high control of machining process, advanced CNC programming, innovative tools, and special fixtures allowing to maintain exactly and rigidly in a unique position of the part during machining. In order to enhance productivity and reduce operation time, thereby increasing parts quality, the machining fixture has to fulfill several requirements such as allowing a correct location with security and repeatability of the workpiece as well as maintaining conformity and interchangeability of the machined parts. This paper addresses the challenge of machining complex geometry parts by development and realization of a dedicated machining fixture (MF) for holding a mobile blade of a gas turbine. The first novelty of this work is in the application of the Plückerian coordinates method for choosing the locator's placement of complex-shaped parts. The choice of the locator's placement during the design process of the fixture is performed based on the maximization of the determinant and minimization of the condition number of the locator matrix (information matrix). The second novelty is in the optimization approach used. The last novelty is in the developed and fabricated machining fixture. The performance of the developed fixture in terms of localization repeatability is evaluated based on the small displacement torsor (SDT) concept. Results show the validity of the developed fixture.

Keywords Machining fixture · Plückerian matrix · Locator's placement · Small displacement torsor · Turbine blade · Repeatability

1 Introduction

Turbine blades are one of the most vital components of gas turbine engines and the key factor that affects their performance. As turbine blades are composed of free form surfaces (sculptured surfaces) that have complex shapes and irregular curvature distribution, its production

with high accuracy and surface quality requires modern advanced manufacturing technologies. Producing parts having complex geometries such as turbine blades is still an important research topic usually motivated by the requirements of the end user of these components such as the energy and aerospace industry. Near-net-shaped blades are traditionally produced using forging or casting operations. However, machining operations are still required in order to bring these semi-finished blades to their desired geometric and surface specifications. On the other hand, with the advent of high-performance multi-axis CNC machining technology, finishing of turbine blades becomes not only feasible but also cost-effective. Nevertheless, in practice, there remain some particular challenges that face the broad implementation of this process including collision detection, holding, close

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tolerance finish requirements, interchangeability, vibration, and deformation. Usually, most of these issues can be addressed through a well-designed and fabricated machining fixture.

It is well known that machining systems directly affect productivity, costs, and product quality. Generally, 10 to 20% of the total cost of a manufacturing system is associated with the design and manufacture of a machining device [1, 2]. Furthermore, the machining fixture can account for about up to 70–80% of the total amount of tooling and the time necessary for production planning for the design and the manufacture of the machining fixture is about 80–90% [3].

According to Nixon [4], about 40% of the machined parts are rejected due to poorly designed fixtures. However, this percentage is expected to rise when machining complex geometry parts. Fortunately, research in flexible fixture and computer-aided fixture design can significantly reduce fixture-related costs [5, 6]. More detailed information on the subject of machining fixture can be found in [7–9].

To have a proper machining fixture for such parts having sculptured surfaces, several factors need to be taken into account such as the type, the geometry, and the material of the supporting and positioning elements (locators) as well as the type of clamping mechanisms. The basic fixation method (plan-line-point or 3–2–1) most commonly used for parts with regular geometry [10, 11] becomes useless for parts with complex geometry. Frequently, the positions of the clamping elements and the clamping forces attributed to these elements are completely based on the designer's experience and the trial-and-error method. Generally, the clamping forces are applied arbitrarily to the parts "just to be in free and secure places." Therefore, considerable deformations are often caused by the non-optimized design of the clamping elements and forces.

To produce accurate finished parts, it is necessary to provide a suitable machining fixture, able to locate, fix, and maintain a succession of parts having the same geometry in identical positions. It is also intended to ensure the machining of various operations in various machine tools. Such fixtures can be in some cases expensive and complex equipment.

According to Wang et al. [12], a machining fixture must comply with the following requirements:

- Good repeatability of loading
- Immobility
- Minimum number of configurations (outlets)
- Accessibility
- Good dynamic performance
- No excessive deformation of the workpiece occurring during holding and machining

However, the big challenge faced the complex parts manufacturers is the repeatability and reproducibility of their machining fixtures. Several research works have

been conducted to address the problem related to holding and machining of complex parts [13–18]. Wang et al. [15] proposed a method based on finite element analysis (FEA) to design a machining fixture for turbine blades by considering the complex contact geometry, and contact status of fixture-component pair using surface-to-surface contact elements. In order to present a fundamental approach to modeling and performance analysis of the blade-fixture system, Wang et al. [16] studied the dynamic behavior of the machining fixture during machining of thin-walled blades. They found that the loaded pressure of clamps has a significant effect on the stiffness and the global performance of the blade-fixture system. The profile error of the blade has also a high impact on the geometric dimension and surface integrity of blades' machining. Calabrese et al. [17] addressed the problem related to the optimization of the performance of the machining fixture during machining of aeronautical thin-walled parts based on the local rigidity characteristics. They concluded that according to the proposed method, it was possible to detect some areas in the design space where materials can be removed, areas where solid materials are necessary, and areas where lattice structure is needed. Wang et al. [18] proposed a methodology to improve the machining performance of thin-walled turbine blades based on the integration of the geometric locating tolerance analysis method and FEM-based structural deformation prediction into one framework. They validated their method numerically and by real machining experiments. They claimed that the proposed method and test fixture have demonstrated their significance. An approach for verifying and improving existing fixture designs is proposed by Kang et al. [19, 20]. Their approach is divided into two major steps, tolerance analysis and workpiece stability.

The issue related to the stability of the workpiece on its fixture during machining is addressed by Kang et al. [20] using a kinetic fixture model and a fixture stiffness matrix. They specified that their method not only solves the problem of fixture stability but can also help in finding the minimum clamping force, fixture deformation, and clamping sequence.

Tao et al. [21] and Cecil [22] discussed the problem related to the optimization of the clamping forces, and design of fastening elements by taking into account the stability and balance of the workpiece. The effect of the clamping and machining forces on the deformation of the workpiece is treated by Krishnakumar and Melkote [23]. They proposed an optimization technique based on the genetic algorithm to find the optimal fixture layout that minimizes the deformation of the machined part during machining. Zirimi et al. [24] proposed a method for choosing and placing the technological elements in contact with the workpiece during the design of the machining fixture. The method is based on maximizing the area of the

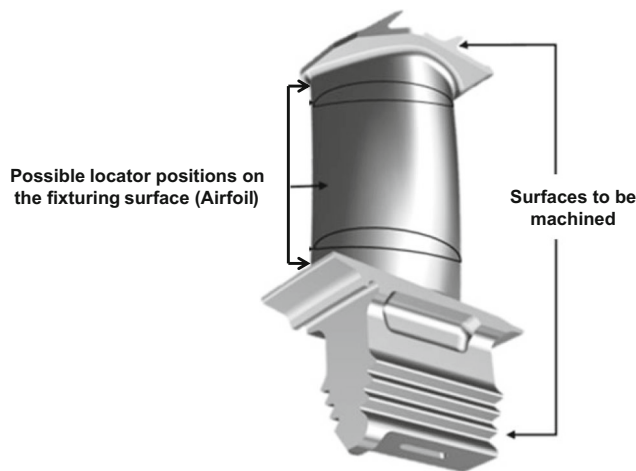


Fig. 1 Schema of the blade showing the possible locator positions and the surfaces to be machined

triangle of support obtained by the three contact points, which is formulated as a nonlinear constrained optimization problem.

In order to achieve high machining quality and part accuracy, Estrems et al. [25] developed a model based on the metrological analysis of a fixture and part. More recently, Dongbo et al. [26] investigated the CNC machining of near-net-shaped thin-walled blades by fixture and deformation control. Their designed machining fixture is analyzed numerically using finite elements and tested experimentally. They found that the main deformation of the blade-fixture occurs in the four clamping heads. A combination of the kinematic method, genetic algorithm, and heuristic design was used by Bausch and John [27] to generate a datum transfer fixture design for turbine blade. The positional accuracy of the designed fixture was compared experimentally to the existing fixture for the same blade. They found that designed fixture provide more accurate results.

Ivanov et al. [28] proposed a method to increase the machining efficiency of lever-type parts by the optimization of the design of a flexible machining fixture based on the appropriate choice of the fixture element.

Duret et al. [29] proposed a method based on the determinant and the condition number for evaluating the quality of machining fixtures. They applied their method on a basic fixture for simple prismatic parts (plane-line-point) and Boys' fixture for cylindrical parts. They claimed that their proposed indicators are simple, robust, and achieving a high practical application. However, the applicability of the method to other types of parts such as complex-shaped parts has not been verified.

Vukelic et al. [30] proposed a method to optimize the locator placement and clamping elements of fixture for machining plastic parts using minimum deformation of parts as objective function.

A multi-objective method implemented with ANSYS was used by Ciota et al. [31] for optimizing the position and the magnitude of the clamping force during milling of a canal in a prismatic part. During their optimization process, they minimize the maximum total displacement and the maximum equivalent stress in the machined part. They found that in some zones the magnitude of the contact force is close to zero; hence, they concluded that those areas have to be avoided for applying clamping forces.

The static deformation of the machined parts due to the clamping force is discussed by Gonzalo et al. [32]. They used the concept of intelligent fixture to minimize the workpiece deformation. Although their approach provides satisfactory results, there are some limitations related to the size and complexity of the systems in certain applications.

Ivanov et al. [3] designed a machining fixture for multi-axis machining of levers in one setup. Based on simulations and experimental results, they concluded that their proposed

Fig. 2 Actual arrangement of the positioning and clamping elements of our assembly on a turbine blade

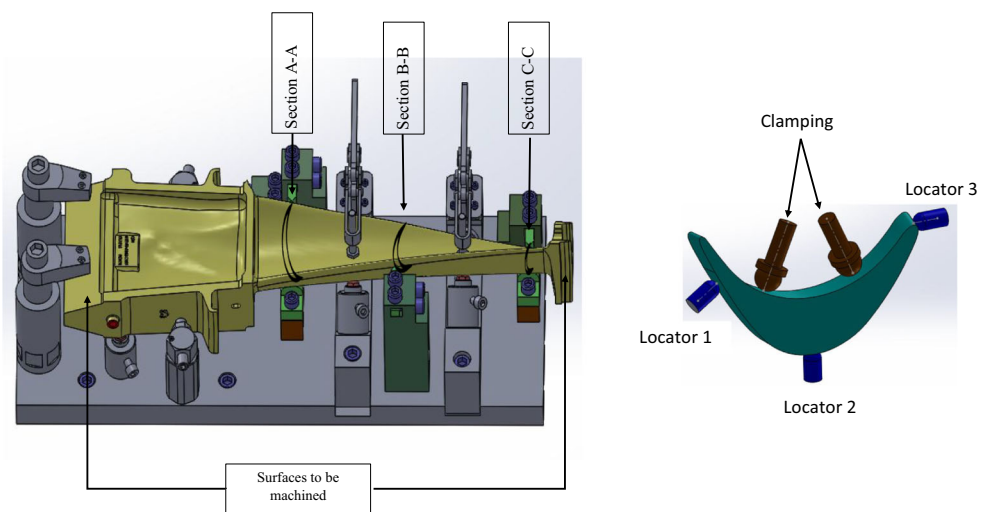
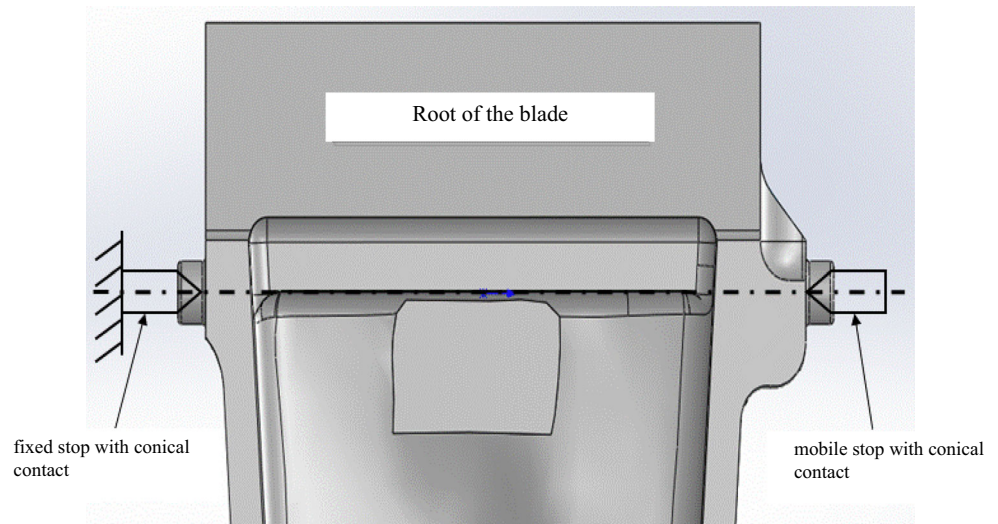


Fig. 3 Schematization of the new reference system after transfer



fixture corresponds to all the accuracy parameters and ensures sufficient tool accessibility Ivanov et al. [3, 33].

The design and fabrication of machining fixtures for parts with free form surfaces and complex geometry pose several challenges in terms of locator's placement choice, positioning repeatability, and accuracy, and interchangeability of the machined parts. As presented above, various approaches and optimization techniques exist and are applied in many published types of research; however, robust and reliable machining fixtures to meet industrial challenges are still required.

Furthermore, up to now, only few works deal with the performance of machining fixtures which affect the dimensional and geometric accuracy of the machined parts [34, 35].

The contribution of this work is therefore to propose a method to automate the process of machining fixture design for reducing the dependency on human designer expertise. The design methodology of the new machining fixture will focus on an industrial application consisting of the machining of a mobile bucket part located in the second stage of a GE FRAME 9000 gas turbine. Such fixture is intended to be used

Fig. 4 Creation of a new referencing system to facilitate the positioning and the holding of the part

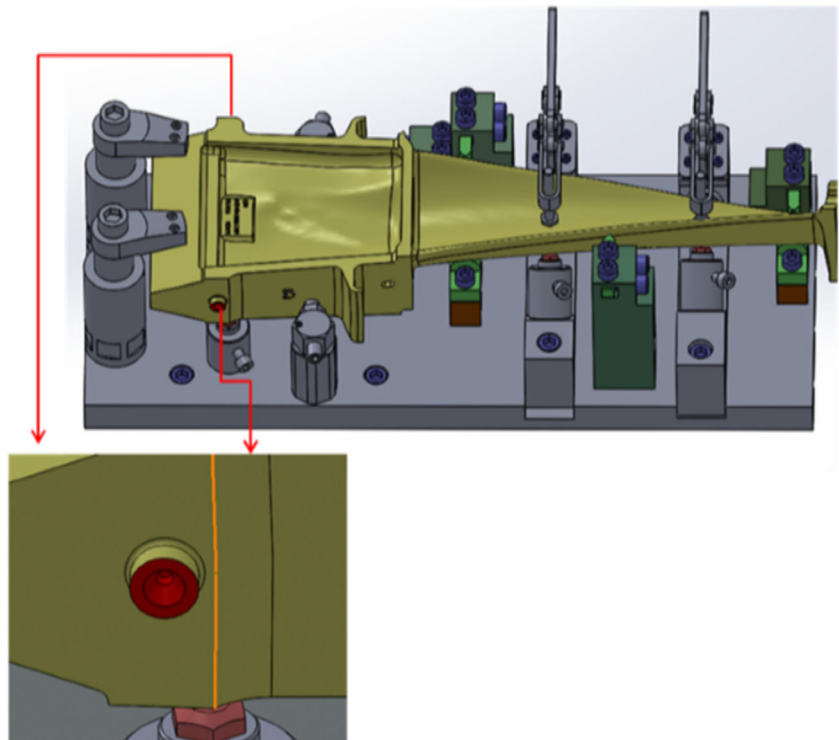




Fig. 5 Machining device for drilling cooling holes at the airfoil of the blade by ECD

in a 5-axis vertical machining center (VMC) to establish the reference system at the root of the blade, and also for controlling the blade after machining using a coordinate measuring machine (CMM).

2 Context and objectives

The manufacturing of turbine blades by any kind of machining such as grinding, milling, EDM (electrical discharge machining), ECM (electro-chemical machining), and even by Laser, requires a well-defined and unique reference. This

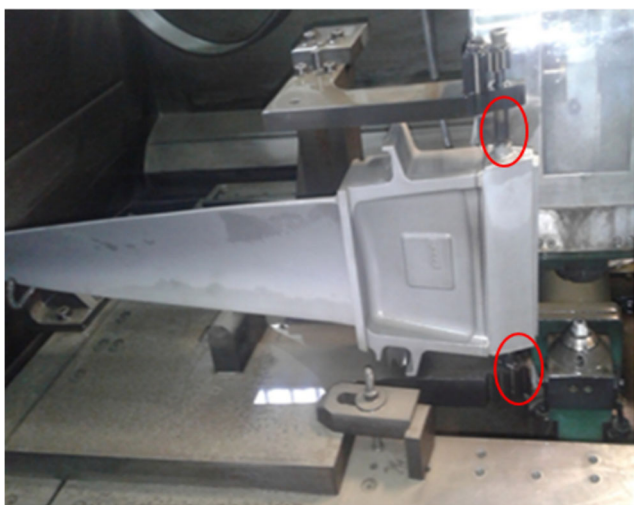


Fig. 6 Machining device intended for machining the tree root of the blade with wire EDM

reference is usually defined by the designer to ensure the positioning of the blades in the 3D space at the wheel (stage) of the turbine rotor.

The machining fixture of this case study is designed referring to this reference specified in the 3D model (IGES) of the gas turbine blade (casting).

This machining fixture will contain six (06) independent positioning elements, which will eliminate the six (06) degrees of freedom of the blade. The six points will be distributed on the fixturing surface at the area of the airfoil (Fig. 1) based on an optimization approach discussed in the following work.

Figure 2 shows a turbine blade, where the positioning features and the clamping elements are placed on the blade airfoil at sections AA, BB, and CC. The surfaces to be machined at the root and the tip of the blade are also shown in this figure. The effect of sections AA, BB, and CC on the localization repeatability is also discussed in this study.

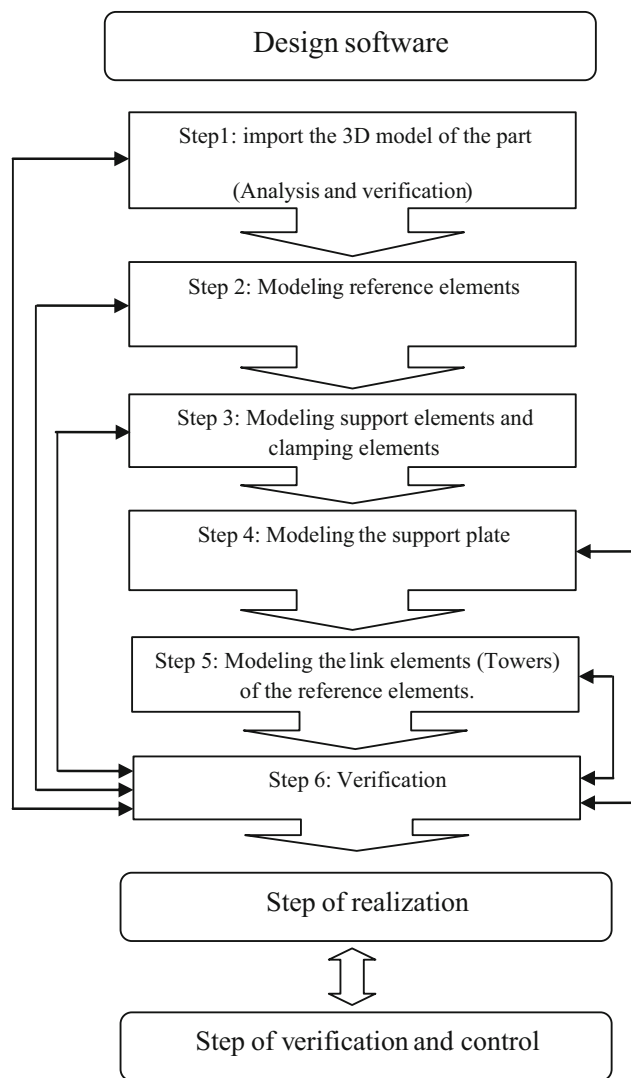


Fig. 7 Flowchart showing the designing steps of the MF

The main objective of this study through this fixture is to create a new reference system on the root of the blade by the transfer and the elimination of five positioning elements equivalent to the five degrees of freedom (03 translations and 02 rotations). The new positioning elements are conical contacts, one must be fixed and the other mobile (Fig. 3).

This new reference system will have to be unique for other machining fixtures in order to facilitate the positioning and the holding of the blades (Fig. 4).

Due to the complexity of the part including the airfoil of the blade where the six reference points are located, and due to the various operations that the blade will undergo, various machining fixtures should be implemented at the base of this new reference. Depending on the nature of the machining process to be used, the new reference created on the root of the blade can be used for drilling of the cooling holes by ECD (Fig. 5) and for machining the tree root of the blade with wire EDM (Fig. 6).

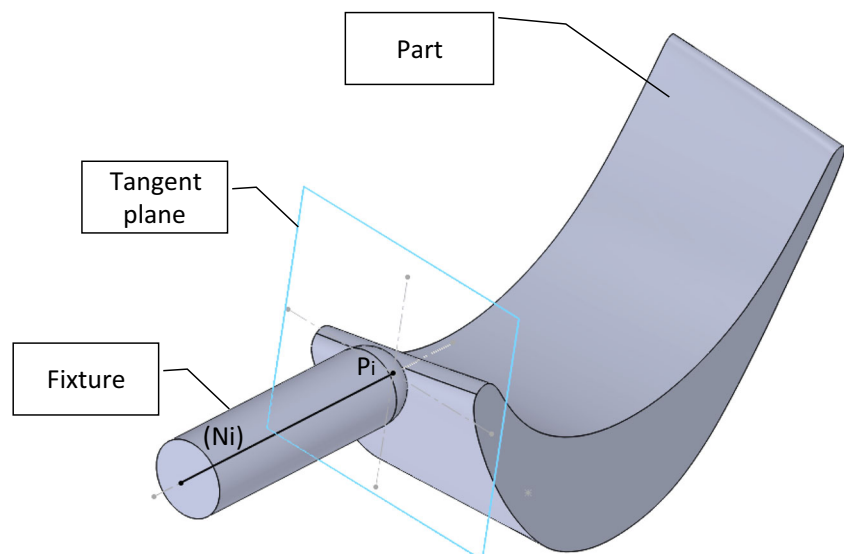
3 Design strategy

In order to perform an optimal design, some technical points have to be taken into consideration:

- The 3D digitized model must be consistent with the model of the real turbine blade.
- The Cartesian coordinates of the blade reference frame with respect to its location in the turbine assembly are known.
- A wide range of standard accessories such as fasteners and support elements to optimize the design time are known.

Based on his technical and experimental knowledge, a skilled designer would be able to design a machining fixture that meets technological and functional requirements, such as:

Fig. 8 Normal line (N_i) to the contact point P_i



- Ensure a good positioning of the part, with a good repeatability, i.e., every part must be located in exactly the same position every time.
- Ensure a good holding of the workpiece (good stability) during machining.
- Facilitate the mounting and dismounting of workpieces in an optimum time.
- Have an open design to facilitate easy access of the cutting tool to the surface to be machined.
- Ensure the safety of the operator.
- Adapt to other functions, such as measurement and sinking EDM operations.

The different constraints influencing the design of the machining fixture are as follows:

- Physical constraints
- Assembly constraints
- Manufacturing constraints
- The aesthetic constraints

The design of the machining fixture is carried out according to the flowchart presented in Fig. 7.

4 Choice of the locator's placement

During this work, we assume that the part to be machined behaves as a rigid body and that our study is limited only to the airfoil of the blade (the part containing the six points of support).

According to Duret et al. [29], two powerful indicators can be used to assess the workpiece localization repeatability and, hence, evaluate the quality of a machining fixture. These indicators are the determinant D of the locators' placement information matrix and its condition number K .

In this work, the information matrix is used to determine the locator’s placement during the design process.

To define the locators’ placement information matrix, a point of contact (P_i) between the part and the fixture is first defined and after having defined the tangent plane, the normal line (N_i) passing through the contact point (P_i) is then created as shown in Fig. 8.

Assuming that the machine tool/machining fixture assembly is associated with a coordinate system R ($O, \vec{x}, \vec{y}, \vec{z}$), accordingly, each normal line can be defined by its Plückerian coordinates [36] as shown in Fig. 9.

$$\vec{n}_i \begin{vmatrix} n_{xi} \\ n_{yi} \\ n_{zi} \end{vmatrix} \text{ and } \overrightarrow{OP_i} \begin{vmatrix} x_i \\ y_i \\ z_i \end{vmatrix}$$

where \vec{n}_i is a unit vector of (N_i).

The vector product is calculated as follows:

$$\vec{V}_{oi} = \overrightarrow{OP_i} \wedge \vec{n}_i \tag{1}$$

The Plückerian coordinates are defined by the following six scalar quantities (components) [36].

$$\{P_i\} = \left\{ \begin{matrix} \vec{n}_i \\ \overrightarrow{OP_i} \wedge \vec{n}_i \end{matrix} \right. = \begin{cases} n_{xi} \\ n_{yi} \\ n_{zi} \\ y_i \cdot n_{zi} - z_i \cdot n_{yi} \\ z_i \cdot n_{xi} - x_i \cdot n_{zi} \\ x_i \cdot n_{yi} - y_i \cdot n_{xi} \end{cases} \tag{2}$$

According to Duret [36], the locator’s placement information matrix can be presented as:

$$\{P_i\} = \begin{vmatrix} n_{x1} & n_{x2} & n_{x3} & n_{x4} & n_{x5} & n_{x6} \\ n_{y1} & n_{y2} & n_{y3} & n_{y4} & n_{y5} & n_{y6} \\ n_{z1} & n_{z2} & n_{z3} & n_{z4} & n_{z5} & n_{z6} \\ y_1 \cdot n_{z1} - z_1 \cdot n_{y1} & y_2 \cdot n_{z2} - z_2 \cdot n_{y2} & y_3 \cdot n_{z3} - z_3 \cdot n_{y3} & y_4 \cdot n_{z4} - z_4 \cdot n_{y4} & y_5 \cdot n_{z5} - z_5 \cdot n_{y5} & y_6 \cdot n_{z6} - z_6 \cdot n_{y6} \\ z_1 \cdot n_{x1} - x_1 \cdot n_{z1} & z_2 \cdot n_{x2} - x_2 \cdot n_{z2} & z_3 \cdot n_{x3} - x_3 \cdot n_{z3} & z_4 \cdot n_{x4} - x_4 \cdot n_{z4} & z_5 \cdot n_{x5} - x_5 \cdot n_{z5} & z_6 \cdot n_{x6} - x_6 \cdot n_{z6} \\ x_1 \cdot n_{y1} - y_1 \cdot n_{x1} & x_2 \cdot n_{y2} - y_2 \cdot n_{x2} & x_3 \cdot n_{y3} - y_3 \cdot n_{x3} & x_4 \cdot n_{y4} - y_4 \cdot n_{x4} & x_5 \cdot n_{y5} - y_5 \cdot n_{x5} & x_6 \cdot n_{y6} - y_6 \cdot n_{x6} \end{vmatrix} \tag{3}$$

From this 6×6 matrix, the associated determinant is calculated. If this determinant is null, it means that the rank of the system is not equal to 6, the mechanism retains degrees of freedom and, therefore, the machining fixture does not perfectly perform their functions.

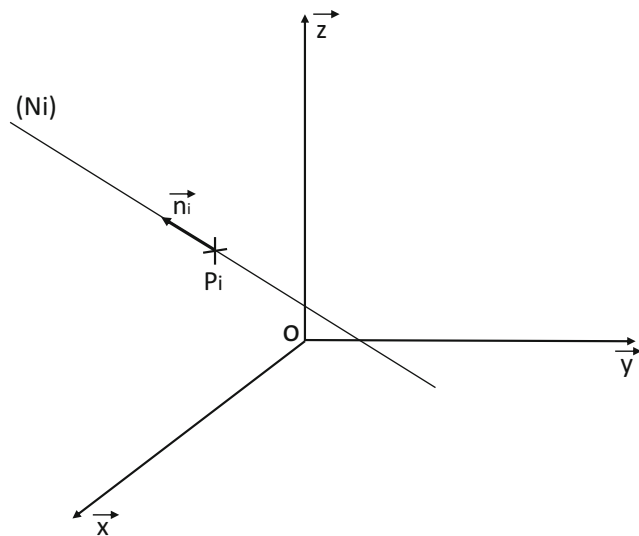


Fig. 9 Position of line (N_i) in the coordinate system R

The second quality indicator is the condition number K of the $\{P_i\}$ matrix. It is well known that a matrix is well or poorly conditioned depending on whether its condition number is small (close to 1) or large. Poorly conditioned matrices often have a high condition number and a determinant close to 0.

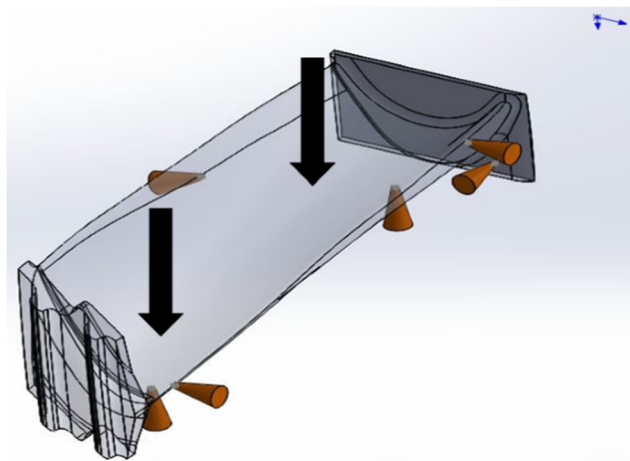


Fig. 10 Locators’ placement and clamping force direction in the turbine blade

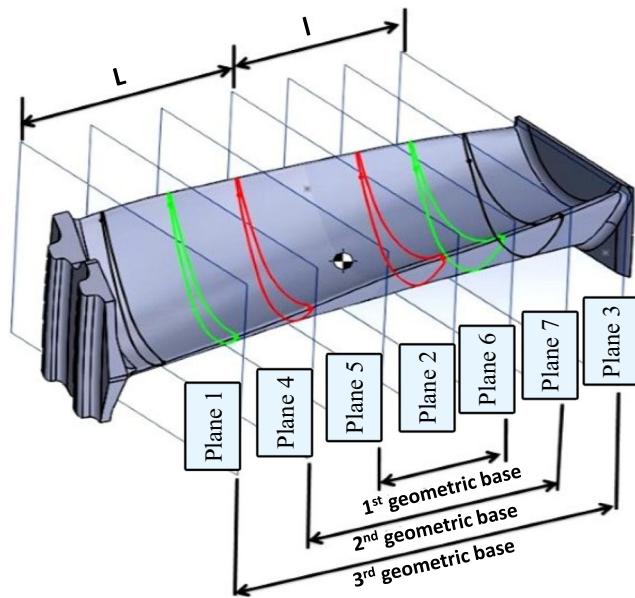


Fig. 11 Presentation of the three geometric bases

Practically, the clamping force (Fig. 10) can affect the workpiece localization and have to be taken into consideration during the design and evaluation of the quality of a machining fixture.

For static equilibrium, the actions of the fixture on the workpiece (F_1, F_2, \dots, F_6) at each contact point can be calculated as follows [36]:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} = [\text{Coord_Pluck}]^{-1} \begin{bmatrix} -P_x \\ -P_y \\ -P_z \\ -y_p \cdot P_z + z_p \cdot P_y \\ -z_p \cdot P_x + x_p \cdot P_z \\ -x_p \cdot P_y + y_p \cdot P_x \end{bmatrix} \quad (4)$$

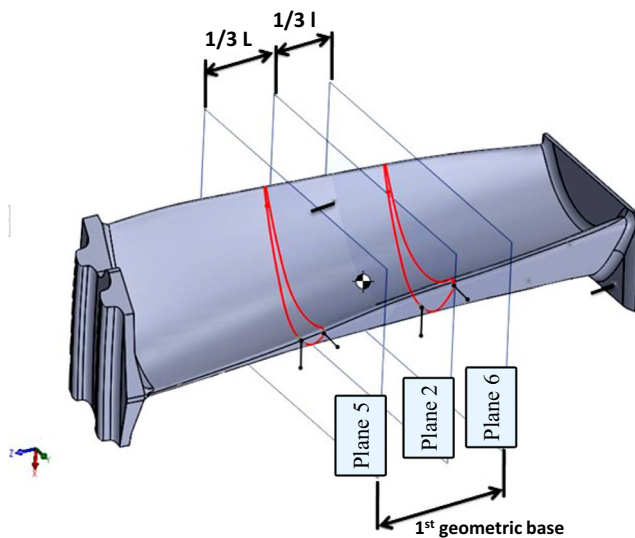


Fig. 12 Presentation of the 1st geometric base with the six normal vectors

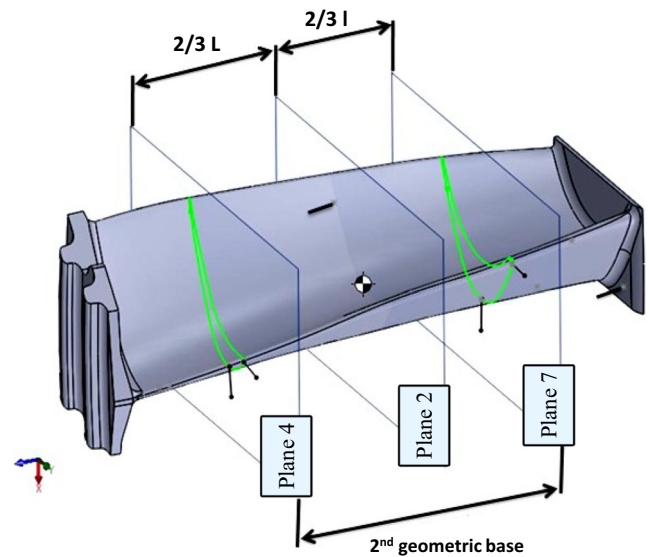


Fig. 13 Presentation of the 2nd geometric base with the six normal vectors

where Coord_Plück is the transformation matrix which represents the relationship between the three components of the clamping force ($P_x, P_y,$ and P_z) while the actions of the fixture on the workpiece are expressed as (F_1, F_2, \dots, F_6).

The accuracy of the estimation is closely related to the condition number of the Coord_Plück matrix.

As shown in Figs. 11, 12, 13, and 14, the airfoil (potential locators' placement area) of the blade is divided into three geometric bases. The six components of the Plückerian coordinates (Table 1) for each geometric base were then identified and the three transformation matrices were developed (Table 2). Only the geometrical base that maximizes the determinant and minimizes the conditioning number of the transformation matrix is taken into consideration during the design process.

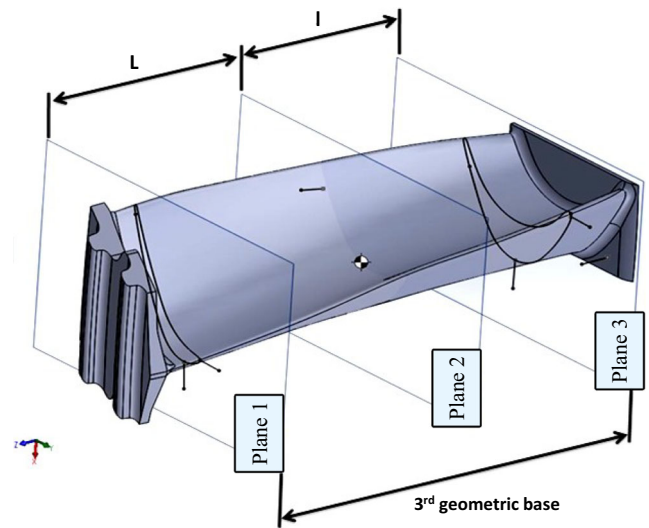


Fig. 14 Presentation of the 3rd geometric base with the six normal vectors

Table 1 The six components of the Plückerian coordinates

	P_1	P_2	P_3	P_4	P_5	P_6
x_i	x_1	x_2	x_3	x_4	x_5	x_6
y_i	y_1	y_2	y_3	y_4	y_5	y_6
z_i	z_1	z_2	z_3	z_4	z_5	z_6
n_{xi}	n_{x1}	n_{x2}	n_{x3}	n_{x4}	n_{x5}	n_{x6}
n_{yi}	n_{y1}	n_{y2}	n_{y3}	n_{y4}	n_{y5}	n_{y6}
n_{zi}	n_{z1}	n_{z2}	n_{z3}	n_{z4}	n_{z5}	n_{z6}

From this table, the Plückerian coordinate matrix for each geometrical base can be established as follow:

$$\{P_i\} = \begin{pmatrix} n_{xi} \\ n_{yi} \\ n_{zi} \\ y_i \cdot n_{zi} - z_i \cdot n_{yi} \\ z_i \cdot n_{xi} - x_i \cdot n_{zi} \\ x_i \cdot n_{yi} - y_i \cdot n_{xi} \end{pmatrix} = \begin{pmatrix} n_{xi} \\ n_{yi} \\ n_{zi} \\ V_{oxi} \\ V_{oyi} \\ V_{ozi} \end{pmatrix} \quad (5)$$

Figure 15 shows the variation of the determinant of the matrix $\{P_i\}$ as a function of the dimension of the geometric base (six locating points of the turbine blade). We can observe from this figure that the 3rd geometrical base has a good quality for the machining fixture, with a determinant of 3.6×10^6 . We can also conclude from this figure that, the greater the “geometric base,” the greater the value of the determinant.

In order to have more accurate optimization results, the orientation angles of the planes containing the four locating points ($P_1, P_2, P_4,$ and P_5) located in the selected geometric base and related successively to the normal vectors ($n_1, n_2, n_4,$ and n_5) as shown in Fig. 16 are included in the optimization procedure. To achieve this

goal, the inclination angles of the planes tangential to the spline of section I (containing P_1 and P_2) and section II (containing P_4 and P_5) presented in Fig. 16 vary according to the sequence presented in Table 3. Accordingly, the normal vectors of each new inclined plane are calculated and represented in Fig. 17.

Figures 18 and 19 show the results of the optimization process. It can be seen from these histograms that the best locations of $P_1, P_2, P_4,$ and P_5 points are in the plane oriented at about 45° from horizontal. This orientation provides the highest determinant and the lowest condition number of the Plückerian matrix. Nevertheless, this location cannot be reached practically, due to the following constraints:

- The need to align the leading edges of the set of blades at a specific angle relative to the transverse plane (plane perpendicular to the axis of the turbine), this constraint is ensured by the two points (P_1 and P_4) as shown in Fig. 20.
- The need to have a homogeneous distribution (balanced) of all the blades around the axis of the turbine (constant volumes between each two successive blades), this constraint is ensured by the two points (P_2 and P_5) as shown in Fig. 20.

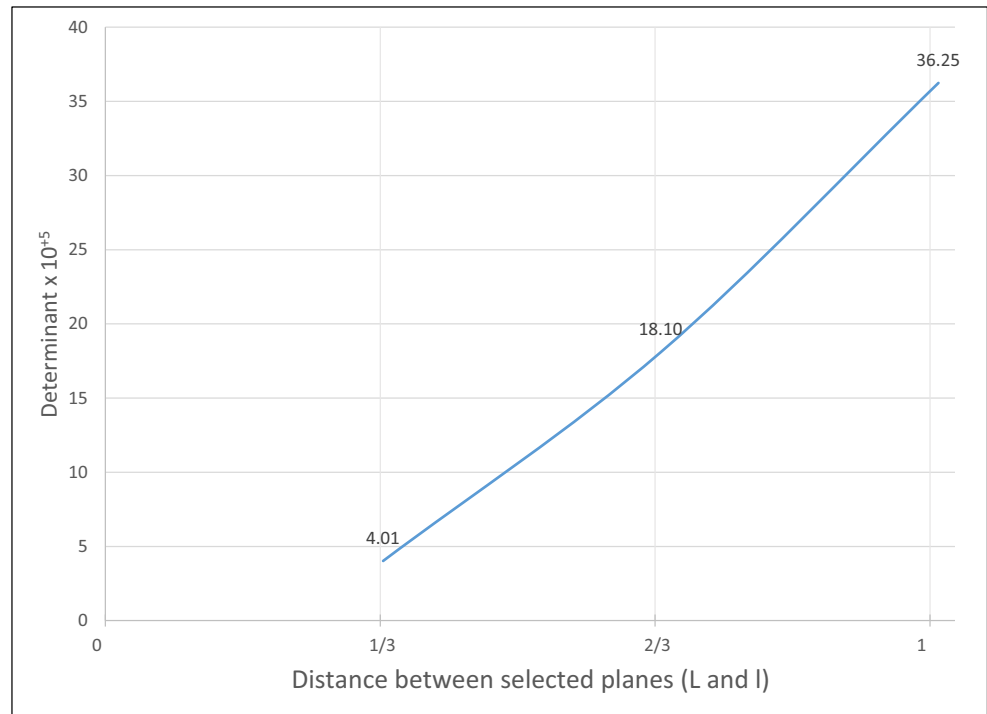
It is worth to mention that the two points P_3 and P_6 do not have a big influence on the variation of the two indicators (the determinant and the condition number), the point P_3 eliminates the rotation around the Z-axis. Practically in the turbine, this point ensures the angle of orientation of the blade airfoil, and therefore the orientation of the burned gases to the next stage of vanes.

Point P_6 eliminates the translation along the Z-axis and practically ensures the radial alignment of the inner bandages (Fig. 21). In fact, this point may coincide with the bandage

Table 2 Plückerian coordinate matrix for each geometrical base

	P_1	P_2	P_3	P_4	P_5	P_6
n_{xi}	$nx1$	$nx2$	$nx3$	$nx4$	$nx5$	$nx6$
n_{yi}	$ny1$	$ny2$	$ny3$	$ny4$	$ny5$	$ny6$
n_{zi}	$nz1$	$nz2$	$nz3$	$nz4$	$nz5$	$nz6$
V_{oxi}	$Vox1$	$Vox2$	$Vox3$	$Vox4$	$Vox5$	$Vox6$
V_{oyi}	$Voy1$	$Voy2$	$Voy3$	$Voy4$	$Voy5$	$Voy6$
V_{ozi}	$Voz1$	$Voz2$	$Voz3$	$Voz4$	$Voz5$	$Voz6$

Fig. 15 Determinant variation as function of the geometric bases



inside the blade root, and it may also coincide with the bandage inside the blade tip.

To confirm the validity of the proposed approach and the quality of isostatism of the part, the analysis of determinant D and the condition number K is applied to another prismatic part (equivalent to our airfoil part). This one includes the same geometrical base but it is located using the conventional 3–2–1 isostatism principle, since this system is the most stable (Fig. 22).

The histograms presented in Figs. 23 and 24 show successively the determinants D and the condition number K , of the new matrix for the three following cases:

- An equivalent prismatic part with the six points of the blade projected on all three sides, concretizing the 3–2–1 location principle, with the abbreviation E.P./P.P.
- An equivalent prismatic part with the conventional 3–2–1 system, with the abbreviation E.P.P.

Fig. 16 Representation of the six points of isostatism and their related normal vectors

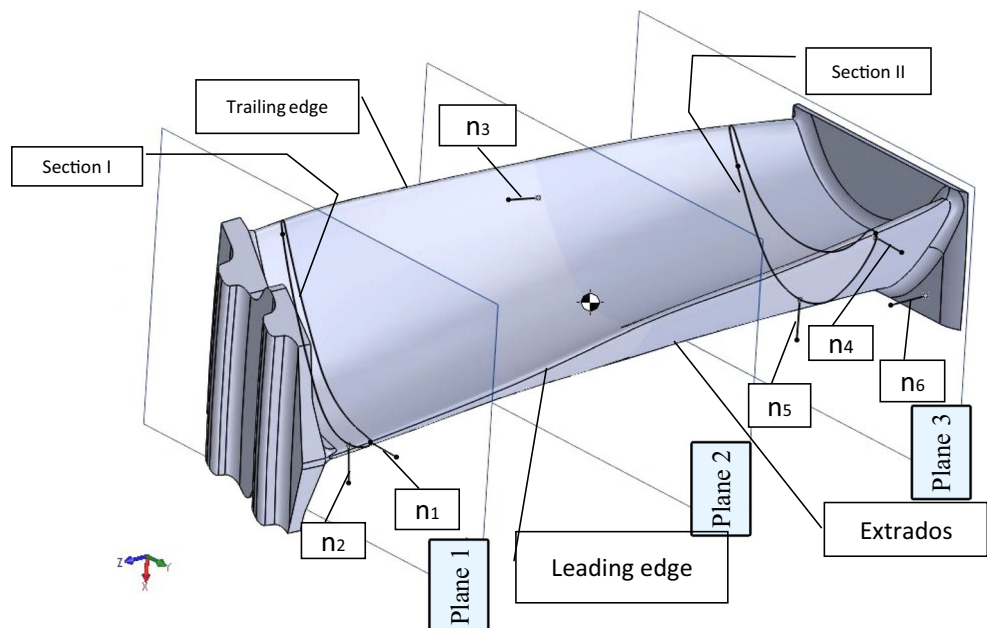








Table 3 Angle of the oriented planes with their associated normal vectors

Color of the normal vector for each new oriented plane	Oriented plane and its normal vector
	n5 normal to plane 0° and n4 normal to plane 90°
	n5 normal to plane 0° and n4 normal to plane 60°
	n5 normal to plane 45° and n4 normal to plane 45°
	n5 normal to plane 60° and n4 normal to plane 60°
	n5 normal to plane 60° and n4 normal to plane 90°
	n5 normal to plane 30° and n4 normal to plane 30°

- The airfoil blade object of study, with the abbreviation PALE.

since the determinant and the condition number of our machining fixture for the gas turbine blade are very close to those of the two equivalent prismatic pieces (E.P.P and E.P.P/P.P).

where

- E.P.P/PP: the equivalent prismatic piece with projected points
- E.P.P: the equivalent prismatic piece
- PALE: the airfoil blade

Results presented in Figs. 23 and 24 show that our machining fixture also has a good localization (isostatism) quality

5 Machining strategy

During the fabrication of the machining fixture, two workstations were coupled for the realization of the various components, the 5-axis vertical machining center (VMC) type DMG with Siemens (Sinumerik 840d) controller (Fig. 25), and the wire electrical discharge machining (EDM) machine type

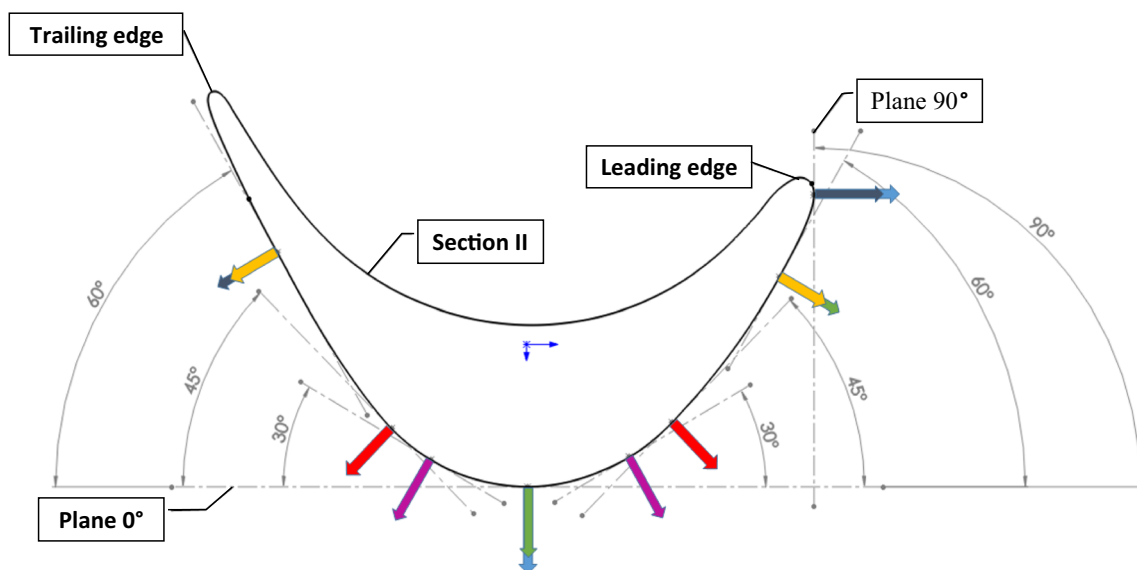


Fig. 17 Inclination angles of the different planes with their associated normal vectors for section II

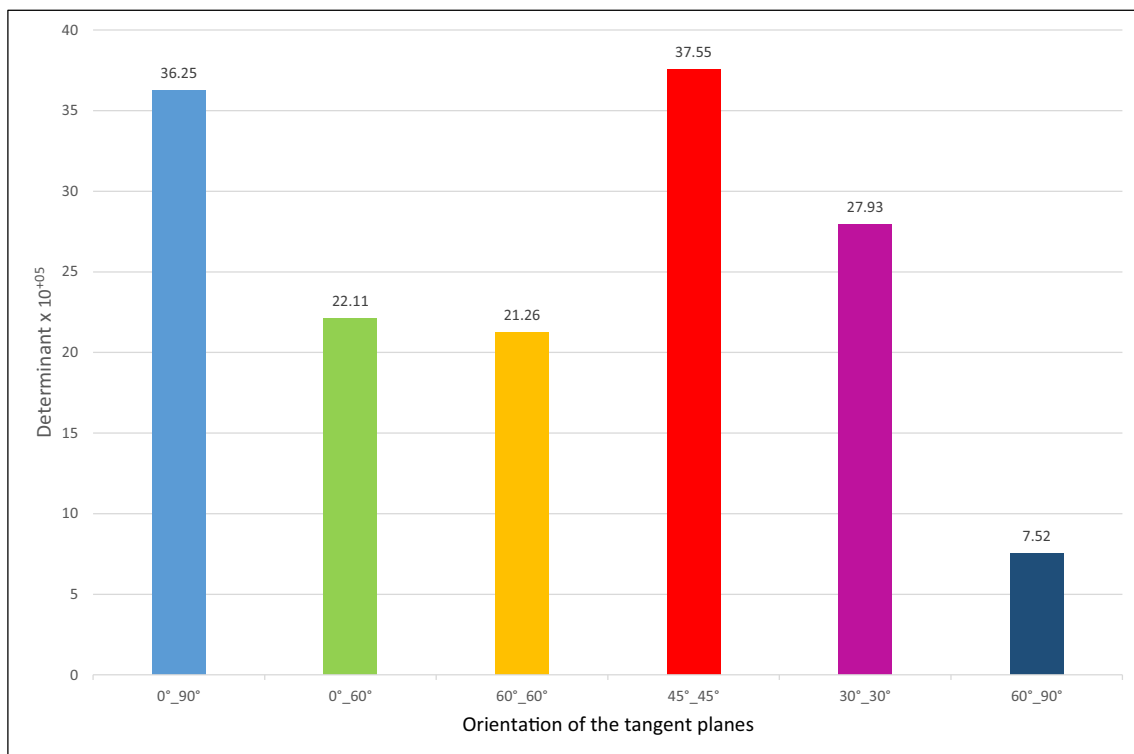


Fig. 18 Determinant variation

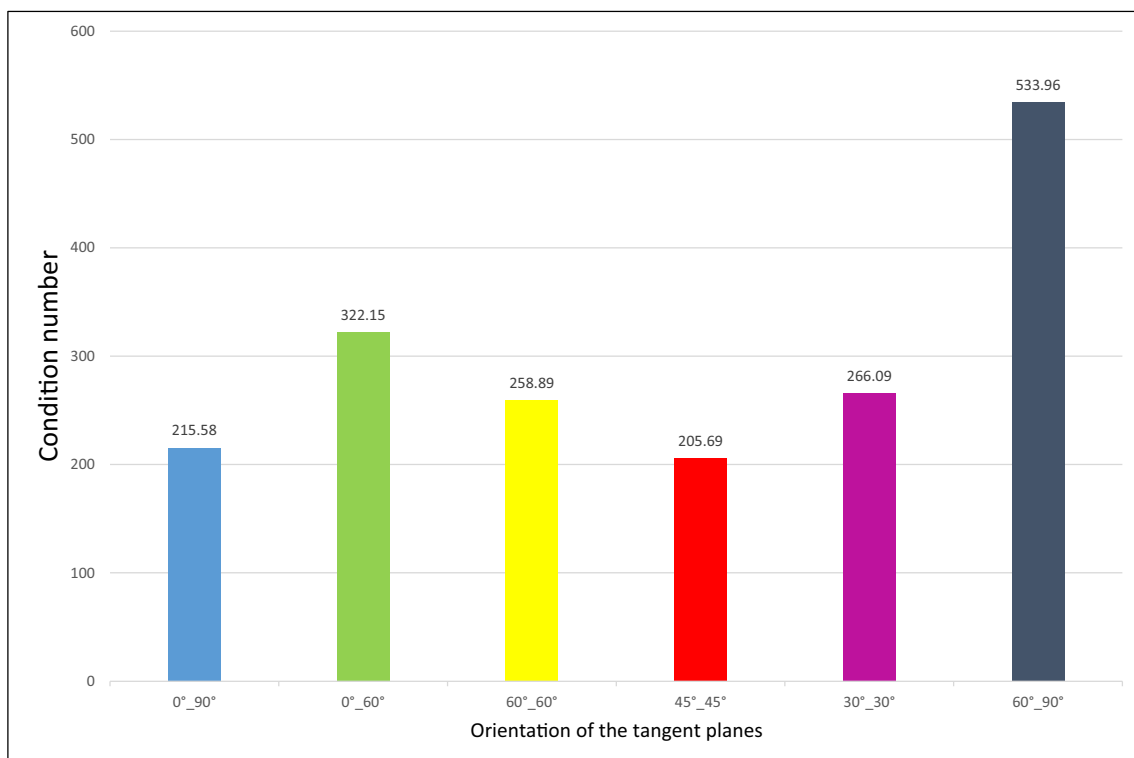


Fig. 19 Condition number variation

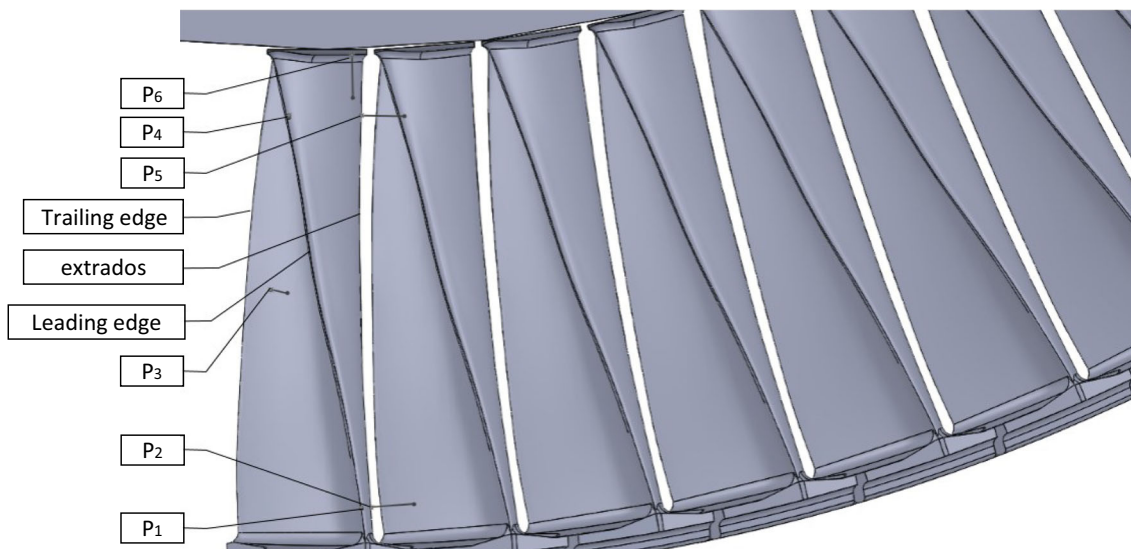


Fig. 20 Distribution of blades around the turbine axis

ONA AF35 (Fig. 26). The quality of the manufactured machining fixture was evaluated based on turbine blade localization repeatability. A hexagon coordinate measuring machine is used for this purpose (Fig. 27).

Several components of the machining fixture have been machined separately from the raw state to the final phase either using the VMC or the wire EDM machine. However, the positioning elements were fabricated using the same way, except for the faces that are in contact with the airfoil of the blade, where they are postponed after the final fixture step. The finishing machining phase of the positioning elements was imperatively carried out on the 5-axis VMC, in a single phase, a single hold, and with the same reference system as that of the design. Two programming modes were used during the realization of the machining fixture components, the direct

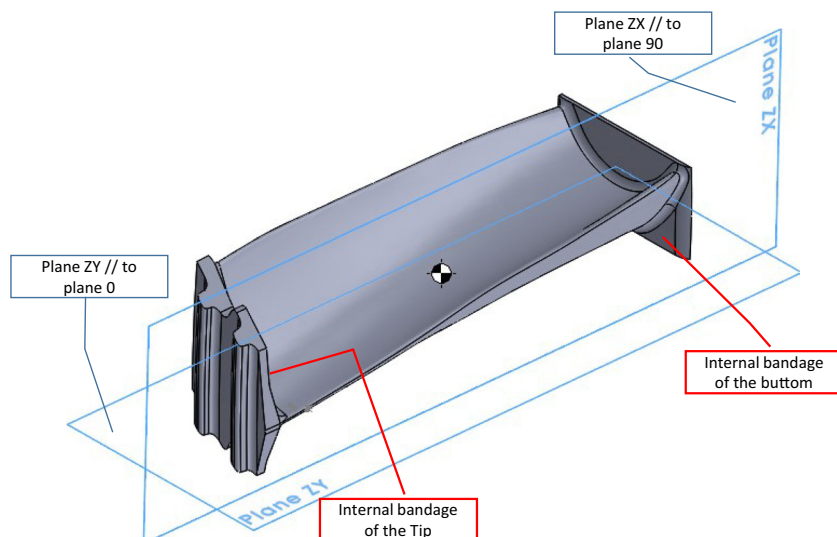
mode on the machine for the 2-axis 1/2 machining by the Shop-Mill software at the VMC, and the ONA AF35 machine software for the wire EDM machine.

Figures 28 and 29 represent respectively the 3D CAD model of the machining fixture and the real (fabricated) machining fixture holding the machined mobile blade.

6 Evaluation of the fixture quality based on turbine blade localization repeatability

The purpose of the quality control of the machining fixture is to guarantee the conformity of our device with the specifications and its correct operation in an industrial environment. It is important to remind in this context that machining fixture is

Fig. 21 Representation of the two inner bandages



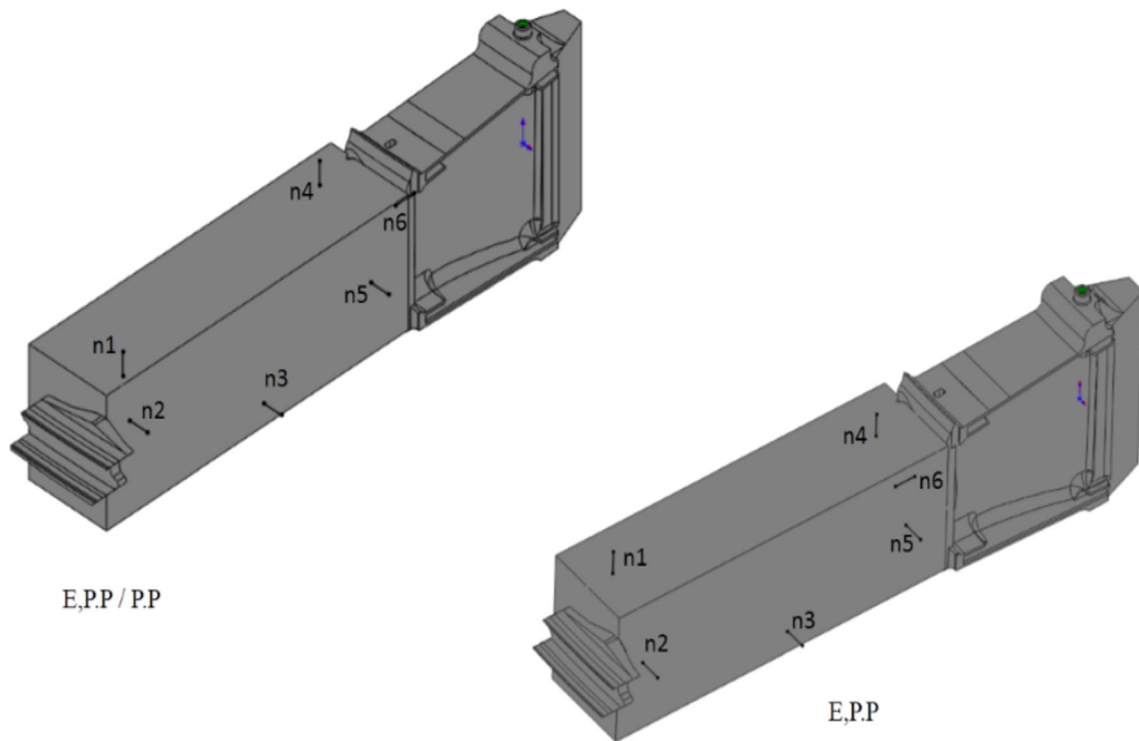


Fig. 22 Prismatic part includes the airfoil

developed especially to create and fabricate a new reference system on the root of the blade. Accordingly, two validation tests were carried out. The first test concerns the evaluation of the static stability of the semi-finished turbine blade on the developed machining fixture without disassembly (Fig. 29),

by the experimental sensation of vibrations and abnormal noises in the machine shop using 100 measurements. The second test aims to analyze the performance of the machining fixture by the evaluation of the localization repeatability of the workpiece on the fixture.

Fig. 23 Comparison of determinants

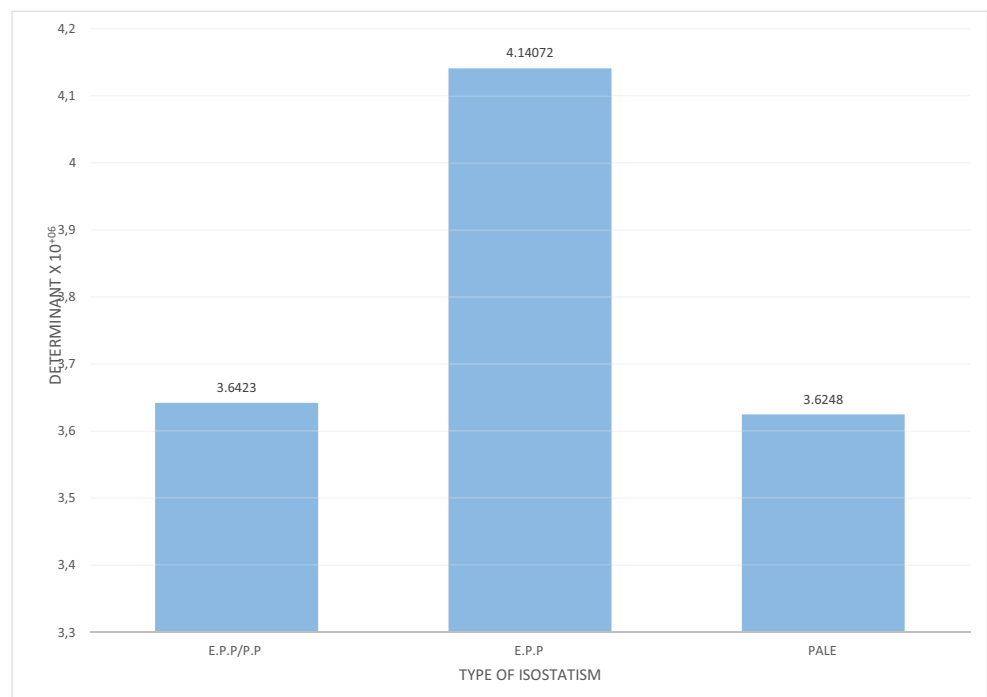
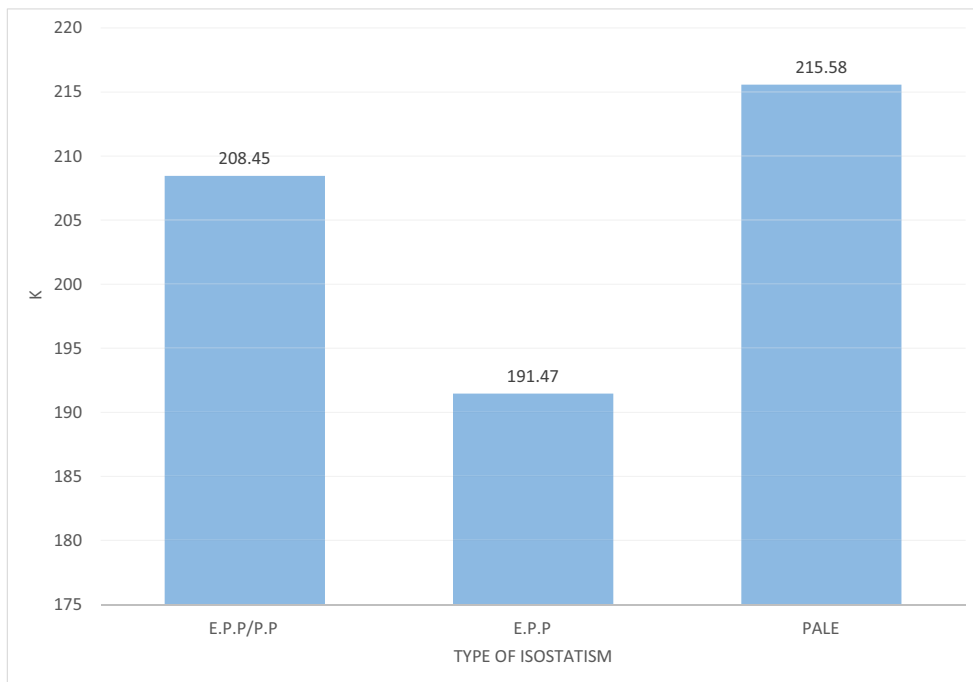


Fig. 24 Comparison of pseudo-condition K



Assuming that the displacements of the workpiece on the machining fixture are small compared with its geometric dimension. In this case, the localization repeatability can be modeled by a Small Displacement Torsor (STD). According to its concept, the STD includes six magnitude scalars, three small rotations (α , β , γ), and three small translations (u , v , w) [29].

As explained above, by using the Plückerian coordinates approach and according to Duret et al. [29], the STD components can be defined as:

$$\begin{bmatrix} V_{ox1} V_{oy1} V_{oz1} n_{x1} n_{y1} n_{z1} \\ V_{ox2} V_{oy2} V_{oz2} n_{x2} n_{y2} n_{z2} \\ V_{ox3} V_{oy3} V_{oz3} n_{x3} n_{y3} n_{z3} \\ V_{ox4} V_{oy4} V_{oz4} n_{x4} n_{y4} n_{z4} \\ V_{ox5} V_{oy5} V_{oz5} n_{x5} n_{y5} n_{z5} \\ V_{ox6} V_{oy6} V_{oz6} n_{x6} n_{y6} n_{z6} \end{bmatrix} \cdot \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_5 \\ \delta_6 \end{bmatrix} \quad (6)$$

where

$$V_{oxi} = y_i \cdot n_{zi} - z_i \cdot n_{yi} \quad (7)$$



Fig. 25 The Five-axis vertical machining center (VMC) type DMG



Fig. 26 The ONA AF35 wire electrical discharge machining machine

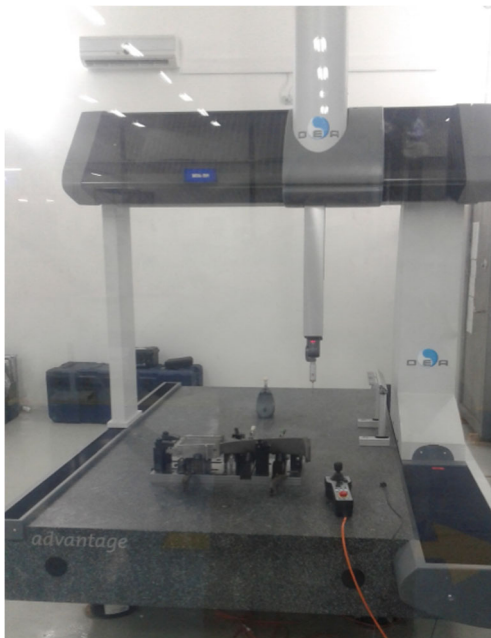


Fig. 27 Hexagon coordinate measuring machine (CMM)

$$V_{oyi} = z_i \cdot n_{xi} - x_i \cdot n_{zi} \quad (8)$$

$$V_{ozi} = x_i \cdot n_{yi} - y_i \cdot n_{xi} \quad (9)$$

$$\delta_{ik} = n_{ix}(x_{ik} - x_{i0}) + n_{iy}(y_{ik} - y_{i0}) + n_{iz}(z_{ik} - z_{i0}) \quad (10)$$

This matrix equation can be rewritten in a simple form as:

$$[A] \cdot [\infty] = [\delta] \quad (11)$$

$$[\infty] = [A]^{-1} \cdot [\delta] \quad (12)$$

This equality presents a system of linear equations. The resolution of this system of equations by least squares gives the six components of the SDT.

To build matrix A, the six theoretical points (six reference points) are first taken from the CAD model. Then, an inspection program based on these six points is developed and applied on a CMM to measure the real six points (contact locators/semi-finished blade) for each configuration. A new

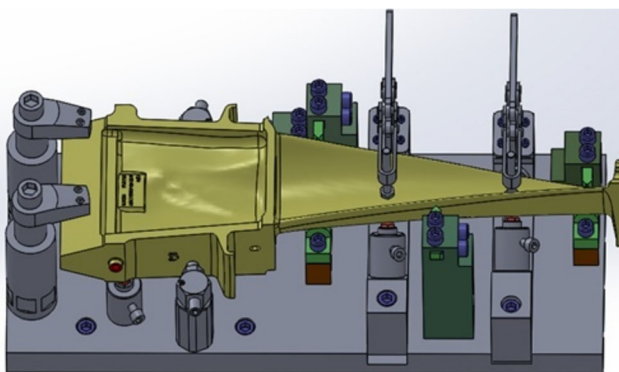


Fig. 28 CAD model of the machining fixture in its final phase

location of the semi-finished blade, defined after each disassembling and reassembling of the semi-finished blade on the fixture, is measured using the same program (six measuring points P_1 to P_6). The measurements are repeated five times; this means that the six components of the SDT are identified five times.

The variability of the six components of the SDT is quantified by an experimental standard deviation. This variability represents the quality of localization of the machining fixture.

During the measurement, the points to be measured may be located in places inaccessible to the stylus tip due to the constraints of contact between locators and the workpiece. However, according to the property of the equiprojectivity, the probing of the six contact points (M_i) for the six positioning locators can be taken anywhere on the normal line (N_i). Accordingly, the measured points have been selected along the normal line (N_i) of each contact point (between locators and the workpiece) but on the opposite side as shown in Figs. 30 and 31.

Figure 32 shows the results of the static stability tests (without disassembly). It can be seen from these results that the variability of the six measured points is very small which means that the measurement noise is minimal. Therefore, it is neglected in the following calculations. This noise can be due to many sources such as operator, equipment, method, machine, and environment.

As mentioned above, for each new location of the semi-finished blade on the machining fixture, the coordinates of 6 points on the blade are measured and the normal vectors n_i for each point are calculated. Furthermore, the error vector between the measured position and the theoretical position δ_i for each point is calculated and projected according to the normal.

After solving the linear equation system, the six unknown components (α , β , γ , u , v , w) of the SDT are obtained (Figs. 33 and 34).

The quality of a machined assembly is certified by the variability of the unknowns. Since the localization test is repeated five times, the variability of the components (α , β , γ , u , v , w) is expressed by an experimental standard deviation and presented in Figs. 33 and 34.

A closer look at these figures reveals that the variability of the SDT components is small which indicates the high localization repeatability of the developed machining fixture. It can be seen also from these figures that the rotational component (∞) along the X-axis is larger compared to the two other components. This may be due to the thin-walled nature of the airfoil and its low stiffness which distort slightly around the X-axis under the action of the clamping force. Figure 34 shows also that the maximum displacement was found along the Z-axis due to effect of the clamping force.

Fig. 29 Photo of the manufactured machining fixture holding the mobile blade

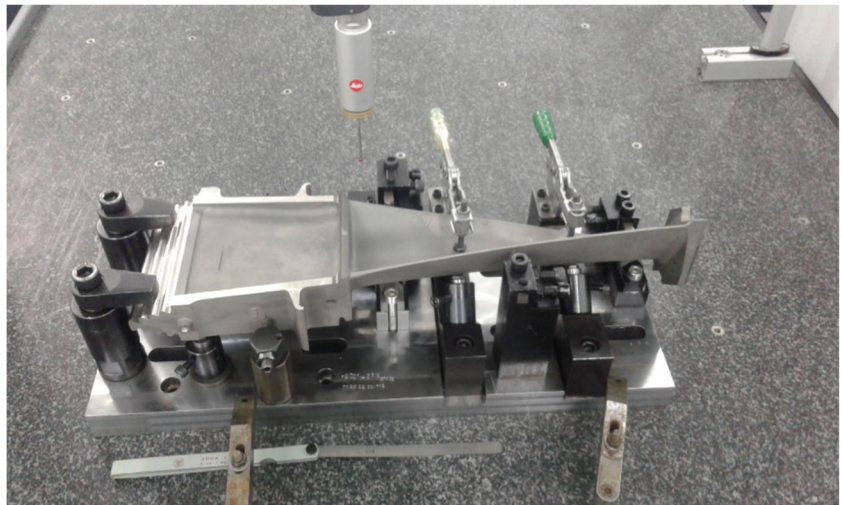


Fig. 30 Schematic illustration of the contact points with their associated normal vectors

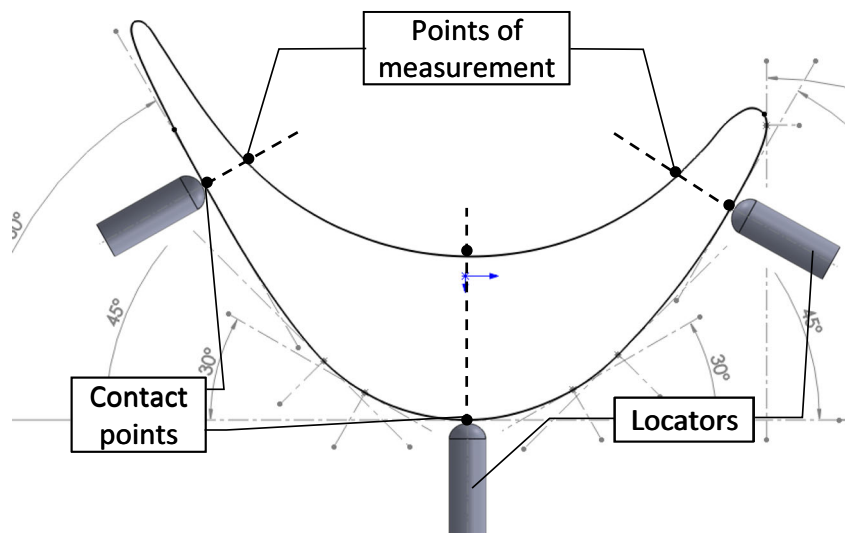
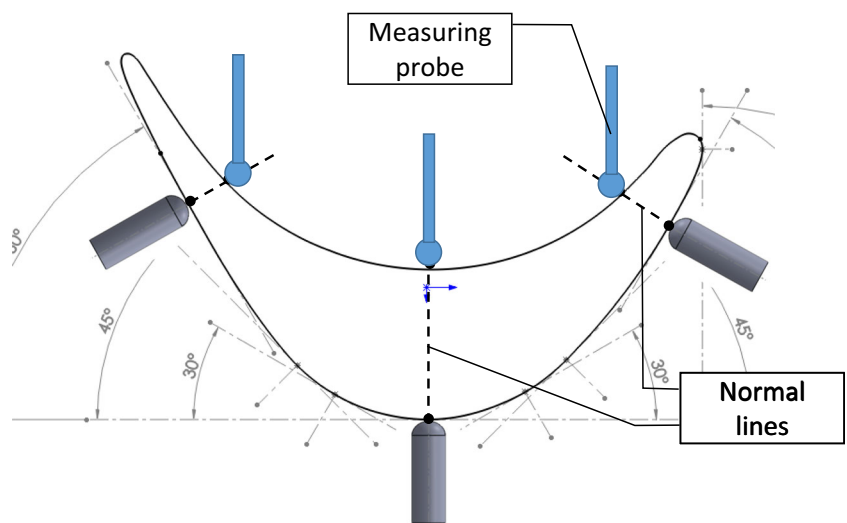


Fig. 31 Schematic illustration of the measuring points for the repeatability tests



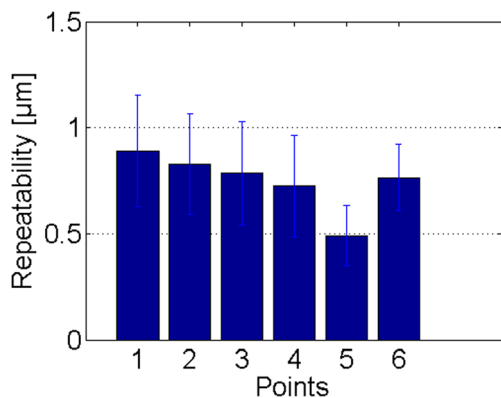


Fig. 32 Quantification of the measurement noises by an experimental standard deviation

It is worth mentioning that, in our case, the permissible error during the machining of the turbine blade is in the order of 100 to 200 μm .

It is noteworthy that the developed machining fixture proved to be effective in practice and is currently used in industrial applications where many references were created with high quality in the turbine blades every day. Accordingly, the created reference in the turbine blade is then used to facilitate the positioning and the holding of the blade during the drilling of the cooling holes by ECD (Fig. 5) and for machining the tree root of the blade with wire EDM (Fig. 6).

7 Conclusion

Machining fixture for components with irregular shape (complex surfaces) such as mobile blade of a gas turbine has a significant impact on the accuracy of the machined parts. In this paper, a special machining fixture for parts with complex geometries was designed and fabricated.

The contents and results included in this paper can be summarized as follows:

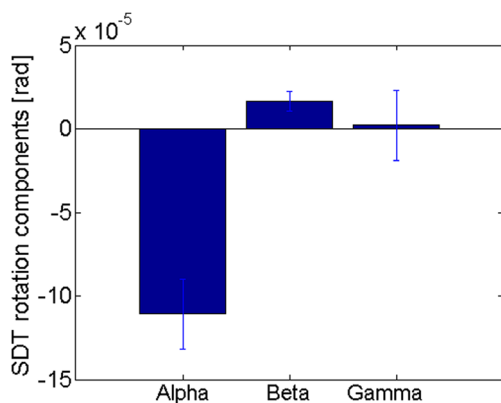


Fig. 33 Variability of the three small rotations (α , β , γ)

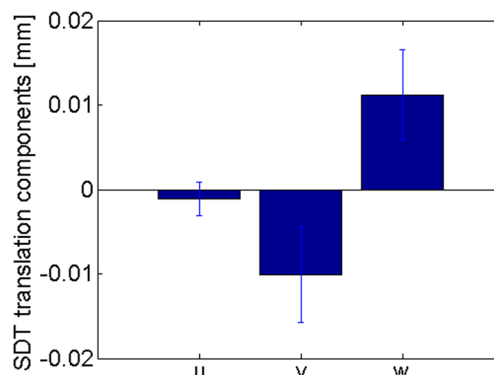


Fig. 34 Variability of the three small translations (u , v , w)

- Plückerian coordinates were used to build the locator matrix;
- The determinant and the condition number of the locator matrix were used as criteria for optimization of the fixture locator positioning;
- Small displacement torsor (STD) concept was used to evaluate the localization repeatability of the workpiece on the fabricated fixture;
- The variability of the six components of the SDT after each disassembling and reassembling of the semi-finished blade was quantified by an experimental standard deviation;
- The results obtained from the static stability tests (without disassembly of the part) showed that the measurement noise was minimal. Therefore, it was neglected in this study;
- Results show that the clamping force and the low stiffness of airfoil zone of the turbine blade were the key factors affecting the localization repeatability;
- The rotational component (∞) of the SDT around the X -axis was found larger compared to the two other components. This may be due to the action of the clamping force and the low stiffness of the airfoil in this direction.
- The maximum displacement was found along the Z -axis due to the effect of the clamping force;
- Results also show that the variability of the computed SDT components was small which indicates the high localization repeatability of the developed machining fixture.

According to the permissible error from the designer (100 to 200 μm), our experimental results show that the developed machining fixture can locate the workpiece at the right position with high repeatability and reproducibility.

Abbreviations *FEA*, Finite element analysis; *VMC*, Vertical machining center; *CMM*, Coordinate measuring machine; *EDM*, Electrical discharge machining; *ECM*, Electro-chemical machining; *ECD*, Electro-chemical discharge; *MF*, Machining fixture; *D*, Determinant of a matrix; *K*, Condition

number of a matrix; P_i , i th point; N , Normal line in the i th point; $\overrightarrow{V_{oi}}$, Product vector; $\overline{n_i}$, Unit vector of (N) in the i th point; $\overline{OP_i}$, Position vector of the i th point; $\{P_i\}$, Plückerian coordinate matrix; R , Coordinate system reference; STD , Small displacement torsor; n_{xib} n_{yib} n_{zib} Three components of $\overline{n_i}$; x_b y_b z_b Three components of P_i ; V_{oxib} V_{oyib} V_{ozib} Three components of V_{oi}

Author contribution Mustapha Arslane was responsible for the literature study, the experimental work, data analysis, and writing the paper. Mohamed Slamani was the supervisor of this work. He proposed the research idea, technical scheme, and all needed support conditions. He has also participated in data analysis and was responsible for completing the article. Jean-François Chatelain was involved in the discussion and significantly contributed to making the final draft of the article. All the authors read and approved the final manuscript.

Data availability All data presented in this paper are available.

Declarations

Ethical approval Not applicable.

Consent to participate All authors contribute and participate in the work carried out in this paper.

Consent to publish The authors of this paper agree to publish this work in the International Journal of Advanced Manufacturing Technology

Competing interests The authors declare no competing interests.

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