

# THE DYNAMIC ANALYSIS OF A TEST BENCH FOR WIND BLADE CUTTING

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**Abstract:** As wind turbines grow larger and more efficient, sustainable manufacturing methods will play a critical role in the future of renewable energy. Wind turbine blades are exposed to both mechanical and environmental stress, which can cause degradation over time. Rather than replacing them entirely, many blades can be refurbished and put back into service, helping to lower costs and minimize environmental impact. The manufacturing of wind turbine blades involves a variety of composite moulding techniques, each with advantages and trade-offs. Glass Fibber Reinforced Polymer (GFRP) composites are used extensively in the wind industry due to their high strength, low weight and durability. However, the process of cutting these materials presents significant challenges, including delamination, overheating, rapid tool wear and tear, and the generation of toxic dust. The paper studies the possibility of cutting parts from wind turbine blade material after operation ends, for recyclable transformation for other purposes. Due to large dimension of the blade, a flexible system is needed that can be moved and positioned along the blade to cut and drill features of reused part. For this purpose, an industrial robot can be a solution, but along with advantage of flexibility there are some challenges to overcome due to low accuracy of the robot and variable stiffness in the workspace. In this context an experimental setup was developed to determine the optimal parameters for milling such parts. The experimental setup is based on the use of robotic cutting technology and a deeper understanding of the behavior of the robot-cutting tool-part-fixtures-table assembly. A preliminary evaluation of the system and a dynamic characterization study are performed.

**Key words:** wind turbine blade, industrial robot, milling, natural frequencies, stiffness.

## 1. INTRODUCTION

Wind energy plays a crucial role in the global transition to renewable energy sources, significantly contributing to the reduction of greenhouse gas emissions and the decrease in dependence on fossil fuels. It is among the most effective and environmentally friendly methods of generating electricity, causing minimal impact on the environment [1].

Wind turbine blades are essential components in the process of converting the transformation of the wind's kinetic energy into mechanical energy, followed by its subsequent conversion into electrical energy. Their performance directly influences the turbine's efficiency and lifespan.

The dynamic behavior of wind turbine blades plays a vital role in their design and performance, as they constantly experience varying loads due to changes in wind velocity, atmospheric turbulence, and aerodynamic influences. Key challenges associated with this dynamic response include mechanical stress and material fatigue, interaction with the wind and effects of extreme weather conditions.

To optimize blade performance and improve their long-term resistance, researchers and engineers in the field are exploring innovative solutions, such as the use of advanced materials, blade condition monitoring techniques, and predictive maintenance methods [2].

With technological advancements, wind turbines are becoming increasingly efficient and cost-effective. Additionally, offshore wind farms (located in seas and oceans) have gained significant traction due to stronger winds and a reduced impact on local communities.

In conclusion, wind energy represents one of the most promising pathways toward a sustainable future, playing a crucial role in the global transition to clean energy.

After use, at the end of their lifespan, the blades are replaced, and old blades can be the subject of a new use through sustainable recycling.

In this context, the transformation of the blade to other destinations represents an important objective. This challenge is based on cutting, milling, drilling technologies, followed by assembly for different purposes [3].

## 2. GLASS FIBER-REINFORCED COMPOSITE (GFRP)

Wind turbine blades are made from materials that must combine high mechanical strength, low weight, and durability under mechanical stress and harsh

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environmental conditions [4]. Due to their optimal strength-to-weight ratio, blades are manufactured almost exclusively from composite materials. The most used materials include:

- *fiberglass-reinforced polymers (FRP)* – lightweight, cost-effective, and resistant to corrosion, fiberglass composites are widely used in wind turbine blades.
- *carbon fiber-reinforced polymers (CFRP)* – offering superior strength and stiffness with lower weight, carbon fiber composites enhance performance but come at a higher cost.
- *epoxy resins* – used as a binding matrix for reinforcement fibers, epoxy resins provide excellent adhesion, durability, and resistance to environmental factors.
- *polyester and vinyl ester resins* – more affordable alternatives to epoxy, these resins are used in combination with fiberglass for cost-effective blade manufacturing.
- *hybrid composites* – combining fiberglass and carbon fiber, hybrid materials optimize performance by balancing cost, weight, and strength.

Glass fiber-reinforced composite (GFRP) is the most widely used material in blade manufacturing due to its good balance between cost and performance [4]. Its structure consists of glass fibers embedded in a polymer matrix (epoxy, polyester, or vinyl ester), which provides the following advantages:

- lower cost compared to carbon fiber;
- good impact resistance and mechanical fatigue durability;
- high durability in humid and saline environments;
- ease of processing and repair.

However, there are some disadvantages to using this material:

- higher density compared to CFRP, which can increase blade weight;
- lower stiffness, potentially leading to greater deformations during operation;
- limited thermal and chemical resistance.

Figure 1 shows possibilities of blade wind recycling.

If the material with fiber orientation (0–90)° and the maximum load direction of 45° are considered, the turbine blades would deteriorate rapidly due to both a decrease in material properties and a significant change in the Poisson's ratio compared to the other two directions.

Special attention must be given to fiber orientation, especially in areas of maximum stress identified through finite element analysis. Tests conducted on the plate at different fiber orientation [–45° / 0° / +45° / 90°] demonstrate significant improvements in terms of much lower variation in mechanical and elastic properties concerning the fiber orientation direction [6].

In Figs. 2, 3 and 4 the angles orientation are represented by: 1 – composite with angle 90°; 2 – composite with angle 0°; 3 – composite with angle 45°, and 4 – composite with random orientation.

Considering that the blade's weight must be as low as possible, adding more fibers is not an option. Therefore, with a minimal fiber volume, maximum strength should

be achieved, which is ensured by the correct fiber orientation.

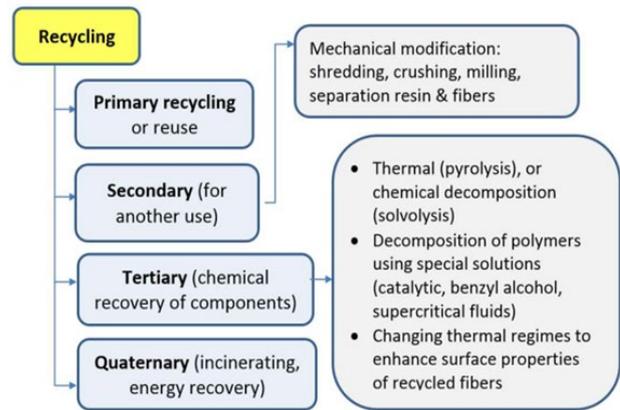


Fig. 1. Possibilities of blade wind recycling [5].

Hardness curve

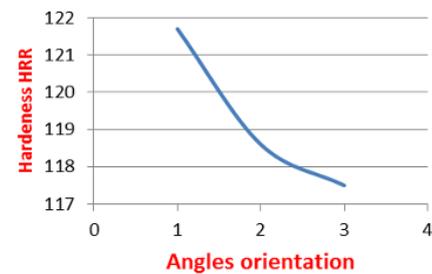


Fig. 2. Hardness curve for different types of angles [7].

Impact Curve

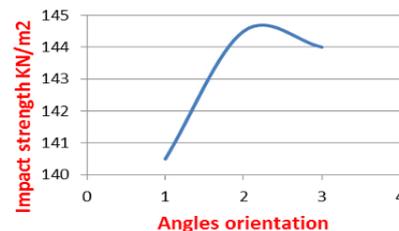


Fig. 3. Impact curve for different types of angles [7].

Tensile curve

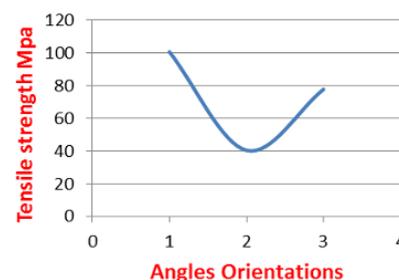


Fig. 4. Tensile curve for different types of angles [7].

### 3. GFRP CUTTING TECHNIQUES

Fiber-reinforced polymer composites have been extensively utilized in numerous industries over the years, primarily due to their high specific strength. The overall strength and stiffness of a composite structure are significantly affected by the sequence and orientation of the plies, so the fiber layer arrangement must be carefully designed to optimize performance.

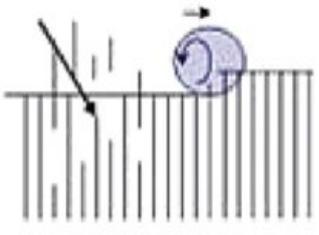
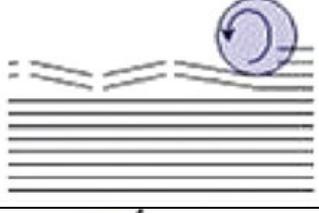
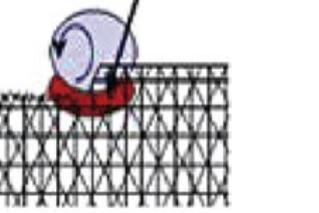
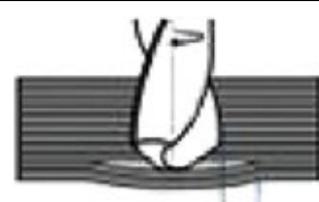
Composite materials are considered challenging for cutting techniques, due to their heterogeneous structure. However, because of their anisotropic and heterogeneous nature, conventional machining methods often lead to defects such as matrix cracking, fiber pull-out, swelling, and delamination (hole surface failure) [7].

Failure behaviors in composite materials arise not only from their heterogeneous and anisotropic structure but also from the machining techniques employed and their interactions. Moreover, the heterogeneous nature of these materials means that traditional machining processes can result in various structural and health-related problems, such as delamination, shortened tool lifespan, fiber pull-out, matrix smearing, and the creation of harmful dust [7].

Despite their high hardness and abrasiveness, sometimes exceeding that of certain tool materials, the nature of composites necessitates fiber crushing during conventional machining to prevent plastic deformation of the cutting tool [7].

Table 1

Surface failures resulting from machining of FRP composite materials [7]

	a Fiber pull out
	b Fiber breakage
	c Matrix smearing
	d Delamination

Due to their complex structure of composite materials (GFRP, CFRP, epoxy and polyester resins), cutting them requires advanced techniques and specialized equipment. The challenges that arise during the cutting of wind turbine blades relate to:

- difficulty of machining of composites due to glass or carbon fibers;
- large dimensions of the blades, especially lengths of (20–100) m, requiring large spaces and robust equipment;
- release of hazardous particles in the form of toxic dust, which requires special safety measures;
- delamination and cracks occurring in case of using improper techniques.

For large dimensions, the cutting must be carried out directly in the field or in specialized factories, using efficient techniques such as: diamond disc cutting (suitable for thick sections and linear cuts, it is used for fast cutting of the blade into smaller segments), waterjet cutting (the most precise technique, without heating the material, is ideal for smooth cuts, without delamination, it is used for cut-outs and preparation of segments for construction), band saw cutting (economical method, used for cutting blades into large fragments, requires stable clamping to prevent vibration), plasma or laser cutting (used in combination with other methods for the metal elements of the blade, the laser provides high precision for internal structures), CNC milling cutter cutting.

#### 3.1. Drilling process of material GFRP

Glass Fiber Reinforced Polymer (GFRP) composites are used extensively in the wind industry due to their high strength, low weight and durability. However, the process of drilling these materials presents significant challenges, including delamination, overheating, rapid tool wear and tear, and the generation of toxic dust.

In their research on drilling-induced surface defects in CFRP and GFRP composite materials, Durão et al. [8] found that lower feed rates lead to reduced axial forces, thereby minimizing the risk of delamination initiation. This makes low feed rates more suitable for drilling composite layers. They also reported that delamination outcomes are significantly influenced by tool geometry, recommending the use of twist drills with a 120° point angle to achieve minimal delamination.

Specific challenges that arise in the GFRP drilling process relate to:

- *Delamination* – layering the material can lead to separation of layers during drilling.
- *Torn fibers and chips* – the edges of holes can become uneven, affecting mechanical integrity.
- *Overheating and resin burning* – high friction can cause material degradation and debris build-up on tool.
- *Accelerated tool wear* – fiberglass is abrasive, which reduces the service life of conventional drill bits.

To minimize defects and improve the quality of the hole, the optimal cutting parameters must be selected:

- speed  $n$  in the range (3 000–15 000) rpm (higher values reduce cutting forces and prevent delamination);

- feed rate  $f_n$ : (0.05–0.5) mm/rev (too high speed can cause cracking and overheating);
- entering angle  $\kappa_r$ : (90–140) ° (to minimize the separation force between layers);
- use of coolant: reduces temperature and evacuates hazardous dust.

Drilling GFRP material requires a careful approach, using specialized tools, optimal speeds and defect minimization techniques. The correct selection of parameters and equipment can significantly improve the quality of holes and the durability of tools, preventing damage to reused wind blades.

In case of milling, the work [9] proposes for the study a ranges of the cutting speed of (500–3500) rpm, feed (0.05–0.13) mm/rev and depth of cut of (1–3) mm. The study proposes for the machinability study the measured parameters the material removal rate (MRR), surface delamination (Df), and surface roughness (SR). The findings reveal the optimal combination consisted of a feed rate of 0.13 mm/rev and a spindle speed of 3500 rpm.

In a the study [10], measuring surface roughness under different cutting directions, Işık et al. observed that channels milled at a 45 ° machining direction exhibited higher surface roughness values compared to those milled at a 90° direction. Their findings indicated that average surface roughness increased with higher feed rates and decreased as cutting speed increased. However, variations in cutting speed had no significant impact on the average surface roughness.

The study [11] by Takmaz et al. reports the lowest surface roughness value of 2.14  $\mu\text{m}$ , achieved using four cutting edges at a cutting speed of  $v_c = 60$  m/min, feed rate  $f_n = 0.08$  mm/rev, and depth of cut  $a_p = 6$  mm.

#### 4. EXPERIMENTAL SETUP

To understand the behaviour of the workpiece during the cutting process an experimental procedure is made to obtain the response of workpiece to identify maximum stiffness.

The experimental procedure is based on robotic cutting in milling process, Fig. 5. To achieve the optimal cutting parameters for milling the dynamic characterisation of the experimental bench is mandatory.

The experimental test bench consists of a Kistler dynamometer for milling forces measurement, the workpiece fixed on the dynamometer, the table structure for workpiece fixture and 3D accelerometer for workpiece vibration during the cutting process, Fig. 6.

First step is to identify the frequency signature of the system components and after to use as base reference for process cutting.

The excitation is generated using an impact hammer and the response is achieved by the 3axial accelerometer mounted in the centre of the workpiece (Fig. 6). The tests were made according to the three-dimensional configuration with impact test hammer on X, Y, and Z direction. For each direction of impact, we measure the impact force on the workpiese and the dynamic response.

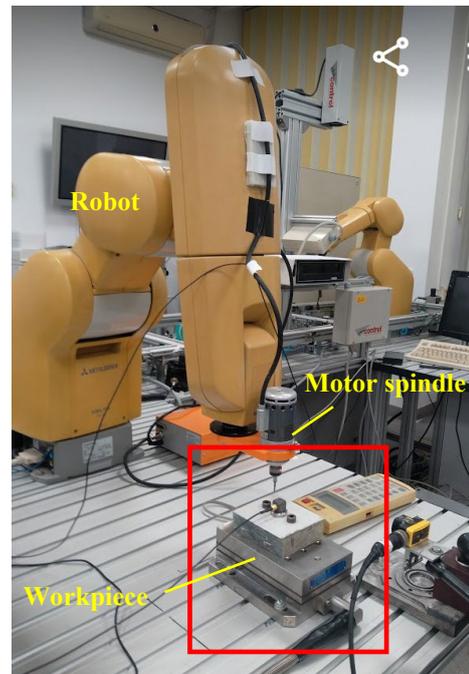


Fig. 5. Test bench of milling blade wind part.

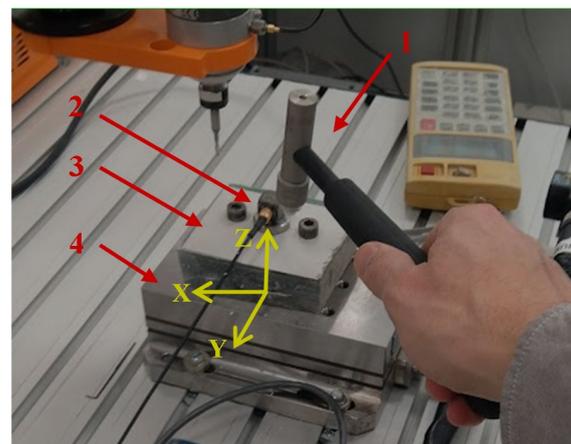


Fig. 6. Impact test of experimental bench: 1 – impact hammer, 2 – three-axial accelerometer, 3 – workpiece, 4 – dynamometer.

#### 5. RESULT ANALYSIS

This paper presents the experimental analysis of a test bench for cutting wind blade part using robotic technology. The determination of natural frequencies is a very important task to knowing the critical speeds and to prepare the experimental protocol for stiffness zones determination of robot.

The experimental results are presented both in time and frequency for each direction. Figure 7 shows the waveform on X direction for time signal of impact force and acceleration.

The frequency signal on X direction shows the most important peak at 31.29 Hz, Fig. 8. The same characteristics are presented in the Y and Z direction. On Y direction the stiffness is higher than X and Z, represented in the Figs. 9 and 10. The lowest stiffness of the test bench is presented on the Z direction, Figs. 11 and 12, where the significant frequency is 8.77 Hz.

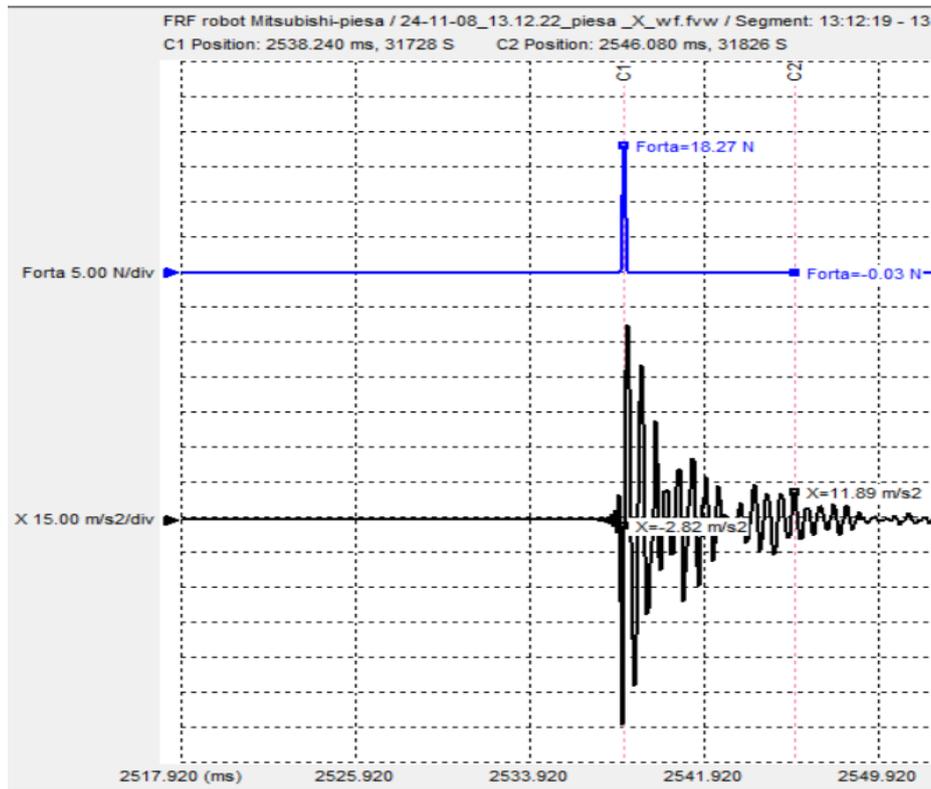


Fig. 7. Wave form signal of impact test on X direction.

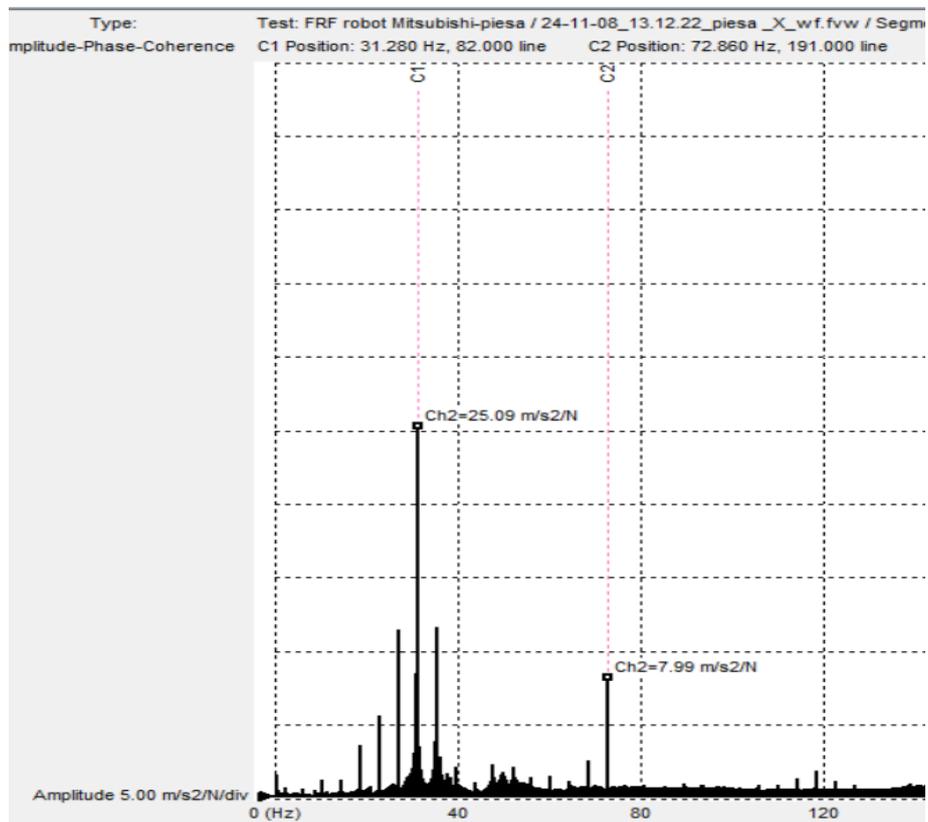


Fig. 8. Frequencies on X direction.

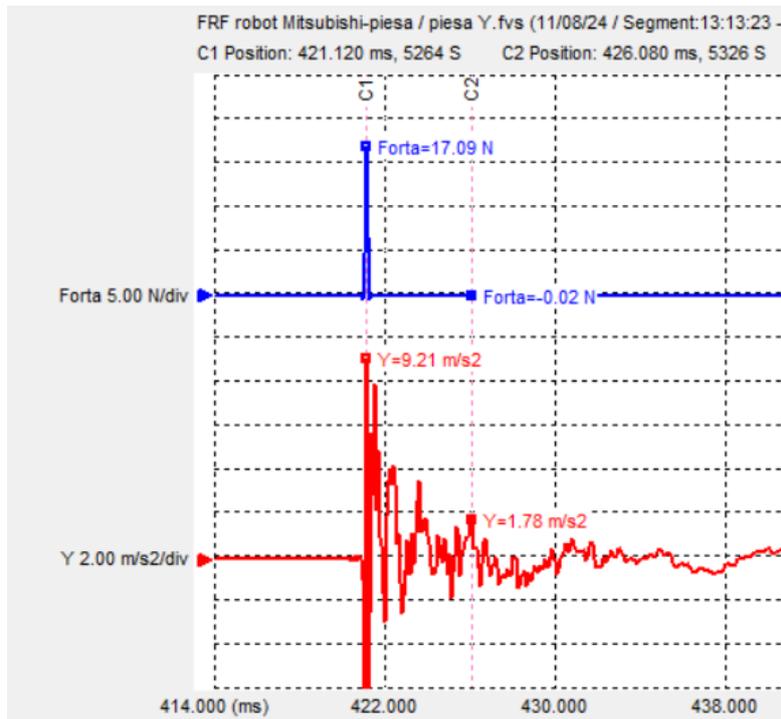


Fig. 9. Waveform signal of impact test on Y direction.



Fig. 10. Frequencies on Y direction.

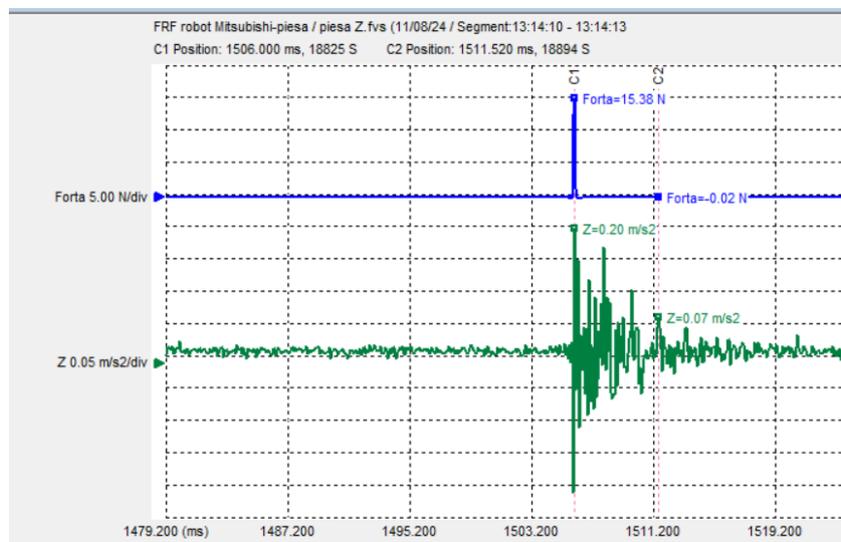


Fig. 11. Waveform signal of impact test on Z direction.

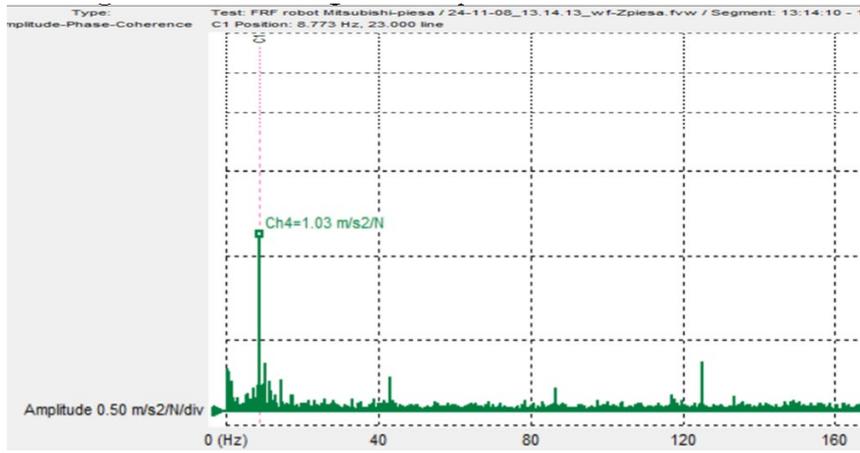


Fig. 12. Frequencies on Z direction.

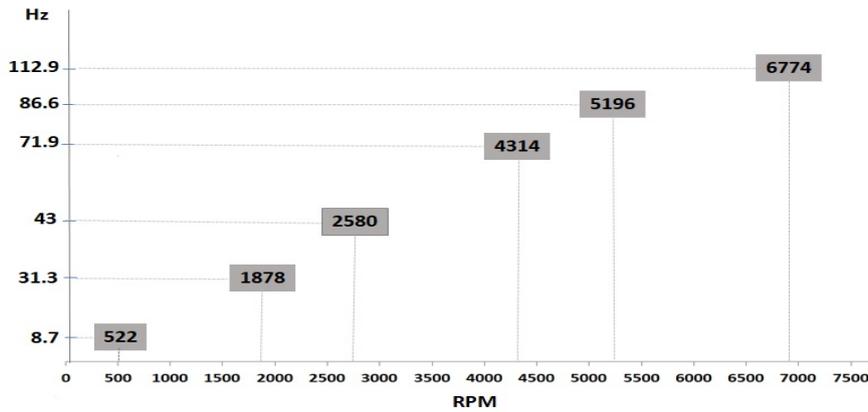


Fig. 13. Critical speed identification.

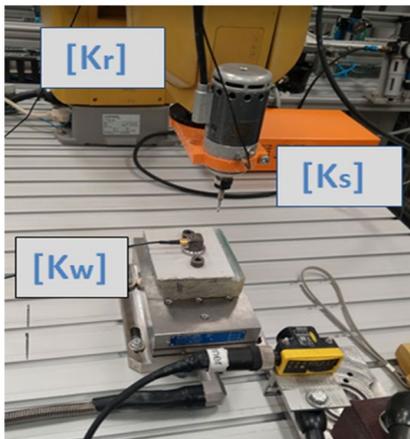


Fig. 14. Stiffness coupling.

The natural frequencies identification is absolute necessary to obtain the critical speed and ensure the stability condition during the cutting process.

The existence of the low stiffness is quite known in the case of robotic cutting and the determination of the critical speed is mandatory to avoid critical speed, Fig. 13.

The experimental procedure is absolute necessary for all types of robotic bench because the dynamic behaviour depends on its own dynamic characteristics.

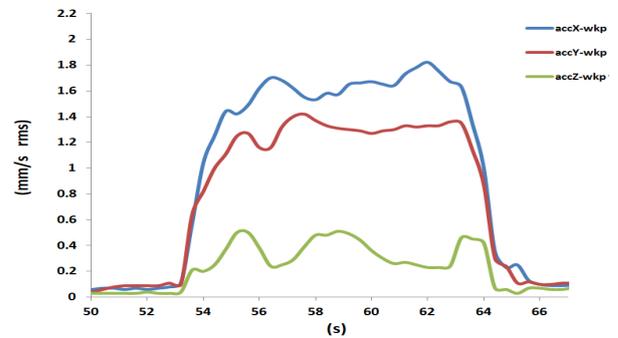


Fig. 15. Workpiece vibration measurement during the milling process.

For milling tests, it is necessary to determine the overall stiffness, Fig. 14. The overall stiffness of the robotic machining system is obtained using a coupling between robot stiffness ( $K_r$ ), spindle stiffness ( $K_s$ ) and workpiece stiffness ( $K_w$ ). Considering that the robot has a lower stiffness than the workpiece, the overall stiffness will be a lower, without any risk of cutting speed.

Under these conditions, the first milling tests were carried out using the following parameters: diameter of milling tool  $d = 3$  mm, cutting speed  $v_c = 93.4$  m/min, feed rate  $f_n = 0.03$  mm/tooth, radial depth cut  $a_e = 1.5$  mm and axial depth cut  $a_p = 1.5$  mm.

The workpiece vibration measured during milling show a stable level with maximum amplitude of 1.8 mm/s rms, on X direction (Fig. 15).

## 6. CONCLUSIONS

Wind turbines have been widely integrated, representing a renewable solution and one of the future solutions for ensuring energy needs. The use of equipment and materials is also subject to the recycling process because of the end of their life. The interest in transforming blade material into various durable objects and parts using robotic machining technology represents a scientific and technological challenge.

Researchers have observed that machining CFRP and GFRP composite materials using conventional methods such as turning, milling, and drilling leads to increased compressive forces when feed rates are higher. Improved hole surface quality has been associated with increased cutting speeds and reduced feed rates. Additionally, some studies have reported the lowest delamination factor when both cutting force and feed rate were kept low. Overall, findings suggest that higher cutting speeds combined with lower feed rates generally result in reduced average surface roughness.

In this paper, the first phase of an experimental study is presented for milling a part of wind turbine blade material by using an industrial robot instead of a milling/drilling machine.

Industrial robots present the advantage of high flexibility in industrial process. For parts where there is no need for high accuracy, the robot is an optimum solution. But some aspects have to be considered when a machining process is planned to be made with the robot. Low accuracy and variable stiffness in the workspace are the challenge of milling and drilling applications.

The objective is to identify the natural frequencies and to determine the critical speeds necessary to avoid during the cutting process.

By knowing that industrial robot has a variable stiffness characteristic, the position of the part in the robot workspace is an important data for stability of the milling process. After the analysis, the lowest stiffness is in the Z direction, while the highest is in the Y direction. The optimal cutting speed can be determined in relation to the tool/material coupling with respect for critical speed.

The preliminary test were carried out showing stable behavior under milling conditions with an industrial robot.

In the next step, a series of tests will be done to analyse the wind blade material machinability after the end of life.

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