Chapter 2
Case Study 1.2: Turning of Low Pressure Turbine Casing

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Abstract In the aeronautic industry the manufacturing of thin-walled components is common. Occurring problems are associated to the poor dynamic performance during the machining process, causing problems like chatter, poor surface quality, low precision or distortions. Furthermore, the use of advanced materials with low machinability amplifies the cited problems. In this case study of the INTEFIX project, the fixture development was oriented to the improvement of the dynamic behaviour of the workpiece using two approaches: (1) "Active modification of mechanical impedance" deals with the use of active vibration reducers that create a counteracting inertial force with a magnetic actuator controlled in a closed loop, minimizing the vibrations during the machining of the workpiece. (2) "Controlled deformation" deals with the use of actuators integrated in the fixture to apply controlled forces in defined areas of the workpiece that modify the clamping state of the workpiece and its dynamic behaviour, leading to a reduction of the vibrations during the machining process. Additionally, the application of CFRP materials to provide a higher damping to the fixture structure is tested. This chapter covers the

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development and integration of the active systems in the fixture prototype, and the results obtained in the experiments.

2.1 Introduction of the Case Study

The objective is the improvement of the turning performance of a turbine case made of low machinability Inconel 718 alloy with 1800 mm in diameter, 550 mm in height and common thickness of 2.5–6 mm, see Fig. 2.1. The steps of the manufacturing process in the analysed fixture involve several turning and grooving operations. The low stiffness and difficult fixturing process affect the manufacturing process, and the performance of the machining process is limited by the presence of vibrations and deformations that lead to limited cutting conditions and reduce the tool lifespan, affecting also the quality and the precision of the workpiece [1]. These problems result in additional reworks to correct the deviations or in the rejection of the component in the worst scenario. In order to minimize the effect of the problems associated to the turning process, the specific objectives are oriented to the following:

- Improvement of the process performance by reducing the vibrations associated to the process forces.
- Improvement of the workpiece behaviour through a modification of the clamping conditions.

The improvement of the workpiece behaviour during processing has been tackled using three approaches:

(1) *Active modification of mechanical impedance*: This solution deals with the use of active vibration reducers. The proposed system creates a counteracting inertial force with a magnetic actuator controlled in closed loop, minimizing the vibrations measured by the integrated accelerometer inside the system. The effect on the workpiece is a reduction of the dynamic amplification factor in a wide frequency bandwidth.

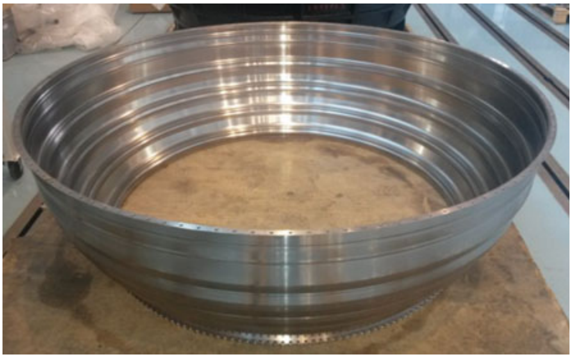


Fig. 2.1 Workpiece under assessment

(2) *Controlled deformation*: This solution deals with the use of four actuators integrated in the fixture to apply controlled forces in defined areas of the workpiece. The objective is the control of the deformation of the workpiece applying forces that increase the stiffness in the area near the cutting tool, avoiding shocks and vibrations. The local contact between the workpiece and fixture is improved and the apparent stiffness of the workpiece is increased. Thus, the workpiece is clamped by an active system under a controlled hyperstatic clamping situation.

(3) *Use of CFRP for locators*: This solution deals with the introduction of passive CFRP elements to substitute the metallic rings used as locators in the current fixture. The use of CFRP increases the damping (10 times higher than steel) of the fixture without reducing the stiffness. In this way, the effect of the shocks can be minimized.

2.2 Analysis of the Fixture and Workpiece

The clamping of the component is made in a fixture with an internal cone shape (see Fig. 2.2) for the machining of the internal face of the workpiece that is performed in a vertical lathe involving turning and grooving operations.

The fixture includes different clamping elements and supports which are shown in Fig. 2.3. These can be summarized in:

- Cast body (Cone shaped) reproducing the negative shape of the workpiece. The contact with the workpiece is limited to certain circumferential surfaces working as locators to provide support for the component. This cast body is the base to include the clamping elements and subsystems of the fixture.
- Circumferential locators: the contact is provided all around the circumference of the workpiece at selected heights. In the new fixture, one of the locators is manufactured in CFRP material in order to improve the damping of the fixture.

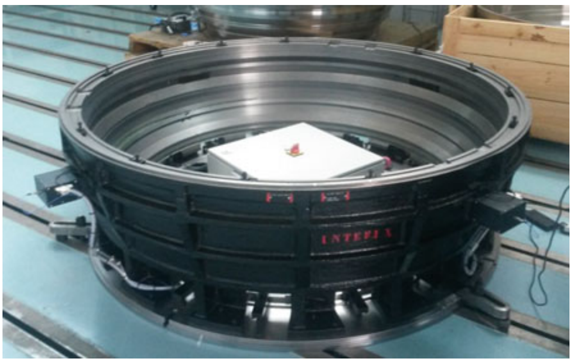


Fig. 2.2 Fixture developed in the INTEFIX project

- Axial clamp: mechanically clamps in the upper and lower flanges of the part to fix the workpiece axially, see Fig. 2.4.

Furthermore, the current fixtures used in production include flexible elements to improve the contact between the fixture and the workpiece. These elements also provide additional support and damping to the assembly.

The analysis done included the review of the current design, FEM analysis of the workpiece-fixture assembly and experimental modal analysis. The information obtained allowed the identification of the current fixture characteristics and working way; it can be summarized in the following points:

- Metallic circumferential locators provide radial stiffness in the tension mode, but in the compression mode only the own stiffness of the workpiece is noticed (see convention for modes in Fig. 2.5).
- The damping provided by the flexible elements is negligible.
- Clamping in the lower and upper flanges contribute to the global stiffness of the workpiece.

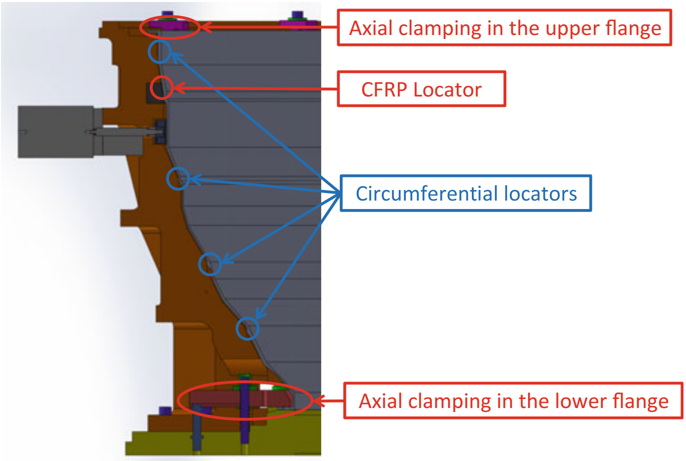


Fig. 2.3 Locators and axial clamping elements of the fixture

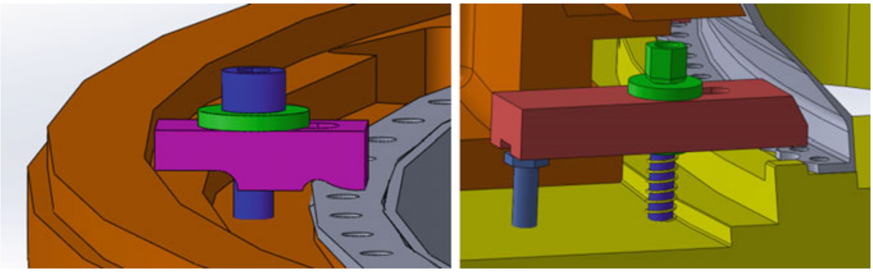


Fig. 2.4 Axial clamping elements (*Left* upper flange. *Right* lower flange)

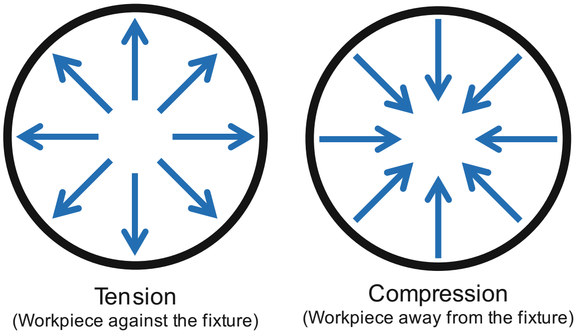


Fig. 2.5 Convention for the deformation of the workpiece

The analysis performed allowed the identification of key points to improve the workpiece-fixture assembly and to minimize the vibrations during the process. The main issue is associated to the contact between the workpiece and the fixture; due to the size and flexibility of the workpiece, and to the fact that the contact cannot be sustained all around the workpiece, the process forces drive to discontinuities in the contact between both elements. This is perceived as a lack of apparent stiffness of the workpiece that finally results in vibrations and deformations during the machining process.

The main conclusion about the current fixture behaviour is the lack of stiffness in the compression mode. This leads to potential vibrations due to (i) variable deformations in different areas of the workpiece associated to the cutting forces, and (ii) the bounce of the workpiece against the fixture resulting in shocks that dynamically excite the component during the machining process [2].

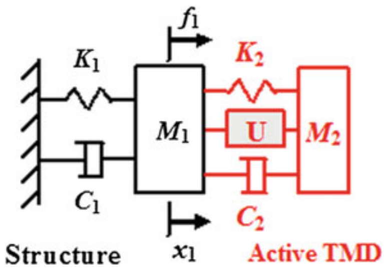
2.3 Fixture Development

In order to solve the main problems and limitations explained above, the design of the new fixture has been done integrating suitable elements and subsystems to achieve the performance of the three approaches explained at the beginning of this chapter:

(1) *Active modification of mechanical impedance*.
(2) *Controlled deformation*.
(3) *Use of CFRP for locators*.

The solution #1 deals with the use of active vibration reducers that create a counteracting inertial force to minimize vibrations. This is achieved using actuators controlled in a close loop with the feedback of sensor data to monitor the vibrations. From a mechanical point of view, the effect in the workpiece is a reduction of the dynamic amplification factor in a wide frequency bandwidth and an increment of the damping ratio. The schema of functioning of this kind of systems is presented in the Fig. 2.6, and this topic is covered in several scientific publications [2, 3].

Fig. 2.6 Schema of an active vibration reducer



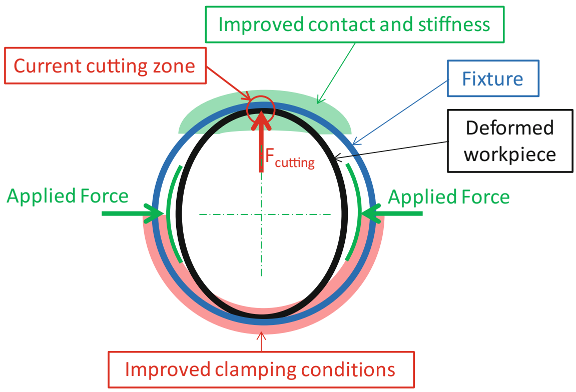
The solution #2 uses some actuators to apply controlled forces and displacements to the workpiece in selected zones to achieve a suitable deformation and clamping of the components. The objective is the control of the deformation and the improvement of the boundary conditions of the workpiece, increasing its stiffness in the cutting zone, as schematically shown in Fig. 2.7. This approach allows the improvement of the workpiece behaviour during cutting process avoiding shocks and vibrations.

The design of the fixture took into account the integration of the required elements (sensors and actuators) for the two approaches explained above, being the main element the actuation subsystem showed in Fig. 2.8.

This developed actuation subsystem can work in both modes (dynamically for "Active modification of mechanical impedance" and quasistatically for "Controlled deformation") with the same actuator using different sensors also integrated in the fixture. The subsystem is based on a MICA200 M [2–4] actuator located in the outside part of the fixture, including a connecting rod joined to an end effector in contact with the workpiece. This assembly needs to be preloaded to ensure the contact with the workpiece during machining using the "Active modification of mechanical impedance" mode.

The mechanical design of the fixture includes the designed actuation subsystem, the required sensors and the electric/control system as shown in Fig. 2.9. The actual fixture also includes conventional clamping elements in the upper and lower flanges

Fig. 2.7 Concept of the controlled deformation functioning



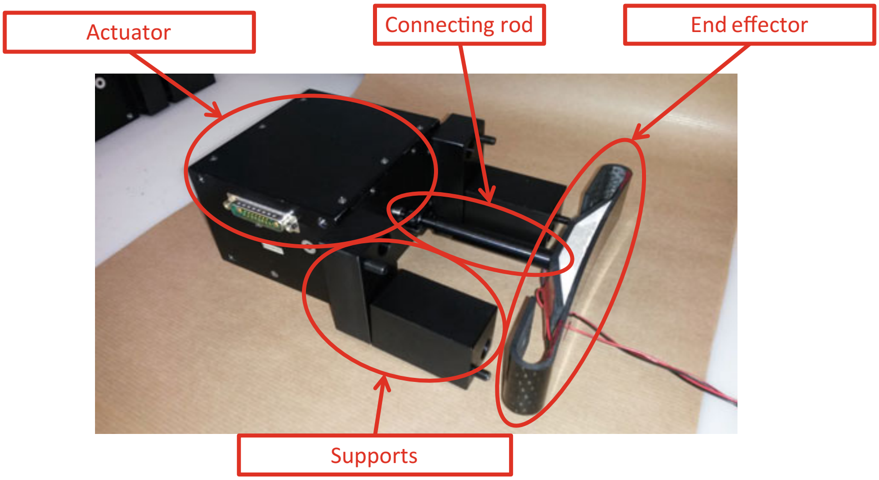


Fig. 2.8 Actuation subsystem used in the “Active modification of mechanical impedance” and “Controlled deformation” approaches

areas as used in the original fixture, and the CFRP locator designed as a third approach to improve the dynamic behaviour during the machining process, see Fig. 2.3.

Figure 2.10 shows the fixture assembly including the four actuation subsystems and a detail of this integration. Also, the CFRP locator ring installed in the fixture and the electric cabinet in the centre of the fixture is visible.

The sensors used in the fixture include one accelerometer in each actuation subsystem and an inductive sensor to establish a rotating reference during the turning process. Additionally, for testing purpose, eddy current displacement sensors and FBG strain sensors have been used to monitor the deformation of the workpiece.

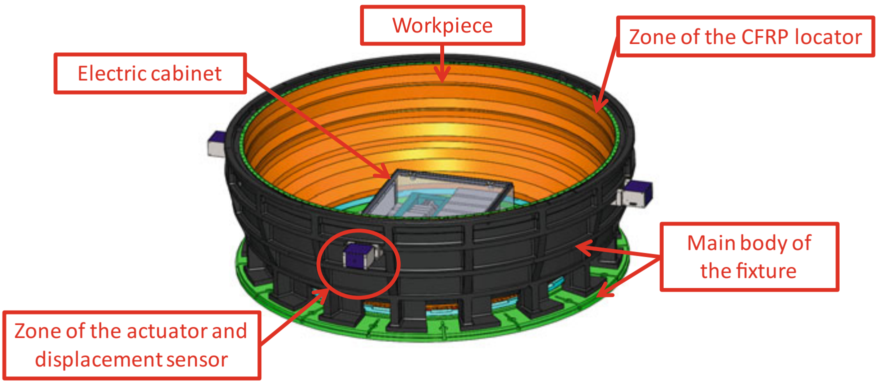


Fig. 2.9 Identification of the elements included in the fixture

Fig. 2.10 Fixture assembly and detail of the actuation subsystem assembly (*Left* External view; *Right* Internal view)

The electric cabinet is mounted in the central area of the fixture with wired connection to all the sensors and actuators used in the final assembly. The main elements are the controller, the drives of the actuators, the conditioners for the different sensors and the battery to power the whole system. Figure 2.11 shows the location of the different elements included in the cabinet. The battery works at 100 V and it is located below the controller and the electric and safety elements.

The control system can manage the system working in both modes ("Active modification of mechanical impedance" and "Controlled deformation") as a standalone controller able to manage the I/O signals without communication with the CNC of the machine tool.

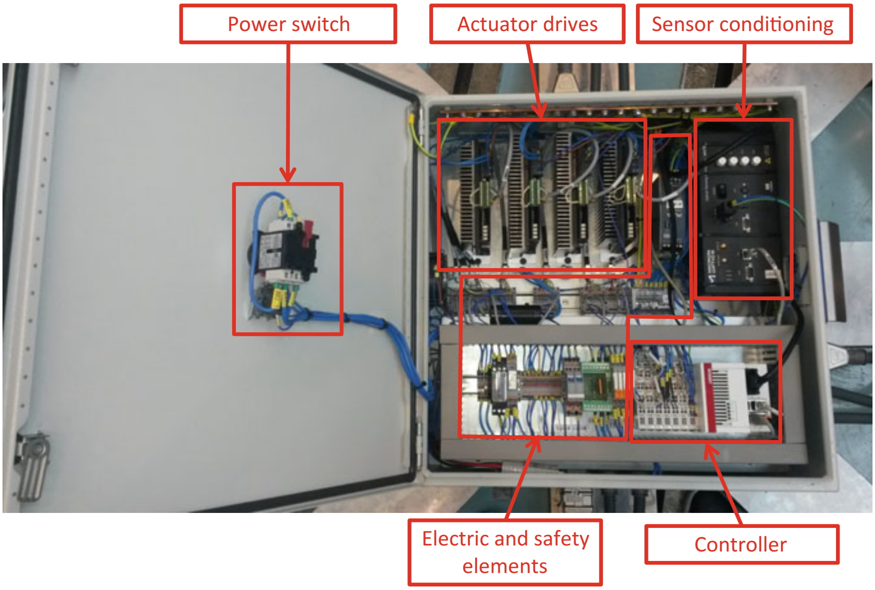


Fig. 2.11 Electric cabinet and components included

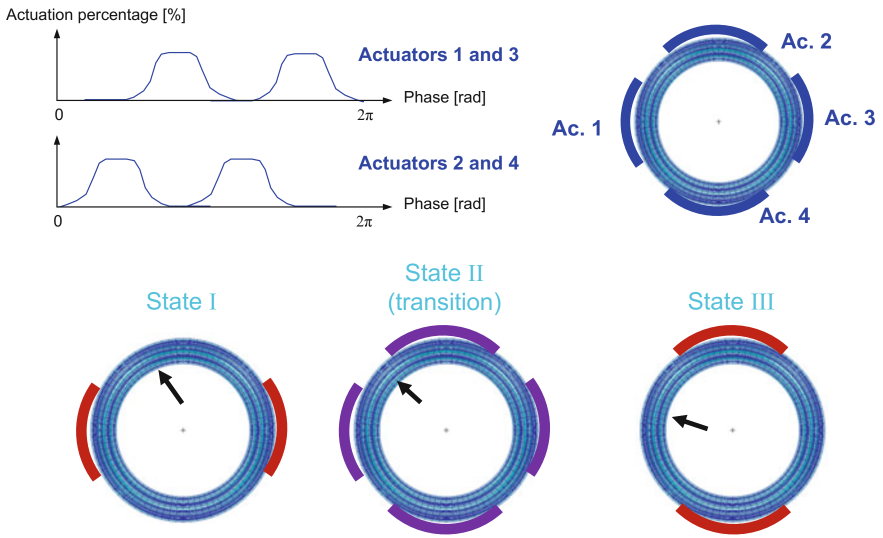


Fig. 2.12 Schema of the control algorithm for the "Controlled deformation" solution (*arrow* indicates the cutting tool position)

The control algorithm for the "Controlled deformation" solution is based on the synchronization of the four actuation subsystems to achieve a suitable result attending to the current cutting tool position. This means that the actuation must be constantly modifying the force exerted by each actuator during a revolution of the workpiece with a common angular reference. The sequence followed by the four actuation subsystems is graphically described in the Fig. 2.12; the control law follows a logistic function with two cycles per revolution of the workpiece.

2.4 Verification and Validation Tests

The tests were performed to evaluate the effects of the fixture working under the modes defined previously: "Active modification of mechanical impedance" and "Controlled deformation". Figure 2.13 shows the referencing of the four active actuation subsystems located in the fixture.

2.4.1 Verification tests

The verification tests were carried out in the laboratory including: (i) static tests to monitor the internal sensors of the system and the workpiece deformation; and (ii) dynamic tests using modal analysis to evaluate the changes in the workpiece

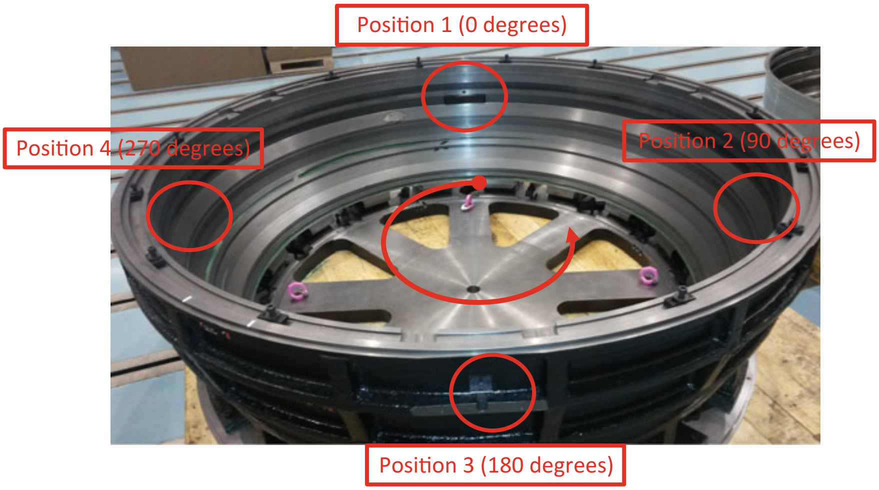


Fig. 2.13 Angular referencing

behaviour due to the actuation. These tests were done without the rotation movement in the workpiece and with the fixture clamped to the ground.

The static tests were used to verify the deformation capabilities of the actuation subsystems in different positions of the fixture, supplying the higher power allowed by the actuator to obtain a theoretical deformation force of 200 N in each actuation point.

The performance of the different actuators was highly variable with values of the measured deformation which differ significantly in the four positions as can be seen in Table 2.1. This variability was attributed to the following issues:

- The MICA 200 M actuators are systems sensible to their internal assembly, so the behaviour can vary according to internal parameters associated to the assembly process.
- The whole actuation subsystem (actuator + supports + connecting rod + end-effector) is subjected to an assembly process for the integration in the fixture that modifies the interaction with the workpiece (contact angle, initial gap…) due to differences in the adjustment and alignment of the elements.

The dynamic tests were used to verify the change of the dynamic behaviour of the workpiece when the actuators are exerting a clamping force according to the

Table 2.1 Variability of the behaviour using the four actuation subsystems

Actuator Id.	Workpiece deformation measured (μm)
Actuator @ 0°	7
Actuator @ 90°	11
Actuator @ 180°	3
Actuator @ 270°	5

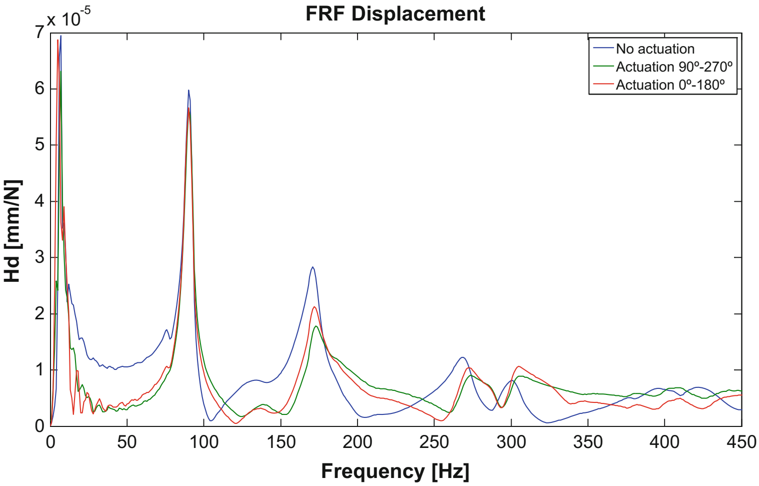


Fig. 2.14 Improved dynamic behaviour: FRF with excitation and measurement in position 1 (0º)

"Controlled deformation" functioning mode. The tests consisted in a series of modal analysis to obtain the FRF under different configurations, as an assessment of the improved clamping condition of the workpiece and the expected improvement to avoid shocks and vibrations during machining process.

The basic information obtained from the modal tests are the FRF for a position with the actuators off, the FRF for a position with the contiguous actuators on (+90° and −90°), and the FRF for a position with that actuator and the opposite on (+0° and +180°). Figure 2.14 shows an example of the measured FRFs in the three situations described above with excitation and measurement in the position 1 (0°), near the position of the actuator.

The measured FRF shows that the use of the actuation (positions 2 and 4; or positions 1 and 3) improves the behaviour of the workpiece with a general reduction of the dynamic amplification factor in the frequency domain, especially near some resonances. This indicated an improvement in the apparent stiffness, resulting in a workpiece with higher rigidity when the actuators are active. Moreover, the width of the resonance peaks indicates that the apparent damping is also increased, so the response of the workpiece against shocks and vibrations is improved. The blue curve is the base situation (without actuation) and the green curve is the situation that occurs during the "Controlled deformation" functioning mode when the cutting tool is passing through the position 1. The improvement in the dynamic behaviour is evident. The red curve is the situation that occurs at 90º of the position of the cutting tool; the amplification factor is also reduced indicating the improvement in the dynamic behaviour in that area.

2.4.2 Validation tests

The validation tests were carried out in the workshop using a GMTK ACCURACER vertical lathe to perform the machining operations. These machining tests have comprised the generation of different geometrical features like horizontal/radial slots, vertical/axial slots and cylindrical surfaces in the workpiece. Figure 2.15 shows an example of the machining tests.

The objective of the validation tests is the assessment of the results obtained during the machining process using the actuation subsystems compared to those obtained with a conventional machining process. The nominal cutting conditions established for the comparison are those currently used in the production of this kind of components.

The fixture was tested to verify the functioning in both modes “Active modification of mechanical impedance” and “Controlled deformation”. During the tests in the “Controlled deformation” mode it was noticed that the rotation movement and the centrifugal forces do not affect negatively the functioning of the actuation subsystems, being the achieved deformation values in the workpiece similar to those obtained in a static situation. According to this behaviour, the machining of the slots using the actuation led to an improved run-out of the machined features. The results showed that the use of actuation produces a run-out value below 0.01 mm, while the conventional machining produces run-out values up to 0.02 mm in some areas. This is considered a consequence of the better clamping achieved in the workpiece observed during the verification tests. On the other hand, the main drawback noticed is the generation of a taper surface during cylindrical turning operations; with a taper ratio of 0.02–0.03 mm in 10 mm. The reason for this behaviour could be the misalignment of the actuation system or the asymmetric deformation of the workpiece when the actuators are pushing it. This is an aspect to consider during the design of this kind of solution for a deformable workpiece.

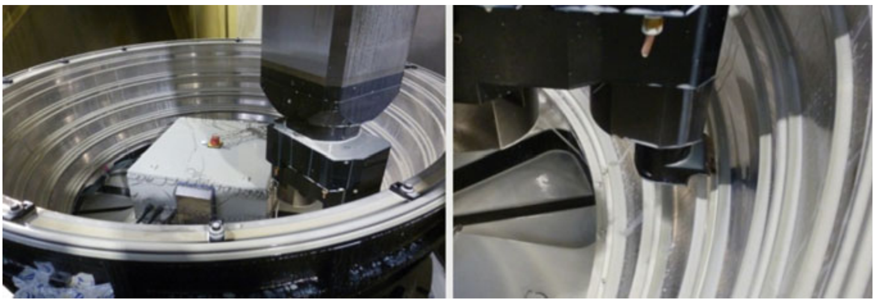


Fig. 2.15 Photographs of the machining of a horizontal/radial slot

2.5 Summary and Conclusion

The development of this case study has been oriented to the reduction of the effects of the vibrations and the low stiffness of the workpiece during the turning of the component. The work has included the development of an active fixture able to adapt the behaviour of the workpiece according to the conditions imposed by the machining process. The developed intelligent fixture allows the improvement of the workpiece behaviour and the precision of the machining process; and considering the lower vibration level, the cutting conditions could also be increased to obtain a more productive machining process.

The main contributions of this case study are the two approaches used "Active modification of mechanical impedance" and "Controlled deformation". The first one is related to the use of active vibration dampers to reduce the vibration of the workpiece during the machining process; while the second one deals with the active modification of the clamping situation of a workpiece in order to adapt the dynamic behaviour according to the cutting tool position during the machining process.

This kind of solutions is mainly oriented to large components with different dynamic behaviour depending on the zone of the workpiece or components that change their shape during the machining process requiring the modification of the fixture configuration to adapt the clamping of the workpiece during the process.

The tests performed allowed obtaining the main conclusions about the capabilities of the use of active clamping elements to apply forces to the workpiece during processing: producing a controlled deformation and working as a vibration absorber. Attending to the technical characteristics and the performance of the subsystems developed and assembled in the fixture, the main conclusions are:

- The actuators produce a deformation as expected during the design phase. This deformation is mainly a local effect, and the actuation must be carefully controlled to avoid undesired effects.
- The designed systems can work in rotating systems without significant drawbacks or malfunctioning.

Attending to the requirements of the case study and the industrial application analysed in the case study, the main conclusions of the work can be summarized as:

- Both solutions ("Active modification of mechanical impedance" and "Controlled deformation") can provide better results attending to run-out, surface roughness and vibration behaviour; being this manly related to the improvement of the clamping conditions and the dynamic behaviour of the clamped workpiece.
- The actuation allows the improvement of the clamping of the workpiece, increasing the apparent stiffness and providing additional damping to the whole system.
- The use of actuators (local deformation) affects negatively some geometrical aspects of the finished workpiece. This is related to the asymmetrical deformation achieved in the workpiece.

The developed solution is specific for the workpiece analysed in this case study, but the same methodology can be used for the development of fixtures for work-pieces with low stiffness and big size that is a common situation in the aeronautic industry in the manufacturing of both, structural and engine components. This kind of solutions is specially indicated for those components that are difficult to clamp avoiding the deformations during the machining process.

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