Adaptive Fixture for Thin Walled Aerospace Parts Using FE Analysis

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Abstract

Fixtures locate and hold workpieces during manufacturing. Due to the dimensional and geometrical tolerances of workpieces and fixture elements errors may occur. The clamped workpiece will consequently have position and/or orientation errors influencing the accuracy of the final machined part. It is estimated that fixture could constitute 10-20% of the total manufacturing cost.

Fixture systems must satisfy two - unfortunately opposite acting - requirements:

- to provide relatively high clamping forces in order to guarantee sufficient stiffness and minimum deflection due to machining forces, and
- to reduce as much as possible workpiece deflection and deformations as well as strains induced in the workpiece in order to avoid inaccuracy after strain recovery.

In this paper a novel active adaptive fixture, based on piezoelectric actuators is presented, applicable to different industrial applications. As an example a case study, machining of a Nozzle Guide Vane (NGV) for aerospace engines, is investigated.

The design and the expected behaviour of the developed fixture during clamping and due to machining forces were supported by modelling with the Finite Element Method (FEM).

The paper describes the novel concept of the clamping device and the related FE analysis. The presented work is part of the EU integrated and collaborative project “Aligning, Holding and Fixing Flexible and Difficult to Handle Components (AFFIX)”.

1 Introduction

1.1 Case study

Because of their modularity, high quality and effectiveness controlled electromechanical fixturing systems have an increasing interest in the industry. Often traditional fixtures are insufficient to fulfil the recent industrial requirements.

In the AFFIX project a typical clamping problem of a thin wall part subjected to machining forces was selected as a case study: The clamping of an aerospace turbine NGV, shown in Figure 1 was investigated during the grinding operations.

Figure 1: *The NGV*

The current clamping procedure is very time consuming. The results depend on the operator skills. During the clamping procedure deformations may appear. The proposed adaptive clamping device has been designed to solve the problems shown, for example, in this case study. The device is innovative and applicable for industrial grinding and milling applications due to its modularity, its ability to clamp workpieces of different dimensions and varying weight in a very short time. The new device does not require any particular operator skills and can be employed for a wide range of tasks, mainly due to the actuator embedded inside the device itself. Having these unique properties the clamping fixture can be defined as a real mechatronic device.

1.2 The design of adaptive clamps

The design of this new adaptive fixture is related mainly to the clamping elements and had to go through some basic procedures in order to be effective. The clamping module, shown in figure 2, consists of an actuator stack embedded inside the mechanical device. This module may clamp different workpieces, and due to the presence of some sensors which can detect any unwanted movements of the workpiece, the actuator can compensate deformations and restore the undeformed configuration. The most relevant critical points during the design of the module are the knowledge of the magnitude of machining forces and the selection of the optimal actuator. Due to its high efficiency, bandwidth, power density, and stiffness one opted for the piezoelectric actuator.

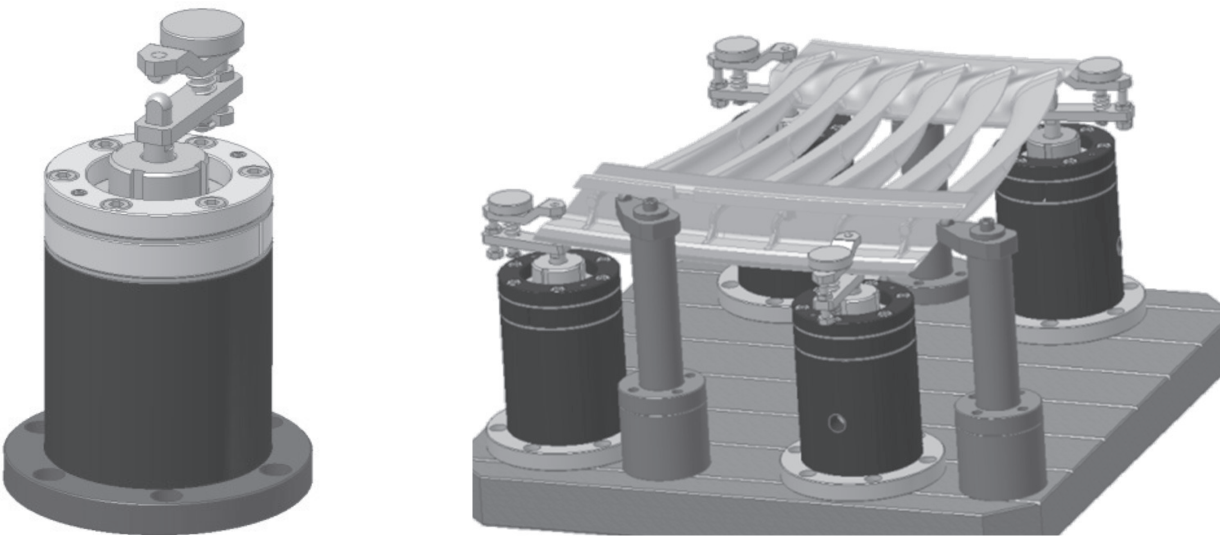

Figure 2: *The adaptive clamping module and the complete fixture platform with the clamping modules*

Experimental tests were carried out in the Fraunhofer IWU in order to find the highest acting forces during the grinding operations. The designed adaptive clamping module is shown in Figure 2 (left). The so-called test-bench fixture platform for the NGV with the clamping modules is showed in Figure 2 (right). The success of the clamping operation do not depend anymore on the operators skills. Furthermore, because the operator must not adjust the part by hand, the positioning time for the NGV is distinctly reduced, solving above mentioned case study problems. The number and types of sensors depend on the specific application (static strain recovery, active vibration control...). In our case the proposed adaptive fixture platform has 4 displacement sensors in order to recover the deflections and the deformations.

2 Mechatronic and finite element analysis

2.1 Mechatronic simulations

An important step in the design process was the analytical validation of the proposed solutions. Particular attention was given to the validation of the working principles as the base for the behaviour of the whole fixture system.

Therefore, FE models of the NGV and the adaptive fixture were developed and applied for several static and dynamic analyses. The FE modelling and the numerical analyses were done using the FE packages MSC.Marc® and MSC.Nastran®. Furthermore, Matlab/Simulink® was used to investigate the assembled structure in combination with the piezoelectric actuator's model. The degree-of-freedom reduction of the FE model was done by means of the Craig Bampton modal reduction method [1]. Figure 3 shows the Simulink scheme of the mechatronic model which is described with more details in [2].

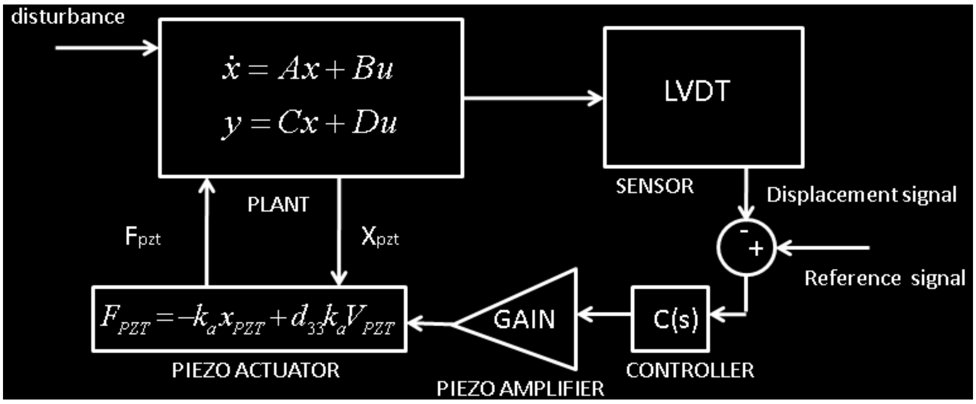

Figure 3: *Scheme of the applied mechatronic model*

2.2 Finite element meshes

Based on a CAD file of the NGV and using the PATRAN volume mesher in the FE program MSC.MARC a hierarchy of resulting volume meshes was created [3].

Furthermore, combining the FE model of the piezoelectric clamping module, shown in Figure 4, with the NGV model, a complete model for the clamping platform has been developed. Figure 5 shows the FE model of the test-bench platform consisting of the NGV, positioned on 3 supporting elements, and clamped with 4 piezo-actuator modules. Since the supports do not have any clamping function and do not exert any loading on the NGV they can be omitted in the test-bench FE model.

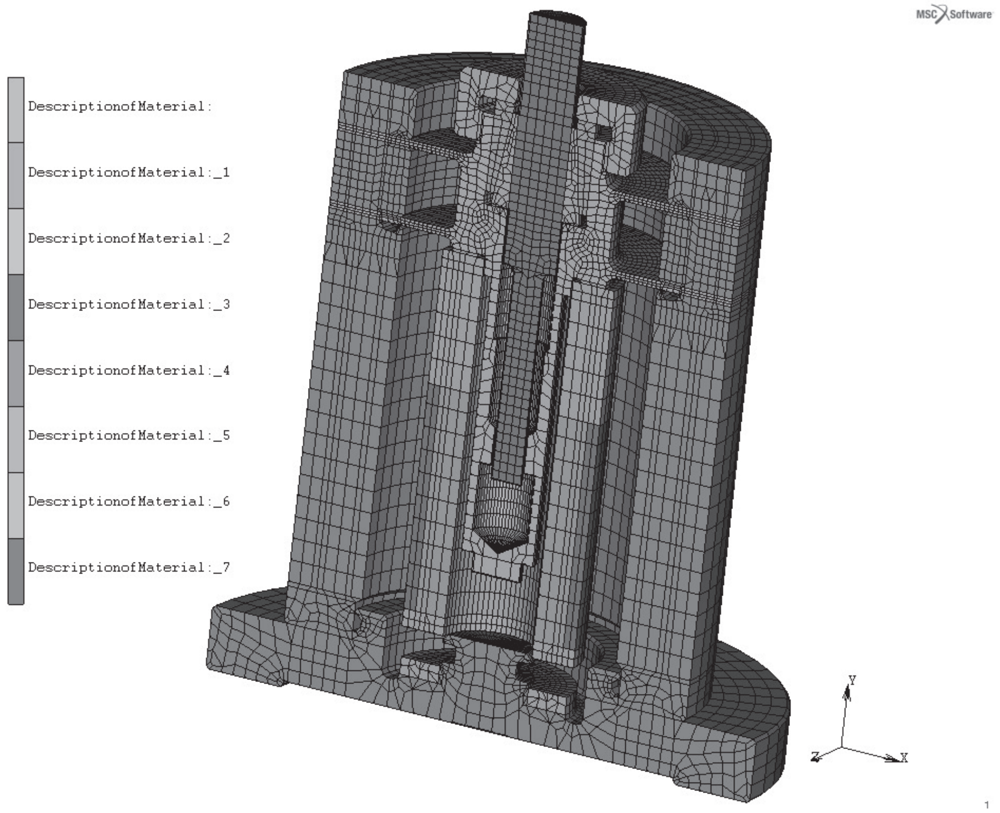

Figure 4: *The FE model of the piezoelectric clamping module (cross section)*

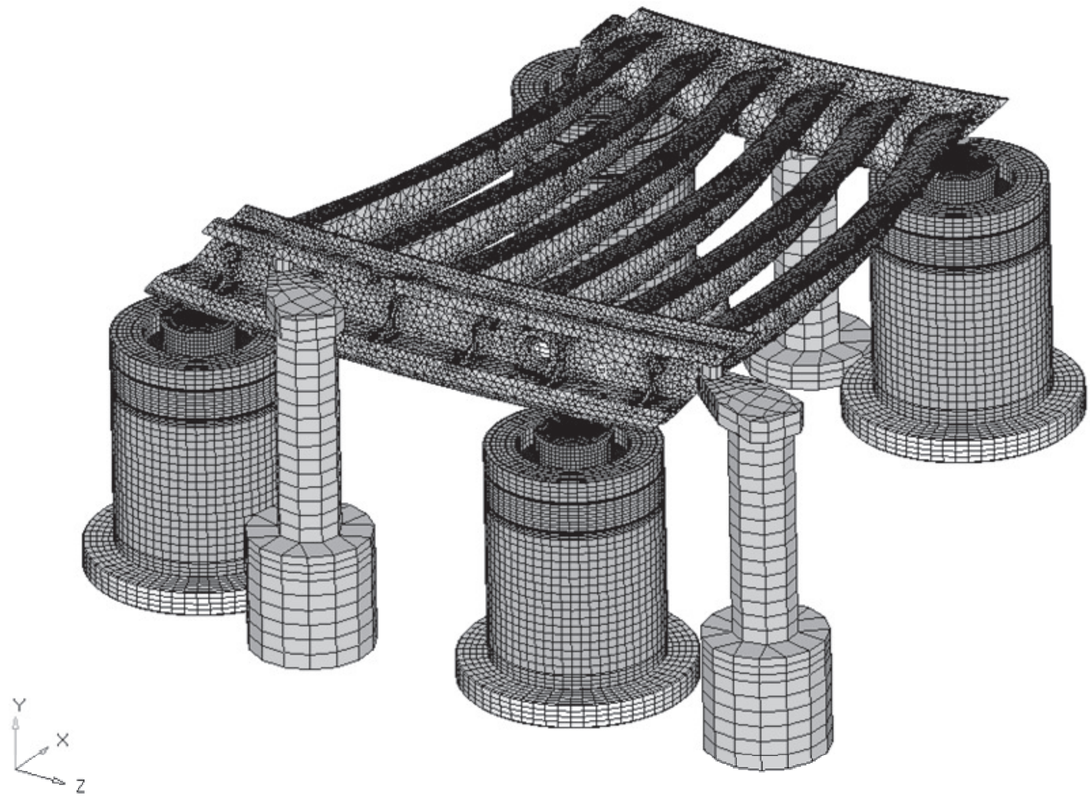

Figure 5: *FE model of the test-bench fixture platform with the mounted NGV*

2.3 Static loading of the clamping platforms due to grinding forces

During clamping and machining operations the NGV is subjected to different static and dynamic forces. The main loads which have to be compensated by the piezo-actuators during machining are the grinding forces. A direct measurement of the machining forces is impossible because of the existing production conditions and the insufficient space for the measurement equipment in the actual machine tool. In order to overcome these problems grinding force measurements have been carried out in the IWU laboratory under grinding conditions which are similar to those used in the original process while machining the original NGV part.

The grinding forces for the different NGV surfaces can be divided into three components according to the coordinate directions. Constant grinding forces F_x, F_y and F_z in the 3 coordinate directions lead to reaction forces in the clamping points as shown in Figure 6. Since the considered model is linear the reaction forces can be scaled in correspondence to the real grinding and clamping forces and combined by superposition in order to calculate the acting forces on the stacks. These acting forces are used for the assessment of the clamps and stacks.

Taking into account the real static and dynamic properties of the clamps and of the clamping stacks one can simulate the real deformation of the whole device during the machining process. Consequently it is possible to calculate the accuracy of the machining process and to define the necessary stiffness of the adaptive clamps and to calculate the reaction characteristic of the piezo-actuators.

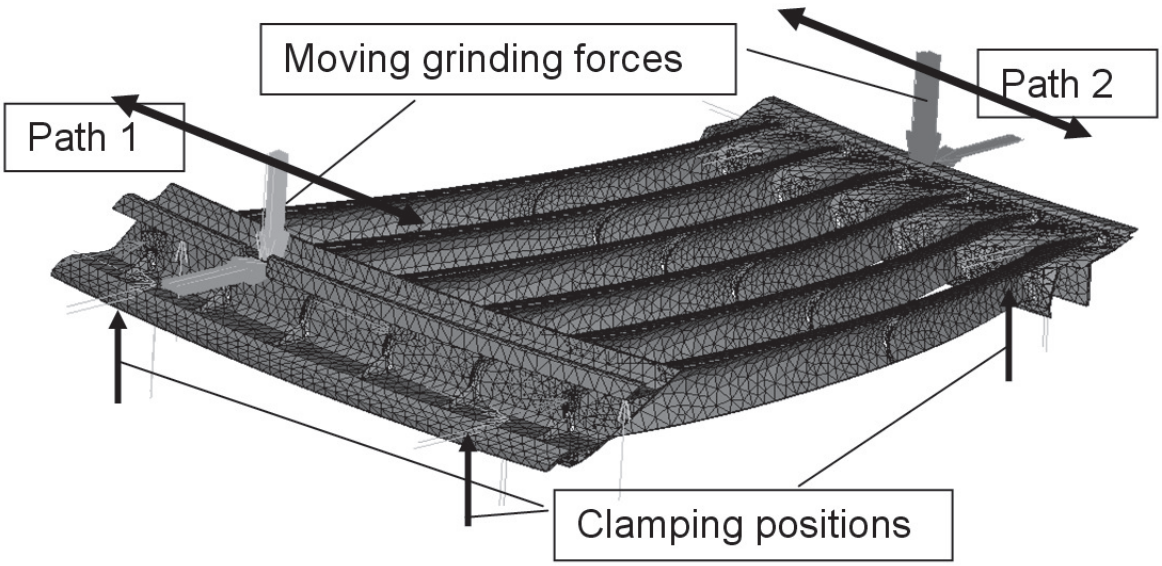

Figure 6: *FE model with fixed clamping positions and moving grinding forces*

During the calculations the following situations were considered:

Assumption of stiff clamps: In this case only the NGV underlies stresses and deformations. During grinding the loads move along the 2 paths shown in Figure 6. A constant moving force in a single coordinate direction causes in the clamping points reaction forces. Due to the linearity of the model these reaction forces can be scaled and super-positioned in accordance with the real forces.

Assumption of flexible piezoelectric stacks: In this case the machining forces cause deformation in the NGV as well as in the clamping points on the top of the piezo-stacks. During grinding the flexibility of the whole clamping platform leads to displacements. FE simulations have been carried out with constant forces, parallel to the coordinate axes and moving along the paths 1 and 2 (Figure 6). The defections of the NGV in the contact points with the grinding wheel influence the accuracy of machining. This displacement caused by the grinding force has been calculated by scaling and super-positioning of the reference values in accordance with the real forces. Figure 7 shows the displacement of the contact point during grinding of the inner perpendicular surface along path 1. The known displacement values can be compensated by active controlling of the piezoelectric clamping devices achieving a clear increase the machining accuracy.

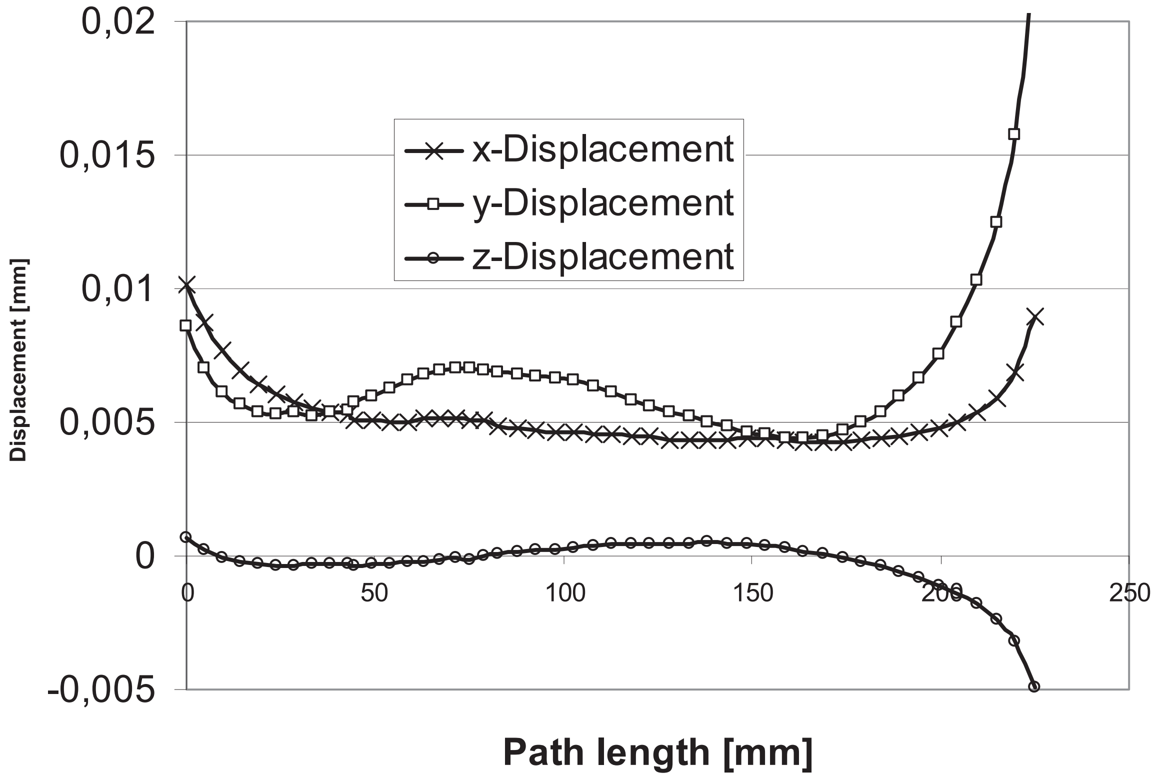

Figure 7: *Displacement of the contact point between wheel and NGV when grinding the inner perpendicular surface along path 1*

2.4 Dynamic loading of the clamping platform

For the full analysis of the mechanical behaviour it is necessary to evaluate also the dynamic characteristic of the platform. The first step was to calculate the eigenfrequencies. It was found that the 10 first eigenfrequencies lie in the range of 636 - 1345 Hz. Excitation frequencies in this range can lead in the machine tool and for the machining process itself to undesirable vibrations. Furthermore, the knowledge of the transient dynamic behaviour is very important.

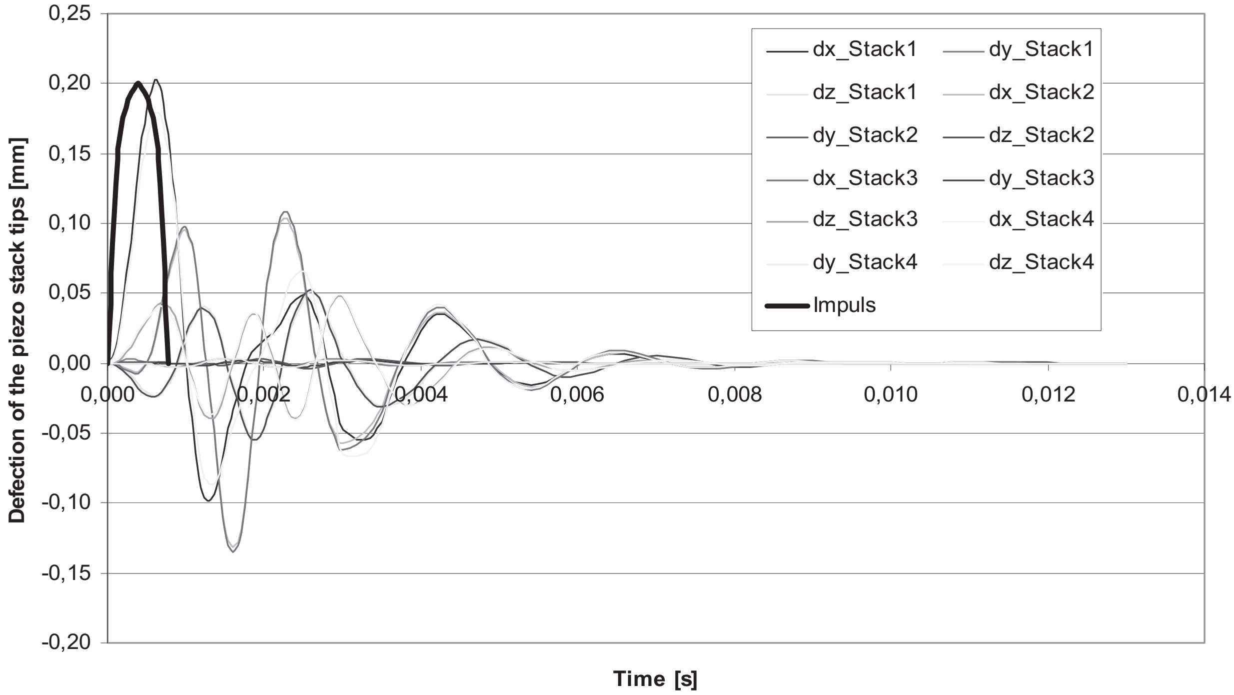

Figure 8: *Transient dynamic behaviour of NGV test-bench clamping platform with piezo-stacks*

Figure 8 shows the calculated transient dynamic reaction of the test-bench fixture platform being subjected to a short-time (0.001 s) impact force of maximal 100 N. No damping of the material, of the clamps, and of the piezo-actuators is considered. Damping will lead to a slight change of the eigenfrequencies and to a faster reduction of the vibrations.

3 Test results with the test-bench platform

Based on the numerical simulation, which confirmed the working principle of the adaptive fixture, the test-bench platform was realised and tested. One aim of the tests was to evaluate the actual axial and radial stiffness as well as the hysteresis of the clamping modules. The test results could verify and improve the numerical model of the device. An additional open loop functional test was carried out in order to check the experimental effectiveness of the working principle.

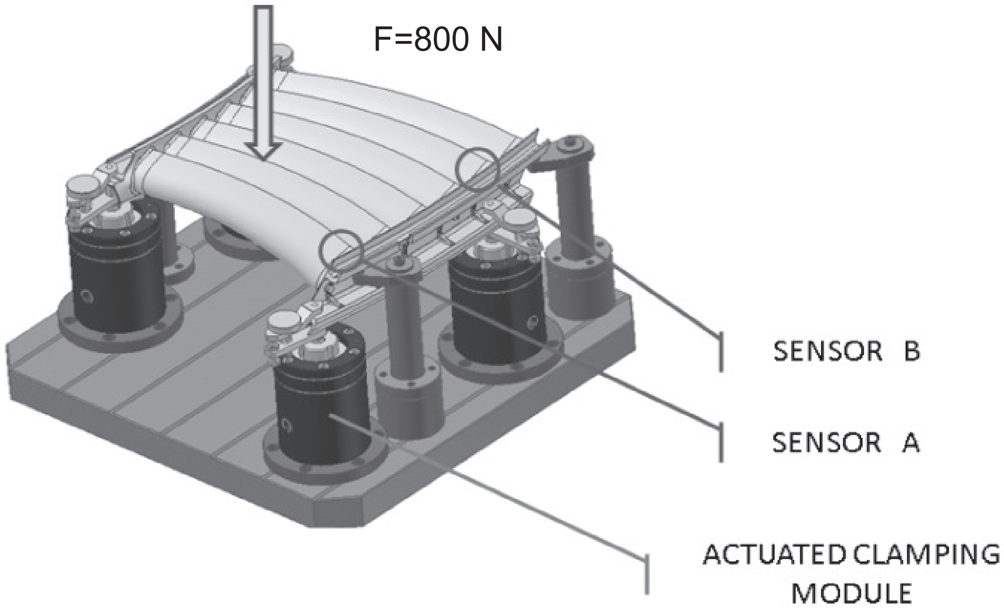

Figure 9: *Layout of the open loop test with an applied force*

One of major issues about piezoelectric actuators is their hysteresis. The hysteresis' knowledge is essential in case of dynamic and feed-forward control. One of the tests focused on the identification of the hysteresis curves.

On the base of experimental results the numerical model could be improved. The maximal achievable movement of each active clamping element was about 40 µm (20 µm in both directions from the pre-set position). This value is in accordance with the requirements for this application. The experimental axial and radial stiffness values differ not more than 10% from the numerical ones, confirming the FE model. Furthermore, open loop functionality test were done with the adaptive platform shown in Figure 9. The test results confirmed that the working principle is suitable for any static deformation recovery.