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ACTIVE ALIGNMENT CHUCK FOR ULTRA-PRECISION MACHINING

Ultraprecision (UP) components have become common in everyday life products such as mobile phones or compact high resolution digital cameras. Thus the need of producing such components with high accuracy and low production cost. UP machine tools are capable of extremely high accuracy in tool positioning but still today the workpiece is positioned by hand, hence the high production cost of UP components. A fully automated chain of production has been developed within the EU-IP project “Production 4 micro”. This paper describes the active alignment chuck for workholding in UP machining. The chuck has been provided with a high damping interface (HDI) and to evaluate its efficiency the chuck has undergone an experimental modal analysis (EMA) as well as machining tests. The chosen operation was grooving by fly cutting using a diamond tool. The EMA showed that the HDI was effective for those modes where there was relative displacement between one side and the other of the HDI. This result was confirmed by the machining tests as well. The HDI resulted being effective in damping high frequency modes (around 4 – 5 kHz), hence one expected benefit would be a longer tool life.

1. INTRODUCTION

Ultraprecision optical components are present in many common products, such as pocket digital cameras and mobile phones. The fast evolution of these products requires these components to be of elevated quality and relatively low price. In order to achieve this it is necessary to manufacture such components in large scales and in an automated manner. As for today, the level of automation in this branch is not as elevated as, for instance, in automotive industry. Workpieces are machined starting from the solid or the workpiece position is derived from test cuts [1]. This way of working requires a large effort in the set up phase, therefore clamping and referencing (i.e. the alignment of the work pieces within the machine coordinate system) become important factors. Beside clamping and referencing, machining system stability is a crucial aspect for the quality of the final product.

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Static stiffness and damping ratio of mechanical components of machine tools are of vital importance for the stability of the cutting process hence for the machining performance 2]. While static stiffness affects the geometrical accuracy of the workpiece, damping is essential for achieving the required surface finish [3]. These two dynamic properties are difficult to separate from each other, it is usually impossible to enhance one without compromising the other and the excess of one has a deteriorating effect on cutting stability as the lack of it [3]. It is nevertheless possible to design a mechanical component in such a way that damping ratio is enhanced and stiffness is minimally compromised by implementation of high damping interfaces (HDI) exploiting viscoelastic (VE) composite materials' damping properties [4],[5],[6].

In this paper the active alignment chuck for ultra-precision (UP) machining, designed within the EU-IP project "Production 4 micro", is described. The active alignment device consists of a System 3R Macro chuck /pallet system which is embedded in a HDI-enhanced flexure joint structure. The dynamic characterization of the chuck and the implementation of the HDI are the main focus of this paper.

2. CLAMPING AND REFERENCING

A major issue when manufacturing UP components is that they must undergo corrective manufacturing, i.e. a mould is produced, then a test lens is formed using this mould and, in case the lens is not complying with the given specifications, the mould is sent back for correction. Thus the importance of referencing the workpiece (the mould in this example) in the machine tool with extremely high accuracy. At the time the "Production 4 micro" project started, positioning and referencing of workpieces in UP machine tools was carried out manually by specialized operators [7]. As UP machine tools are capable of tool positioning accuracies below 100 nm, it is very unlikely for a human operator to reach such levels of precision [7]. Thus a completely automated workpiece handling system with matching precision is necessary in order to utilize the full potential of the UP machine tool.

The project outcome has been a fully automated manufacturing chain. In this section the solution designed for clamping and referencing of the workpiece in the machine tool will be illustrated.

In order to assure accurate positioning repeatability for several workpieces it was chosen to adopt a System 3R Macro chuck/pallet system. These chuck systems are widely used in high precision applications where also high stiffness is a strong requirement. The high stiffness is obtained thanks to the applied principle of having three orthogonal reference planes in the coupling interface. The z-plane is defined by the upper surface of four ground posts. This ensures a very high and solid stiffness in the z direction. The alignment in the xy plane is done by four pair of elastic tongues, on the pallet, being in contact with corresponding bars on the chuck. This gives a symmetric and self-aligning system. The very high repeatability in this alignment is also a result of the elastic averaging contact between the tongues and the bars (see Fig. 1).

In order to attain complete control of the positioning procedure the chuck system has been integrated in the appositely designed flexure joint [7] (see Fig. 2). The joint has been

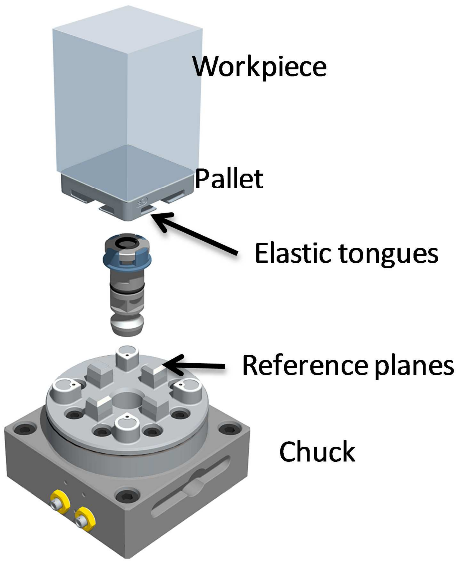


Fig. 1. System 3R chuck/pallet system

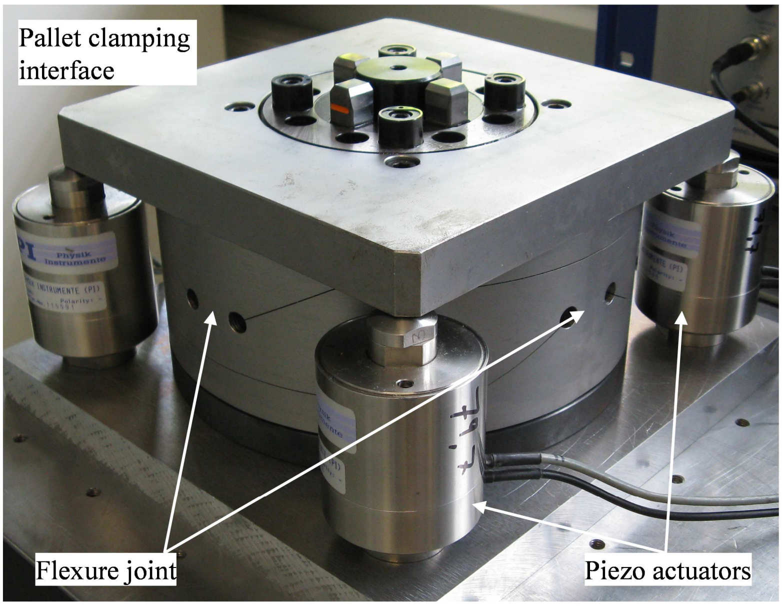


Fig. 2. Active alignment chuck. The chuck is composed by a System 3R chuck, a flexure joint and four piezo actuators [7]

designed to allow pitching and rolling thanks to four piezo actuators. All pallets are provided with reference marks and all machining stations are provided with high-precision CCD cameras. The basic principle is to reference measure all workpieces, assign an ID to them and use this data when they are moved from one machine to another. The task of the active alignment is to align the pallet to the same position it had on the reference station using the CCD cameras [1],[7]. Hence the workpiece can also be reintroduced in the production chain at any point for corrective manufacturing.

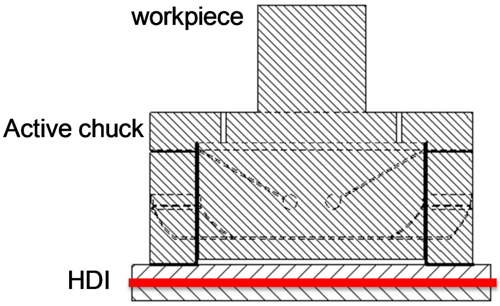


Fig. 3. Section view of the active chuck after implementation of HDI

3. DYNAMIC PROPERTIES

Referencing and clamping accuracy are two important aspects of UP machining, on the other hand, to assure high accuracy of the produced surfaces as well as longer tool life, the machining system should be able to operate in stable conditions over a large range of cutting parameters. For this purpose a HDI was implemented in the flexure joint, positioned at the interface between the joint and the machine table (see Fig. 3). In order to establish the effectiveness of the HDI, the active alignment chuck has undergone a comparative experimental modal analysis (EMA) and machining tests.

3.1. EXPERIMENTAL MODAL ANALYSIS

Method: EMA was carried out using impact hammer and accelerometers.

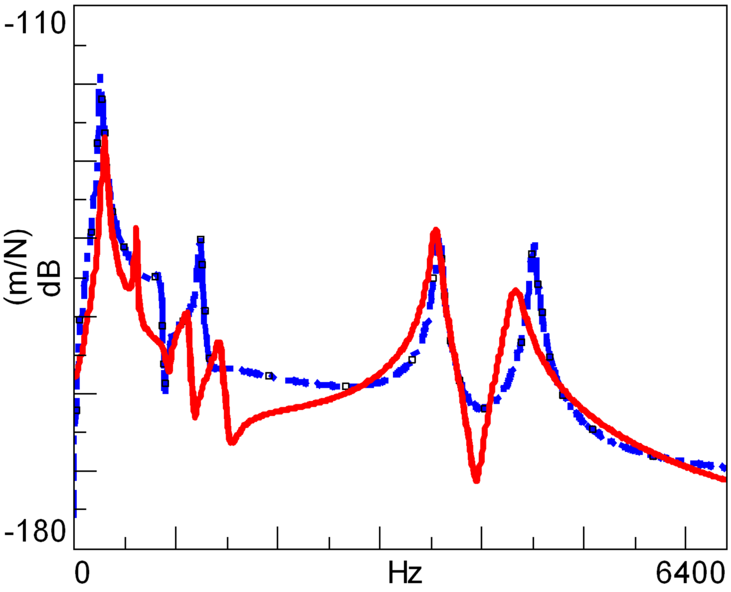


Fig. 4. EMA, compliance diagram before (dashed blue) and after (red) HDI implementation

Results: The EMA revealed that the effect of the HDI is a considerable improvement of dynamic stiffness at the first, third, fourth and sixth mode (see the compliance diagram in Fig. 4). Their respective shapes (see example in Fig. 5) reveal a relative displacement between the two sides of the damping interface.

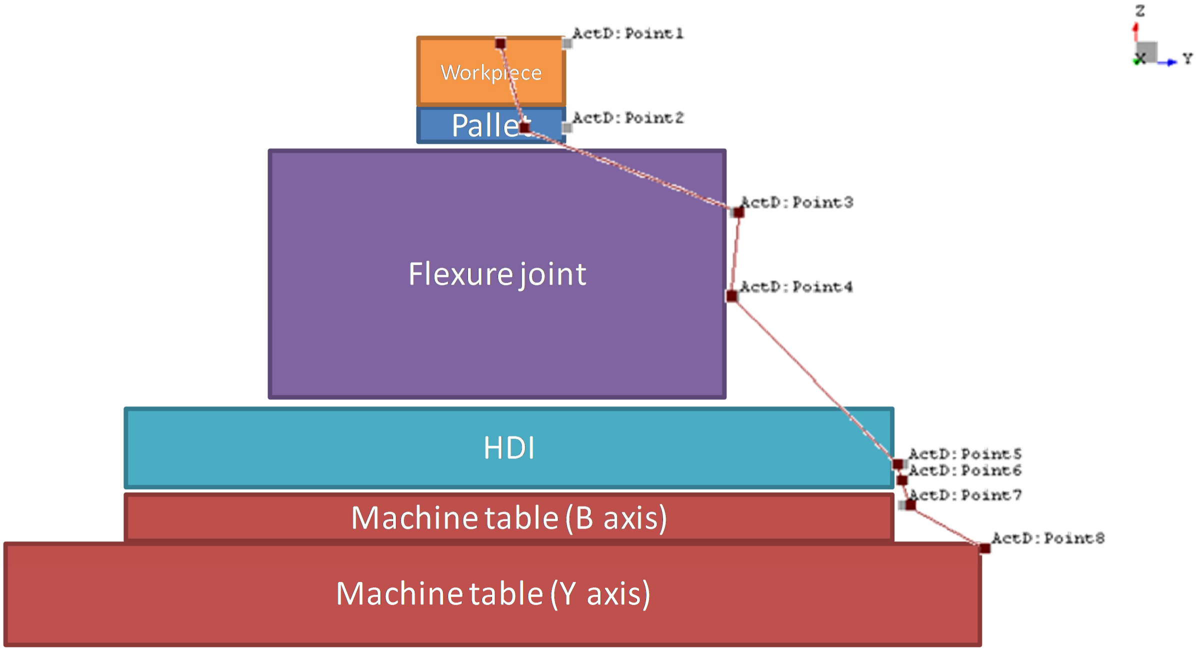


Fig. 5. Mode shape for the sixth mode of the active chuck with HDI

3.2. MACHINING TEST

Method: Pertaining the machining tests, the chosen operation was grooving through fly cutting with mono-crystalline diamond tool (Fig. 6). In this case the feed rate and the cutting speed had the same direction.

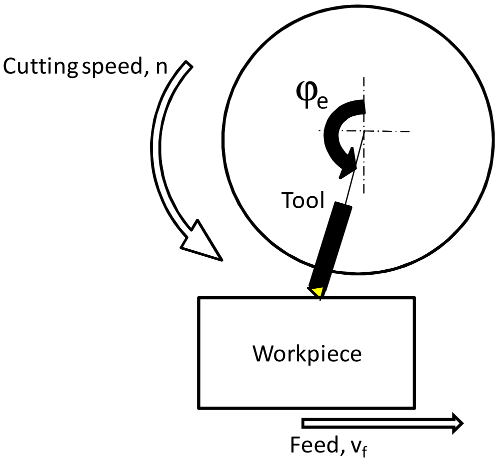


Fig. 6. Grooving by fly cutting. Cutting speed and feed rate have the same direction

The workpiece material was aluminium and vibration was recorded through a tri-axial accelerometer glued on the side of the workpiece as shown in Fig. 7.

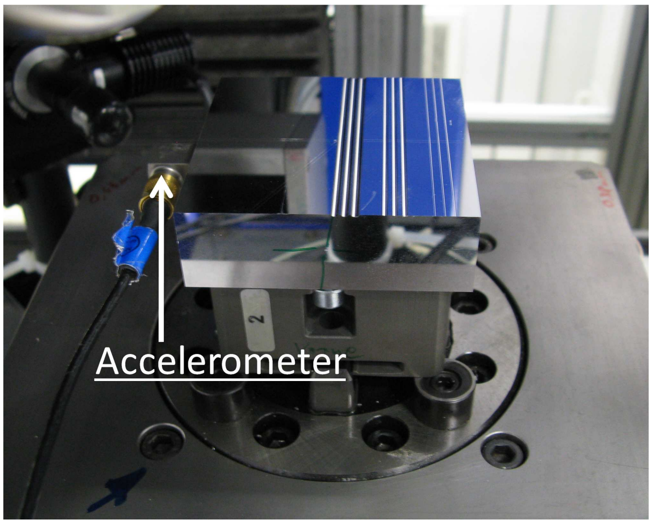


Fig. 7. Machining configuration. The accelerometer is glued on the side of the workpiece

The tests were run at all possible combinations for the cutting parameters summarised in Table 1. Fly cutting is basically a one-tooth milling operation carried out with a cutting tool resembling a common turning tool mounted on a spindle. This type of operation is therefore characterised by the very short time the tool is engaged compared to the time it takes to the next engagement. This time can be computed by first calculating the entrance angle according to Berglund [8].

$$\varphi_e = \cos^{-1}\left(\frac{a_p - \frac{D}{2}}{\frac{D}{2}}\right) \tag{1}$$

Where D is the cutter diameter and a_p the cutting depth. Hence the time of engagement per tooth is easily computed as:

$$t = \frac{\pi - \varphi_e}{\omega} \tag{2}$$

Where ω is the spindle speed in rad/s. Bearing in mind that the cutter diameter is about 500 mm and taking in consideration all the parameters in Table 1, the order of magnitude of the time of engagement can be estimated at 10^{-4} seconds. The cutting force can be therefore treated as a pulse train where the repetition frequency is equal to the tool engagement frequency; the representation in time domain would appear as shown in Fig. 6. Such a signal is characterized by a broadband power spectral density (PSD), as shown in Fig. 9.

Results: The time record of the signal acquired during machining (Fig. 10) shows the typical character of the response to an impulse excitation, i.e. free vibration. This behavior can be explained by the very nature of the chosen machining operation due to the short time of tool engagement. As this type of excitation is characterized by broadband frequency content (as previously shown, see Fig. 9), the frequency content of the machining signal (Fig. 11) resembles the frequency response obtained through the EMA. Therefore the improvements noticed in the EMA results are directly reflecting on the machining tests result.

Table 1 Cutting parameters

Parameter	***Values***
Spindle speed (n)	500 and 1000 rpm
Feed rate (v_f)	20, 50 and 100 mm/min
Depth of cut (a_p)	10,100 and 500 μm

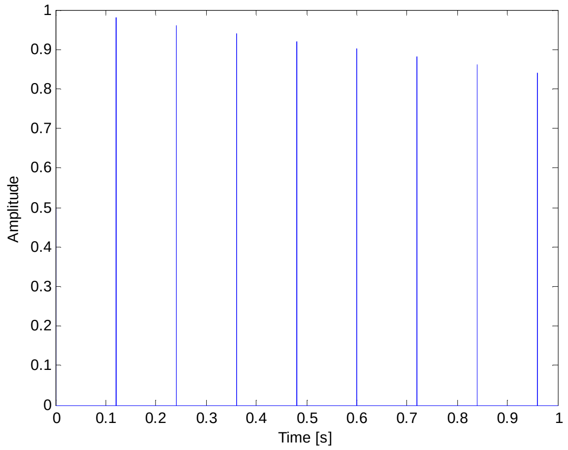


Fig. 8. Time domain representation of a 1N amplitude cutting force when machining at 500 rpm

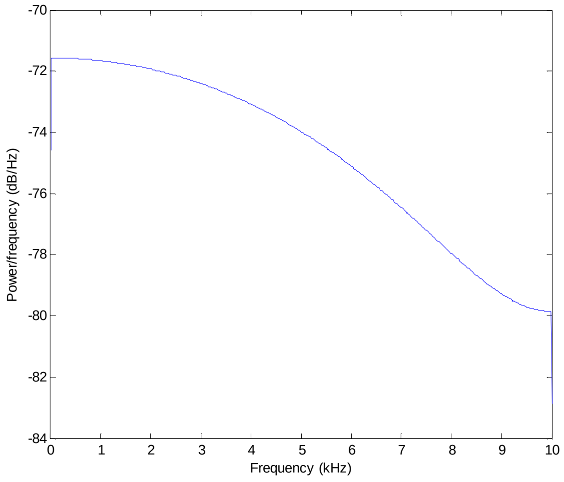


Fig. 9. Welch power spectral density estimate of the cutting force signal

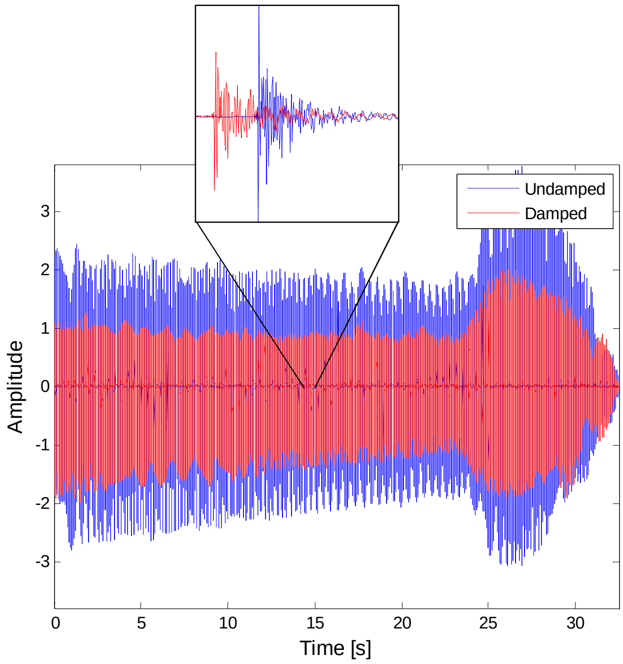
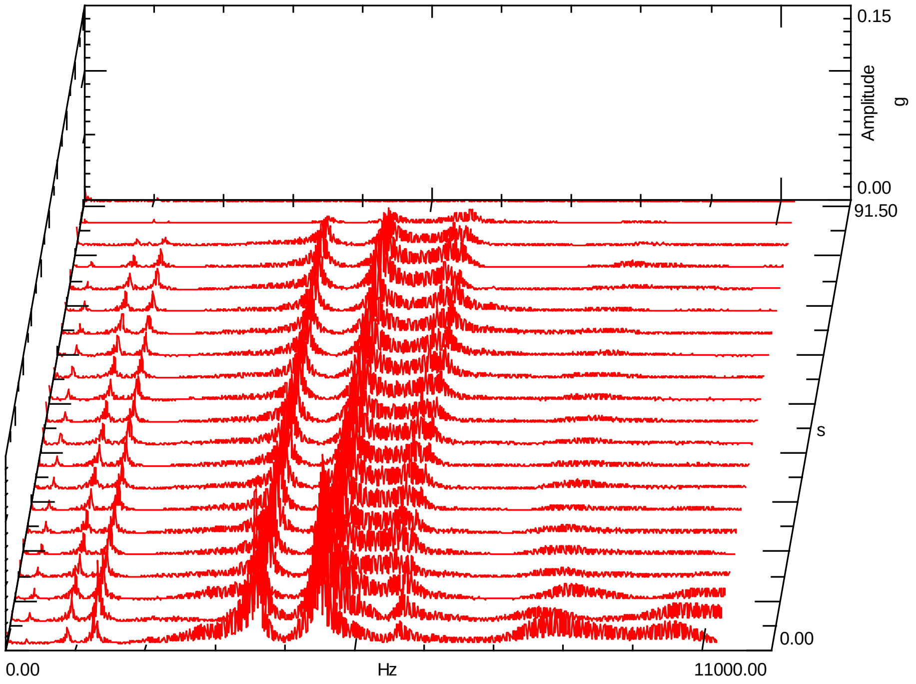


Fig. 10. Time record of signal acquired by the accelerometer in the feed direction
(n=1000 rpm, v_f=100 mm/min, a_p= 500 µm)

Fig. 11 shows the waterfall representations of the power spectral density of the signals collected by the accelerometer in the feed direction when machining at n=1000 rpm, vf=100 mm/min, ap= 500 µm. The comparison shows a general improvement (Fig. 10) particularly at the higher frequencies, around 4000-5000 Hz (Fig. 11). Similar results were obtained at the other combinations of cutting parameters.



a)

b)

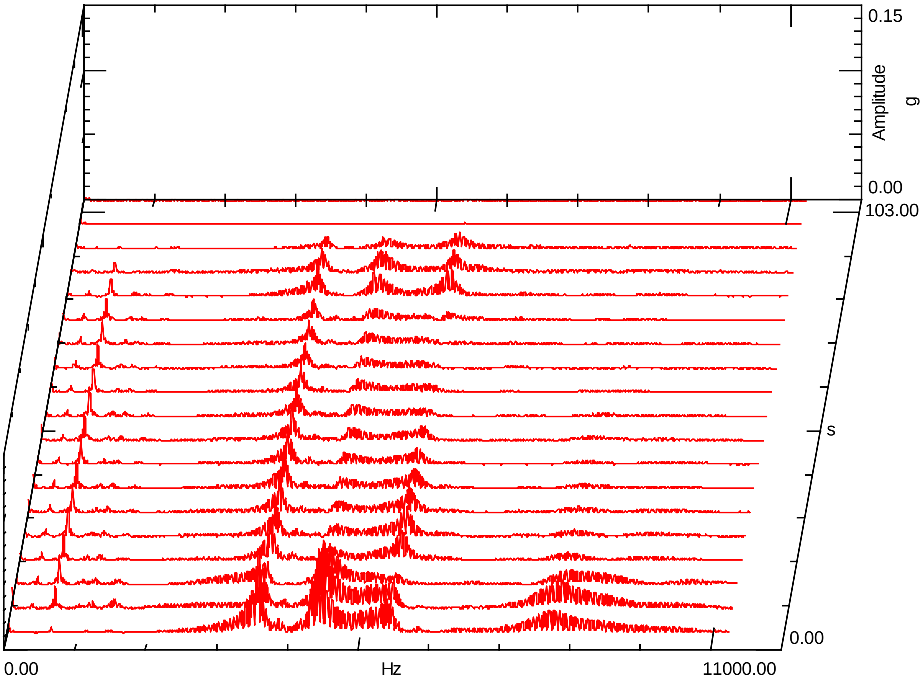


Fig. 11 Waterfall representation of power spectral density of the accelerometer signal. Active chuck before (a) and after (b) implementation of HDI. n=1000 rpm, v_f=100 mm/min, a_p= 500 μm

4. DISCUSSION

The EMA demonstrated that the implementation of the HDI has the effect of damping those modes that involve a relative movement between the two sides of the interface. The short tool engagement time characterizing ultra-precision fly cutting provokes an impulse-like excitation during machining. The response measured with accelerometer confirms this assumption. Out of the machining test can be observed that forced vibration is not relevant in this case. The frequency content of the response shows that the free vibration generated by the impulse excitation is dominating. Thus the machining tests verified the results of the EMA and showed that the implementation of the HDI in the active chuck causes a decrease of vibration amplitude at higher frequencies. High frequency vibration are considered to be responsible for tool wear [9], hence an improvement in these regards is to be expected and might be subject for further investigations.

5. SUMMARY

This paper has introduced the active alignment chuck developed within the EU IP-project “Production 4 micro”. The focus of this paper has been on the implementation of the HDI in such chuck. The chuck has undergone a dynamic characterisation, i.e.

experimental modal analysis (EMA) and machining tests. The HDI have been proved by the EMA to be effective on those modes which shapes show a relative displacement between the two sides of the HDI itself. The machining tests confirmed this result and showed that, when it comes to the chosen operation, an improvement at high range frequencies is observable.

REFERENCES

[1] BRECHER C., F. NIEHAUS M. WEINZIERL et al. 2009. Microscale Mass Production. *MICROmanufacturing*, 44 - 47.

[2] DAGHINI L., ARCHENTI A., NICOLESCU C. M., 2009, Design, Implementation and Analysis of Composite Material Dampers for Turning Operations. *In*: *ICME 2009: International Conference on Mechanical Engineering*. Tokyo, 613-620.

[3] RIVIN E I., AGAPIOU J., BRECHER C., et al. 2000, Tooling Structure: Interface between Cutting Edge and Machine Tool. *In*: *CIRP Annals - Manufacturing Technology*, 591-634.

[4] DAGHINI L., ARCHENTI A., NICOLESCU C. M., 2010, Design and Dynamic characterization of Composite Material Dampers for Parting-off Tools. *Journal of Machine Engineering*. 10/2/57-70.

[5] DAGHINI L., ARCHENTI A., NICOLESCU C. M,. 2010, Design, Implementation and Analysis of Composite Material Dampers for Turning Operations. *International Journal of Mechanical Systems Science and Engineering*. 2/2/65-72.

[6] RASHID A., 2005, *On passive and active control of machinig system dynamics*. Stockholm: Royal Institute of Technology, KTH Production Engineering.

[7] BRECHER C., WEINZIERL M., 2009, New approaches for an automizes production in ultra-precision machining. *The International Journal of Advanced Manufacturing Technology*. 47/1/47 - 52.

[8] BERGLUND A., 2008, *Characterization of Factors Interacting in CGI Machining*. Stockholm: US-AB.

[9] MEHTA N., K., PANDEY P. C., CHAKRAVARTI G., 1983, An Investigation of Tool Wear and the Vibration Spectrum in Milling. Wear, 219-234.