Evaluation of an Experimental Modal Analysis Device for Micromilling Tools

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Abstract Stable machining conditions in the micromilling process are critical to increase the production of small components. Precise frequency response measurements are essential to generate the stability diagrams. Therefore, impact hammer application which mostly relies on operator's skill and experience is very time-consuming and can produce imprecise results. This study aims to analyze a device developed to perform the experimental modal analysis of micromilling tools. The device facilitates the positioning of a fixed point Laser Doppler Vibrometer (LDV) as well as providing automatic and reproductive impact tests. Two mirrors supported by kinematic mounts are used to position the laser beam on the micro milling tool surface. The impact hammer is composed of a force sensor attached to a custom designed flexure-based body, in which an automated electromagnetic releases the mechanism. A set of experiments were conducted to perform the precision positioning of the laser beam and the impact hits. The impact force repeatability in terms of the magnitude and impulse duration were also investigated. The application of the device was demonstrated through modal testing of two micromilling tools with two different diameters.

Keywords Micromilling · Experimental Modal Analysis · Vibration

1 Introduction

The micromilling process has the advantage of machining surfaces with complex geometries to manufacture small components for biomedical, optics, electronics, aerospace, sensor industries, etc [5].

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In order to become economically viable, the removal rate must be increased. Due to small tool diameters, the cutting tool stiffness is very low which cannot take high chip load, being extremely sensitive to vibrations. This harms the microparts in terms of dimensional accuracy and surface finish. Hence, the choice of cutting conditions like spindle speed, feed and depth of cut depends on the dynamic interaction between the tool and the workpiece.

Vibration can be minimized when the dynamic response of the micromilling system and the workpiece material properties are known. Through the Stability Lobule Diagrams SLD a more productive and suitable cutting conditions for material removal can be selected [1, 7, 9, 12, 13, 15, 17, 18].

The generation of SLD for micromachining is still a challenge, as it requires the correct measurement of the Frequency Response Function FRF at the tip of the microtool attached to the tool holder set [23]. Experimental modal analysis EMA is the most common method of determining the tool FRF. However, due to very small tool size, the experimental methods are still difficult to be applied.

The excitation method is vital for the EMA. An excitation device must be able to excite all modes of interest. In other words, the excitation bandwidth needs to cover the frequencies of the modes of interest [10].

The dynamic analysis of micro tools by the experimental method using a mini impact hammer and laser vibrometer was reported by [19, 20, 27]. However, the measurements performed by Singh and Singh showed uncertainties, which were attributed to noise presented in the responses captured by the laser displacement sensor and imprecision in the positioning of the excited and the measured points [27]. The reported problems are contextualized by the image of the experiment carried out by Matuszak et al. in Figure 1 [20].

Mascardelli et al. points out that numerous excitations with the mini impact hammer were necessary to obtain a consistent result. In addition, the difficulty in positioning the laser beam on axis of the tool was also reported [19].

Some other methods have been developed to determine the FRF in micromilling. Jin and Altintas determined the FRF using a specially designed a piezoelectric actuator to excite the micro-endmill tool tip [15]. Wiederkehr et al. investigated the excitation micromilling tools using bearing balls, shot by compressed air. With the proposed approach the FRFs at different spindle speeds within a wide frequency range was obtained. The impact force magnitude, necessary to calculate the FRFs, were simulated the using finite element method [28].

Ahmadi applied the Operational Modal Analysis OPA method based on excitation by acoustic method to excite micromilling tool. The author used the experimental modal test with impact excitation to validate the frequency values found by the OMA method [2].

Hybrid methods combining experimental and analytical or numerical approaches has also been applied. En example is the receptance Coupling Substructure Analysis proposed by Schmitz and Donalson that has been an alternative to characterize the dynamics of micromilling systems [25]. Its has the

Fig. 1 Tool impact test: a) view of impact hammer and tool, e b) scheme of measurement points [20]

advantage in reducing the time spent on experiments when new modal tests are required for different tool-holder-spindle assemblies [8, 19, 22, 26, 27, 29]. Even using hybrid processes, it is necessary to use conventional EMA.

In order to make EMA an operator-independent process and therefore more reliable, different automated devices has been developed. Taking the macro milling as example, an automatic hammer was used by Dunwoody to obtain the tool tip FRF on the machine tool. The device consists of a solenoid actuated plunger with a force sensor on the end to hit the tool, and a capacitive displacement sensor to measure the response [11].

Ganguly investigated the spindle dynamics under different rotation speeds for the macro milling. A first setup was designed based on a oscillating impact hammer, which translates along a linear bearing. A second device was designed, in which a force sensor was mounted on a parallelogram leaf spring flexure. In both setups a Laser Doppler Vibrometer LDV was used to measure the response of the structure [14].

Brüggemann et al. developed an automated modal impact hammer based on the pendulum principle to obtain the FRF of the milling tools [6]. Postel et al. constructed an automated impulse hammer for using in a 5-axis CNC milling machines. The working principle is based on an axially moving bolt which is accelerated through a compressed spring and pulled back by a linear actuator [24].

In relation to automatic systems for dynamic analysis of small-sized structures, Ozturk et al. developed an automated set-up with impact hammer and vibrometer in order to obtain FRF of a macro milling tool dynamics [21]. A standard impact hammer is clamped on a flexible plate that is attached on to the table of the machine. The response of the tool is measured using a laser vibrometer. Bediz et al. studied an impact excitation system for modal testing of miniature structures using a flexure-based body and an automated electromagnetic release mechanism. With this system repeatable, high-bandwidth, controlled-force modal testing of miniature structures was possible [3].

Fig. 2 Experimental modal analysis device and main components

The main advantage of an automated modal analysis system is that an operator-independent process is achieved. With that, the need for a highly-skilled operator is eliminated, the repeatability of results of measurements increases, and the testing time can be reduced.

Therefore, this work aims to present and test a device capable of positioning a laser vibrometer and impact hammer, as well as the automation of the exciting process. The work is divided into description of the device, positioning test and impact force and finally its application in FRF determination.

2 Device description

The device consists of two systems, the first one the impact hammer and the second one the vibration measurement. It was developed to be easily mounted on the machine tool table, as well as the quick positioning of the laser beam and impact hammer. Further, the impact excitation system must not influence the measurement one, which means that the vibration energy must not be transported by the device structure in order to excite the mirrors that conduct the laser beam.

Figure 2 presents the elements of the EMAD according to the 1 - Impact hammer system, 2 - laser beam positioning system, 3 - Device base.

2.1 Impact hammer system

A schematic drawing of the impact system is shown in Figure 3. This consists of an electromagnet, a force sensor mounted on flexure mechanism and the

Fig. 3 Impact hammer system parameters

micromilling tool. It is also possible to see in this figure the two adjustable parameters, the distance x_e between electromagnet and the sensor and the distance x_t between the sensor and the micromilling tool.

A miniature ICP force sensor, from PCB Piezotronics model 209C01 with a sensitivity of 489.9 mV/N , was used as impact hammer. An aluminum made tip was attached to the flat face of the force sensor with Loctite Super Bonder adhesive. Two tip geometries cylindrical and spherical were used.

In the force repeatability tests, a spherical tip was used so that contact with the flat surface was always punctual, absorbing small misalignments between the excitation mechanism and the micromilling system. In the tests using the dummy tool or the micromilling tool, a cylindrical tip was used.

The force sensor was attached to the end of a parallel-leaf spring flexure. This mechanism has the advantage of having approximate a straight displacement, hitting the tool at same incidence angle.

The electromagnet provides initial deflections and enables repeatable release of the flexure-based hammer. The initial deflection x_e was adjusted varying the distance between the force sensor and the electromagnet. A carriage on which the electromagnet is mounted was moved along linear guides. A micrometer with a resolution of 0.01 mm was used to measure the displacement and thereby regulate the distance x_e . The distance x_t between the impact hammer and the tool was adjusted by controlling the positioning of the machine tool spindle. A UNO arduino was used to drive the model SRD-05VDC-3L-C relay that controls the 12 V electromagnet. The magnetization and demagnetization times of the electromagnet was programmed in the code running on UNO arduino board, which contributes to hit the structure only once at a time.

2.2 Vibration measurement system

A commercial single-point laser vibrometer Polytec PDV-100 was tripod mounted and used to provide the non-contact measurements of the tool response. It is capable to measure up to 22 kHz of frequency bandwidth with a sensibility of 8 mV/mm s^{-1} . The vibrometer measures the velocity of the target along

Fig. 4 Vibration measurement system elements

the direction of the laser beam. To convert to receptance, the mobility was multiplied by $i\omega$.

Since the vibrometer was mounted on a tripod relatively distant from the tool, the great challenge was to perform the experimental modal analysis, positioning the laser beam spot at different points on the tool. Therefore, any small displacement in the measurement region required an even smaller displacement in the tripod head, making the adjustment process even more difficult.

As the vibrometer is a relatively large device, the alternative found was to keep it mounted on a fixed position as close as possible to the machine tool and move the laser beam at different points on the tool.

Two broadband dielectric mirrors from Thorlabs Inc (BB1-E02) were used, which reflect $> 99\%$ of light between 700 and 1150 nm at a 45° angle of incidence. The laser beam hit the two mirror surfaces that were mounted on kinematic mounts. The mirrors were angular adjusted in order to positioning the laser beam spot on desired target. The mechanism is shown in Figure 4.

Manual adjustment of lower mirror along the Z axis was done via graduate knob with 10 divisions, enabling the 1 mm pitch M12 feedscrew the positioning with a 0.1 mm resolution. The upper mirror was fixed and didn't move along the z axis. To minimize the effect of backlash, a spring was adopted to pre-tension the translation mechanism. The coarse positioning of the laser beam was carried out by rotating the support of the mirrors around the Z axis at the angles θ_1 and θ_2 . Since the mirrors were mounted on a kinematic mounting, the fine adjustment was carried out by adjusting two M3 screws, rotating the mirrors in two directions, according to the angles θ_3 and θ_4 .

3 Device evaluation

The objective of the automated device was to provide repeatable modal testing of the micromilling tools. This means that location of the hits and the vibration measurement, as well as the force magnitude applied to the tool could be controllable and reproducible.

3.1 Location variability analysis

Experiments were carried out in order to obtain the characteristics of the impact test and the vibration measurement location variation using the EMAD.

3.1.1 Impact location variability

The repeatability of the impact location was assessed by comparing the area of marks generated by the impact hammer on a flat surface. The impact device was attached to the machine table. A prismatic workpiece was positioned in front of the impact hammer. The workpiece surface was aligned perpendicularly to the impact hammer using a dial indicator. A thin layer of white powder was deposited on the workpiece surface in order to highlight the point of contact after the hammer impact. Ten consecutive hits were performed using the automated impact hammer. The marks left on the workpiece surface were captured with the ZEISS stereoscope model Discovery V8.

Figure 5 a) show the experimental results with the automated impact hammer. This test demonstrated that the device tends to hit at the same position when compared to the obtained results using a miniature impact hammer manually as presented by Bediz et al. and shown in Figure 5 b). From the tests using manual hits, it is possible to observe great variability in the impact location [3].

The impact area for manual hits obtained by Bediz et al. [3] was calculated as 10.94 mm^2 , while the impact area for the automated device was 0.07 mm^2 for a maximum impact force of 6.83 N and a tip radius of 1.0 mm .

In contrast with a manual application of a miniature impact hammer, an automated device provides a high level of impact location repeatability.

3.1.2 Laser spot location analysis

In this experiment, a prismatic workpiece was also used. A millimeter paper was fixed on the workpiece surface to serve as a reference. Figure 6 illustrates the experimental setup.

Images were taken with a Canon 5D Mark IV DSLR camera, 30-megapixel full-frame sensor ($5.6 \mu\text{m}$ pixel size), equipped with Tokina AT-X M100 PRO D Macro (100 mm f/2.8) lens with the closest focusing distance of 195 mm that yields a 1:1 reproduction ratio. This distance was closed to that used to measure the micromilling tool.

Fig. 5 Comparison of location variability obtained with a) automated hit and b) from manual hits using a miniature impact hammer [3]

Fig. 6 Laser beam positioning test: a) Experimental setup, b) Mirrors and the projected laser spot c) Fitted circle on the laser spot

A high brightness point light source (bright spot), was projected onto the reference surface. The spot image was then photographed with the DSLR camera. After new positioning of the laser beam, a new image was remotely took and saved on computer for post-processing. Measurements were made every 1 mm in the Z-direction by moving the lower mirror, from the bottom upwards over 24 mm, totalling 25 measurement points.

The coordinate of the bright spot was offline processing using a Matlab (Mathworks Inc.) program. First the captured images were converted from RBG into grayscale. Afterthat the the brighter pixels are selected and a circle was fitted using the method of least squares. The radius and the coordinate

Fig. 7 Laser beam position error in the Z and X directions for different positions along Z direction

of the laser spot were calculated and converted to *mm*. The algorithm used is described in [30].

The positioning repeatability in the Z-direction was calculated in relation to the first position, while in the X-direction the deviation was computed by the distance from the spot center to the adjusted line passing through the first position.

Figure 7 presents the laser beam position error in the X and Z directions (radial and axial). The maximum position deviation P was calculated considering the average of the measures $\bar{U}$ and standard deviation σ , according to the relationship $P = \bar{U} + 2 \cdot \sigma$. The maximum positioning error in the Z direction was 0.20 *mm*, while in the X direction was 0.14 *mm*.

3.2 Force excitation analysis

The force impact analysis were conducted with regard to the influence of the distance between impact hammer and tool, the existence of a double hit and the repeatability of the force magnitude.

Fig. 8 Maximum excitation force depending on the distance between the workpiece and the hammer

3.2.1 Distance between tool and impact hammer

The impact momentum depends on the impact velocity and mass. For a given mass, obtaining repeatable impacts with limited force necessitates providing an accurate and repeatable impact velocity.

Tests were carried out to determine the influence of the distance between the sensor and the tool x_t on the maximum impact force.

The initial distance $x_t = 0 \mu\text{m}$ was adjusted to obtain the maximum impact force. With $x_t = 0 \mu\text{m}$, the sensor reaches the maximum velocity and hence the maximum impact force (maximum impact moment) is obtained. After that point, the leaf spring acts decelerating the sensor, decreasing the impact force. The automated release mechanism provides the distance x_e between the electromagnet and the sensor and hence initial deflection. It was adjusted so that the maximum force measured by the sensor does not exceed 9.8 N (the maximum allowable force).

Three impacts were performed for each distance and the result is shown in Figure 8. The result of the maximum force as a function of the distance x_e presented a behavior that approaches a second order curve and can be used to adjust the impact force.

3.2.2 Double hit effect

Double hit is a very common problem during impact testing. It occurs when there are multiple impulses after one hit due to structure rebound. When it

Fig. 9 Impact result with a) single hit b) double hit

happens, the spectrum of the excitation is distorted and force spectrum has no longer the wide band constant type.

The phenomenon is influenced by the hammer tip hardness, by the dynamic characteristics of the structure and by the excitation device. Therefore, in conducting the experimental modal analysis, the selection of impact points is important to avoid the occurrence of double hit.

Two experiments were carried out to illustrate the double hit phenomena. A cylinder dummy tool (H13 tempered steel) with a diameter of 3 mm and a length of 50 mm was attached to the machine tool spindle with a 30 mm overhang. The hit points on the tool were 4 and 8 mm away from the holder face.

Figure 9 illustrates the effect of the hit position on the double hit phenomenon. Exciting the structure at 4 mm, impact force without double hit is obtained (Figure 9 a), while exciting at 8 mm the effect of double hit can be observed (Figure 9 b).

3.2.3 Impact force repeatability

The Figure 10 presents the result of 10 consecutive hits on a plane surface performed using the impact hammer device. It is possible to observe that the curves have the same trend, showing a good reproducibility. The average maximum force was $\mu = 6.83 \text{ N}$ and the standard deviation $\sigma = 0.12 \text{ N}$, given the coefficient of variation $\sigma/\mu = 1.7\%$, which means a satisfactory value. Analyzing the interval in which the sensor is in contact with the tool, the mean time was $\mu = 167.15 \mu\text{s}$ with a standard deviation of $\sigma = 6.06 \mu\text{s}$, given

Fig. 10 Impact force variability result

approximately $\sigma/\mu = 3.6 \%$. This data is important, since it is associated with bandwidth, showing that it is also reproducible.

4 Experimental validation and application

To test of the EMAD, impact test of a blank cylinder was first experimentally obtained. The results were compared against the analytical results. In a second part the dynamics of two micromilling tools with different diameter were conducted. The calculation of modal parameters like natural frequency ω_n , damping ratio ζ and stiffness k_n were extracted from the frequency response function FRF at the tool tip. They are required to construct, for example, the SLD, which is necessary to choice stable cutting conditions.

4.1 Experimental Setup

Experiments were performed on a KERN pyramid nano-machining center with a vertical spindle and a Heidenhain Controller. Figure 11 shows the EMAD mounted on the machine table.

In this figure, it is possible to observe the laser beam and the impact hammer systems. In the same figure, enlarging the cutting tool region, it is possible to observe point 1 where the tool is impacted by the hammer and point 2 where the vibration response is measured by the laser vibrometer.

Adjusting the positioning of the impact hammer and laser beam spot in relation to the experimental points on the cutting tool follow the procedure described below.

Fig. 11 Experimental arrangement - excited point (1) and measured points (1 and 2)

First, the position of the tool in relation to the impact hammer was adjusted. This was done by referencing the hammer tip in relation to the machine tool with a probe. The hammer tip coordinates was then obtained in relation to the machine tool coordinate system. In addition, the actual tool diameter and length mounted in a holder was taken from a tool presetter and are calculate with respect to the machine tool coordinate system. In this way, the coordinates of tool can be computed such that the impact point on the tool coincides with the tool tip during the test.

After positioning the impact hammer, the laser beam spot must be positioned relative to the tool. For that, the bottom mirror was moved to the height corresponding to the vibration measurement point on the tool. Rotating the mirror support, a coarse angular position on the tool was achieve. Two screws were used for fine adjustment, always seeking to obtain the maximum intensity of the signal indicated on the display on the laser vibrometer as shown in Figure ??.

When the process begins, the electromagnet pulls the impact hammer, thereby providing an initial deflection to the flexure-based body. When the relay is switch off by the arduino UNO, the electromagnet releases the body and the impact hammer moves along a well-described trajectory. The arduino UNO was programmed in such a way that after the impact hammer hits the sample surface, the relay switches the electromagnet on pulling back the impact hammer so that the procedure can be repeated.

Fig. 12 Experimental results using a dummy tool a) Impact hammer and tool vibration responses and b) imaginary part of FRF

The impact and vibration response signals were acquired by a Bruel & Kjaer - Type 3160-A-024 data acquisition hardware. The software PULSE LabShop Fast Track v. 16.1.1.24 was used to obtain the experimental FRFs.

The acquisition rate used was 16.4 kHz . To avoid aliasing, the acquisition rate was set to approximately 3 times the bandwidth excited by the hammer. Rectangular and exponential windows were applied to the force pulse and vibration response respectively to avoid leakage. Each FRF was obtained considering the average of five measurements.

The data were transferred to a PC. Using the Matlab software the modal parameters were calculated using the peak-picking method.

5 Analysis with a cylindrical dummy tool

An excitation force was applied to dummy tool at 6.5 mm , and the tool vibration was measured at $6.5, 12.5, 18.5, 14.5$ and 29.5 mm from the holder face.

The analytical solution of the natural frequencies and mode shapes for a cantilever beam was obtained according to [4]. The parameters used in calculation are the elastic modulus, mass, and geometry of dummy tool. In order to get a more accurate results, the Young's modulus was obtained from a tensile test and yields 164 GPa . The calculated natural frequencies were $2117, 13269$ and 37152 Hz .

Figure 12 a) shows the signals measured during the impact test of the dummy tool where it is possible to observe the impact hammer signal, as well as the tool vibration response measured by the vibrometer. In relation to the impact hammer signal, it is to observe a impulse force with maximum level of about 5.6 N . When the impact hammer moves back, it collides with the release mechanism and therefore a small force oscillation can be observed.

These experimental results served to calculate the FRF. The existence of a dominant mode around 1995 Hz was observed, which is close to the first

theoretical natural frequency of circa 2117Hz , i.e. a difference of about 6 %. The imaginary part of the experimental FRFs was used to determine the first vibration mode of the cylinder blank, as shown in Figure 12 b). By normalizing the amplitude of the imaginary part by the maximum value and comparing it with the analytical result obtained according to [4], the average error between the five experienced points was around 14 %.

It can be considered that an error around 6 % in the natural frequency and 14 % in the amplitude of the first vibration mode are satisfactory to validate the device.

6 FRF of micromilling tools

A significant aspect in micromilling process dynamics is obtaining frequency response function on the tool tip. Due to the small dimensions and the complex geometry, the excitation cannot be applied with an impact force hammer directly on the tool tip. With this regarding the modal synthesis for finding frequency response function on tool tip is normally used. Tool response is measured directly at the tool tip with laser vibrometer, while excitation from impact hammer is applied on the shank of micromilling tool. Another important fact is that, the dominant mode of the tool is the most important to calculate the SLD and the first mode is the dominant in general.

To demonstrate the application of the device, two microtools DIXI model 7242 with tool tip diameter of 0.2 mm and 1.0 mm were investigated.

The tool holder set was attached to the machine spindle and the measurements were carried out directly at the KERN Pyramid Nano machining center. The impacts were performed at 4 mm from the holder and the vibration response were measured at this point and at the tool tip. FRFs were obtained based on five measurements per position.

Five measurements was carried out to perform the FRF at point 1 - H_{11} and point 2 - H_{21} , as shown in Figure 11. The coherence were also analysed for both FRFs.

The numerical modal analysis was conducted to obtain the natural frequencies and mode shapes of the micromilling tools using the software Abaqus. The solid model was meshed using linear hexahedral elements of type C3D8R (a 8-node brick element with reduced integration). The overhang length of tool is kept at 25 mm . The properties of the tungsten carbide tool is taken as density $\rho = 14,300\text{ kg/m}^3$, Young's modulus $E = 580\text{ GPa}$, Poisson's ratio $\nu = 0.28$ and damping ratio of 1%. The fluted section of the end mill was modeled as a solid cylinder, considered to be 80% of the total diameter, as presented by Kops and Vo [16].

Figure 13 presents the finite element simulation of the first vibration mode for the 0.2 mm tool diameter. The first three natural frequencies were $4,944\text{ Hz}$, $29,298\text{ Hz}$ and $42,800\text{ Hz}$. The first two are bending modes and the third is a torsion mode.

Fig. 13 Finite element simulation of the first vibration mode for a 0.2 mm diameter micromilling tool

The experimental FRFs of the spindle-tool structure and the coherence functions for the 0.2 mm tool diameter are presented in Figure 14. Three resonance peaks were detected at approximately 1590 Hz, 2350 Hz and 4144 Hz. It was observed that the closest natural frequency to that obtained from the simulation is the third one, about 4144 Hz. According to the natural frequencies between the experimental and the simulated, the difference was approximately 19 %.

The first and second resonance peaks can be associated with a natural frequency of the spindle, of the tool holder or even of the experimental device. In the frequency range of 0 – 1000 Hz the FRF magnitude showed a disturbed signal that is caused typically by the integration of the noise in velocity measurement and hence was not shown.

The frequency bandwidth obtained in the tests was in the order of 5.7 kHz, which means that the device is suitable to excite the first vibration mode of the micromilling tool.

For FRF H_{11} , the measurement was closer to the holder face and hence the tool was stiffer, so the vibration speed is lower, which worsens the quality of the FRF. This fact is noticed mainly in the anti-resonance regions and above 5 kHz. For the H_{21} , the interval between 1000 and 6000 Hz the coherence result provided evidence of an excellent performance. Coherence values were above 97% within the measured range, except when the measured response was small, including the anti-resonance and the low frequency regions.

The Figure 15 presents the experimental results for the 1.0 mm diameter of the cutting part of the micromilling tool. As in the previous test, three natural frequencies are also presented.

The first two frequencies were close to the found in the test of 0.2 mm tool diameter. The third, of about 4878 Hz was assigned to the cutting tool. The numerical result obtained in Abaqus simulation for the 1.0 mm tool diameter was 5280 Hz, which means an error of 8.2 % between the frequencies.

An explanation for the difference found in the first natural frequency between the simulated and the experimental results can be explained based on

Fig. 14 Experimental FRF-receptance and coherence for experiments H_{11} and H_{21} and $\phi = 0.2 \text{ mm}$ tool diameter

the work of Mascardelli et al. [19]. They pointed out that the effects of the imperfectly constrained tool holder, as well as the effects of the spindle modes on the tool mode, can significantly decrease the tool mode frequency.

Table 1 shows the modal parameters extracted for the two tools. The experimental modal parameters of the system, i.e. natural frequencies, modal damping ratio and modal stiffness were obtained through the curve fitting using the peak-picking method.

Comparing the results of the FRF H_{11} and H_{21} at the frequencies 1590 and 2530, it was observed that there was no significant difference in the parameters modal damping ratio ζ and modal stiffness k_n between the cutting tools. In the third natural frequency, a change was observed in both the modal damping ratio and the modal stiffness, as expected.

The modal damping ratio ζ decreased from 2.0 to 1.6 for H_{11} and from 2.2 to 1.7 for H_{21} with the increase in the diameter of the cutting part of the tool was observed. Regarding the modal stiffness, the relative difference between the two tool diameters increases 104 % and 71 %, for H_{11} and H_{21} , respectively. Therefore, for the micro-cutter with the larger diameter of the cutting part, the stiffness is greater, while the modal damping ratio decreases.

The reliable frequency range of the FRF obtained with the proposal device was between 1 kHz and 5.7 kHz, which is satisfactory to determine the FRF of the most flexible mode of the micromilling tool. This FRF is used then

Fig. 15 Experimental FRF-receptance and coherence for experiments H_{11} and H_{21} and $\phi = 1 \text{ mm}$ tool diameter

Table 1 Extracted modal parameter (f_n (Hz), ζ (%), k_n (kN/mm)) from FRF for $\phi_1 = 0.2 \text{ mm}$ and $\phi_2 = 1 \text{ mm}$

ϕ_1					ϕ_2				
H_{11}			H_{21}		H_{11}			H_{21}	
f_n	ζ	k_n	ζ	k_n	f_n	ζ	k_n	ζ	k_n
1590	1.7	217.2	1.7	162.3	1590	1.8	219.1	1.5	164.4
2530	2.5	75.5	2.9	30.2	2430	2.7	83.9	2.7	39.4
4140	2.0	90.8	2.2	13.1	4878	1.6	185.0	1.7	22.4

the calculation of the Stability Lobes Diagram or in simulation of the process dynamics in the time domain.

7 Conclusion

The impact hammer test of micromilling tools is a difficult task. The frequency response function accuracy relies on the operator's skill. In order to turn the process more reliable and less time-consuming, a device that can facilitate the positioning of the laser vibrometer beam directly at certain points on micromilling tool and enable the automatic hit process of the impulse hammer was investigated. The laser beam was guided from the laser vibrometer to the micromilling tool by two mirrors. One mirror was linearly displaced

positioning the laser beam along the tool axial direction, while the angular adjustment moves the mirror in the radial direction of the tool. Analyzing the maximum positioning error of laser beam spot in the axial and radial directions, the results were satisfactory. Regarding the impact hammer, the tests showed that the reproducibility of the impacts location was considerably better than the manual hits, compared to those in the literature. Moreover, it could be shown that the device can provide repeatable, controlled-force, and adequate bandwidth excitations for modal testing. Using a cylindrical dummy tool the device was evaluated in terms of modal testing, showing satisfactory agreement with analytical results. Impact tests of two micromilling tools with different diameters were carried out to show the device application. The FRFs were satisfactorily obtained for both tools and the modal parameters extracted for the first vibration mode. In addition, modal parameter was effectively extracted to use to construct the Stability Lobes Diagram. The investigated device still requires some expert knowledge on modal testing and a technician to set it up, however due to its modularity it is easily installed in a machine tool. The laser beam and the impact hammer were easily adjusted. The results showed that the device can provide a satisfactory alternative method for manually operated impact test. Further works, provides the development of a system that can be permanently installed in the machine tool in order to conduct a fully automated experimental modal analysis without any external intervention.

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Declarations

Ethics approval All authors have read the manuscript, and the data are true. This paper is new. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal.

Consent to participate All authors agree to participate in this manuscript.

Consent for publication All authors agree to submit and publish this manuscript in The International Journal of Advanced Manufacturing Technology as a full-length article.

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