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OPERATIONAL MODAL ANALYSIS DURING MILLING OF WORKPIECE, FIXED ON A STIFFNESS CONTROLLABLE JOINT

Vibration in metal cutting processes has been studied to a great extent resulting in for instance stability lobe diagrams under which stable machining parameters can be selected. One limitation of accurately estimated stability diagrams is the change in process and dynamic characteristics of the machine tool under operation. The machine tool dynamic response is often analysed with experimental modal analysis under off operational conditions. One drawback with this approach is the large number of measurements required to fully describe a machine tool and workpiece in different positions and time of machining. Another drawback is that the change of dynamic characteristics under operation is excluded. Operational modal analysis has been applied in machining under different conditions resulting in successfully improved stability lobe prediction. This research includes operational modal analysis of the workpiece, fixed on a stiffness controllable joint and stability prediction to stress the importance of various machining conditions.

1. INTRODUCTION

A machining system consists of the necessary components and process in order to remove a chip by cutting. These components are: Machine tool, Cutting tool, Fixture, Workpiece and Cutting process. The structural components in a machining system are always of stable dynamic character whereas the system, under influence of the cutting process can be unstable. Tobias investigations [1] lead to a basic force model coupled with the equation of motion used for calculating the limiting cutting parameters for a stable system, known as chatter theory and stability lobe diagram. The theory was later extended by Budak [2] among others and used for selecting optimised cutting parameters. One limiting factor for applicability of a generic stability lobe diagram is the requirement of accurate modal data to describe the dynamic characteristic of the system. Various researchers such as Özşahin *et al.* [3] and Gagnol *et al.* [4] investigated the influence of boundary conditions when experimentally obtaining the frequency response function of a machine tool whereas Hanna and Kwiatkowski [5] investigated the change of spindle

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dynamics under different spindle speeds. Zaghbani and Songmene [6] used operational modal analysis in order to identify the change of the modal parameters during the machining process. The drawback with operational modal analysis is the unknown excitation which leads to unscaled frequency response functions. Powalka *et al.* [7] used the modal mass obtained by impact testing (with non-rotating tool) in order to scale the modes from operational modal analysis.

This paper will stress the importance of accurate modal data if general stability lobe theory is to be effective. Spatial changes of modal parameters are presented as well as operational modes indicating the complex problem of machining system dynamics. Stability lobes for different cases will be presented and a conclusion as well as future work is given in the end.

2. EXPERIMENTAL PROCEDURES

The machining system with instruments (Fig. 1), was tested off-line with classical impact testing and on-line, during machining, with operational modal analysis. The workpiece, fixture and machine tool table response was measured with accelerometers while the cutting tool response was measured with a laser Doppler vibrometer. The impact testing gives the mode parameters under free condition when both impact force and response are measured to create the frequency response function, H_1, and further synthesised by using PolyMAX estimation algorithm [8]. The cutting tool used in this experiment is a 3 flute insert end mill with a diameter of 20mm and 55mm overhang. The machining parameters were 10mm depth of cut, 0.0215mm/tooth feed and 3100RPM spindle speed, down milling with an entry angle of 90 degrees.

a) b)

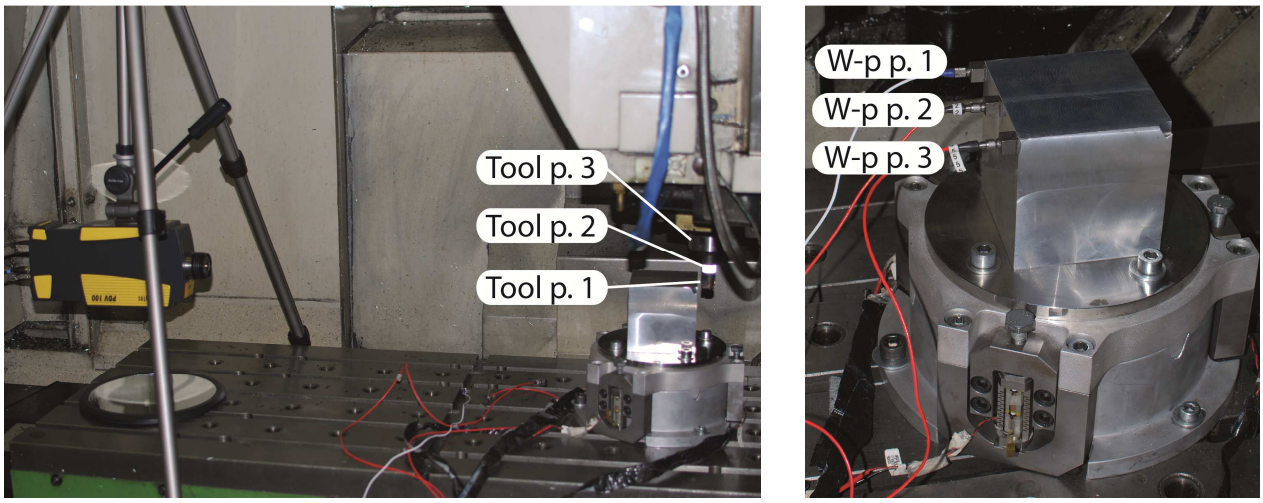

Fig. 1. Machining system set-up - a), workpiece and fixture during modal analysis - b)

A cubic workpiece, side length 96mm, was fixed on a joint with changeable stiffness. The change in stiffness is achieved by controlling the voltage supplied to the piezo-electric actuators, located on the periphery of the work holding device, Fig. 1b. The piezo-electric element in the actuator expands with increased electric potential, thus compressing the joint which leads to a higher pre-stress and thus higher stiffness.

2.1. OFF-LINE MEASUREMENTS OF SYSTEM RESPONSE

The synthesised frequency response functions obtained with impact testing can be seen in Figs. 2 to 4. The presented response points on the cutting tool are: Tool p. 1 – tool tip, Tool p. 2 – middle of tool, Tool p. 3 – clamped base of tool, as seen in Fig. 1. Tool p. 2 was used as the excitation point and the responses were then calculated to give the response for each point when the excitation is at the tool tip, as during cutting.

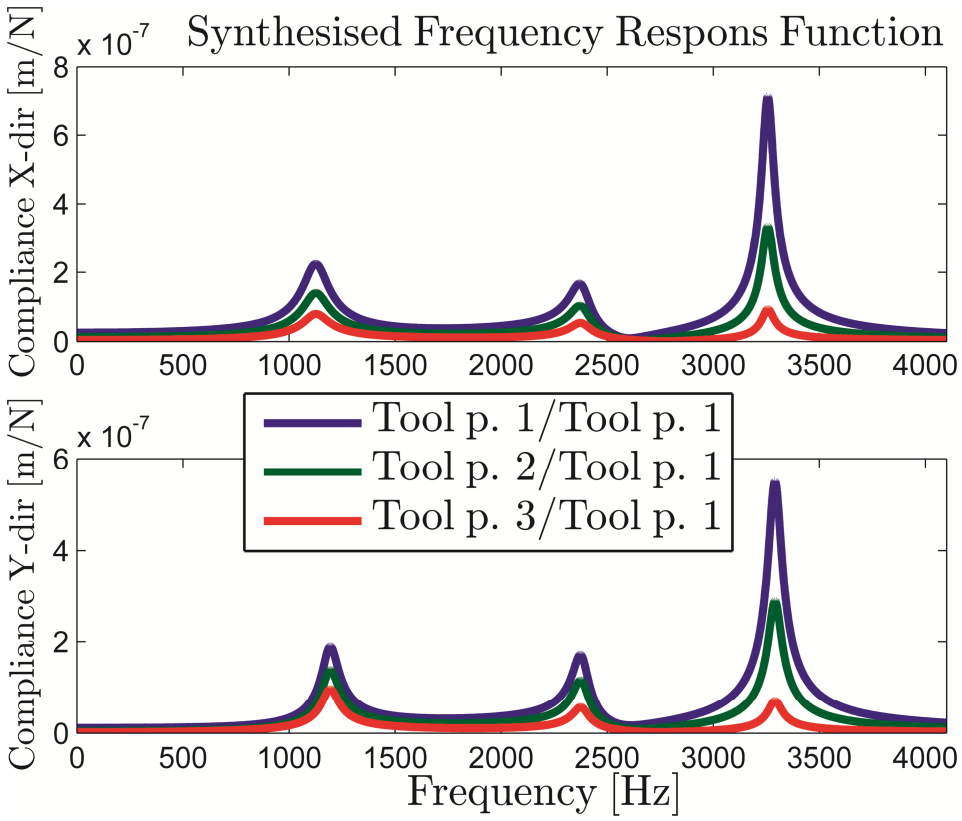

Fig. 2. Cutting tool synthesised frequency response function

The workpiece response, Fig. 3 and 4, shows the direct compliance for each measured point, given in Fig. 1b. Fig. 3 shows the compliance for the set-up with low stiffness and Fig. 4 shows the high stiffness set-up.

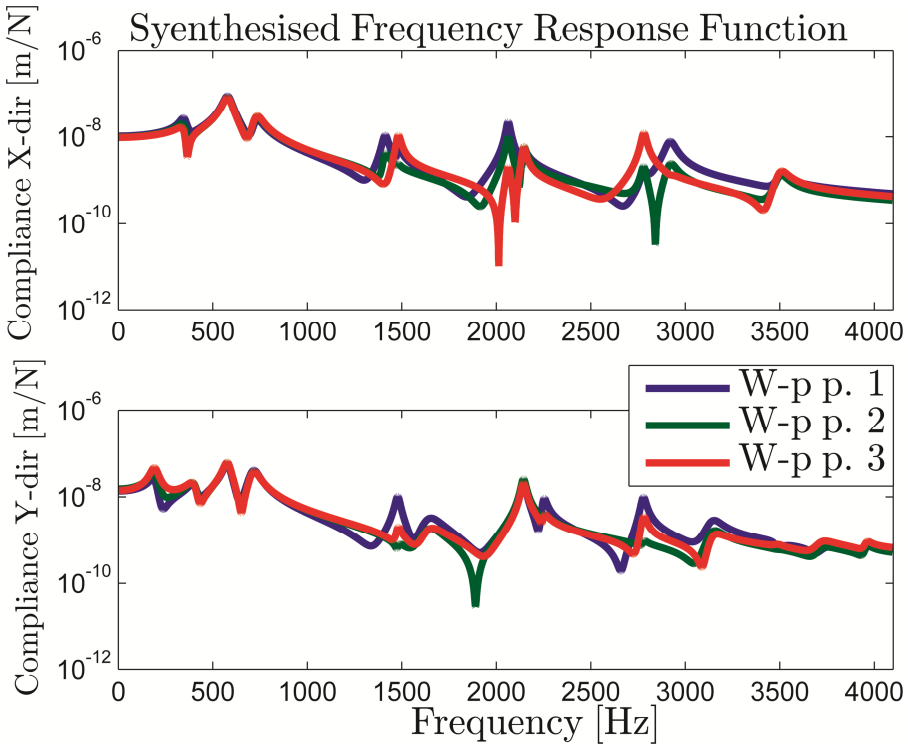

Fig. 3. Synthesised compliance function from top of workpiece at low stiffness set-up

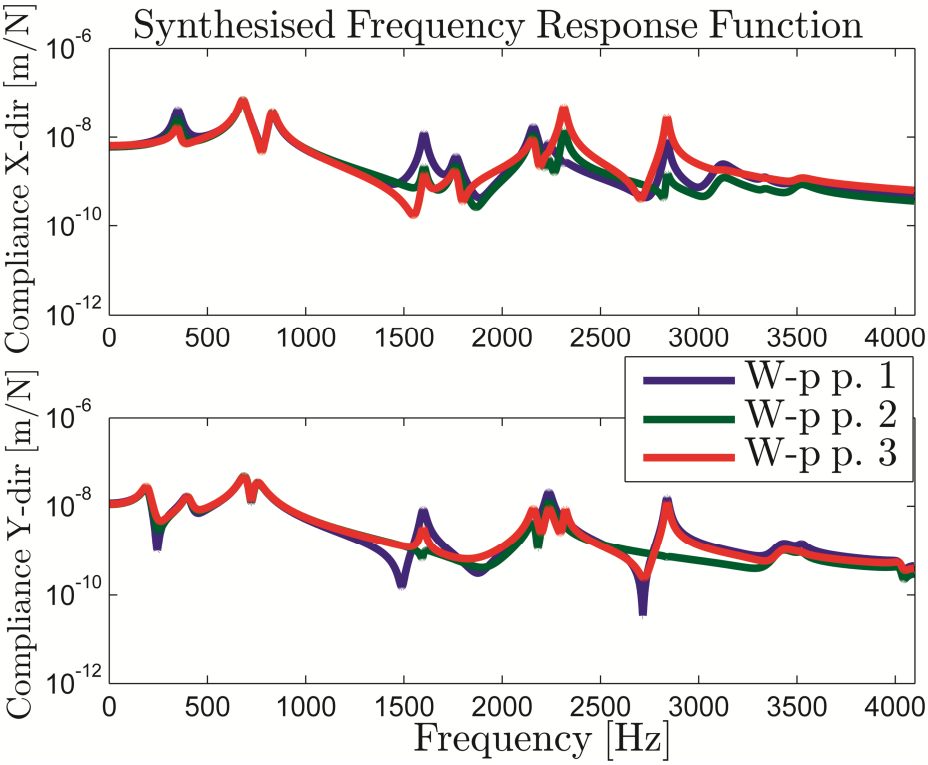

Fig. 4. Synthesised compliance function from top of workpiece at high stiffness set-up

2.2. ON-LINE MEASUREMENTS OF SYSTEM RESPONSE

One reason for on-line measurements of the response is to investigate which modes are excited during machining. The cutting force will excite some modes more than others as well as introducing a non-structural dependent component at the tooth engagement frequency and its harmonics. Operational modal analysis uses an assumption of the input force since it is not measured. In this case, a white noise signal was used for calculation of the frequency response function. The justification of using white noise as input derives from the impact between the cutting teeth and the workpiece thus leading to an impulse which is a broad band source. The cutting force was simulated as a function of theoretical chip thickness variation during cut (with the same machining parameters as used in the cutting test) and Fig. 5 shows the power spectral density plotted together with the power spectral density of the white noise. As can be seen, the lower frequencies will be slightly over estimated whereas higher frequencies will be slightly underestimated. The tooth engagement frequency (and its overtones) can clearly be seen in the power spectral density of the simulated cutting force. The least square frequency domain method was used to derive the system modal parameters.

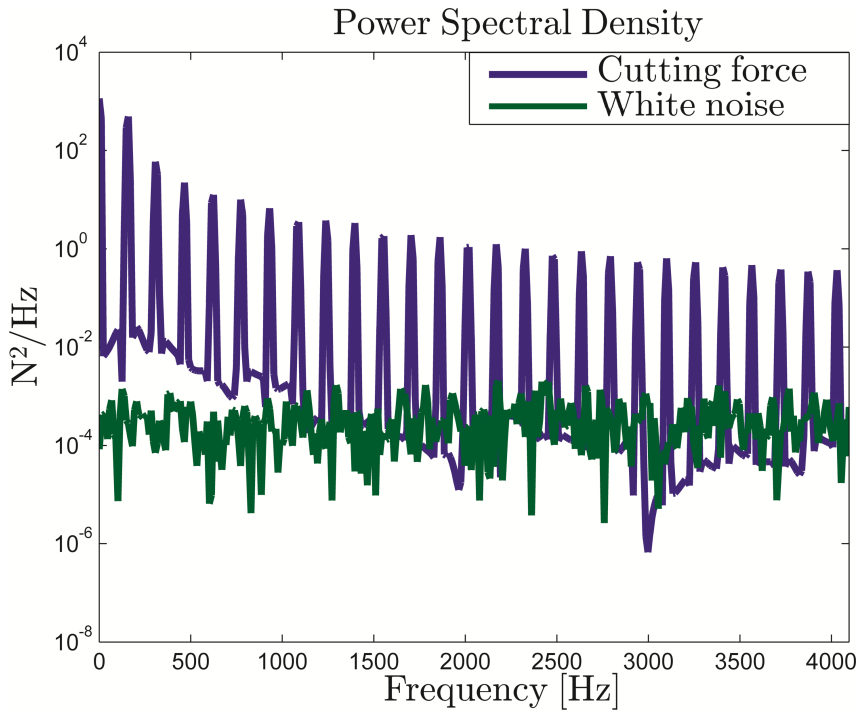

Fig. 5. Power spectral density of simulated cutting force and white noise used for operational modal analysis

The data used for operational modal analysis was a 15 second record, starting at t = 15s and ending at t = 30s, see Fig. 6. The reason for excluding the signal at start of cutting and at the end is due to the change in process dynamics at the edges.

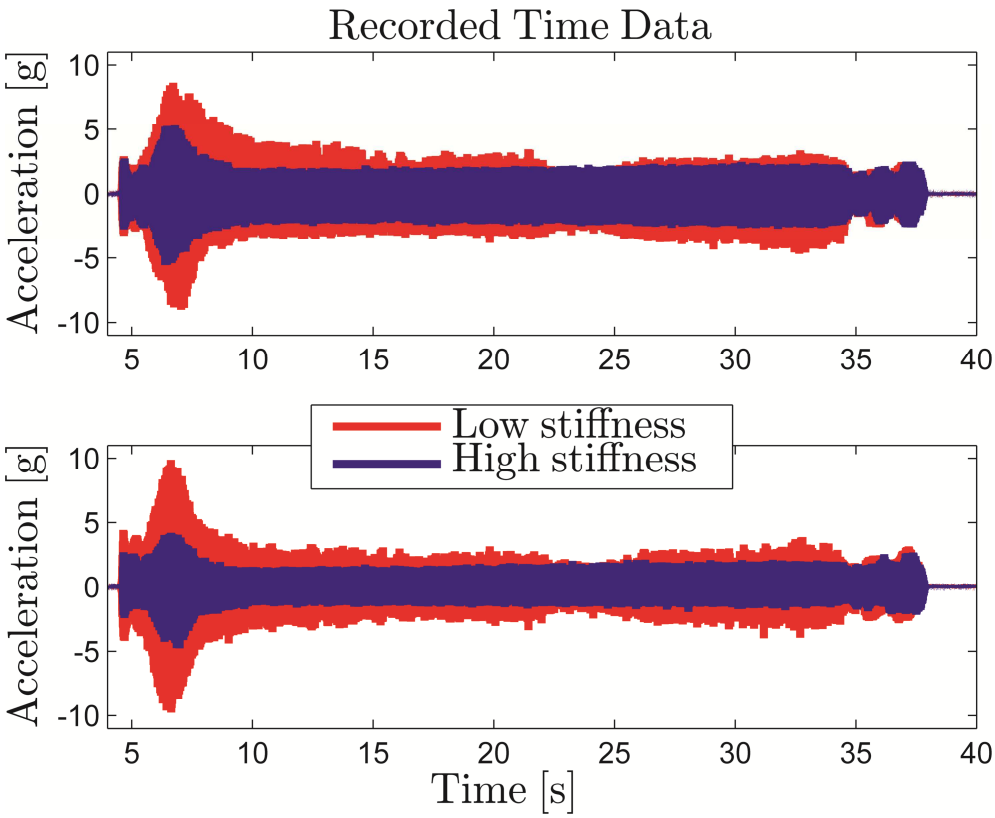

Fig. 6. Time record from machining in x and y-direction

The obtained cross powers, response acceleration multiplied with white noise in frequency domain, can be seen in Figs. 7 and 8, as well as its synthesised counterpart.

2.3. COMPARISON BETWEEN ON-LINE AND OFF-LINE DATA

By comparing the off-line and on-line results it can easily be seen that some of the modes are dominating while others are not so easily excited during machining. The compliance from impact testing and the unscaled compliance from operational testing are given in Figs. 9 and 10. The resonance frequencies and deflection shapes (from the operational modal analysis) are later matched with eigen-frequencies and mode shapes to scale each mode with the modal mass obtained by impact testing for calculation of stability. Note that some modes shift in frequency during operation; this indicates a stiffness change since the modal mass change is assumed to be negligible.

The stability lobes calculated, Figs. 11 and 12, from modal data obtained by off/on-line testing shows the same shift in frequency as the operational modal analysis (closely spaced lobes in lower spindle speed). The damping also changes, since the two substructures of cutting tool and workpiece are interacting. The increase in damping and stiffness gives a negligible change in the absolute stability criteria whereas the performance at resonance is improved which can be seen from the high peaks in the stability lobes.

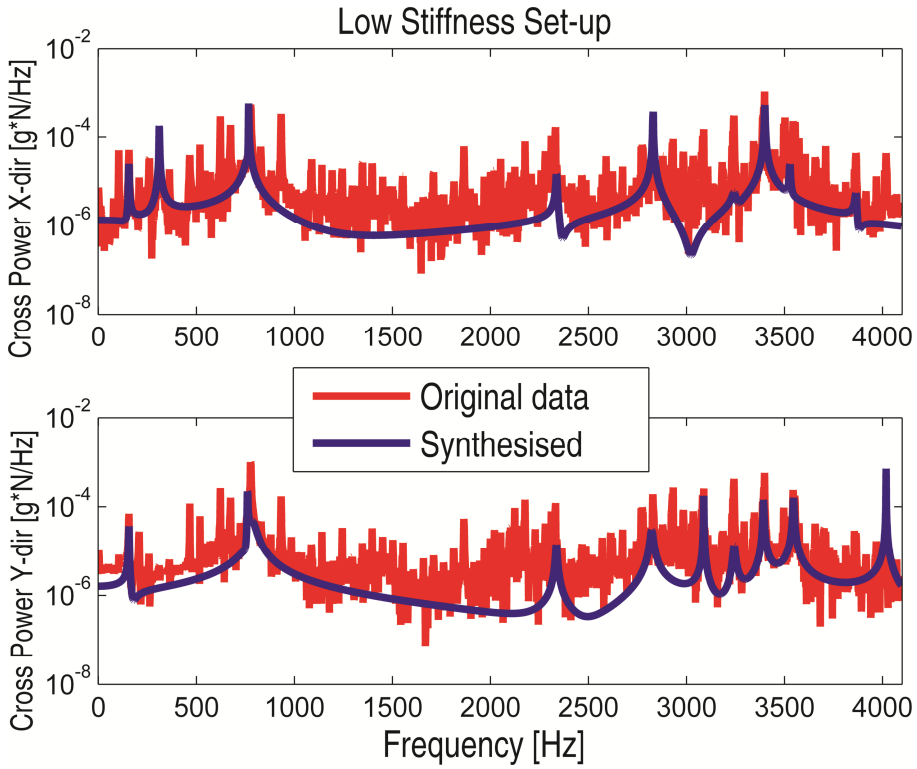

Fig. 7. Cross power spectral density of workpiece acceleration and white noise during machining with low stiffness set-up, in x and y-direction

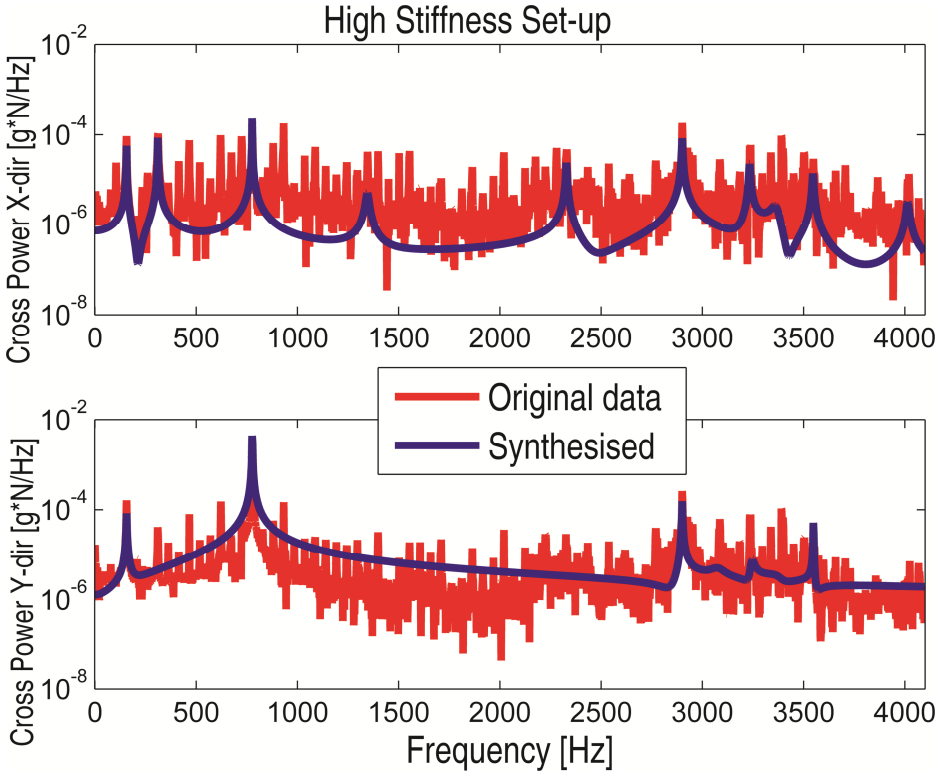

Fig. 8. Cross power spectral density of workpiece acceleration and white noise during machining with high stiffness set-up, in x and y-direction

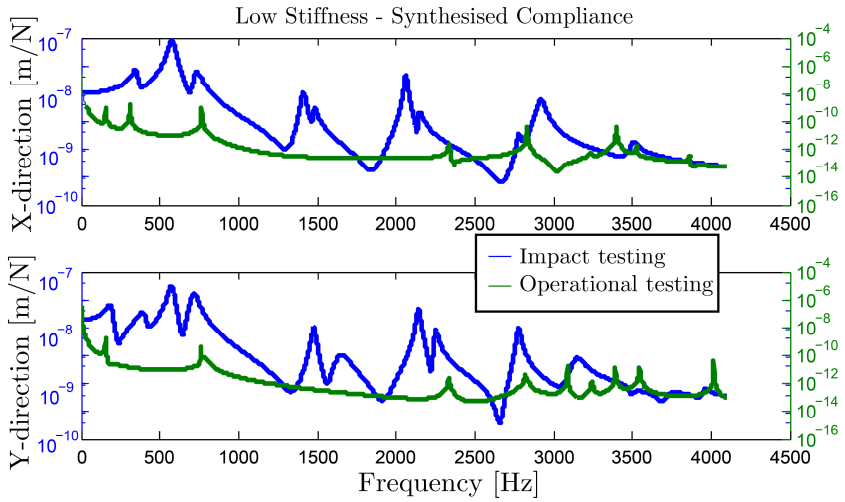

Fig. 9. Comparison between compliance functions obtained with impact and operational testing for the low stiffness set-up

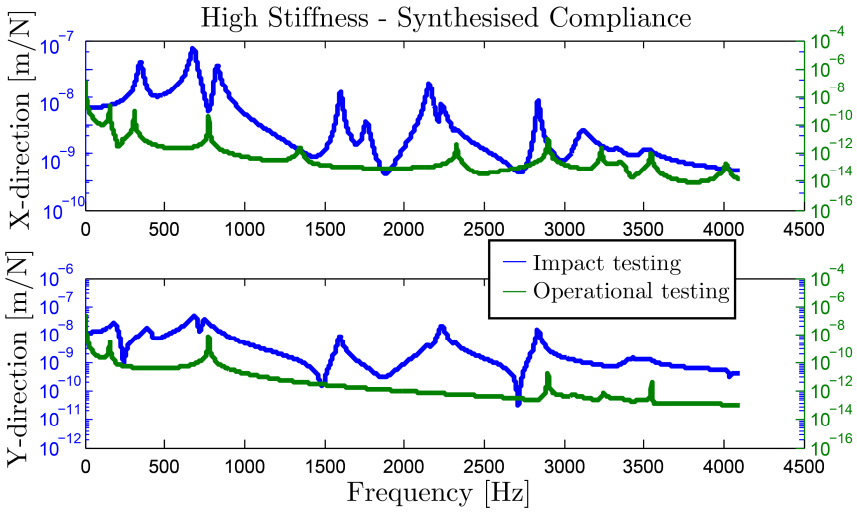

Fig. 10. Comparison between compliance functions obtained with impact and operational testing for the high stiffness set-up

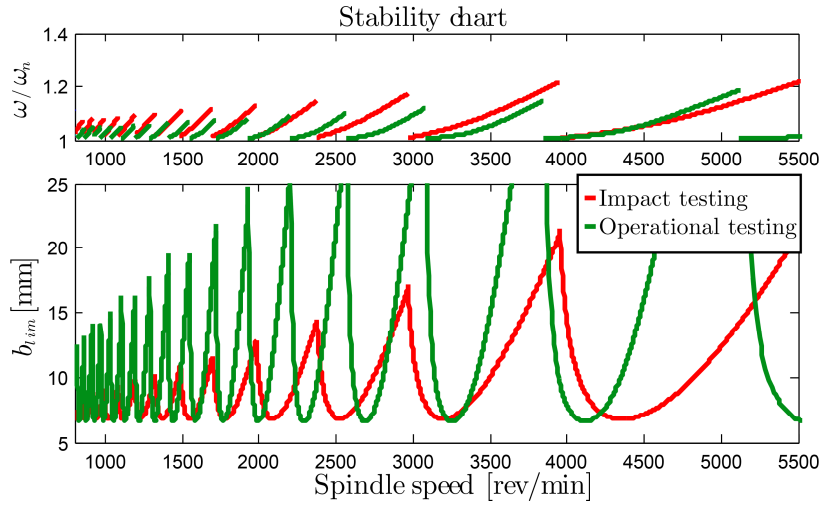

Fig. 11. Stability lobe comparison between low stiffness on- and off-line tests

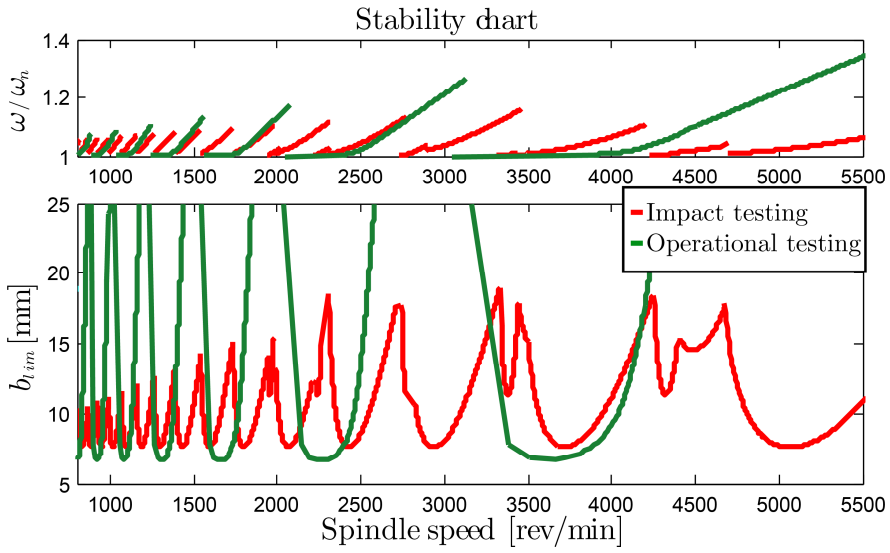

Fig. 12. Stability lobe comparison between high stiffness on- and off-line tests

3. CONCLUSION AND DISCUSSION

Machining system dynamics are complicated and measurement during operational condition improves the prediction of accurate stability lobe diagrams. The dynamic characteristic changes not only with the spatial location of cutting tool and workpiece but also with process parameters. The tool engagement frequency can clearly be seen in Figs. 7 and 8 and may result in undesired quality loss due to forced vibration. The same figures also show the coupling between cutting tool and workpiece. To further improve modal parameter extraction in machining for accurate stability lobe prediction it is recommended to use non-contact measurement under operation.

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