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3D Finite Element Modeling of Holder-Tool Assembly for Stability Prediction in Milling

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Abstract

Receptance coupling substructure analysis (RCSA) allows to estimate tool-tip FRF of different spindle-holder-tool configurations with the minimum set of measurements. This technique requires accurate holder-tool connection modelling. In this paper fully predictive modelling strategies of holder-tool connection are presented. Proposed procedures are implemented in FE environment, without the use of any tuning experimental test, using solid elements to model the most common connection types. The main advantage of proposed approaches is to model the entire toolkit without requiring lumped stiffness and iterative procedures. Resulted toolkit FE model can be used in RCSA providing accurate tool-tip FRF for chatter prediction.

Keywords: Milling; Finite element method (FEM); Modeling; Chatter; Tool.

1. Introduction

Machine tool dynamics is essential to accurately model different aspects of machining cutting operations [1], such as cutting forces simulation [2], surface finish and generation model [3]. Moreover it is the most important input for chatter vibration modeling [4], key factor in improving machining performance. Machine tool dynamics is usually driven by tool-tip Frequency Response Function (FRF), except specific cases (e.g., thin-wall machining [5]).

Experimental Modal Analysis (EMA) is generally performed to obtained such data: this procedure is time-consuming and costly because it has to be repeated for each toolkit coupled to the machine [6].

This aspect limits machining simulation diffusion in industry, in which prediction is hence replaced by experimental cutting tests [7] or trial and error approaches.

In order to overcome this limitation, Receptance Coupling Substructure Assembly (RCSA) methods have been applied to machine tool dynamics identification [6, 8]. These techniques allow tool-tip FRF to be estimated in different configurations with a minimum set of measurements. Starting from experimental test on the machine without tool clamped (the fixed part), tool dynamic contribution (changeable part) is numerically added to compute assembled configuration FRF.

The main drawback of these approaches is the high sensitivity to input data, in particular FE model accuracy on simulating toolkit dynamic behaviour in free-free boundary condition. Inaccurate FE model results in wrong tool-tip FRF estimation, compromising chatter prediction.

Different modelling techniques have been applied: Schmitz et al. [6] initially propose to use Euler-Bernoulli beam model, later Timoshenko beam was found more accurate to simulate dynamics [9]. Beam model allows to implement RCSA quickly and easily but could lead to inaccuracies, due to one-dimensional simplification.

As already mentioned, RCSA effectiveness is predicting tool-tip FRFs performing a single test for machine tool, independently from the toolkit (holder-tool assembly) clamped on it. To achieve such result, entire toolkit should be assumed as the changeable part, hence it should be FE modelled [10, 11]. Holder-tool joint modelling is hence a key

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factor to achieve an accurate FRF prediction. Several papers investigate this connection by means of lumped stiffness applied between holder and tool model: Movahhedy et al. [12] proposed a joint modelling method with two parallel linear springs, Ahmadi and Ahmadian [13] used a distributed elastic layer including damping. However all these methods introduce an iterative procedure based on experimental tests to identify connection stiffness: elastic elements parameters are computed minimizing difference between measured and calculated FRFs of the holder-tool assembly. Therefore a new modal testing on the toolkit is required for each connection, increasing the number of experiments. Since the goal of RCSA methods is reducing the number of tests required this procedure makes the method less attractive, limiting its industrial application.

In this paper FE modeling strategies of holder-tool connection are presented. Proposed procedures are fully implemented in FE environment without using any tuning experimental test. To achieve this goal, 3D solid FE modeling technique is applied in place of 1D beam modeling, generally adopted. The most common connection types are investigated: collet chuck, shrink-fit and hydraulic clamping. The main advantage of these novel techniques is modeling connection and contact properly without requiring lumped stiffness and iterative identification procedures.

The accuracy of the proposed modeling techniques was experimentally evaluated: a set of test cases (toolkits) was tested, performing EMA in free-free boundary conditions and experimental results were compared to the predicted ones. Furthermore, thanks to RCSA technique [8], tool-tip FRF was predicted with both traditional modeling approach (1D Timoshenko beam [9]) and proposed approach comparing them with experimental results. The influence of toolkit connection modeling accuracy on RCSA approach is hence presented. Finally predicted and experimental tool-tip FRFs are compared in terms of Stability Lobe Diagram (SLD) [14].

2. Proposed modeling techniques

In this section tailored modeling techniques for the most common connection types are proposed. A brief overview of analyzed connections is presented:

- Collet chuck: an elastic sleeve (collet) is tightened around tool shank by means of a shaped bolt, providing required contact force.
- Shrink-fit: the holder is heated up, causing radial thermal expansion of tool housing, tool shank is then fitted and clamped by holder shrinkage during its cooling.
- Hydraulic chuck: tool housing is surrounded by a pressure chamber filled with oil that can be compressed by means of a screw-driven piston. Oil compression causes pressure chamber deformation allowing tool clamping.

Proposed modeling techniques are developed in MSC Nastran commercial FE solver. Holder and tool are FE modeled using solid 3D elements allowing an accurate connection stiffness modeling to be achieved. Components mesh size has been chosen smaller than required by convergence analysis allowing a better part description. Toolkit components (holder-tool) are assembled by means of MSC Nastran glued contact feature [15]: a linear double sided contact algorithm that allows joining components with non conformal interfaces, i.e., different meshes. The reason of using such a solution is twofold: it allows to achieve a better component description since mesh pattern and size can be different with respect to the component and it reduces pre-processing time since conformal mesh interfaces are not required.

As highlighted in Fig. 1, where proposed modeling workflow is shown, different connections follow specific pre-processing operations requiring different modeling efforts. Details of modeling procedures are given in following sub-sections.

2.1. Collet chuck

Collet chuck working principle is outlined in Fig. 2a: nut fastening pushes collet inside holder conical housing, tightening it around tool shank allowing spindle torque to be transmitted. Since tool and holder are not directly in contact, connection flexural stiffness will be influenced by collet stiffness.

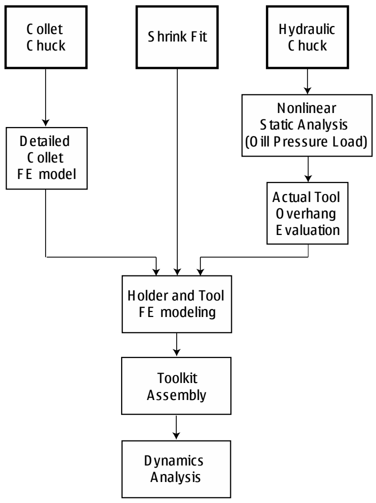

Fig. 1. Proposed modelling workflow.

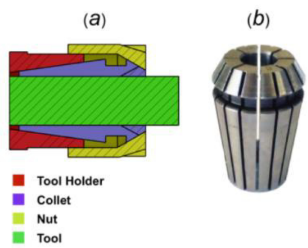

Fig. 2. (a) Collet chuck main components (b) tapered collet example.

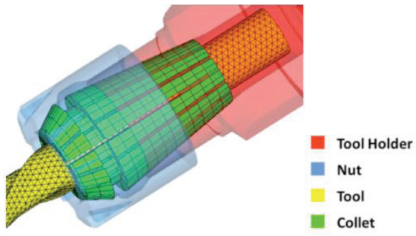

Fig. 3. Collet chuck connection modelled according to the proposed technique

According to previous considerations, proposed approach is creating a toolkit model including collet component, avoiding geometry approximations that could lead to incorrect stiffness estimation. Fig. 2b shows a tapered collet: basically it is metal sleeve with longitudinal slots to increase its compliance. To achieve an accurate modeling of collet stiffness, slots should be included in the model. In Fig. 3 collet chuck connection modeling technique is shown: collet is modeled including longitudinal slots and all the components are joined using glued contact. It is clear that such a model could not be implemented using beam elements, unable to give an accurate description of collet complex geometry.

2.2. Shrink-fit

In shrink-fit toolkit, connection is provided by thermal shrinkage of holder. In Fig. 4a an example of thermal chuck connection is given. Although Schmitz et al. [11] present a complex modeling technique for shrink-fit connection, in this paper shrink-fit connection is considered rigid: thermal tightening allows this joint type to provide a very high connection stiffness. Proposed approach is hence modeling holder and tool, joining components interface nodes without adopting specific pre-processing techniques. In Fig. 4b proposed modeling technique for shrink-fit toolkits is shown. According to these guidelines, this connection is the less difficult to be modeled: beam modeling technique could therefore provide an accurate prediction of shrink-fit toolkits dynamics, as already proven in [10].

2.3. Hydraulic chuck

In hydraulic chuck toolkits, clamping is achieved by compressing the oil inside the pressure chamber that undergoes a radial deformation, tightening tool shank. Fig. 5a shows hydraulic chuck toolkit working principle, while in Fig. 5b an axial cross section of a real hydraulic holder is shown.

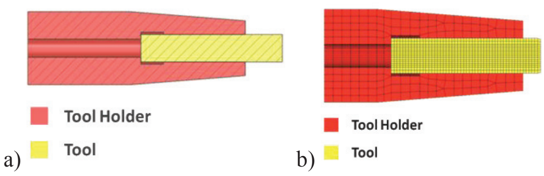

Fig. 4. (a) Shrink fit connection example (b) shrink-fit proposed modelling technique.

The main issue in hydraulic connection modeling is actual overhang identification: it is known that in such toolkits, ending sections of the holder do not clamp tool shank [16], resulting in an increased projection length. This phenomenon occurs because oil compresses both inner and outer faces of the chamber causing its radial deformation, hence leading to separation of tool shank and tool housing in dependence of holder elasticity.

Tool overhang has a great influence on toolkit dynamic behavior [8], therefore to achieve an accurate modeling, actual projection length should be determined. Proposed approach is simulating oil pressure effect by means of non-linear static simulation. As shown in Fig. 6 a FE model of holder and tool portions corresponding to the clamping region is implemented in MSC Nastran. Toolkit axisymmetry is exploited modeling just a 90° sector and imposing symmetry constraints. A uniform pressure load is applied on pressure chamber faces. Pressure magnitude is set to 300 MPa, according to commercial hydraulic holder pressure range [16]. Nastran standard one-sided contact algorithm is used to model holder-shank interface. Proposed simulation results are shown in Fig. 8: a non-contact region is present in the ending portion of the holder, resulting in an increased overhang as earlier mentioned. Non-contact region length can be identified from static analysis results, allowing complete toolkit to be modeled. As shown in Fig. 9, tool nodes corresponding to non-contact region are not constrained to holder, allowing actual overhang to be modeled. Comparing all the proposed modeling procedures, hydraulic chuck is the most demanding connection in terms of pre-processing operations. Furthermore, proposed overhang estimation technique can be carried out only by means of a 3D model, making beam elements unsuitable for proposed hydraulic toolkit modeling.

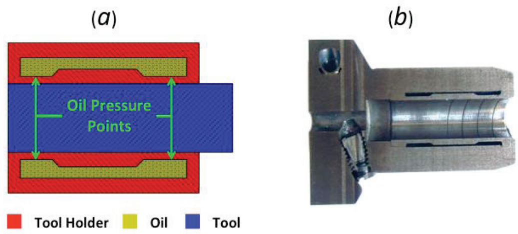

Fig. 5. (a) Hydraulic holder working principle (b) real component cross-section

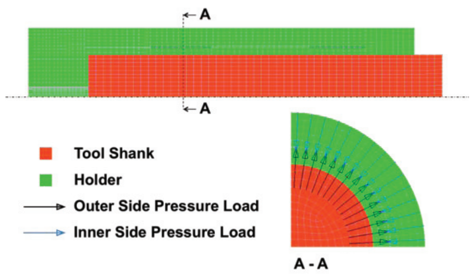

Fig. 6. Proposed non linear simulation for overhang estimation

3. Connection modeling validation

To prove the accuracy of proposed modeling techniques an experimental validation analysis was carried out on a set of test case toolkits, shown in Fig. 9a. Collet chuck test case is composed by an Iscar MULTI-MASTER tool (diameter: 12 mm, shank total length: 70 mm)) clamped on an HSK32E tool holder (manufacturer: Diebold) with 19.5 mm overhang. For shrink-fit toolkit, an Iscar MULTI-MASTER tool (tool diameter: 12 mm, shank length total: 130 mm) has been connected to an HSK63A tool holder (manufacturer: Iscar) with a 100.6 mm overhang. For hydraulic chuck toolkit the same tool of the previous test case has been connected to a HSK63A hydraulic tool holder (manufacturer: Kennametal) with a 100.5 mm nominal overhang, while pre-processing analysis estimated a 106.7 mm actual overhang. Modeling validation was performed in free-free boundary condition to evaluate toolkits dynamics modeling accuracy. Experimental tests were carried out via impact testing technique: a Bruel&Kjær 8202 impact hammer (sensitivity: 0.98 pC/N) was used for the excitation, while vibration responses were acquired using two PCB 352C22 (sensitivity: 10 mV/g, mass: 0.5 grams) and two ENDEVCO 2250AM1-10 (sensitivity: 10 mV/g, mass: 0.4 grams) piezoelectric accelerometers. Signal acquisition and conditioning were performed using a LMS Scadas 3 Frontend acquisition system. FE models of the selected toolkits were implemented according to proposed techniques, as shown in Fig. 9b. As earlier mentioned, components were modeled using different mesh sizes to achieve an optimal geometry description.

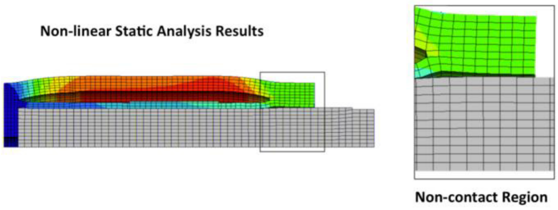

Fig. 7. Results of proposed non-linear simulation

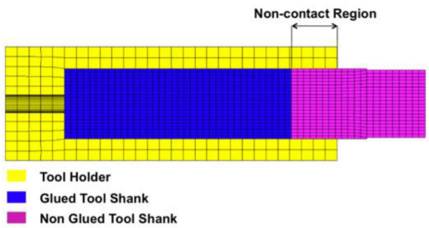

Fig. 8. Proposed hydraulic toolkit modelling technique.

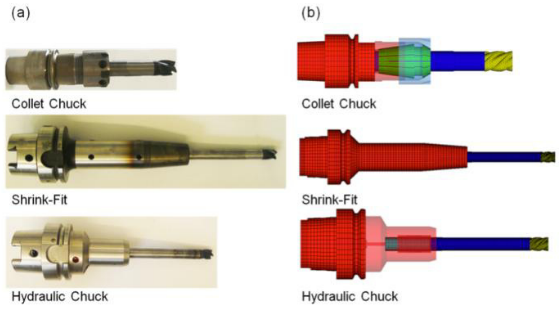

Fig. 9. (a) Test case toolkit (b) FE models of test case toolkits

Analyses were carried out using a PC with an Intel i5-2410M dual core (2.3GHz) CPU and 4Gb RAM. In Table 1 a report on normal modes computation time and models size is presented. Hydraulic chuck analysis was the most demanding one because of the pre-processing static analysis.

Table 1: Computation time and model dimensions report.

Connection	Nodes	Analyses Time [s]
Collet Chuck	52309	158
Shrink Fit	59673	172
Hydraulic Chuck	59081	597

In addition test case toolkits were modeled using Timoshenko beam elements [9], a widely used method, according to established procedures. Accelerometers mass-loading effect was taken into account, introducing in the models concentrated mass elements in correspondence of accelerometers positions. Standard values have been used for material properties, as reported in Table 2.

Toolkits were hang on a support framework by means of a soft spring, to achieve free-free boundary condition [17] (e.g., in Fig. 10). Toolkits FRFs were acquired and toolkits modes were identified by means of modal parameter extraction algorithm Polymax [18]. Modeling accuracy was evaluated comparing experimental and models natural frequencies. In Table 3 comparison between predicted and experimental values of the two first flexural modes and percentage errors are presented. Proposed solid modeling techniques achieves high accuracy in natural frequencies prediction for every connection type, computing first natural frequency with a percentage error below 1%.

Table 2. Material property values.

Property	Carbide	Steel
Young Modulus (MPa)	6.00E+5	2.06E+5
Mass Density (kg/m^3)	1.4E+4	7.8E+3
Poisson Ratio	0.24	0.3
Structural damping coefficient	1.5E-2	1.5E-2

Table 3. Comparison between experimental, beam and solid model natural frequencies.

Collet chuck	Experimental	Beam model	Solid model
Mode 1 (Hz)	4610	5284 (14.6%)	4634 (0.5%)
Mode 2 (Hz)	12744	14182 (11.3%)	12750 (0.0%)
Shrink-fit	**Experimental**	**Beam model**	**Solid model**
Mode 1 (Hz)	1195	1254 (5.0%)	1204 (0.7%)
Mode 2 (Hz)	3423	3469 (1.3%)	3419 (-0.1%)
Hydraulic chuck	**Experimental**	**Beam model**	**Solid model**
Mode 1 (Hz)	1304	1531 (17.4%)	1301 (0.2%)
Mode 2 (Hz)	4696	5696 (19.0%)	4767 (1.5%)

On the other hand Timoshenko beam modeling accuracy strongly depends on the connection type: in collet-chuck and hydraulic connections errors are very high (about 15%), while reduced values are observed in shrink-fit toolkit (less than 5% error). These results allow to draw conclusions about 1D modeling accuracy. In shrink-fit toolkits, the high contact stiffness allows to assume rigid connection approximation without introducing significant errors. On the other hand hydraulic and collet chuck require the connection zone to be modeled in detail to evaluate contact stiffness. Therefore, since beam technique is not able to accurately model the connection zone details, 1D approach leads to larger errors in dynamics prediction of hydraulic and collet chuck. On the opposite, beam modelling provides accurate results for shrink-fit toolkits, since rigid connection approximation does not introduce remarkable errors in contact stiffness estimation. In conclusion proposed 3D modeling techniques provide high-accurate results of toolkits dynamics without the need of experimental tuning tests, generally adopted for connection stiffness identification.

4. Tool-tip FRFs and SLDs prediction

To evaluate the influence of modeling accuracy on tool-tip FRF prediction, a further evaluation test was carried out. Test case toolkits were connected to a milling machine tool (Mori Seiki NMV 1500 DCG for collect chuck test case, Fagima JAZZ for shrink-fit and hydraulic chuck test cases), acquiring tool-tip FRFs via impact testing.

Fig. 10. Experimental set-up

Tool-tip responses of such machine-toolkit assemblies were computed using the RCSA approach proposed by Park et al. [8], and adopted in other works [19]. Both proposed solid models and Timoshenko beam models, showed in section 3, were coupled with machine tool FRFs. Connection point between experimental and numerical model was set in correspondence of the ending section of the standardized holder portion. The adopted layout allows performing RCSA approach for every toolkit compatible with the machine with a single set of tests. In Fig. 11 tool-tip FRFs of the three different toolkits are presented: experimental results is compared to the predicted ones. As expected, similar trend of free-free validation is obtained. Proposed solid models are in good agreement with experimental tool-tip FRFs in the three cases. As clear from the Fig. 11c Timoshenko beam model fails in computing tool-tip FRFs in hydraulic connection. On the contrary, Timoshenko beam and proposed solid model provide similar results for shrink-fit toolkit, in agreement with experimental FRF (Fig. 11b). For what concerns collet chuck, an intermediate condition is obtained (Fig. 11a): beam model accuracy is worse than proposed solid but closer compared to the high error obtained for hydraulic connection. These results show the high sensitivity of RCSA methods to toolkit FE models accuracy. Proposed modeling approaches improve tool-tip FRF prediction performance, however natural frequencies can not be predicted as accurately as in free-free condition (Table 3): these errors (about 3%) are thought to be related to approximation introduced by RCSA method.

The main goal of such methods is generally chatter prediction. In order to show predicted FRFs application, SLDs of the three toolkits are computed.

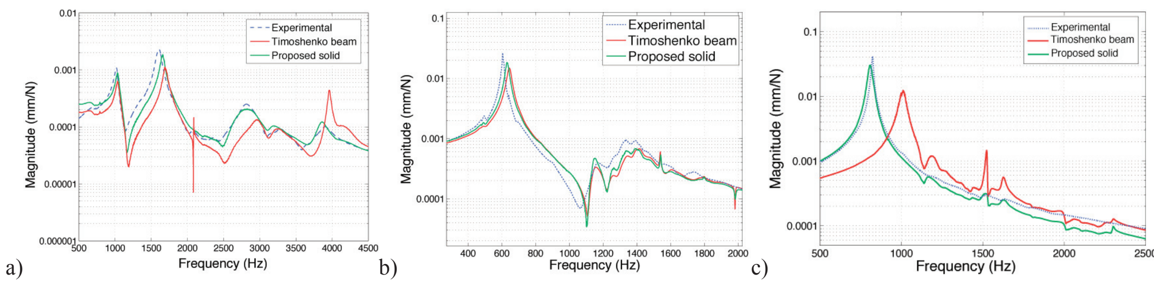

Fig. 11. Tool-tip FRFs comparisons: (a) Collet chuck (b) Shrink-fit (c) Hydraulic chuck

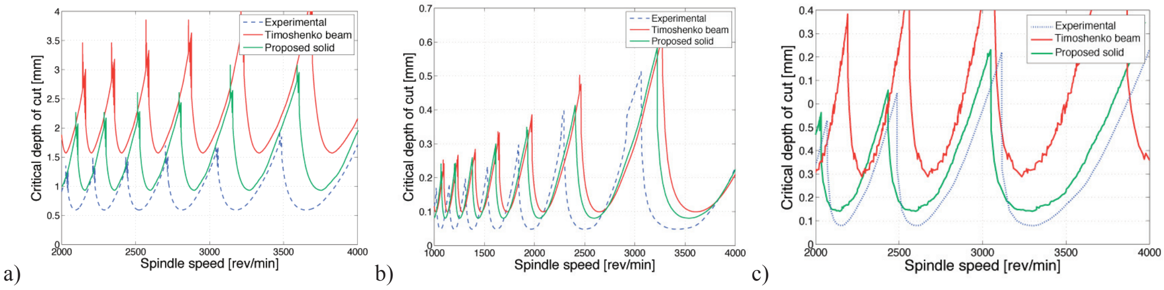

Fig. 12. SLDs comparisons: (a) Collet chuck (b) Shrink-fit (c) Hydraulic chuck

Zero-order analytical approach proposed by Altintas and Budak [14] was applied to evaluate SLD. Chatter stability was predicted for a 1.5 mm radial depth of cut flank milling operation on steel (Ktc=2258 MPa, Krc=1554 MPa) for each different toolkit using experimental and predicted FRFs. Results are shown in Fig. 12. As expected, obtained SLDs are in agreement with tool-tip FRF prediction results. Stability prediction with 1D beam modeling is not reliable, especially for hydraulic toolkit. On the contrary proposed solid modeling strategies are in any case able to return good results. However some discrepancies, mainly in the predicted critical depth of cut, are obtained confirming the high sensitivity of SLD prediction to tool-tip FRF.

5. Conclusions

In this paper a novel fully predictive modeling approach for holder-tool connection is presented. The three main connections (collet chuck, shrink-fit, hydraulic chuck) are analyzed and specific methods, based on 3D solid elements, are proposed. The breakthrough of developed techniques is modeling connection without lumped stiffness and iterative identification procedures, reducing the number of experiments required. Experimental validation, carried out in free-free condition, shows that proposed modeling technique achieves high accuracy in toolkit dynamics prediction, while traditional 1D Timoshenko beam does not provide reliable results, especially for hydraulic chuck. RCSA implementation confirms the influence of toolkit FE model on predicted tool-tip FRF, showing proposed solid modeling high accuracy. Finally SLDs, based on experimental and predicted FRFs, are presented, highlighting chatter stability prediction sensitivity on tool-tip FRF accuracy. In conclusion this work shows how exploiting complex FE modeling technique could support the effective implementation RCSA approach for chatter prediction.

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