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Application of substructure techniques to predict cutting stability for mobile machine tools

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Abstract

Mobile machining solutions use autonomous machining units that can be transported to different part locations, making possible easy maintenance and repair of large industrial equipment. Every new part and location results in different boundary conditions for the mobile machine tool-part system; influencing the dynamics of the combined system and necessitating different strategies for part/machine referencing and clamping. To facilitate efficient mutability and modularity in mobile machining solutions, this paper presents a dynamic substructuring strategy that combines the response characteristics of the mobile machine unit with different base models to obtain the synthesized mobile machine tool dynamic response. Numerical and experimental verification of the approach is provided. Framework presented can also combine measured response of parts for which models may not be available a priori. Methods presented provide experimental guidelines for establishing strategies for planning of machining strategies based on the evaluated dynamics.

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Keywords: Dynamics; Machine tool; Chatter; Substructuring

1. Introduction

In situ and on site machining, repair and maintenance of large parts is made possible by moving mobile machine tools directly to the part locations. Moving the machine to the part results in significant savings in time, energy and transportation costs that would otherwise be incurred from moving large parts to the machine's location [1,2]. An example of such a mobile machine tool developed at the Fraunhofer IWU [2,3] is shown in Fig. 1. The machine has a novel five-strut parallel kinematic configuration. A modular design allows it to be positioned at/on various parts and locations to facilitate in situ on site multi axis machining.

Despite its advantages, every new part and location that machine is moved to results in different boundary conditions for the machine-part system. Varying kinematic configurations and base/part/contact characteristics significantly contribute to and influence machine dynamics. Changing dynamics interact with the cutting process and the control loop of the drives to influence and limit machining stability and accurate tracking and positioning of the tool. Since in situ machining solutions are essentially turn-key, there is a clear need for predicting the dynamics before moving the machine to the part location such as to guide selection of appropriate machining and control parameters that guarantee stable cutting and robust control.

However, neither modelling each new machine setup prior to each job assignment nor measuring the complete setup on-site is an technically or economically feasible approach to predict dynamic behavior. While building and calculating complete models is very timer consuming and always required sufficient date, measuring on site contradicts the idea of planning ahead and thus shortening setup time.

To address this gap, this paper presents a dynamic substructuring scheme that facilitates beforehand prediction of mobile machine tool dynamics under varying influences. Substructuring provides ways of obtaining the structural dynamics of large and/or complex structures by combining

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measurements and/or models of individual components/substructures for which the dynamic behaviour is generally easier to determine. It will be shown how a substructuring framework for mobile machine tools is established and how it can benefit the planning of processes and machining strategies.

The main idea is to couple known dynamics of the mobile machine tool with measured dynamics of the base/part, measured separately at location to predict the assembled system response. Since, obtaining machine dynamics in the unsupported free-free configurations is non-trivial, substructure decoupling is deployed to instead extract these dynamics from known dynamics of the mobile machine tool mounted on a calibration base. Extracted dynamics are subsequently coupled to another base model using the substructure coupling scheme. An overview of the proposed (de)coupling scheme is shown in Fig. 1.

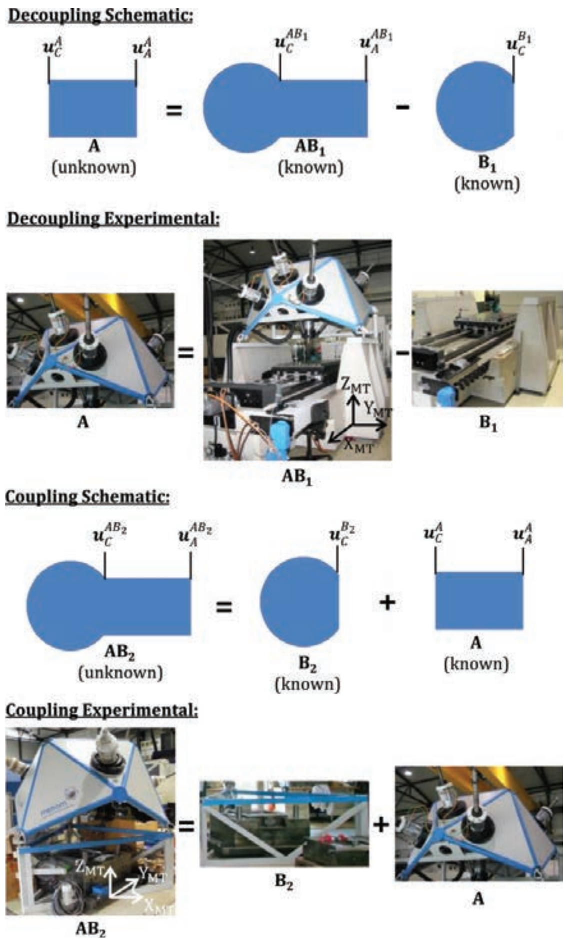

Fig. 1. Substructure decoupling and coupling schematic. AB1 – mobile machine coupled to the first base type (five point coupling); B1 – first base type only; A – extracted mobile machine tool; B2 – second base type; AB2 – mobile machine coupled to the second base type (three point coupling).

Each substructural component can be represented by their spatial data, modal data, or their receptances, i.e. frequency response functions (FRFs). Spatial and modal representations form part of the family of the generalized component mode synthesis approach [4], and have been used previously in the design and analysis of machine tool concepts [5-6]. In the present case, the frequency based substructuring (FBS) methods [7] that instead use measured and/or modelled FRFs to describe each subsystem are preferred. With the FBS method we can synthesize FRFs of parts/bases measured at location with the dynamics, i.e. FRFs of the mobile machine response as desired.

Special cases of the FBS methods otherwise referred to as the receptance coupling substructure analysis (RCSA) approach, have found much use in machine tool applications to predict tool point dynamics [8,9]. Earlier use of RCSA/FBS methods that reported on the simple case of substructures in end-to-end contact, e.g. tool and tool-holder connections were subsequently extended in recent works for modelling complete machine tool substructures simultaneously in contact at multiple locations [10,11]. Most of the reported work on RCSA/FBS methods was concerned with the coupling problem, which combines response of subsystems to predict the assembled system response. However, sometimes the reverse problem of decoupling becomes necessary. Examples of decoupling include the trivial cases of accelerometer mass cancellation, to the more sophisticated examples of joint identification [12], and extraction of rotational FRFs at coupling points using the inverse RCSA techniques [9, 12].

Methods described in this paper build on our preliminary substructure coupling work [14], and are thought to be novel extensions and applications of otherwise well-developed FBS based substructuring methods [7, 13].

Substructuring is illustrated for the example shown in Fig. 1. The two step procedure consists of first extracting the machine response, i.e. response of subsystem A from measurements made on the machine in the assembled configuration, i.e. system AB1, and measured dynamics of only the residual base system, i.e. subsystem B1. In the second step, the extracted mobile machine tool response is then coupled with another subsystem B2 to predict assembled system response AB2. Assembled system AB1 in this case represents the machine mounted on a calibration base, while the assembled system AB2 represents the machining of a large part using only a simple support structure. These cases are representative of potential usage scenarios of the mobile machine tool.

2. Substructuring framework

2.1. Substructure decoupling

The decoupling problem is formulated as one of finding the behaviour of subsystem A as part of the assembled system AB1 when additional opposing forces are applied at the interfaces such that subsystem A experiences no connection forces from subsystem B1. Formulations presented here are for the ‘standard decoupling’ case [13], which requires that compatibility and equilibrium be satisfied only at the interface