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Global stability predictions for flexible workpiece milling using time domain simulation

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ABSTRACT

This paper describes the use of peak-to-peak (PTP) force diagrams for machining stability prediction and validates its suitability for milling processes where the workpiece is considerably more flexible than the machine-tool system. These diagrams result from numerous executions of a time domain simulation which includes both the tool and workpiece dynamics and a mechanistic force model. The applicability of the PTP force diagram is validated experimentally through peripheral milling tests of thin-walled structures. Measured and simulated cutting forces are compared. It is shown that the PTP diagrams offer the global stability information which is provided by the traditional lobe diagram, while preserving the detailed, local information provided by time domain simulation.

1. Introduction

High performance application fields, such as the defense, power, and aerospace industries, benefit from the enhanced product quality and reduced cost associated with machining thin-walled, metallic structures over traditional fabrication and assembly methods (e.g., sheet metal buildups). A methodology for machining compliant aluminum workpieces described in [1–3] has been widely adopted in the aerospace industry. The manufacturing strategy for these components consists of selectively removing material, via high-speed machining, from a solid billet to yield a monolithic component [4].

The superior mechanical properties of difficult-to-machine materials, such as titanium and nickel alloys, make them ideal candidates for compliant, thin-walled structures. However, the same machining methodology that has been applied to aluminum is often not appropriate for these materials due to the high material costs and removal rate limitations imposed by tool wear [5]. Near net shape techniques have been used to manufacture compliant structures composed of hard-to-machine materials, but these techniques are often unable to achieve the required dimensional tolerances. Due to the inherent compliance of the preforms, stable machining is difficult to achieve. Prediction of stable machining parameters is critical for the finish machining of such compliant workpieces.

The purpose of this study is to evaluate the stability of milling operations where the workpiece is considerably more compliant than the machine-tool system. The evaluation is performed by implementing peak-to-peak (PTP) force diagrams as described in [6]. These diagrams result from multiple time domain simulations (TDS) completed over a range of spindle speeds and axial depths of cut. The outcome of an individual time domain simulation contains information specific to the spindle speed-axial depth of cut combination (i.e., cutting force, tool/workpiece deflection), while the PTP force diagrams contain the global information provided by a stability lobe diagram. By proper choice of spindle speed and axial depth of cut according to the PTP force diagrams, stable machining parameters may be selected.

In this paper, a time domain simulation model is described which includes a mechanistic force model and Eulerian integration approach for solving the dynamic equations of motion. The applicability of the simulation is validated through milling experiments where stability predictions are made based on pre-process knowledge of the tool/workpiece dynamics and cutting force model. Simulated preforms are machined in order to illustrate the process and show typical results. The conclusions summarize the usefulness of the simulation and highlight further work being conducted to improve the predictive capabilities of the model.

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2. Time domain simulation model

Based on the “Regenerative Force, Dynamic Deflection Model” described in [6–9], the time domain simulation determines the instantaneous chip thickness, calculates cutting forces, and uses Euler (fixed time step) numerical integration of the equations of motion to determine tool/workpiece deflections at each incremental time step. It is able to account for the nonlinearity which occurs during the milling process when the deflection of the tool/workpiece become large enough that contact is lost [10]. The underlying assumptions built into the model include the circular tooth path approximation and a mechanistic force model [11].

The instantaneous chip thickness depends on the feed per tooth, the relative vibration of the tool/workpiece in the surface normal direction for the current and previous cutting teeth, and cutter runout. Therefore, instantaneous chip thickness is expressed as:

$$h(t) = f_t \sin(\varphi) + n(t-\tau) - n(t) + r \tag{1}$$

where $f_t \sin(\varphi)$ is the nominal, tooth angle dependent chip thickness, $n(t-\tau)$ is the relative vibration of the tool/workpiece in the direction of the surface normal of the previous tooth, $n(t)$ is the current, relative vibration of the tool/workpiece in the surface normal direction, and r is the tooth specific cutter runout. In these expressions, f_t is the feed per tooth, φ is the cutter rotation angle, t is the current time, and τ is the tooth passing period. The vibrations in the direction of the surface normal depend on the relative vibrations between the tool and workpiece in the x and y directions as well as the cutter rotation angle and may be expressed as:

$$n(t) = -(x_t - x_w)\sin(\varphi) - (y_t - y_w)\cos(\varphi) \tag{2}$$

where x_t and y_t are the vibrations of the tool in the x and y directions, respectively, and x_w and y_w are the vibration of the workpiece in the x and y directions, respectively.

Cutting force calculations are based on the mechanistic force model presented by Budak et al. [11] and augmented with a process damping force [12]. At each incremental time step, the chip thickness is evaluated and, in the case where the tool has vibrated out of the cut (i.e., chip thickness is found to be less than or equal to zero), the instantaneous tangential, radial, and axial cutting forces are set to zero. For the case where the instantaneous chip thickness is non-zero, the instantaneous tangential, radial, and axial cutting forces can be expressed, respectively, as:

$$F_t^{i+1} = K_{tc} b h^{i+1} + K_{te} b - C_t b \frac{\dot{r}^i}{V} \tag{3}$$

$$F_r^{i+1} = K_{rc} b h^{i+1} + K_{re} b - C_r b \frac{\dot{r}^i}{V} \tag{4}$$

$$F_a^{i+1} = K_{ac} b h^{i+1} + K_{ae} b \tag{5}$$

where b is the axial depth of cut and h^{i+1} is the instantaneous chip thickness for the current time step. K_{tc}, K_{rc}, and K_{ac} are the tangential, radial, and axial specific cutting force coefficients, respectively, which are associated with “cutting” or shearing. The tangential, radial, and axial edge force coefficients, K_{te}, K_{re}, and K_{ae}, capture the ploughing effect which occurs at small chip thicknesses. The expressions $C_t b\dot{r}^i/V$ and $C_r b\dot{r}^i/V$ are the process damping forces in the tangential and radial directions, respectively, where C_t and C_r are the tangential and radial process damping coefficients, $\dot{r}^i$ is the velocity in the radial direction calculated in the previous time step, and V is the cutting speed. These instantaneous cutting forces are then transformed into the coordinate system shown in Fig. 1.

The equations of motion are solved in modal coordinates using Euler integration. The dynamics of the tool and workpiece are represented using modal parameters for an arbitrary number of degrees of freedom. The tool dynamics are considered in two orthogonal directions in the plane of the cut and the workpiece dynamics are considered in all three orthogonal directions. In modal coordinates the dynamic equation of motion may be expressed as:

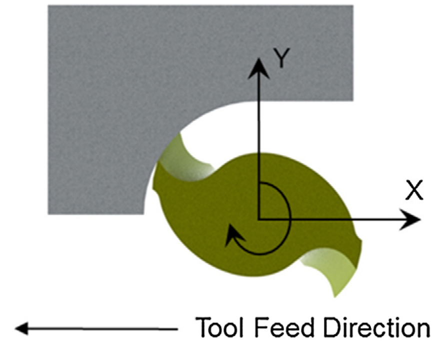

Fig. 1. Coordinate system definition for the time domain simulation model. A down milling configuration is shown.

$$F_q^i = m_q \ddot{q}^i + c_q \dot{q}^i + k_q q^i \tag{6}$$

Then, as an approximated solution for velocity, $\dot{q}^{i+1}$, and displacement, q^{i+1}, via Euler integration:

$$\ddot{q}^{i+1} = \frac{(F_q^i - c_q \dot{q}^i - k_q q^i)}{m_q} \tag{7}$$

$$\dot{q}^{i+1} = \dot{q}_i + \ddot{q}^{i+1} \Delta t \tag{8}$$

$$q^{i+1} = q^i + \dot{q}^{i+1} \Delta t \tag{9}$$

where m_q, c_q, and k_q are the mass, damping, and stiffness values, respectively, expressed in modal coordinates, and Δt is the time step.

Additionally, the simulation model allows for a variety of tool geometries including an arbitrary number of cutting teeth, variable teeth spacing, different helix angles for each tooth, and cutter teeth runout. As a practical consideration it is important to select a time step which is sufficiently small that the Euler integration method provides a numerically stable solution. A rule of thumb is that the time step should be at least ten times smaller than the period associated with the highest oscillation frequency present in the system being modeled. Also, the number of time steps (i.e., cutting tool revolutions) should be sufficiently high for the initial transient behavior to decay.

As previously mentioned, the outcome of individual time domain simulations contains information specific to the individual spindle speed-axial depth of cut combinations. This includes the instantaneous cutting forces and tool/workpiece deflections, velocities, and accelerations. The PTP force diagrams represent numerous time domain simulations performed over a range of spindle speed-axial depth of cut combinations. The range and step size of the spindle speed and axial depth of cut is specified, and the time domain simulation is performed for each combination. At the conclusion of each simulation the steady state portion of the time domain cutting forces are examined for the maximum peak-to-peak (PTP) force difference. The PTP force for each combination of spindle speed and axial depth of cut is used to generate a contour map over the range of spindle speeds and axial depth of cuts; see Fig. 2. The result is analogous to the traditional stability lobe diagram in the sense that it conveys a global representation of stable and unstable spindle speed and axial depth of cut combinations while retaining the specific, local information of the individual combinations.

Example results, given in Fig. 2, illustrate the stability regions and the stabilizing effects of process damping which occurs at low