Introduction

Parallel-process machining (PPM), from an intuitive perspective, occurs on machine tools that have either multiple spindles or multiple slides. The first known applications appeared early in the twentieth century due to their potential to increase productivity. Those applications include simultaneous boring of multiple engine cylinders and using multi-drill heads to generate hole patterns. Modern applications also include simultaneous turning of journals on engine camshafts and multi-spindle screw-cutting operations. Specific advantages of PPM may include:

- reduced cycle time, including rapid traverse and workpiece handling (idle) times,
- shorter tool change times and machine changeover times,
- improved accuracy due to the elimination of multiple set-ups,
- floor-space savings up to 30%.

Approach

Industrial interest in PPM has been growing due to the aforementioned potential advantages. A benchmark survey done by the authors concluded that most major machine-tool manufacturers produce parallel-process machine tools, with PPM being particularly common in transfer-lines. While some research has focused on operations/planning issues, little research has addressed the mechanical issues, such as maximizing productivity by understanding and modeling the process-to-process interactions. This effort aims to take a first step in that regard by mathematically posing the problem and then formulating an analytical stability solution for the case of symmetric (i.e., having identical conditions) processes.

For the discussion to follow, a cutting process involves the removal of a chip at a single cutting tooth whereas a machining process involves one or more teeth experiencing the same kinematics (cutting and feed motions).

Results

The intuitive perspective of PPM relates to the number of tools being used on the machine — for instance, two tools machining one or two workpieces (2T1W or 2T2W, respectively). However, from a mathematical perspective, PPM relates to the number of dynamically dependent cutting processes. Dynamic dependence means that the relative tool-work displacements of the cutting processes in question are not related through kinematics alone but rather through a dynamic (frequency-dependent) coupling. This mathematical perspective is best understood by illustrating with a multi-tooth machining process, such as face milling.

From the intuitive perspective, a multi-tooth milling process is single-process in nature. First, consider the workpiece to be (comparatively) rigid. If the relative tool-work displacements at each tooth are related kinematically, a case that arises when the face mill cutter-body is “rigid”, the face-milling process is single-process in nature, mathematically speaking. In contrast, if the relative tool-work displacements at each tooth are not related through kinematics alone, such as when the cutter-body itself is flexible, the face-milling process is parallel in nature, again, mathematically speaking. An analogous case (1T2W) occurs for a single rigid face mill simultaneously cutting either multiple workpieces or a single workpiece with spatially varying dynamics (e.g., the deck of an engine block).

The above demonstrates how an intuitively single-process case is actually parallel in nature. That said, the opposite can hold — that is, intuitively parallel multiple processes need not be parallel in nature from the mathematical perspective. Consider two relatively rigid turning tools attached to opposite sides of a slide. If the slide itself rigidly connects these tools while a dominant flexibility exists in the machine bed to which the slide is attached, and furthermore there is no appreciable workpiece coupling, then these two machining processes act as a single, multi-tooth, machining process. In other words, the two cutting processes are dynamically independent, and thus this is not a case of PPM.

In the single-process problem, the dynamic tool-work displacement at each tooth is characterized by the response at any single location. For N-dimensional dynamics (where the displacement is an N-dimensional vector), the off-diagonal terms of the frequency response matrix represent dimension-to-dimension coupling and ultimately have no effect on stability. In PPM (single- or multi-dimensional), the response vector required to characterize the machining process includes responses at more than one location in the system. As such, the off-diagonal terms represent location-to-location coupling in addition to dimension-to-dimension coupling, the former being of critical importance in the PPM stability problem.

The analysis formulated applies only for cases with process symmetry (i.e., same speed, feed and depth of cut). For a case of structural symmetry as well, Fig. 1 shows how the overall solution is a superposition of the solutions corresponding to in-phase and out-of-phase chatter responses. The analytical solution is compared to experimental results (non-symmetric structural dynamics) in Fig. 2 showing good agreement.

Benefits

- Perplexing effects of flexible cutters and spatially varying workpiece dynamics are explained through the mathematical definition of PPM.
- Limits on process-to-process dynamic coupling may be specified so that a PPM application does in fact result in productivity and cost benefits relative to using multiple single-process machine tools.