A Unique Methodology for Chatter Stability Mapping in Simultaneous Machining

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A novel analytical tool is presented to assess the stability of simultaneous machining (SM) dynamics, which is also known as parallel machining. In SM, multiple cutting tools, which are driven by multiple spindles at different speeds, operate on the same workpiece. Its superior machining efficiency is the main reason for using SM compared with the traditional single tool machining (STM). When SM is optimized in the sense of maximizing the rate of metal removal constrained with the machined surface quality, typical "chatter instability" phenomenon appears. Chatter instability for single tool machining (STM) is broadly studied in the literature. When formulated for SM, however, the problem becomes notoriously more complex. There is practically no literature on the SM chatter, except a few ad hoc and inconclusive reports. This study presents a unique treatment, which declares the complete stability picture of SM chatter within the mathematical framework of multiple time-delay systems (MTDS). What resides at the core of this development is our own paradigm, which is called the cluster treatment of characteristic roots (CTCR). This procedure determines the regions of stability completely in the domain of the spindle speeds for varying chip thickness. The new methodology opens the research to some interesting directions. They, in essence, aim towards duplicating the well-known "stability lobes" concept of STM for simultaneous machining, which is clearly a nontrivial task. [DOI: 10.1115/1.2037086]

1 Introduction and a Review of Single Tool Chatter

We present a new methodology on the stability of *simultaneous (or parallel) machining (SM)*, where multiple tools operate at different spindle speeds on the same workpiece. It is obvious that such an operation, as opposed to conventional single tool machining (STM) (also known as *serial process*), is more time efficient [1–5]. It is also known that its dynamics is considerably more complex. When metal removal rates are maximized, the dynamic coupling among the cutting tools, the workpiece, and the machine tool(s) become very critical, regenerative forces become pronounced, etc. The dynamic stability repercussions of such settings are poorly understood at present even in the mathematics community. In fact, there is no analytical mechanism available to assess them and no evidence in the literature addressing the stability of simultaneous machining.

It is well known from numerous investigations that the conventional single tool machining (STM) introduces some important stability issues when it is optimized. Similar problems result in much more complex form for SM. Due to the lack of a solid mathematical methodology to study the SM chatter, the existing practice is likely to be (and it really is) suboptimal and guided by trial-and-error or ad hoc procedures. There is certainly room for much-needed improvement in the field.

Optimum machining aims to maximize the material removal rate, while maintaining a sufficient stability margin to assure the surface quality. The machine tool instability primarily relates to "chatter." As accepted in the manufacturing community, there are two groups of machine tool chatter: *regenerative and nonregenerative* [6]. Regenerative chatter occurs due to the periodic tool passing over the undulations on the previously cut surface, and nonregenerative chatter has to do with mode coupling among the existing modal oscillations. This text evolves primarily on regenerative type, thus we refer to it simply as "chatter" for the rest of the paper.

In order to prevent the onset of chatter, one has to select the operational parameters appropriately, namely chip loads and spindle speeds. Existing studies on machine tool stability address conventional single-tool machining processes. They are inapplicable, however, to SM because of the substantial difference in the underlying mathematics. Leaving the details to the later sections, we can say that *simultaneous machining* gives rise to a complex mathematical characterization known as "*parametric quasi-polynomials with multiple delay terms*." There is no practical methodology, known at this point, to resolve the complete stability mapping for such constructs. This text presents a unique procedure in that sense.

Machine tool chatter is an undesired engineering phenomenon. Its negative effects on the surface quality, tool life, etc. are well known. Starting with the early works of [7–10], many researchers meticulously addressed the issues of modeling, the dynamic progression, structural reasoning, and stability limit aspects of this seemingly straightforward and very common behavior. Further research focused on the particulars of parameter selections in machining to avoid the build-up of these undesired oscillations and on the analytical predictions of chatter. Some interesting readings on this are [6,10–12]. Most commonly chatter research has focused on the conventional single tool machining (STM). The aim, again, is to increase the metal removal rate while avoiding the onset of chatter [13–15]. A natural progressive trend is to increase the productivity through simultaneous (or parallel) machining. This process can be further optimized by determining the best combination of the chip loads and spindle speeds with the constraint of chatter instability. For SM, however, multiple spindle speeds, which cross-influence each other, create governing differential equations with multiple time delay terms. Their characteristic equations are known in mathematics as "quasi-polynomials with multiple time delays." Multiplicity of the delays presents enormously more complicated problems compared with the conventional single-tool machining (STM) chatter.

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