Chapter 1
Introduction

You have to learn the rules of the game. And then you have to play better than anyone else.

- Albert Einstein

In today's information driven society, it could be argued that the relative significance of a topic is measured by the number of web sites identified by an Internet search. The search term "Super Bowl", for example, yields approximately 63,000,000 sites[1], which tops "World Cup" at 57,300,000. "Nanotechnology" and "machining" score similarly to one another at 12,300,000 and 12,100,000 sites, respectively. Among recently developed manufacturing technologies, selected results include "high speed machining" – 423,000, "laser assisted machining" – 370,000, "laser machining" – 290,000, "friction stir welding" – 101,000, and "selective laser sintering" – 87,400. Refining the high-speed machining search to "high speed machining dynamics" reduces the count by more than four times to 90,900. However, this is almost exactly two times the number of sites (45,400) related to "chinch bugs", a known predator of St. Augustine grass. Apparently, reading this text places you in select company, but not quite as exclusive as those interested in a particular Florida lawn pest!

While this nonscientific survey was performed somewhat tongue in cheek, it does indicate that, although interest in high-speed machining continues to grow (nearly half a million web sites with related content), widespread awareness of the importance of considering the role of the process dynamics in its successful implementation has not yet been achieved. There is still work to be done! Increasing this process dynamics understanding for those interested in "playing the game better" is the intent of this text.

[1] The Internet searches were completed in April, 2008 using the Google™ search engine.

T.L. Schmitz, K.S. Smith, *Machining Dynamics*, DOI 10.1007/978-0-387-09645-2_1,

1.1 The big picture

Discrete part production by machining remains an important manufacturing application. In commercial situations, the focus is naturally on producing accurate parts in the required time frame under conditions of maximized profit. Unfortunately, a number of factors can influence our ability to do so. Important contributors to process efficiency include:

- workpiece loading/unloading from the machine;
- fixturing, including clamping/unclamping the workpiece on the machine;
- machining parameters, such as spindle speed, depth of cut, and feed rate;
- path planning strategies;
- tooling and holder selection;
- tool wear;
- tool changes;
- coolant management;
- chip evacuation;
- tool and workpiece vibrations, including chatter and errors due to the cutting forces (we refer to the latter as surface location errors);
- part measurement (on machine or post process); and
- machine accuracy, including geometric errors in the machine construction, thermally induced errors from heat sources associated with the machining process, and trajectory following errors caused by controller and machine structural dynamics.

We will focus our attention on process parameter selection to enable high material removal rates without introducing significant part errors due to cutting forces and the resulting dynamic tool deflections. The remaining issues, while important, are outside the scope of this text. Figure 1.1.1 displays an overview of our focus areas. There are two critical items upon which our modeling efforts are based: the frequency response function, FRF, and the force model. These are identified in the central portion of the figure (boxes with heavy solid lines). In milling, for example, we require knowledge of the tool-holder-spindle-machine FRF as reflected at the tool point. We can obtain the necessary assembly dynamics through modal testing techniques or by a combination of testing and modeling using the Receptance Coupling Substructure Analysis, RCSA, approach. For the force model, the required coefficients can be determined from cutting tests carried out on a force dynamometer. Given the tool point FRF and force model, we can choose either: 1) a time-domain simulation strategy to predict stability and surface location errors, SLE; or 2) a frequency-domain approach to stability and SLE predictions. For time-domain simulation, an additional step of modal fitting is required to obtain modal parameters that describe the system FRF. We detail each of these topics in Chapters 2 through 7.

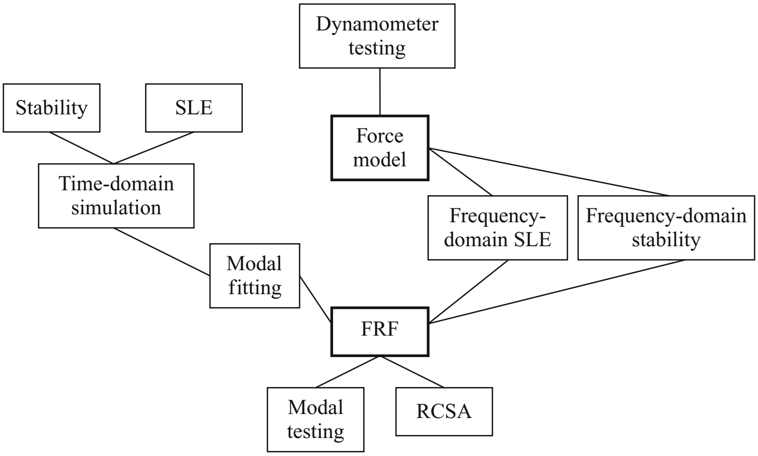

Fig. 1.1.1 Focus areas for study of machining dynamics. The critical frequency response function, FRF, and force model are indicated by the heavy solid lines

1.2 A Brief Review

We cannot hope to capture all the significant contributions to machining science that have been previously reported in the literature and we are wary of accidental omissions. However, we would like to provide a brief review of the foundational work that has led to our modern understanding of machining process dynamics. Clearly, with the process descriptions and models provided in this text, we are "dwarfs standing on the shoulders of giants (*nanos gigantium humeris insidentes*)"[2].

A primary building block for the study of machining is Taylor's "On the Art of Cutting Metals" [2]. This paper established an empirical basis for the relationships between cutting parameters and process performance; contemporary research efforts still rely on variations of Taylor's tool life model, for example. Later, Merchant's work provided a mechanics-based understanding of cutting forces, as well as the corresponding stresses and strains during material removal [3]. Within the broad view of machining encompassed by these and other early efforts, researchers have subsequently studied such basic aspects of machining as chip geometry, shear stresses, friction, and cutting temperatures [4]. In this text, we do not attempt to address these issues, but rather focus on the process dynamics. The contributions of chip formation to turning and milling behavior are indirectly included through the force models, which effectively treat this

[2] This quote is attributed to the 12th century philosopher Bernard of Chartres (*Bernardus Carnotensis*) [1].

complex behavior using "process coefficients" that relate cutting force levels to the uncut chip area [5].

While advances in computer simulation of machining processes continue, the foundation for much of this work can be traced to papers by Tlusty, Tobias, and Merrit [6-9], which, in turn, followed earlier work by Arnold [10] and others. Based on these efforts, an understanding of the regeneration of surface waviness during material removal as the primary mechanism for self-excited vibrations (or chatter) in machining was established. When combined with the effects of forced vibrations during stable cutting, we have the basis for exploring the role of machining dynamics in discrete part production. Comprehensive reviews of subsequent modeling and experimental efforts have been compiled and presented in the literature. We refer the reader to [4, 11, 12, 13, 14, 15, 16, 17], for example.

1.3 Roadmap

Figure 1.3.1 shows a modified version of Fig. 1.1.1, where we have now identified the relevant sections that detail these focus areas. The FRF is defined in Sections 2.2 and 2.4. Its measurement is outlined in Sections 2.5 through 2.7, while its prediction using the RCSA method is detailed in Section 7.6. The cutting force model is described in Section 3.1 for turning and Sections 4.1 and 4.7 for milling. Experimental methods for identifying force model coefficients in milling are covered in Section 4.7 as well. Time-domain simulations are provided in Section 3.5 (turning), Sections 4.4 through 4.6 (milling circular tooth path), and Section 5.3 (milling cycloidal

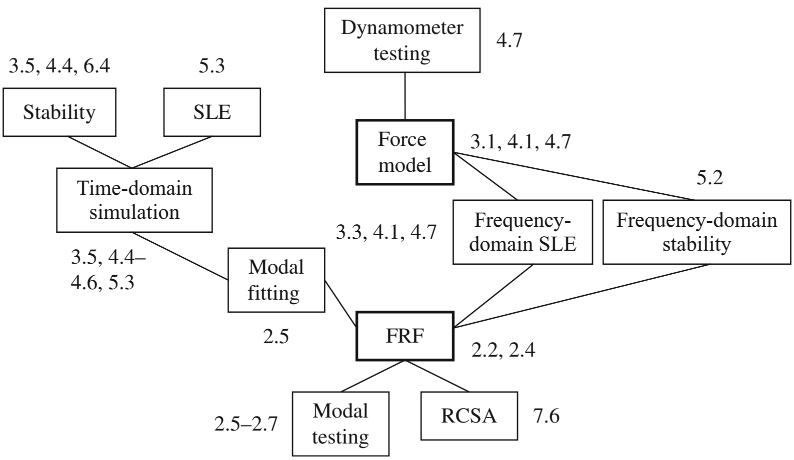

Fig. 1.3.1 A roadmap for the text is shown; section numbers are identified for each focus area

tool path). The necessary modal fitting step for determining the modal mass, damping, and stiffness coefficients used in the time-domain simulation equations of motion is reviewed in Section 2.5. Application of time-domain simulation to turning stability is shown in Section 3.5. Low radial immersion milling stability is described in Section 6.4 and surface location error prediction is included in Section 5.3. Frequency-domain techniques for stability analysis are described in Section 3.3 for turning and Section 4.3 for milling (two methods are included). The frequency-domain analysis for milling surface location error is provided in Section 5.2.

While the content of this book is mathematical by its nature, it is possible to gain an understanding of the basic concepts and some ability to apply them without a detailed understanding of the mathematical formalities. Throughout the text, there are number of explanations/analogies labeled ***For instance*** or ***In a nutshell*** which attempt to convey the essence of the topic to the non-mathematical reader.

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