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Milling Force Modeling: A Comparison of Two Approaches

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Abstract
This paper evaluates the dependence of cutting force coefficients on milling process parameters including feed per tooth, spindle speed, and radial immersion. Two methods are described for determining the cutting force coefficients: 1) the average force, linear regression method; and 2) the instantaneous force, nonlinear optimization method. A series of test cuts were performed and the cutting force coefficients calculated using the two methods are compared. Milling stability experiments were then conducted to validate the calculated cutting force coefficients. It was found that feed per tooth, spindle speed, and radial immersion exhibit a nonlinear relationship with the cutting force coefficients.

Keywords: Milling, stability, chatter, force, model, coefficients, regression, optimization

1 Introduction

The modeling of machining processes has been an important research topic for over a century and is motivated by the requirements of both machine tool users and builders. The machine tool user aims to reliably predict key process outputs, such as cutting forces, which affect workpiece surface quality, geometrical accuracy, and process stability. From the builder's perspective, the cutting forces represent a critical design metric because they dictate the required spindle power and torque as well as the required rigidity of the machine tool's structural loop. In machining process simulation and optimization, cutting force modeling strongly affects the accuracy of the results.

Mechanistic cutting force models assert that the instantaneous cutting forces are proportional to the uncut chip area through one or more empirical coefficients (Ehmann, et al., 1997). Early work in mechanistic force modeling for milling operations was reported by Martellotti (Martellotti, 1941), Koenigsberger et al. (Koenigsberger & Sabberwal, 1961), and Sabberwal (Sabberwal & Koenigsberger, 1961). The literature highlights two mechanistic force models. The first relates instantaneous cutting forces and uncut chip areas to the specific (cutting) force coefficient, K_s, and resultant cutting force angle, β. This single specific force coefficient captures the effect of both cutting

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(shearing) and ploughing (due to friction at the cutting edge) which occurs during chip formation. The ease of implementation and predictive capabilities provided by this model have resulted in its widespread application in industry and research. The second, published in later work by Budak et al. (Budak, et al., 1996), extends the mechanistic cutting force model to include separate empirical coefficients to capture the chip formation mechanics of both shearing and ploughing.

In (Schmitz & Smith, 2008) and (Altintas, 2012) a method for the identification of the empirical coefficients, commonly referred to as cutting force coefficients, is presented. The procedure applies a linear regression of measured, average cutting forces over a range of feed per tooth values, while holding other process parameters, such as cutting speed and cut geometry, constant. This method requires numerous cutting tests and provides results which are specific to the selected cutting tool geometry and workpiece material combination. The regression analysis assumes that the cutting forces are linearly dependent on feed per tooth and independent of other machining parameters, such as cutting speed and feed, cut geometry, and cut direction (i.e., up milling/down milling). Other methods, such as those presented in (Gonzalo, et al., 2010) and (Campatelli & Scippa, 2012), use nonlinear optimization methods to perform a least squares fit of simulated cutting forces to measured cutting forces. This approach requires force measurement from just a single cutting test and, again, results in cutting force coefficients which are specific to the selected machining parameters. As such, the cutting force coefficients may be considered to be a function of not only the cutting tool geometry and workpiece material, but also machining parameters. The nonlinear optimization method provides a tool for studying the effects of these machining parameters on dynamic cutting forces.

In this paper, a study is described where the cutting force coefficients of the mechanistic force model are determined using both linear regression and nonlinear optimization methods. The paper is organized as follows. First, the mechanistic force model is detailed and the two methods (i.e., linear regression and nonlinear optimization) of cutting force coefficient determination are described. Next, the experimental method, which includes the cutting force measurement and the stability testing setup, is detailed. Finally, the resultant cutting force coefficients are compared and the practicality of the nonlinear optimization method is demonstrated in the framework of a milling stability prediction via time domain simulation and experimental validation. This is followed by a discussion of the experiment results and their impact on finish milling operations at low radial immersion.

2 Mechanistic Force Model

The mechanistic force models are based on the assumptions that: 1) the instantaneous cutting force is proportional to the cross sectional area of the uncut chip through empirical cutting force coefficients; and 2) the instantaneous cutting forces are independent of other machining parameters. Although this assumption provides a reasonable degree of accuracy for milling stability prediction using stability lobe diagrams (Schmitz & Smith, 2008), it has been shown that cutting forces are dependent on cutting speed and feed (Campatelli & Scippa, 2012). The mechanistic force model used in this study includes instantaneous cutting forces in the tangential, F_t, normal, F_n, and axial, F_a, directions and six corresponding cutting force coefficients; see Equations (1)-(3):

$$F_t = k_{tc}bh + k_{te}b \tag{1}$$

$$F_n = k_{nc}bh + k_{ne}b \tag{2}$$

$$F_a = k_{ac}bh + k_{ae}b \tag{3}$$