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Impact of feed axis on electrical energy demand in mechanical machining processes

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A R T I C L E I N F O

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A B S T R A C T

To reduce energy demand in manufacturing, it is important to make products using the most energy efficient process plan and resources. In machining, understanding the factors that influence the electrical energy demand for CNC toolpaths is vital in order to determine the optimum machining conditions to minimise energy demand. In this study, a new model for estimating the electrical energy demand of machine tool feed axes which incorporates the weights of feed axes and weights of the materials placed on the machine table is presented. This was achieved by studying the electrical energy demand for machine tools when air cutting in defined axis directions, carrying a range of masses, and in actual cutting, while the electrical current was measured. The newly proposed model was validated on milling CNC toolpaths. The information enabled the development of suggestions for reducing energy demand. The energy reduction hypothesis developed was explored and validated by machining components in defined orientations on the machine table. The results are important for manufacturers in industry when process planning. The information is also valuable for the range of machine tool design and manufacturing companies in the development of energy efficient machine tools.

1. Introduction

Electrical energy demand modelling and reduction in manufacturing is important because of energy costs and the carbon footprint associated with energy generation. The electrical energy consumed by machine tools throughout their use phase results in increased environmental impact. For example, Diaz et al. (2010) conducted life cycle analysis of two milling machines and reported that 60%–90% of CO_2 equivalent emissions result from the use phase of milling machines. Santos et al. (2011), performed a life cycle analysis and reported that 46% of the environmental impact of the machine tool was attributable to its electricity consumption during its use phase. While the above life cycle analysis did not focus on the embodied energy of materials production it is clear from literature that when machine manufacture and machine use are considered, the environmental impact during the use phase is a significant factor that needs to be considered and managed.

Developments in Europe, such as the European Association of Machine Tool Industries (CECIMO)'s Self-Regulatory Initiative (SRI), aim for ecological improvements and energy saving of machine tools (CECIMO, 2009). In 2012, Duflou et al. outlined a number of energy demand reduction strategies applicable to machine tools. These included: more efficient machine tool components such as drives, pumps and spindles; technology leaps; recovery of waste streams such as heat losses within a machine tool; and integrated or central delivery of consumables (Duflou et al., 2012). Prior work by these authors has demonstrated that cutting conditions can be selected to minimise energy footprint (Mativenga and Rajemi, 2011) and the selection of tool path strategies can lead to energy savings in machining processes (Aramcharoen and Mativenga, 2014). Kara and Li (2011), advocated that a reduction of energy consumption and improvement of environmental performance can be applied proactively during product design and process planning stage.

To model and reduce the energy demand in CNC toolpaths, there is need to understand the effect of interpolation modes and table feed on energy demand in machining. While a number of studies have looked at the machining process as a whole, the energy demand for interpolation modes is relatively unexplored.

Machine tool feed drives control the relative motion between the workpiece and cutter, as well as determining the workpiece geometry (Altintas et al., 2011). Thus, the performance of machine

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tool feed drives significantly influences the productivity and quality of machine tools (Xie et al., 2015). The feed mechanism consists of the electrical units (i.e. feed motors) and the mechanical units (i.e. ball/lead screws). Control signals are sent from the machine tool control unit to activate the feed drive motors. This ensures the rotation of the ball/lead screws to position the machine tool spindle and the work table. Angular motion to the workpiece or cutting tool is provided by the spindle drives which rotate over a wide range of speeds. The feed drive mechanism converts the angular motion of the motors to linear motion of the guide ways and work table (Altintas, 2012).

Feed drives are either powered by linear motors directly, or by rotary motors via ball screw and nut assembly (Altintas, 2012). Few researchers have modelled the feed drives. For example, Avram and Xirouchakis (2011) modelled the power of the feed axes based on the torque supplied by the servomotor of each axis. Unfortunately, weights of the axes, workpiece, and machine vice were not considered in the model. He et al. (2011) considered the importance of feedrates in their feed axes power demand model while the weights of the axes, workpiece, and machine vice were not considered. Calvanese et al. (2013) modelled the feed axes by considering the mechanical power and the dissipated power. However, their model did not consider the feed axes, workpiece, and machine vice weights. Xie et al. (2015) utilised an object-oriented simulation approach to model the feed drives. However, energy demand of the feed drives was not considered. Lv et al. (2014) modelled the power requirements of the feed motor P_f using Equation (1).

$$P_f = A_1 v_f + B v_f^2 \tag{1}$$

where v_f is the feedrate in mm/min, A_1 and B are constants related to loading and friction respectively. The feed drive of the considered CNC lathes in their work was powered by an AC servo motor connected to the ball screw. Other researchers, Li et al. (2013), assumed that the operational power for feed motor follows an approximate linear relationship with the feedrate and modelled it as shown in Equation (2).

$$P_f = A_2 v_f + C \tag{2}$$

where v_f retains its usual meaning, A_2 and C are constants. The feed drive of the CNC machine tool considered in their work was driven by rotary motors via ball screw and nut assembly. Campatelli et al. (2014) presented an analytical model of the energy demand for feed axis as, taking into account the effect of masses and friction. The analytical approach is interesting in that it proposes a basis for the key parameter constants within the energy demand model. This is shown in Equation (3).

$$P = \int_0^S \Big((M_x a_x + \mu_x M_x g) + M_y a_y + \mu_y M_y g \Big) ds \tag{3}$$

where M_x and M_y are the equivalent masses of the axes in *kg*, a_x and a_y the instantaneous accelerations in m/s^2, μ_x and μ_y are the equivalent friction coefficients for the x and y axes for the length of the toolpath. The parameter g is the acceleration due to gravity in m/s^2 and s is the distance along the toolpath length in *mm*. In their work, the feed drive of the considered 5-axis CNC machining centre was powered by rotary motors for the x- and y- axes, and by direct drives motor for the B and C axes.

From Equation (3) it was assumed by Campatelli et al. (2014), that the energy demanded by the table motions was independent of feedrate. In 2015, Guo et al. (2015) used air cutting experiments to develop a power demand model for the feed drives. This is shown in Equation (4).

$$P_{axes} = A_3 v_f^2 + D v_f \tag{4}$$

where P_{axes} is the power demand for the specified axis in *W*, A_3 and D are constants while v_f retains its usual meaning.

Recently, Lee et al. (2016) proposed a model for estimating the power demand of feed axes. This is shown in Equation (5).

$$P_{feed} = C_{0f} \cdot v_f + C_{1f} \tag{5}$$

where P_{feed} is the feed drive power consumption in *W*, C_{0f} is the gradient of the power model of the feed drive, v_f is the specified feedrate in *mm/min*, C_{1f} is a constant.

Equations (1), (2), (4) and (5) by Lv et al. (2014), Li et al. (2013), Guo et al. (2015), and Lee et al. (2016) respectively model the importance of feedrate, but do not capture the impact of weights on the energy demanded by the machine table feed.

From the literature, it is clear that there is no general agreement on the dominant factors that control energy demand for machine tool table feed axis. In light of this, the importance of moved weights by the feed drive (i.e. weights of feed axes, workpiece, and machine tool vice), feedrate, and direction of axis travel on power demand are considered in this study in order to improve the prediction capability of feed axes power demand models. Therefore, developing this knowledge is important for evaluating the energy demand in toolpaths and in developing strategies for energy demand reduction.

The motivation of this study was to contribute towards and better the understanding of the power required and hence energy demanded by machine tool axes. The ultimate motive is to enable the generation of guidelines for industry in support of energy smart machining, thus reducing the energy and carbon intensity of machined products, as well as energy costs.

1.1. Research aim and objective

This work is aimed at assessing the electrical energy demand of machine tool feed axes in order to develop recommendations for modelling and energy consumption management. This study will contribute towards the development of a robust model for estimating the electrical energy demand of feed axes, taking into consideration the weights of the feed axes and materials placed on the machine table, as well as the feed force acting on the machine table. Thus, the knowledge acquired in this study shall aid in contributing towards better understanding of factors influencing the energy demand of feed axes, as well as providing suggestions for minimum energy consumption.

2. Experimental details

2.1. Research methodology

The research methodology was based on energy evaluation in milling, focussing on the net power and energy demanded by table feed axes. The evaluations were done when (i) executing table feed without any workpiece on the table and with no spindle rotation, (ii) when the machine is carrying different weights (surrogate for workpiece weight) and with no spindle rotation, and (iii) when machining components. To elucidate the impact of individual axis, the motions of the feed table were made in the x, y and z axes directions. The current and voltage drawn by the CNC machine were directly measured using the 3-phase FLUKE 434 Power Quality Analyser which enabled the calculation of power requirements