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Research paper

Combination of simulated annealing and pseudo spectral methods for the optimum removal rate in turning operations of nickel-based alloys

J.A. Palacios[a], D. Olvera[a], G. Urbikain[b], A. Elías-Zúñiga[a,*], O. Martínez-Romero[a], L.N. López de Lacalle[b], C. Rodríguez[a], H. Martínez-Alfaro[a]

[a] Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, Nuevo León 64849, México
[b] Department of Mechanical Engineering, University of the Basque Country, Alameda de Urquijo s/n, Bilbao, Bizkaia C.P. 48013, Spain

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ABSTRACT

In this paper, an approach that combines simulated annealing technique (SA) with the Chebyshev collocation method (CCM) or with the Enhanced Multistage Homotopy Perturbation (EMHPM) is established. Then, these two new approaches are applied to find optimal cutting conditions in turning operations of nickel-based superalloy (Inconel 718©) by using SNMG and VBMT tool-inserts. To validate the proposed approaches in terms of material removal rate and stability, a series of turning cutting tests were carried out. Numerical results show that when the CCM is combined with SA technique, the optimum stable cutting conditions such as the axial depth of cut and the spindle speed, were estimated 100 times faster than from the CCM. Furthermore, experimental data and numerical results confirmed that the productivity by using a tool-SNMG insert is 19% higher than when using VBMT tool-insert, which is mainly due to the tool stability dynamic response.

1. Introduction

Nickel-based super alloys are spreading within the aerospace engine industry. In particular Inconel® 718, a Nickel–Chromium alloy containing 53.60% of Ni and 18.30% of Cr as principal components, has good mechanical properties at high temperature. However, this material presents low machinability because of factors such as: i) the highly abrasive carbide particles that are contained in their microstructure, ii) low thermal conductivity, iii) high chemical affinity which leads to wear by diffusion, iv) welding or adhesion of the material to the cutting tools, v) high resistance, and high shear forces that increase tool wear and excite the machine tool system to generate undesirable vibrations and vi) tendency to strain hardening due to the rubbing effect of tool nose on machined surfaces [1].

Poulachon et al., [2] claimed that one of the main difficulties for machining aerospace parts is related to tool-insert life and its relationship with productivity. In an attempt to overcome the rapid degradation that carbide tools in the turning of Inconel 718 superalloy, many researchers focused their efforts on identifying the best tool grade [3]. In fact, recent studies concluded that tool geometry is one of the major factors to improve turning productivity, surface finishing and integrity of the workpiece [4–6]. Therefore, the optimization of the turning parameters will allow to increase material removal rate however, one needs to take into account workpiece surface quality as a primary concern. In aerospace, nickel-based alloys components such as disk, cases, ring or shafts are manufactured with turning cutting operations. The fabrication of these type of components by turning operations in general involve longitudinal turning and slotting with large tool overhangs, where tangential modes and the cutting speed could be a source of undesirable dynamic effects such as chatter [7]. Chatter produces a poor surface finish, high tool wear, and can even damage machine tool because of the regenerative effect. In this sense, the determination of stability lobe diagrams is a very well known, off-line strategy used to find the optimum stable cutting conditions to avoid chatter [8–10]. In general, the stability lobes are calculated by using a cutting process dynamic mathematical model that help the machinist to identify optimum cutting parameters to increase not only the productivity, but also to avoid undesirable regenerative vibrations [11]. However, the available numerical methods used to find the stability lobes diagrams [12–14], demands a large computation effort for low turning operation spindle speeds and then, new computational schemes are needed to implement solutions in real time [15].

There is some evidence in the literature of attempts made to implement optimization algorithms that that could help to optimize cutting parameters to increase removal material rate during machining operations such as neuronal networks [16], adaptive control optimization [17], and genetic and meta-heuristic algorithms [18], to say a few. These strategies can be classified as follow: a) those related to the

* Corresponding author.
E-mail addresses: aelias@itesm.mx (A. Elías-Zúñiga), norberto.lzlacalle@ehu.es (L.N. López de Lacalle).

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development of rules or analytical models to optimize cutting parameters, and b) those strategies that include soft-computing techniques that work like black-boxes i.e., it is feed with input values and then, the applied strategy provides the output values. The first group includes techniques like decision trees, fuzzy rules or analytical solutions, while the second group include artificial neural networks, neuro-fuzzy models, support vector machines and decision trees, as discussed by Chandrasekaran et al. [19] and Abellan-Nebot et al. [20]. Of course, the optimization of turning parameters become important to increase productivity.

Therefore, the aim of this study focuses on combining numerical methods used to solve dynamic mathematical models that describe turning operations with Simulated Annealing (SA) optimization technique [21], to determine stable cutting parameters for optimal material removal rate during turning operations of Iconel 718, by considering SNMG and VBMT tool-inserts.

2. Mathematical modeling of turning operations

2.1. Dynamic model for turning operations in Inconel® 718

According to Urbikain et al., [22], the dynamic equations that described turning operation for long tool overhangs can be expressed as follows:

$$m_1\ddot{y}_1(t) + c_1(\dot{y}_1(t) - \dot{y}_2(t)) + k_1(y_1(t) - y_2(t)) = F_{y,1} \quad (1)$$

$$m_2\ddot{y}_2(t) + c_2\dot{y}_2(t) + k_2y_2(t) - c_1(\dot{y}_1(t) - \dot{y}_2(t)) - k_1(y_1(t) - y_2(t)) = F_{y,2} \quad (2)$$

where y_i are the modal coordinates, m_j, c_j, and k_j with $j = 1, 2$ are modal parameters related to each vibration mode, $F_{y,j}$ are the dynamic forces that depend on the relative displacement of the tool. These system parameters can be experimentally determined by impact tests. As pointed out by Urbikain et al. [23], the weakest tool direction is in the tangent direction and then, the thickness of the chip changes when the tool cutting edge is removed from the plane in the direction of the cutting speed. This distortion is accompanied by a horizontal movement that can be described by the relation $\delta x = \nu\, \delta y$, where ν is the dynamic displacement coefficient that depends on the vibration frequency, as discussed in Urbikain et al., [24]. Thus, dynamic tests are needed to quantify its dynamic effects. The regeneration of chatter in the XZ plane is due to the chip thickness variation in the X direction, which depends on the tangent distortion (δy), as illustrated in Fig. 1. The dynamic displacement coefficient can be determined using the following expression:

$$\nu = \frac{k}{K_{cy}\ a_p}\left[\left(\frac{\omega_c}{\omega_n}\right)^2 - 1\right] \quad (3)$$

where k is the modal stiffness, ω_n is the natural frequency, K_{cy} represents the cutting force coefficients, a_p is the depth of cut, and ω_c is the measured cutting vibration frequency value.

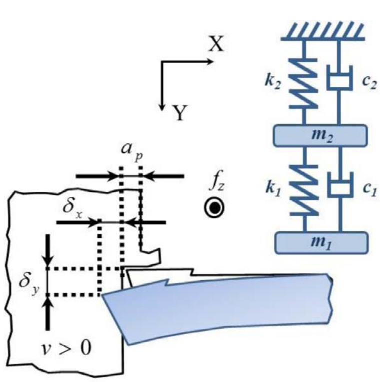

Fig. 1. Schematic of the system dynamics.

Note from Eq. (3) that if $\nu < 0$ then, the cutting edge is displaced against the workpiece. This value increases the chip thickness and reduces the vibrational frequency. However, if $\nu > 0$ then, the cutting edge moves away from the workpiece and the entire mechanical system tends to be stable i.e., the sign of ν depends on the frequency of vibration during the cutting process which is responsible for having stable or unstable system behavior. Therefore, for a 2DOF model, the chip thickness can be computed as follows:

$$h(t) = -\sum_{i=1}^{2} \nu_i(y_i(t) - y_i(t-\tau)) \quad (4)$$

where ν_i are the dynamic displacement coefficients, $y_i(t)$ and $y_i(t-\tau)$ are the current and the previous movements of the i mode, respectively. For longitudinal lathing operations, the following dynamic force model is considered:

$$F_{y,i} = K_{cy}\ a_p\ \nu_i[-(y_i(t) - y_i(t-\tau))] \quad (5)$$

where τ represents the delay time. To take into account tool flexibility, vibrational modes in the Y direction, as well as shear forces in the tangential direction, are considered. Therefore, Eqs. (1) and (2) can be expressed in matrix form as:

$$\mathbf{M}\ddot{\mathbf{y}}(t) + \mathbf{C}\dot{\mathbf{y}}(t) + \mathbf{K}^{*}\mathbf{y}(t) = \mathbf{K_c}\mathbf{y}(t-\tau) \quad (6)$$

where

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}; \mathbf{C} = \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1 + c_2 \end{bmatrix}; \quad (7)$$

$$\mathbf{K}^{*} = \begin{bmatrix} k_1 + K_{cy}a_p\ \nu_1 & -k_1 \\ -k_1 & k_1 + k_2 + K_{cy}a_p\ \nu_2 \end{bmatrix}; \mathbf{K_c} = K_{cy}\ l\begin{bmatrix} \nu_1 & 0 \\ 0 & \nu_2 \end{bmatrix} \quad (8)$$

This dynamic system (6) can be decoupled by using the transformation relation introduced by Gu et al., [25]:

$$\mathrm{p}(t) = \mathrm{M}\dot{\mathrm{y}}(t) + \mathrm{Cy}(t)/2 \quad (9)$$

By rearranging terms and by using the state-space system representation, yields:

$$\begin{Bmatrix} \dot{\mathbf{y}}(t) \\ \dot{\mathbf{p}}(t) \end{Bmatrix} = \mathbf{A}\begin{Bmatrix} \mathbf{y}(t) \\ \mathbf{p}(t) \end{Bmatrix} + \boldsymbol{B}\begin{Bmatrix} \mathbf{y}(t-\tau) \\ \mathbf{p}(t-\tau) \end{Bmatrix} \quad (10)$$

where

$$\mathbf{A} = \begin{bmatrix} -\mathbf{M}^{-1}\mathbf{C}/2 & \mathbf{M}^{-1} \\ \mathbf{C}\mathbf{M}^{-1}\mathbf{C}/4 - \mathbf{K}^{*} & -\mathbf{C}\mathbf{M}^{-1}/2 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ \mathbf{K_c} & 0 \end{bmatrix} \quad (11)$$

To determine the stability bounds at which the turning operation process becomes stable, the solution of Eq. (10) will be obtained by using the Enhanced Multistage Homotopy Perturbation (EMHPM), as well as the Chebyshev Collocation Method (CCM) by following the solution algorithms discussed in Olvera et al., [8].

2.2. Experimental setup

The experimental tests were carried out in a slant bed CMZ® 4 axis lathe, model TC25BTY with a maximum rotational speed of 4000 RPM, and a FANUC® 31iT HVi CNC control. The y-axis was chosen to be perpendicular to the X–Z plane for tools positioning. The lathe force measurements were performed by using a Kistler® 9192AA dynamometer, its axes were aligned with the radial, the tangent, and the axial cutting force component (Fig. 2a). A multichannel analyzer Oros35 NV-Gate by Oros® was used to collect the cutting force magnitude values. These force values were filtered and post-processed by using an in-house computer script run in Matlab® software.

Two different cutting tool inserts were used: SNMG 120408 PM, and VBMT160408PR. Their corresponding geometries are displayed in