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ORIGINAL ARTICLE

Spindle speed variation in turning: technological effectiveness and applicability to real industrial cases

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Abstract Spindle speed variation is a well-known technique to suppress regenerative machine tool vibrations especially for low spindle speeds. Although a lot of research effort was made over the years the technique is not widespread in real turning applications. In this paper, the reasons that can limit the diffusion of the spindle speed variation were investigated. Therefore, the analysis of spindle speed variation strategy was not only focused on its chatter suppression properties but also on some more general technological aspects: the surface quality of the machined components, the cutting edge-spindle bearings load and the thermal overload the electrical spindle motor is subjected to when the speed modulation is used. A time-domain numerical model of the turning process was developed and exploited to support the analysis. A lot of cutting tests were also performed both to validate the numerical model and to evaluate the effect of variable spindle speed on surface quality. Finally, some real industrial applications were analyzed focusing on thermal overload issue of the spindle motor.

Keywords Cutting process stability · Regenerative chatter · Spindle speed variation

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1 Introduction

The problem of self-excited vibrations in metal cutting process has troubled the manufacturing community for many years. Extensive academic and industrial research has been performed in order to study the physical basics of chatter phenomenon and try to suppress it, [1]. Regenerative chatter causes a poor surface quality, unacceptable inaccuracy, an excessive tool wear, and a waste of materials and energy, limiting the achievable material removal rate. During the last decades, different chatter mitigation techniques have been developed [2]. The spindle speed variation (SSV) method that consists in a continuous variation of the cutting speed during machining bases its effectiveness on disturbing the regenerative mechanism. The application of SSV to turning and milling operations has been studied in literature by different authors; the first pioneering studies were outlined by Stoferle and Grab [3] who introduced the basic ideas in the 1970s. Even if a lot of researchers have focused on the application of the SSV to milling (i.e., [4–8]) this chatter mitigation technique seems more promising in turning.

Inamura and Sata [9] first studied the stability of the turning process with variable spindle speed: their experimental results were not as good as the theoretical ones. Takemura et al. in [10] used an energy balance to analyze the stabilizing effects of different speed laws such as triangular, rectangular and sinusoidal. Sexton and Stone [11–13] developed a more realistic model to study SSV technique; they observed some good results especially for low spindle speeds.

De Canniere et al. [14] used the perturbation theory to study the stability of the delayed differential equation representing a turning operation with SSV. Lin et al. in [15] also demonstrated that the sinusoidal speed law can be more easily tracked by the spindle control system than other periodic functions. Due to these properties, Sinusoidal spindle speed variation (SSSV) has been the more widely adopted technique, but no robust guidelines were defined to select the proper values of speed modulation amplitude and frequency. In [16], Jemielniak et al. studied the effects of SSSV on vibration amplitude but the simple proposed model that considers only the vibration amplitude increment of every workpiece revolution is too approximated and not suitable to outline robust technological considerations. Moreover in this paper, the outlined observations were not extended to a wide range of spindle speeds. Some authors proposed alternative modulating spindle speed laws: Yilmaz for instance in [17], proposed a random spindle speed trajectory for turning operations. Jayaram et al. [18] combined the Fourier expansion with Bessel functions expansion to determine the stability charts also for SSV turning process. The model was validated using the results of numerical time-domain simulations and experimental tests. Yang et al. [19] applied a multiple time-varying parameters technique to suppress regenerative chatter in turning: experimental tests were conducted varying both the spindle speed (sinusoidal law) and the tool rake angle (adopting a triangular law). The results showed that the proposed combined approach is more effective than varying only one parameter. Al-Regib et al. in [20] introduced an energy-based stability analysis of variable speed machining and proposed a criterion to select the parameters of SSSV. Experimental turning tests confirmed the effectiveness of the technique especially at low spindle speeds. Applying the semi-discretization method, Insperger et al. [21] observed that SSSV is more effective than the saw teeth modulating law. The same authors [22] used the semi-discretization method to get a stability diagram in turning with SSSV. Numerical results show how the stabilization effect is stronger for high-speed modulation and for low spindle speed domain. In [23, 24], Namachchivaya et al. developed a perturbative method to study the effect of SSV on chatter suppression. The performed analysis shows a modest increase of stability and complex nonlinear dynamics close to the new stability boundary.

Wu et al. in [25] successfully applied SSV to non-circular turning. The stability charts both for constant speed machining (CSM) and for SSV were computed and compared.

Even though the SSSV in turning has been studied for years, a widespread industrial diffusion has not yet emerged. For this reason, in this paper, the technique was evaluated focusing on the different technological aspects that are important to spread the technique also in industrial applications, displacing the focus from the explanation of the physical phenomena to their effects on the process quality. The SSSV effectiveness as a vibrations mitigation technique was investigated using both a numerical and experimental approach. The SSSV parameters combination selection was critically evaluated considering the effect on cutting forces and on surface roughness both in unstable and stable operations. This analysis allows to outline some indications regarding the workpiece surface quality and the cutting edge load entailed by the spindle speed modulation. In section 2 and 3, the developed turning models and the experimental setup are described. Some test results are reported in order to validate the numerical models, section 4. In section 5, results from the experimental tests and some numerical simulation campaigns are reported.

Section 6 completes the study analyzing the feasibility of SSSV application in the industrial context, taking into account, for example, the technological limitations due to spindle motor characteristics.

2 Numerical models

In this section, the numerical models used to analyze in depth the effectiveness of SSSV technique and to set-up the experimental tests are described. A turning process model was developed in Matlab/Simulink® environment to support the analysis. It was designed to be coupled with machine dynamic models, enabling a complete functional simulation of turning operations taking into account machine–process dynamical interactions. Both for machine and workpiece, complex dynamics can be used (Fig. 1) but in this particular context a single dof (degree of freedom) dynamic is considered. As it will be described in the following section, the main compliance is located in the workpiece. Generally two dof models can be used to take into account coupled mode chatter (flutter, i.e., [26]), but in this work, the focus is mainly on regenerative

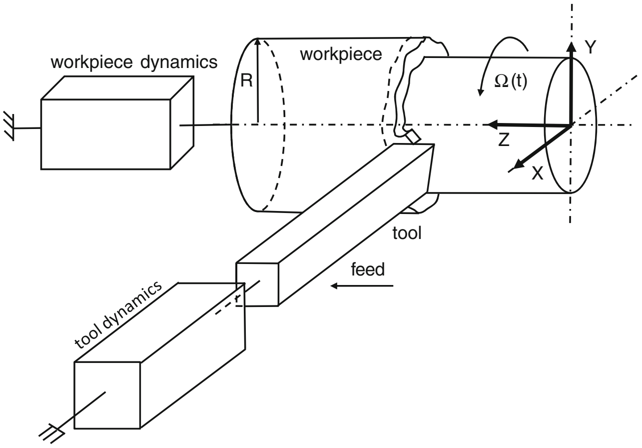


Fig. 1 Cutting process model and reference frame

chatter. Furthermore, from the analysis of some industrial cases, it was observed that the flutter phenomenon occurs only for higher depth of cuts compared to regenerative instability.

Some works (i.e., [27]) used two dofs only to consider analytically the dependence of the time delay to the system state but this effect is absolutely negligible at common feed rates. Moreover in these papers, having adopted a diagonal matrix for the machine dynamic compliance, the flutter phenomenon was not considered.

The simulation model allows the prediction of dynamic cutting forces and the chatter occurrence in the time domain. Nonlinear effects due to tool–workpiece detachment and the nonlinear dependence of the cutting force on the chip thickness were also considered in this work.

These modeled nonlinearities allow to take into account some phenomena like the subcritical Hopf bifurcation and the pre-chatter chaotic or random-like small amplitude cutting vibrations (i.e., [28]) that can affect the vibration level during cutting. The model is the simplest one, which still explains the basic stability problems and nonlinear chatter vibration arising in machining; however it can serve good results, [29].

The cutting process model receives as input the workpiece's actual rotational speed $\Omega(t)$ and the relative position between the tool and the workpiece with respect to a fixed reference frame (Fig. 1) then it returns the cutting force (on tool and workpiece) with respect to the same frame.

The algorithm consists in the following steps:

1. The radial engagement of the tool tip (due to the flexibility of both the tool and the workpiece) is computed, determining the actual radial depth of cut (b). Basically, the distance between the tool tip and the workpiece axis (that is assumed to be the Z axis of the fixed reference frame) is compared with the workpiece radius R;
2. The chip thickness is computed as the difference between the actual Z component of the tool tip position and the same component at the previous workpiece revolution, i.e., $h=z(t)-z(t-\tau(t))$; the value of $\tau(t)$ is expressed analytically solving the following implicit form, Eq. 1:

$$\int_{t-\tau(t)}^{t} \Omega(t)dt = 2\pi \tag{1}$$

the sinusoidal spindle speed modulation law is generally described using Eq. 2:

$$\Omega(t) = \Omega_0 \cdot (1 + RVA \cdot \sin(RVF \cdot \Omega_0 \cdot t)) \tag{2}$$

where Ω_0 is the nominal spindle speed, RVA (sinusoid amplitude/nominal spindle speed) and RVF (sinusoid frequency/nominal spindle speed) are dimensionless parameters.

Since argument of the integral in Eq. 1 is transcendent, an explicit expression of $\tau(t)$ cannot be computed; for this reason, a four-order Taylor expansion has been adopted in the model as a suitable approximation.

Moreover, in order to make the delayed position available, the Z value in the interval $t-\tau(t)$ is stored in a proper buffer;

3. If the chip thickness drops to zero, a tool detachment is detected: the buffer representing tool–workpiece relative position is fed again with $z(t-\tau(t))$, so that the overall delay is doubled, tripled, and so on, making available the values $z(t-n\tau(t))$ with n indicating the number of "jumps" as described in [30];
4. Cutting force components (feed and tangential) are computed. The forces values depend on run-time variable (chip thickness h and depth of cut b) as well as on some parameters that define the cutting force model [31]: Eqs. 3 and 4.

$$F_t = bK_{tc}(\alpha, \mathrm{V})h^p + \frac{b}{\sin\chi}K_{te}(\alpha, \mathrm{V}) \tag{3}$$

$$F_f = bK_{fc}(\alpha, \mathrm{V})h^p + \frac{b}{\sin\chi}K_{fe}(\alpha, \mathrm{V}) \tag{4}$$

Where

   a. K_{tc}, K_{te}, K_{fc}, K_{fe} are cutting coefficients that are functional to the rake angle α, cutting velocity V, lead angle χ, and lubrication condition. Literature suggests some empirical formulas, but in most of cases these coefficients can be kept constant;
   b. p is a parameter for modeling the exponential decay of shear pressure as the chip thickness increases;

5. The feed and tangential cutting force components are projected into the fixed reference frame and assigned to the output.

Since vibration problems usually occur during roughing operations, that is when the tool nose radius is usually negligible with respect to the required depth of cut, the effect of such a radius has not been represented in the present simulation model.

Although widespread stability criteria methods generally allow to easily generate stability charts both for CSM and variable speed machining (VSM), the above-mentioned turning model was developed in order to be able to perform more general technological considerations concerned with the effectiveness and the applicability of the SSSV technique. Therefore, the model was used not only to perform a stability analysis but to get information about the amount of vibration and the force level involved with the use of SSSV both for unstable and stable turning operations.

In order to evaluate the applicability of the SSSV technique also to real industrial contexts, it is important to analyze the motor overload considering its characteristic curve. This curve must be compared with the root mean squared (RMS) value of the motor torque that is strictly related to the thermal issue. The RMS torque required to perform a turning operation with variable cutting speed ($C_{V\mathrm{RMS}}$) can be computed writing the dynamic torque balance at the motor:

$$C_V = F_{tV} \cdot \delta \cdot \frac{D}{2} + J_{TOT} \cdot \frac{d}{dt}\left(\frac{\Omega_0}{\delta} \cdot (1 + RVA \cdot \sin(\Omega_0 \cdot RVF \cdot t))\right) \tag{5}$$

where D is the workpiece diameter, J_{TOT} the global spindle inertia (motor, transmission, and workpiece) reduced to the motor and δ the spindle transmission ratio. The C_V considers both the torque required to change the cutting speed and the cutting torque associated to the VSM cutting force (F_{tV}).

This leads to the desired relationship:

$$C_{VRMS} = \sqrt{\frac{1}{T}\int_0^T \left[F_{tSSSV} \cdot \delta \cdot D/2 + J_{TOT} \cdot \frac{d}{dt}\left(\frac{\Omega_0}{\delta} \cdot (1 + RVA \cdot \sin(\Omega_0 \cdot RVF \cdot t))\right)\right]^2 \cdot dt} \tag{6}$$

$C_{V\mathrm{RMS}}$ can be directly used to evaluate the motor load. In order to ease the comparison with the normal motor load, a specific ratio OR (overload ratio) can be defined as follows:

$$\mathrm{OR} = \frac{C_{V\mathrm{RMS}}}{C_{\mathrm{RMS}}} \tag{7}$$

Where C_{RMS} is the RMS torque required to perform the same turning operation but without the spindle modulation. In section 6, the ratio given in Eq. 4 will be compared with the characteristic curve of the motor (see Fig. 8) in order to assess SSSV industrial applicability.

The motor thermal overload was also considered during special workpiece design (section 3) and the SSSV feasibility analysis. Moreover, in order to verify the dynamic properties of the control system, a simple model of the spindle drive [32] was developed.

3 Experimental setup

A special workpiece was designed and created in order to mimic a single dof dynamics along axial direction (Z). A workpiece made of steel (S355—EN10025; yield strength, 355 MPa) was chosen but the analysis results are not influenced by the selected steel alloy.

The workpiece is composed of two co-axial cylindrical pieces (see Fig. 2a). The internal shaft is inserted with backlash in the hollow external cylinder and suspended by two flexible reeds connected at the two sides (see Fig. 2b): flexible reeds are used to constrain the workpiece and to calibrate the relative axial stiffness. The workpiece is designed in order to place the nominal spindle speeds in the high order lobes region of the stability diagram where SSSV seems very effective [22]. The spindle motor thermal limits and the dynamic performance of the NC system were considered.

The workpiece is mounted on the lathe between the self-centering chuck and the tailstock. In order to measure the workpiece vibration, a laser beam displacement sensor is used (as done in [8]). The optical triangulator described in [33] is characterized by a worse accuracy (≈1 μm) and somewhat limited range (≈500 μm) of linear operation.

Combining the laser measurements with the data from the encoder, it is possible to experimentally reconstruct the

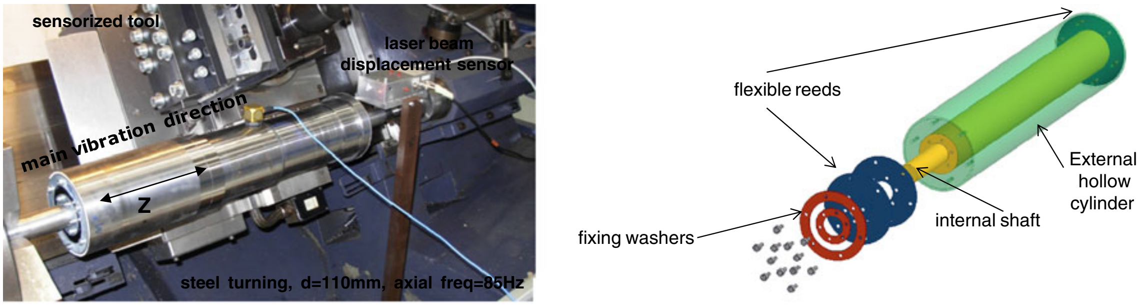
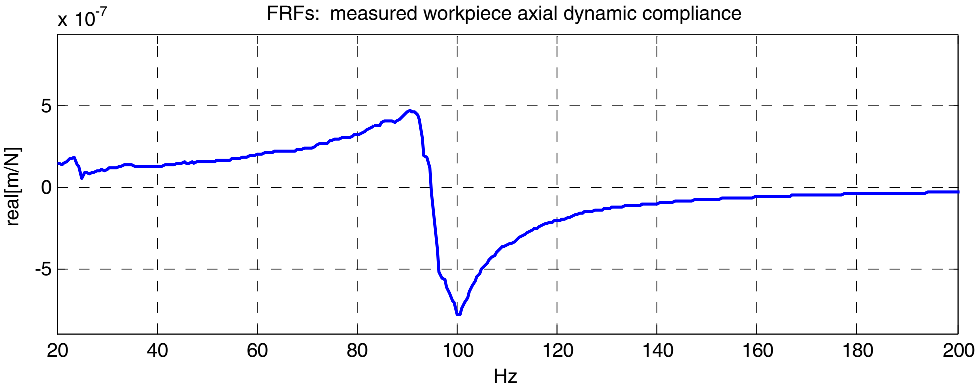


Fig. 2 **a** Experimental setup, **b** designed workpiece with calibrated axial compliance

Fig. 3 Experimental axial dynamic compliance of the workpiece



inner-outer chip thickness modulation entailed by the regenerative phenomenon. An experimental modal analysis was performed on the workpiece in order to assess the correctness of the design procedure. The measured axial dynamic compliance is depicted in Fig. 3; resonant frequency close to 100 Hz can be appreciated. The selected workpiece frequency allows to overcome the motor-drive limits (linked to the available lathe) and consequently to perform cutting tests in a high order lobes region where the SSSV seems to be promising. Finally, it was verified that the tool compliance along *Z* direction is negligible compared to the workpiece one.

An insert with a lead angle χ=90° was adopted (ISO standard code: TNMG220404-M5 5615) and it was fixed on a tool holder (ISO code MTJNL2525M22).

The lathe used to perform cutting tests is equipped with an old analogical Numerical Control (NC). In order to implement the speed modulation on it, the speed control loop was bypassed; thus the speed reference signal was generated directly from an external computer and sent to the spindle motor drive, Fig. 4. An acquisition board (National Instruments 6259) was used also to read the encoder signals and as an interface from the computer and the NC.

The SSV technique can be more easily implemented on modern lathes. For instance, synchronized actions (Siemens) allow you to execute external code in parallel to the NC normal mode. The written synchronized action can be called directly from the part program. The user has to choose the SSV parameters. No additional devices or sensors are needed in these cases.

4 Cutting process model validation

In order to validate the turning process numerical model, some specific experimental tests were performed. Figure 5 shows the comparison between the dynamic chip thickness computed by the model and that extracted from experimental data. The experimental chip thickness was reconstructed combining the axial displacements measured by the laser beam sensor with the workpiece angular position given by spindle encoder. The correctness of the kinematic chip thickness during stable cutting with SSSV demonstrates that the variable time delay is modeled with sufficient precision. Moreover, even during unstable operations, the final vibrations level is predicted with sufficient precision. In particular, it can be noted that the phenomenon of tool–workpiece detachment is well addressed: when it occurs, the regenerative mechanism is temporarily arrested, just like in the real process, and the vibrations do not reach unrealistic values. Therefore, it can be stated that the model can be effectively exploited to analyze the technological key performance indicators related to turning process, in particular making quantitative considerations about the amount of vibrations and the cutting force level involved during different cutting conditions.

Fig. 4 Lathe NC modifications

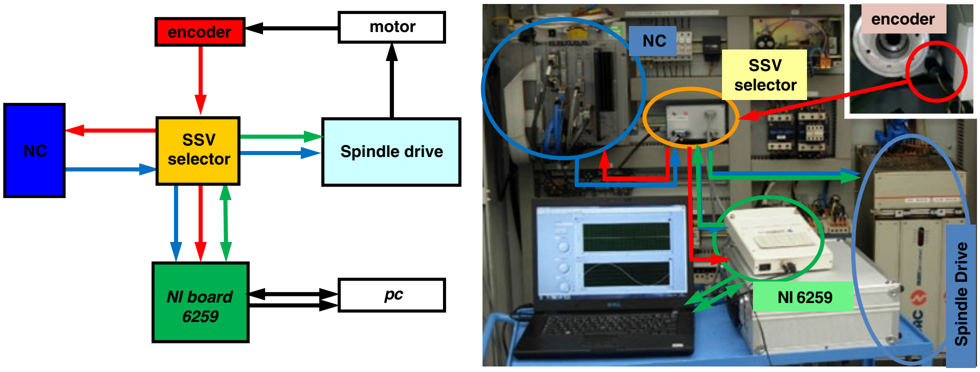
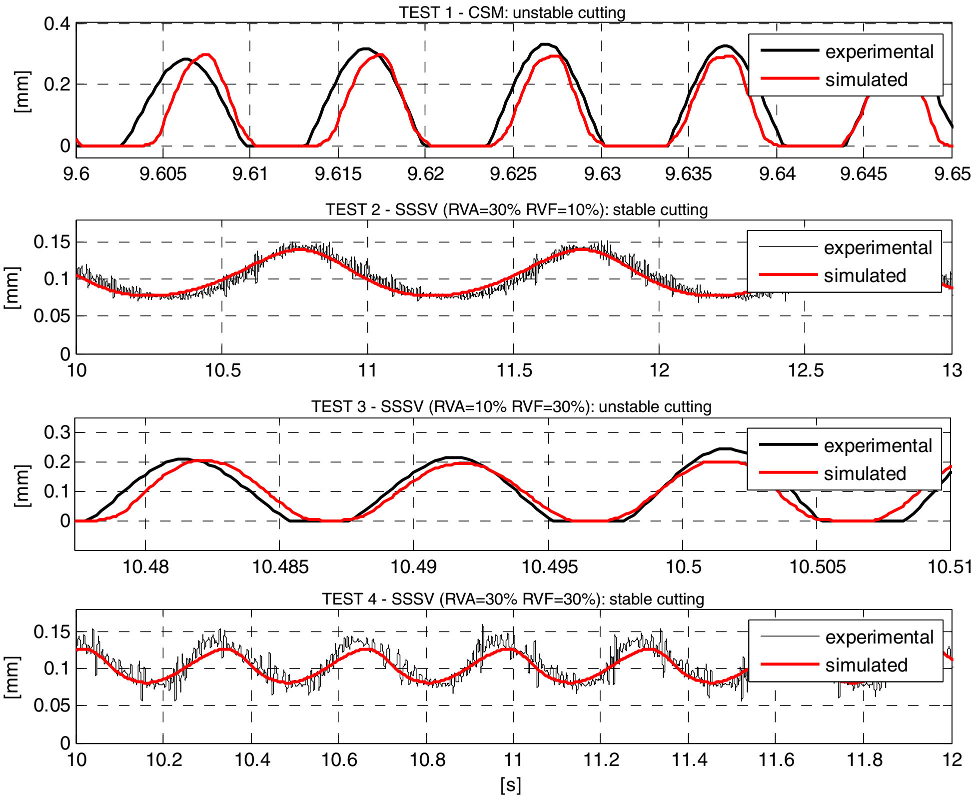


Fig. 5 Numerical–experimental comparisons, chip thickness, 620 rpm, b=1 mm, 0.1 mm/tooth rev



5 SSSV effectiveness and feasibility

The SSSV analysis was not strictly focused on the regenerative chatter stability, but the considerations were more generally extended to the vibration level (RMS) and to the cutting forces (RMS). In Figs. 6 and 7, the comparison between the numerical results of CSM cutting and VSM cutting is presented. Both the percentage reduction of workpiece vibration and cutting force are evaluated for two RVA–RVF parameters combinations: RVA=0.3, RVF=0.1 and RVA=0.1, RVF=0.3. It can also be observed that applying SSSV to stabilize the turning operations does not involve a significant increment of the RMS value of the cutting forces: this evidence suggests why no chipping phenomena occurred during cutting tests.

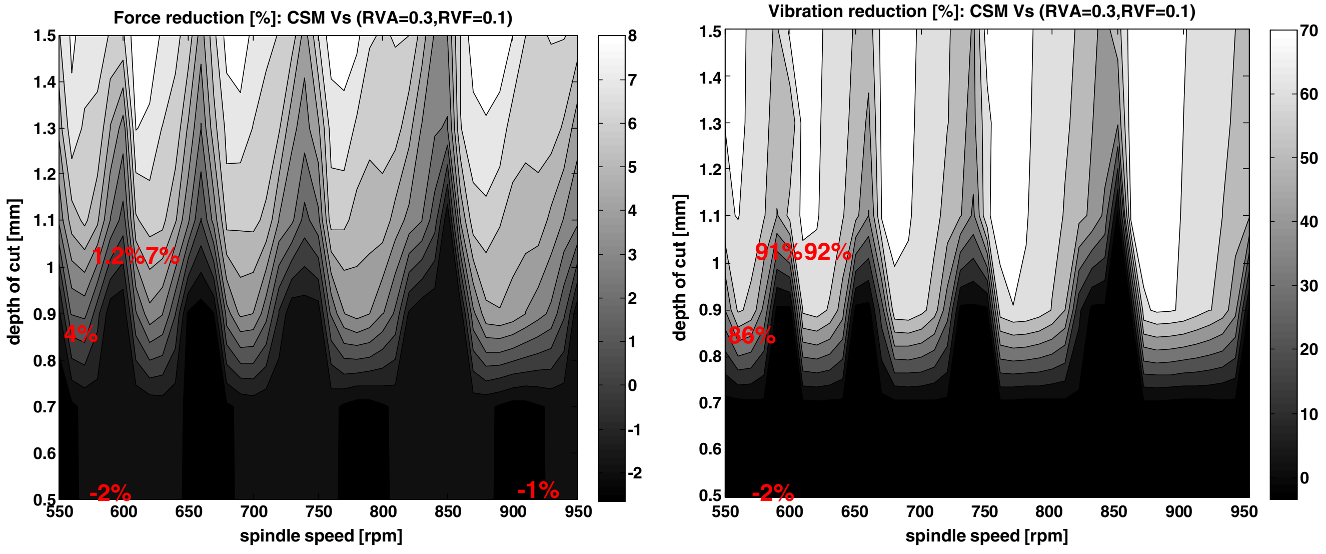


Fig. 6 CSM vs SSSV **a** vibration RMS reduction (percent); **b** force RMS reduction (percent) non linear cutting process model

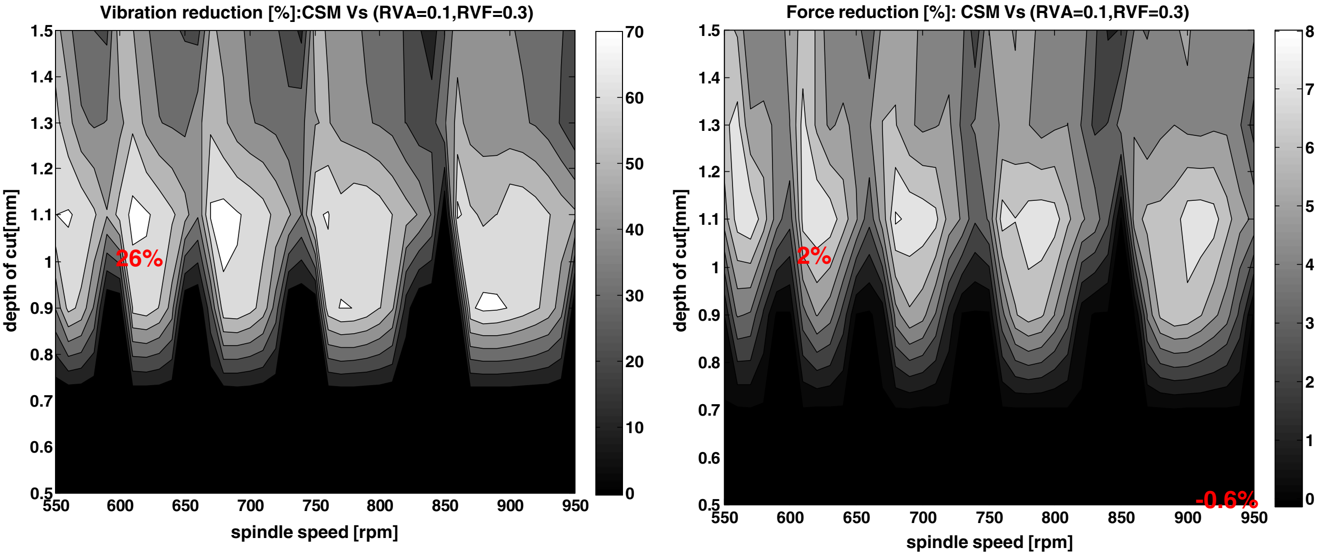


Fig. 7 CSM vs SSSV **a** vibration RMS reduction (percent); **b** force RMS reduction (percent) non linear cutting process model

The results of the cutting tests are presented (see Tables 1 and 2) in order to analyze the effect of SSSV on the surface quality. The surface roughness (Ra) was measured and reported for each cutting test. The surface quality of the stabilized turning operations can be considered adequate, especially during roughing operations. It can be noted, both from experimental and simulated results, that the RVA–RVF combination selection is not particularly critical. In order to exploit the stabilizing effects of the SSSV technique, it is important that the RVA–RVF parameters overcome a given threshold, in order to guarantee that their combined effect is able to interfere with the regenerative phenomenon. The SSSV allows important increment of the turning productivity without a significant raising of the cutting edge chipping phenomenon and without increasing the spindle bearings load.

Indeed, the chatter occurrence strongly depends on the system's dynamic behavior; on the other hand, the industrial practice suggests that often a turning vibration problem can be ascribed to a single dominant natural frequency, just like the case tackled by the present study. Moreover, the material and the tool geometry influences are often limited to the determination of the absolute level of the stability limit, but they do not affect the overall strategy for the application of the SSV. Hence, the results presented here represent a reasonable picture of a general turning operation.

6 Industrial applicability and thermal motor load

In addition to the evaluation of the effectiveness of SSSV, the motor thermal overload involved in the use of the speed modulation was evaluated considering some real industrial cases (see Table 3).

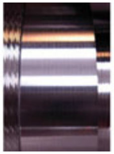
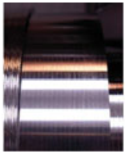
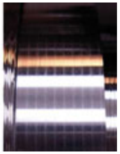
In Fig. 8, the ratio defined in Eq. 7 was computed and compared with the motor characteristic curve in S1 regime for each industrial case. The available motor torque was normalized to the required torque at CSM too.

This allows to compare, for each case, the available torque and the required torque to perform the SSSV over the wide range of nominal cutting speeds, i.e., from 70 to 500 m/min (that can be considered the widest cutting speed range for steel working): if the dashed line is below the corresponding solid line, the spindle can perform the cutting using continuously the SSSV technique, otherwise the motor could be damaged.

Table 1 Effects of SSSV on unstable operations

	n=910rpm, b=1.7mm (RVA effect on unstable cutting)				n=910rpm, b=1 mm (RVF effect on unstable cutting)			
CSM SSSV	CSM	RVA=0.1 RVF=0.1	RVA=0.2 RVF=0.1	RVA=0.3 RVF=0.1	CSM	RVA=0.1 RVF=0.1	RVA=0.1 RVF=0.2	RVA=0.1 RVF=0.3
Surf. quality								
Proc. Status .	unstable	unstable	stable	stable	unstable	stable	stable	stable
Ra [µm]	11.39	8.27	2.15	2.12	9.91	2.11	1.79	1.98

Table 2 Effects of SSSV on stable operations

	n=910rpm, b=0.5mm (SSSV effect on stable cutting)				
CSM SSSV	CSM	RVA=0.1 RVF=0.1	RVA=0.1 RVF=0.3	RVA=0.3 RVF=0.1	RVA=0.4 RVF=0.05
Surface quality					
status	stable	stable	stable	stable	stable
Ra[μm]	1.29	1.34	1.36	1.38	1.45

It is clearly visible that the application “B” and “C” can easily adopt the SSSV cutting strategy without dangerously overloading the spindle motor. Also the application “D” seems very promising because generally these high diameter steel workpieces are not machined at very high cutting speeds in order to increase the tool life and thus to avoid too frequently insert changes. The cutting parameters for this application have been taken directly from the factory floor practice. Only for the industrial application “A” the SSSV feasibility may be considered critical.

The indication outlined from the thermal load analysis fully agrees with the technological suggestions: the SSSV is more effective when used to enhance the cutting stability of turning operations in the high order lobes region of the stability chart, namely at low spindle speed. Indeed, the case “A” is characterized by a small workpiece diameter, hence, in order to reach a suitable cutting speed, the adopted spindle speed is relatively high and the SSSV law becomes too demanding in terms of inertial overload.

7 Conclusions

Sinusoidal spindle speed variation was studied as a vibration mitigation technique for high order stability lobes where the technique seems more promising, i.e., steel or titanium cutting; however, the application strategy does not depend on a specific material. The SSSV analysis was not only focused on the regenerative chatter stability but on more general technological considerations regarding the vibration level and the forces on the cutting edge.

A cutting process numerical model was developed, validated, and used to evaluate the effects of SSSV both on stable and unstable turning operations. Despite a $\chi=90°$ case was considered, the remarks about the effectiveness and the feasibility of the SSSV were not skewed, as most of the situations can be traced back to an equivalent single dof dynamics with a force model represented by average cutting coefficients. Different combinations of RVA/RVF parameters were investigated. The SSSV has a stronger effect on the vibration level than on the cutting force; this means that the speed modulation technique can be used without dangerously overloading the tool edge and the spindle bearings.

The SSSV showed high vibration mitigation properties and the modulating parameters selection does not represent a critical issue. The RVA is the more effective parameter.

Experimental cutting tests were also performed in order to evaluate the quality of the machined surface both with CSM and VSM: it was observed that the SSSV does not make worse the surface roughness even if it is used for stable turning operations. Finally, the feasibility analysis for some industrial turning applications were also carried out: the thermal overload of the

Table 3 Analyzed industrial cases, steel turning

Case	Workpiece diameter [mm]	Workpiece length [mm]	Spindle type	Natural freq/Ω_0
A	32	100	Electrospindle	2
B	500	200	Electrospindle	18
C	500	200	Motor spindle	18
D	7,000	400	Motor spindle	376

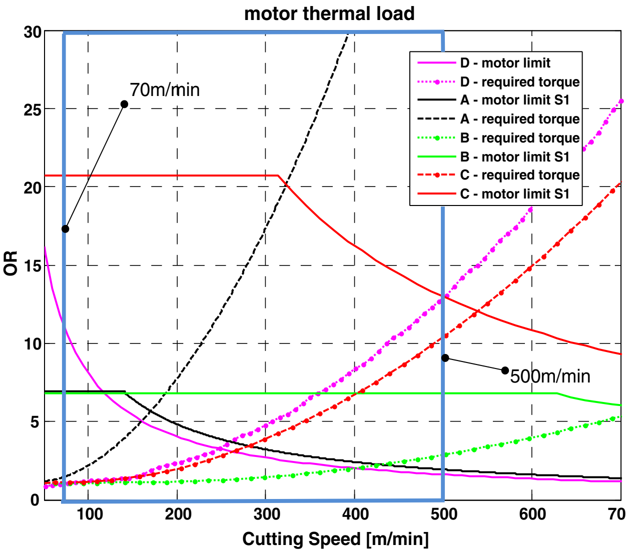


Fig. 8 Motor thermal load and SSSV applicability domain, RVA=0.3, RVF=0.1

electrical motor was evaluated and compared to the motor data specifications.

Future research activities will be focused on the effect of the speed modulation on tool wear phenomena and on the energy consumption of the spindle motor. Furthermore, a more complex SSV implementation will be developed: the idea is to develop a soft real time application that is able both to detect chatter vibration and to implement a vibration mitigation strategy based on SSSV. The optimal SSSV parameters (that is the parameters that assure a chatter free cutting condition limiting the motor overload and the power consumption) will be selected adaptively.

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