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Applications of torsional vibrations for vibro-drilling operations

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1. Introduction

Vibratory drilling and other machining operations are known to be very effective when vibrations of high frequency (f = 20 - 50 kHz) and small amplitude (A = 5 - 20 μm are generated in the direction of feed [1-5]. Then:

1) rigidity of a technological system increases and cutting forces decrease, while accuracy and efficiency of processing rise;

2) deep holes of relatively small diameter can be drilled throughout without repetitive insertion and withdrawal of a drill from drilled hole cycles as it is common in conventional drilling;

3) chips are shattered into small segments, thus easing their removal from the hole.

In technological devices of vibratory drilling high frequency vibrations may be excited by piezoelectric generators. However, these devices are relatively expensive and they can be economically used only when production is either fairly large or specific (e.g. airspace or military industry). In ordinary practice of mechanical processing, when producing small serial items, many advantages of vibratory drilling may be achieved by applying simpler and cheaper technological devices. Authors of this article propose generation of torsional vibrations in a drilling operation with a generator of simple design. The operational principle of this generator is based on the interaction of permanent magnets placed on driving and driven links [6, 7].

2. Study of drill torsional vibrations generated by noncontact magnetic mechanism

Fig. 1 presents the scheme of a generator of torsional vibrations designed for drilling operations. The generator is mounted on the spindle of a drilling machine. This generator comprises a noncontact magnetic mechanism consisting of two links: driving element *7*, which is rigidly fixed on the machine shaft *3* and rotates together with spindle, and driven element *8* which is elastically fixed on a frame of drilling device *6*. *Z* pairs of permanent magnets *4* are mounted on both links separated by gap δ.

In the process of drilling, when drill rotates with angular speed ω and is moved along its axis, the whole drilling device is moving in vertical plane (Fig. 1) guided by the sliding guides *9*.

When a spindle *1* is subjected to external torque M misalignment of the axes of the poles of permanent magnets placed on different links occurs, magnetic conductivity of gap δ varies and the magnetic field in gap δ redistributes.

For this reason the tangent resistance forces of

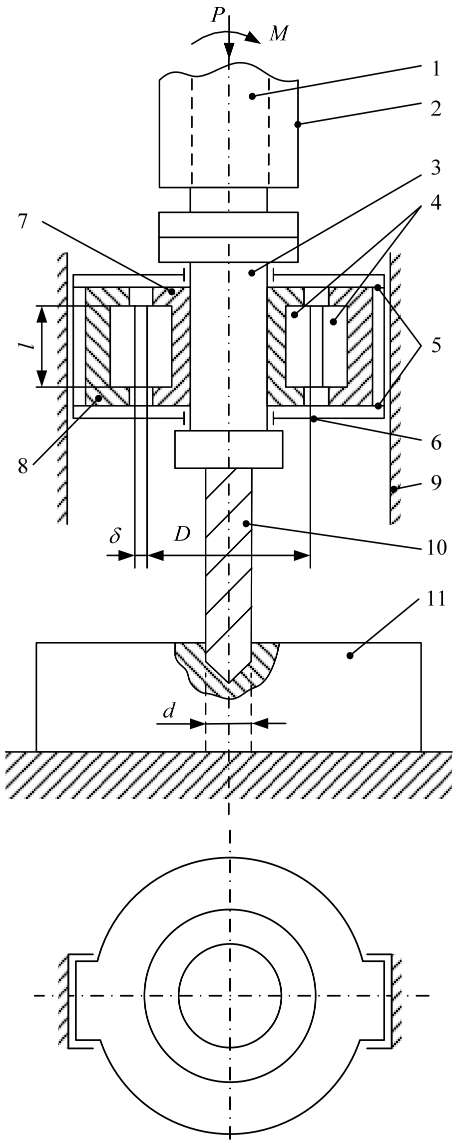


Fig. 1 Scheme of the generator of torsional vibrations designed for drilling operations: *1* – spindle; *2* – fixture of spindle; *3* – shaft of drilling device; *4* – permanent magnets; *5* – elastic elements; *6* – frame (protective hood); *7* – driving link; *8* – driven link of generator; *9* – sliding supports; *10* – drill; *11* – blank to be drilled

magnetic fields of each magnet pair appear, which attempt to reset both links (driving and driven) to the conjunction position of the axes of permanent magnets poles. Since external torque M is significantly greater than resistance moments of z magnetic fields, the rotation of the spindle takes place at frequency ω simultaneously with its torsional vibrations. The frequency of torsional vibrations changes with the change of parameters z and ω and may be adjusted by changing quantity and placement of magnets. In the case of placement of the same permanent magnets equally on both links, the frequency of torsional vibrations would be $z\omega$. In the case when poles of the magnets on both links are situated alternately, the frequency of torsional vibrations would be $z\omega/2$.

The amplitude of torsional vibrations changes with the change of the magnitude of gap δ, the magnitude of coercive force of permanent magnets, their overlapping length l, etc. Driving link *8* has a passive role and it performs only torsional vibrations and moves vertically together with frame *6* of the device while drill *10* goes into the drilled blank *11*.

To avoid the presence of chips formed during the operation in the magnetic field, protective hood (frame) *6* made of insulating material is used.

During the operation when a drill deepens into the hole drilled in blank *11*, resistance moment M_p emerges, therewith the drill is subjected to axial force P_0. When the operating conditions of the system are beyond resonance, its simplified differential equations may be approximately expressed in the following way

$$\left.\begin{aligned} I_1\ddot{\varphi}_1 + (\varphi_1 - \varphi_2)M_{12} + C_1\varphi_1 = M - M_p \\ I_2\ddot{\varphi}_2 - (\varphi_1 - \varphi_2)M_{12} + C_2\varphi_2 = 0 \end{aligned}\right\} \quad (1)$$

where I_1, I_2 are moments of inertia of a driving link and driven link together with the machine tool spindle, respectively; φ_1, φ_2 are angular displacements of driving and driven links, respectively; M_{12} is moment of magnetic fields forces of z pairs, M is external torque of the spindle; M_p is moment of resistance; C_1, C_2 are angular rigidities of fixtures of driving and driven links, respectively.

Having rearranged Eq. (1) we obtain

$$\ddot{\beta} + p^2(t)\beta = W(t) \quad (2)$$

where

$$\beta = \varphi_1 - \varphi_2, \; p^2(t) = p_0^2 + p_1^2 \cos z\omega t,$$
$$p_0^2 = \frac{H}{I_1 \cdot I_2}, \; p_1^2 = \frac{M_{12}(I_1 + I_2)}{I_1 \cdot I_2},$$
$$H = C_1 I_2 = C_2 I_1 .$$

Function $W(t)$ consisting of two moments M and M_p may be considered to have constant and variable components:

$$W(t) = \frac{1}{I_1 I_2}\left[M - M_p\right] = \frac{1}{I_1 I_2}(M_0 + M_{01}\sin \omega t) \quad (3)$$

where M_0, M_{01} are constant and variable components of the moments of external forces, respectively; ω is angular speed of spindle rotation; t is time.

The moment of magnetic field forces defines the efficiency of magnetic mechanism [8].

When magnetic poles are placed in two links of magnetic mechanism in the same order (Fig. 2, a)

$$M_{12} = \frac{1.43 \cdot 10^{-2} \pi D^2 l B^2 z}{\mu_0} \quad (4)$$

where D is diameter of permanent magnets distribution on a driving link; l is length of permanent magnet; μ_0 is magnetic permeability of a gap; B is induction of magnetic field in a gap; z is number of permanent magnet pairs.

Then the excitation frequency will be $z\omega$.

When magnetic poles are alternately placed in both magnetic mechanism links (Fig. 2, b)

$$M_{12} = \frac{8(\Sigma F)^2 D^2 l f_F \mu_0}{(\pi b)^2} \quad (5)$$

where ΣF is total magnetic force generated by both magnetic mechanism links; f_F is static force function depending on the width of permanent magnets poles, interrelation of their step and operating gap; b is distance between the poles. Then the excitation frequency will be $\frac{z}{2}\omega$.

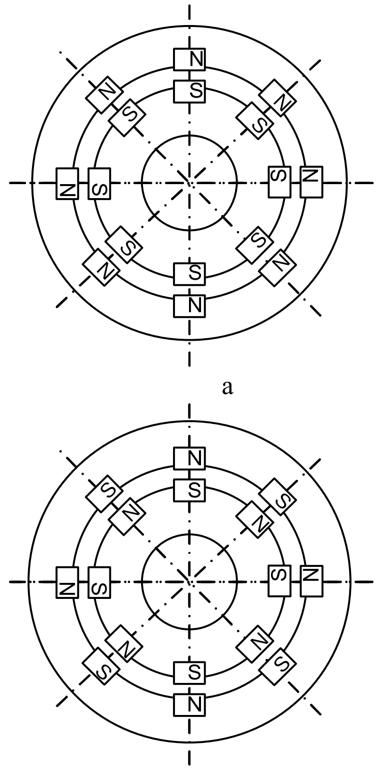


Fig. 2 The order of magnets placement in the driving and driven links: a – in the same order; b – interchangeably

Taking into account specificity of the magnetic mechanism operation it is expedient to study the possibility of the appearance of parametric vibrations. Therefore, instead of Eq. (2) we will study the equation

$$\ddot{\beta} + p^2(t)\beta = 0 \quad (6)$$

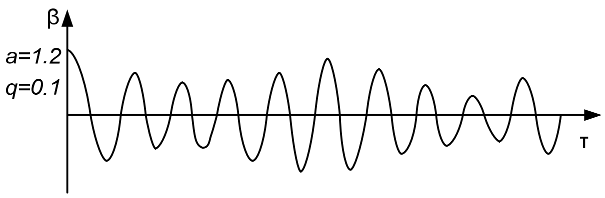
Eq. (6) is rearranged and reduced to the standard Mathieu equation form. Assuming that magnetic poles in magnetic mechanism links are placed alternately, we will have

$$\frac{d^2\beta}{d\tau^2} + (a - 2q\cos 2\tau)\beta = 0 \qquad (7)$$

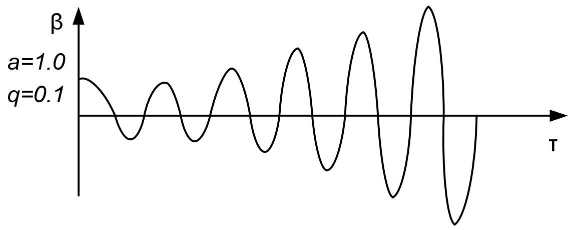
where

$$\tau = \frac{z\omega t}{4}, \quad a = \frac{16H}{z^2\omega^2 I_1 I_2}, \quad q = \frac{8(I_1 + I_2)M_{12}}{z^2\omega^2 I_1 I_2} \qquad (8)$$

Eq. (7) characterizes parametric torsional vibrations in the system. Their nature depends on the values of parameters a and q. Here two cases are possible (Fig. 3): 1) when the parametric vibrations amplitude is steady, the vibrating system is stable (Fig. 3, a); 2) when the parametric vibrations amplitude is growing – the vibrating system is unstable (Fig. 3, b).



a



b

Fig. 3 Type of system parametric vibrations at different values of the parameter [9]: a – when $a = 1.2$; b – when $a = 1.0$

The state of the system can be evaluated by means of Ince-Strutt diagram (Fig. 4), which is constructed in the plane of parameters a and q. Knowing the values of parameters a and q we determine the area in which there is he intersection point of the values of these parameters: if this point falls on the hatched diagram area, then the system state is unstable. As seen from Fig. 4, in the plane of t parameters a and q the stable areas are alternating with the unstable ones.

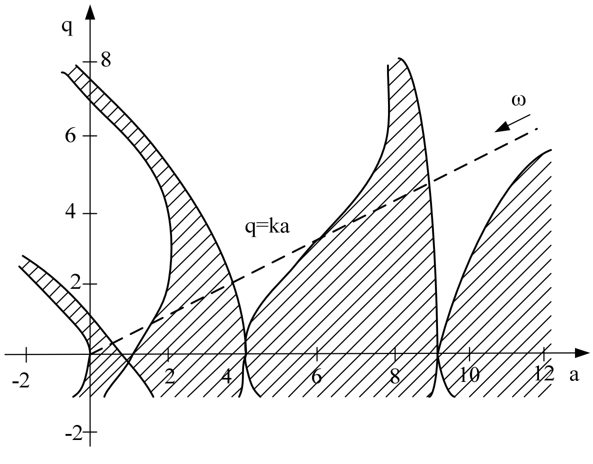


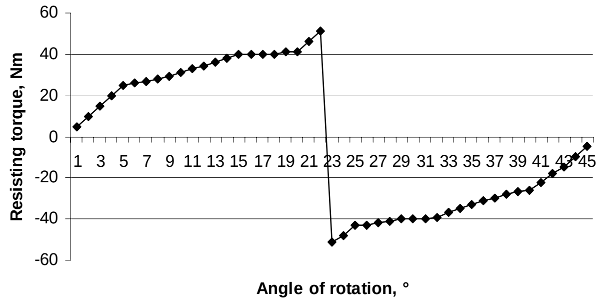
Fig. 4 Fragment of Ince-Strutt diagram [9]

By changing the values of parameters a and q it is possible to achieve that their intersection point fell on to the stability area. Note that with the increase of z and ω both parameters (a and q) proportionally decrease. Since the relation of both parameters is stable $k = \frac{q}{a} = \frac{(I_1 + I_2)M_{12}}{2H}$, the states of the serially changing system are outlined by the points of straight line $q = ka$ crossing the origin of coordinates (Fig. 4).

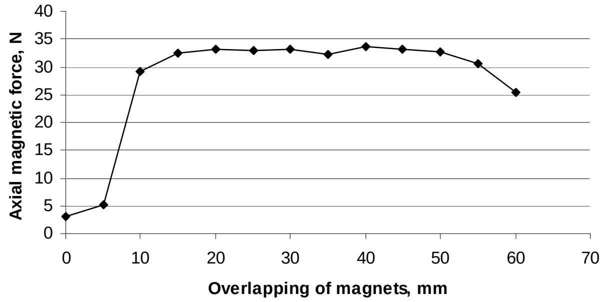
3. Experimental study of a prototype of generator of torsional vibrations

In order to ascertain validity of theoretical considerations the prototype of torsional vibrations generator has been made [7] and experimentally studied in stationary and dynamical conditions. The main parameters of the generator are:

- the number of permanent magnet pairs $z = 8$;
- magnet poles in both links of a magnetic mechanism are placed alternately;
- the diameter of magnets arrangement on a driving link $D = 92$ mm;
- gap $\delta = 2$ mm;
- the length of magnets overlapping $l = 60$ mm;
- coercive force of magnets $F_k = 230\,A/m$;
- magnetic induction of magnets $B = 0.124\,T$.



a



b

Fig. 5 Torque (a) and axial force (b) of the developed generator

Resisting torque and axial magnetic force of the generator of torsional vibrations have been measured experimentally (Fig. 5). Change of the torque direction (Fig. 5, a) is caused by the change of position of the magnets. The magnets are attracting each other till the angle of generators rotation is less then 22.5 deg. Later the magnets are pushing each other. Therefore torsional vibrations of the moving link are generated while the spindle of the drilling machine is rotating.

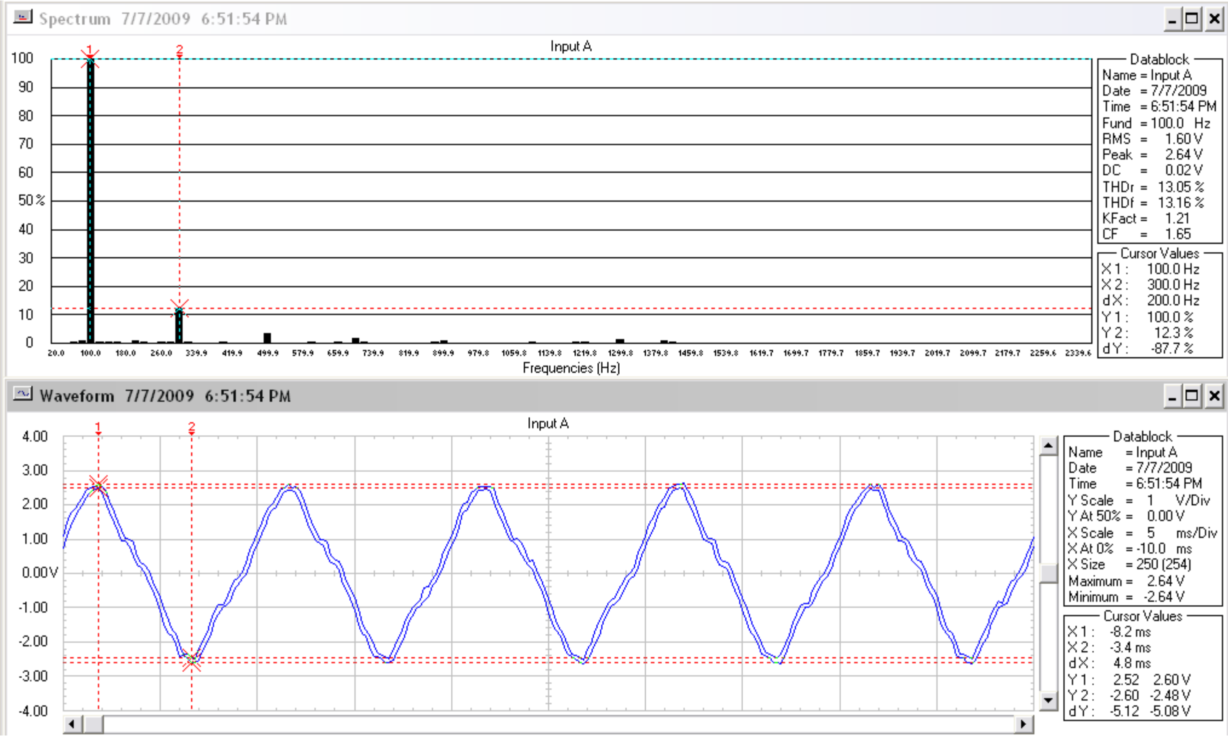


Fig. 6 Spectral composition and waveform of torsional vibrations when ω = 50 Hz

Axial magnetic force depends on the type of magnets and the level of their overlapping. Therefore it may be controlled by displacement of magnetic segments in axial direction.

Fig. 6 presents spectrum and time domain signal of generated vibrations when frequency of the spindle rotation ω = 50 Hz. The main component of the spectrum is $\frac{z}{4}\omega$=100 Hz. Spectrum components of 300 and 500 Hz (6ω and 10ω) are also noticeable. Vibrations of other frequencies are negligible.

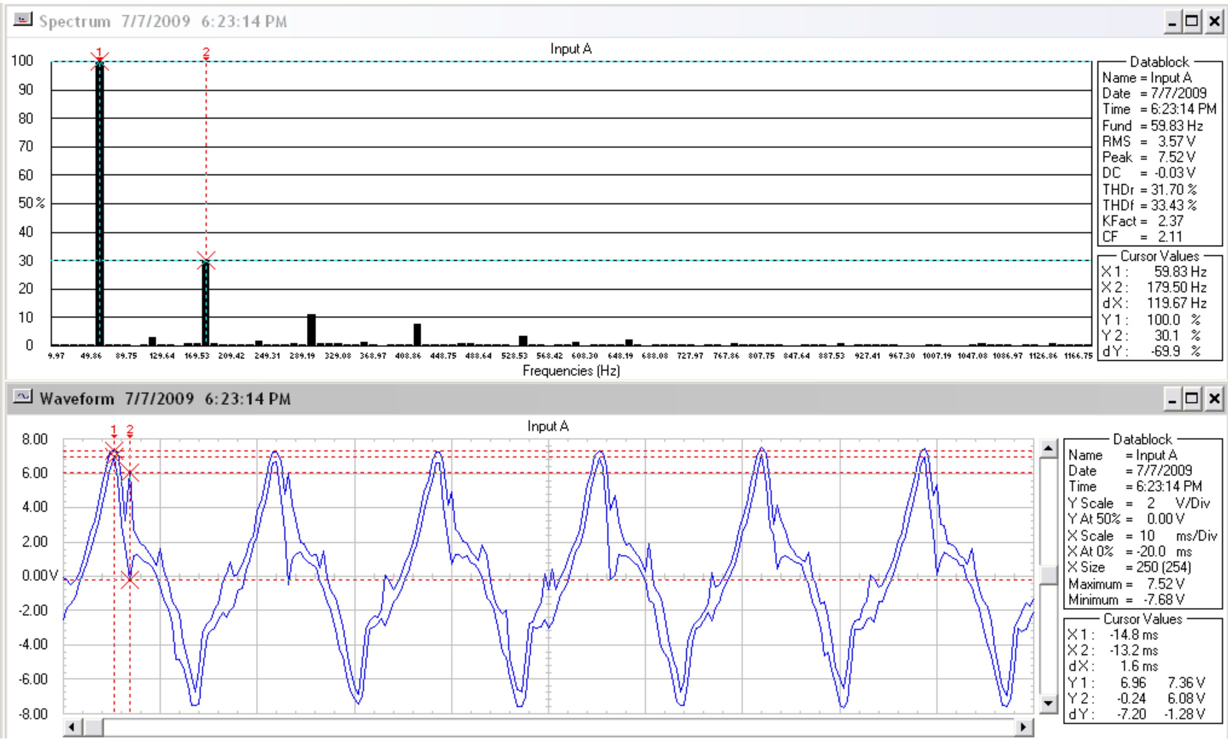


Fig. 7 Spectrum (top) and time domain signal of torsional vibrations. Frequency ω = 30 Hz

The largest amplitudes of torsional vibrations have been obtained for frequency of the spindle vibrations ω = 30 Hz (Fig. 7). The dominant component of the spectrum is also 2ω. However components of 6ω, 10ω, 14ω

and 18ω may be noticed. Root mean square value of amplitude in this case has been measured 3.57 V, what is approximately 2.5 times more a in the case of over resonance vibrations (ω = 50 Hz).

4. Conclusions

Theoretical and experimental studies indicate that relatively simple generator of torsional vibrations, which operation principle is based on the interaction of permanent magnets placed on driving and driven links, can be applied for vibratory drilling fulfilling the condition that vibration speed is larger than the cutting speed.

More comprehensive experimental studies will enable determination of the limits of technological possibilities of this processing method.

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SUKAMŲJŲ VIRPESIŲ GENERATORIAUS PANAUDOJIMAS VIBRACINIO GRĘŽIMO OPERACIJOSE

R e z i u m ė

Straipsnyje nagrinėjamas grąžto sukamųjų virpesių sužadinimo gręžimo operacijos metu uždavinys, naudojant paprastos konstrukcijos sukamųjų virpesių generatorių, kurio veikimo principas pagrįstas pastovių magnetų, išdėstytų ant varančiosios ir varomosios generatoriaus grandžių, sąveika. Kai gręžimo staklių suklį veikia išorinis sukimo momentas, tai dėl kintamo magnetinio standumo generuojami grąžto parametriniai sukamieji virpesiai, kurių dažnis priklauso nuo suklio sukimosi dažnio, pastovių magnetų porų skaičiaus ir jų polių išsidėstymo tavrkos.

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APPLICATIONS OF TORSIONAL VIBRATIONS FOR VIBRO-DRILING OPERATIONS

S u m m a r y

The paper deals the problem of generation of a drill torsional vibration during drilling, applying a new type of vibration quite simple design exciters of torsional vibrations, which operation is based on the interacting of permanent magnets situated on input and output elements. External torque of a machine spindle generates parametric torsional vibrations of the drill because of variable magnetic stiffness. Frequency of vibrations depends on rotation frequency of the spindle, the number of pairs of permanent magnets and the order of their poles placement.

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