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Periodic Machining Errors: A Review

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Abstract—The periodic errors in machining are analyzed. Mathematical models are presented.

Keywords: mechanical vibration, vibrational frequency, amplitude, undulation, height, pitch

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Between 1970 and 2000, periodic errors in machining were intensely studied. Various models and formulas were proposed by methods such as correlation analysis [1] and spectral analysis [2] (Table 2, items 1 and 8).

Research expanded to embrace discontinuous cutting (Table 2, items 2 and 3) [3, 4]; grinding with submicronic accuracy [5]; and the influence of discontinuous wheels (Table 2, item 17) [6]. Two reasons were identified for the appearance of undulation (Table 2, item 12) [7]: (1) tool motion along specific tracks; (2) transfer of the tool's geometric error to the workpiece. Computer calculation of complex dimensional chains was employed [8].

However, these examples relate only to errors corresponding to one or two periods. The prediction of machining errors over many periods (10–20 or more) is very difficult [9]. The description of the variational method used to calculate machining errors only includes one example relating to calculations for periodic machining errors and relates to ground surfaces of an uncommon type (produced by errors of the positional screw) [10].

Standardization, monitoring, prediction, and minimization of surface undulation were discussed concisely in [11].

In machine tools, the main reason for undulation of machined metal surfaces is vibration of the machining system. Forced or self-induced vibration may be responsible. Forced vibration is produced by centrifugal forces associated with imbalance of the rotating workpiece, the tool, and other system components (pulleys, gears, joints, shafts, etc.). Self-vibration is due to interaction (including frictional interaction) of the workpiece, the tool, and other system components.

Vibration cannot be eliminated but may be decreased. Devices have been proposed for decreasing vibration [11]. In turning and boring, such devices include a viscous-friction damper; a dynamic vibrational damper; a damping stay; a swinging damper; elastic elements at thin-walled parts; a Sheptalin damper; impact dampers; damping coatings; and specialized boring bars. Vibrationally stable sprung cutters developed by Lakur quench vibrations. The independent operation of two cutters has been proposed. An automatic system that damps cutter vibrations decreases undulation [12]. The dry-friction dampers used in milling contain frictional disks and sprung inertial masses. A flywheel on a machine-tool spindle and an elastically deformed element with a corner plate on the tool holder operate analogously. The flywheel housing is mounted on the spindle, while the damper (two suspension elements) is connected on the tool holder. In machining nonrigid parts, damping stays are employed.

However, changes in the production technology are more effective [13–15].

Three basic approaches to decreasing the height of the surface undulation have been identified (Fig. 1) [11, 13, 15]: (1) adjustment of the mutual trajectory of the tool and workpiece; (2) change in the workpiece setup; (3) change in the discontinuity of the cutting process. The options in the first approach (Fig. 2) are to deform the mutual trajectory (I) and to change the positions of tool and workpiece (II). Deformation of the mutual trajectory may correspond to variation in factors such as the height or pitch of the undulation; the width and position of the troughs and peaks; and their radius of curvature. Possibilities include increase or decrease in the wavelength L_w; increase or decrease in half the pitch of the wave $L_w/2$ (extension or compression of the waist with corresponding change in inclination); change in peak position (displacement or suppression); trough displacement; and increase in radius of curvature of the troughs and peaks. Other approaches are also possible.

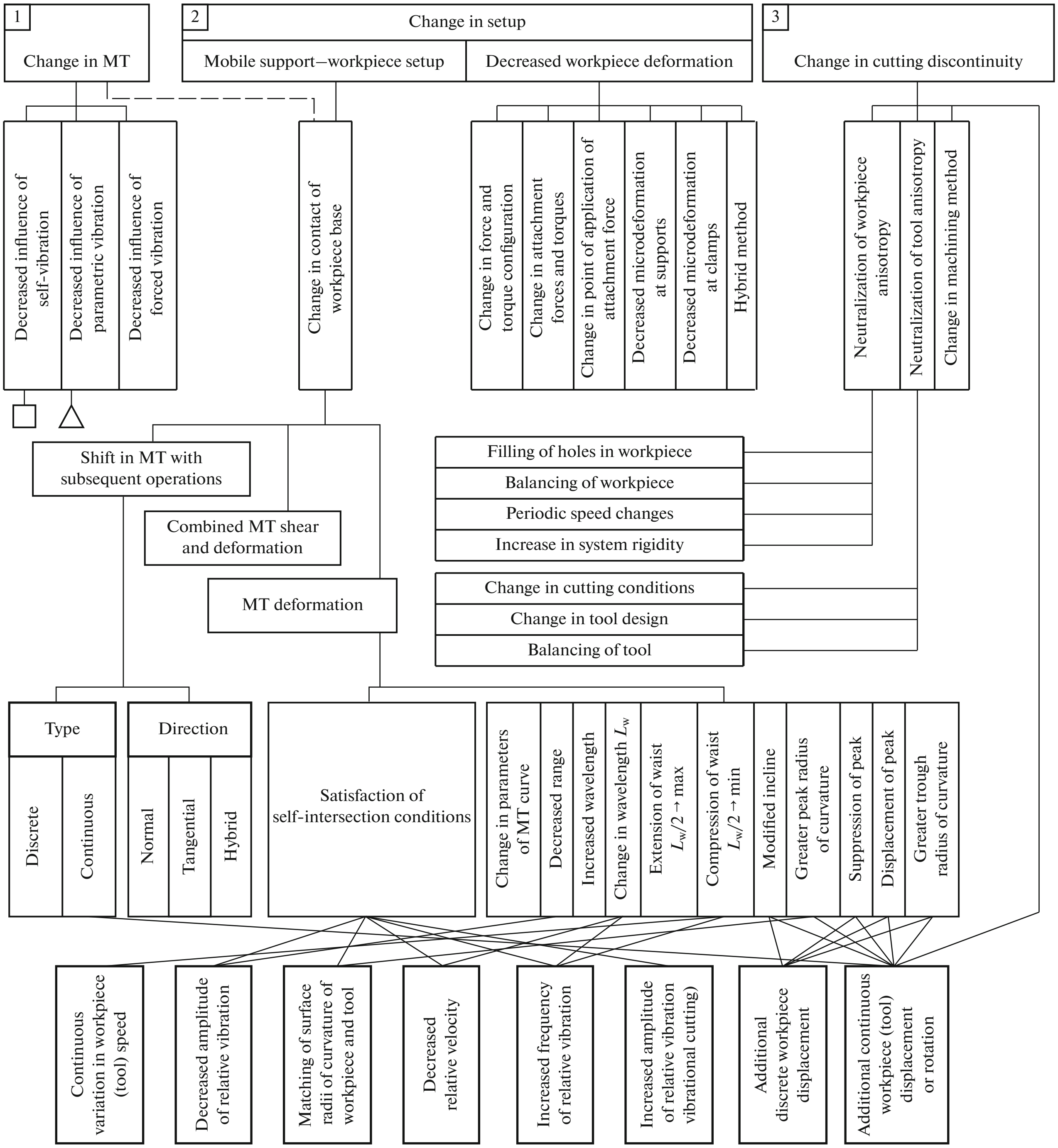

Fig. 1. Approaches to decreasing the undulation height [15]: (□) UAPK algorithm; (△) UVPK algorithm; MT, mutual trajectory of the workpiece and tool.

Self-intersection of waves begins under the following condition [15]: $R_{\text{to}} = R \geq v^2/(\nu^2 A k^2)$ when $W_z < 2A$. Correspondingly, four possible control approaches are possible: increase in the vibrational frequency ν; increase in the amplitude A; decrease in the relative velocity v of the tool and workpiece; and closer values of the tool radius R_{to} and the radius R_{ms} of the machined surface.

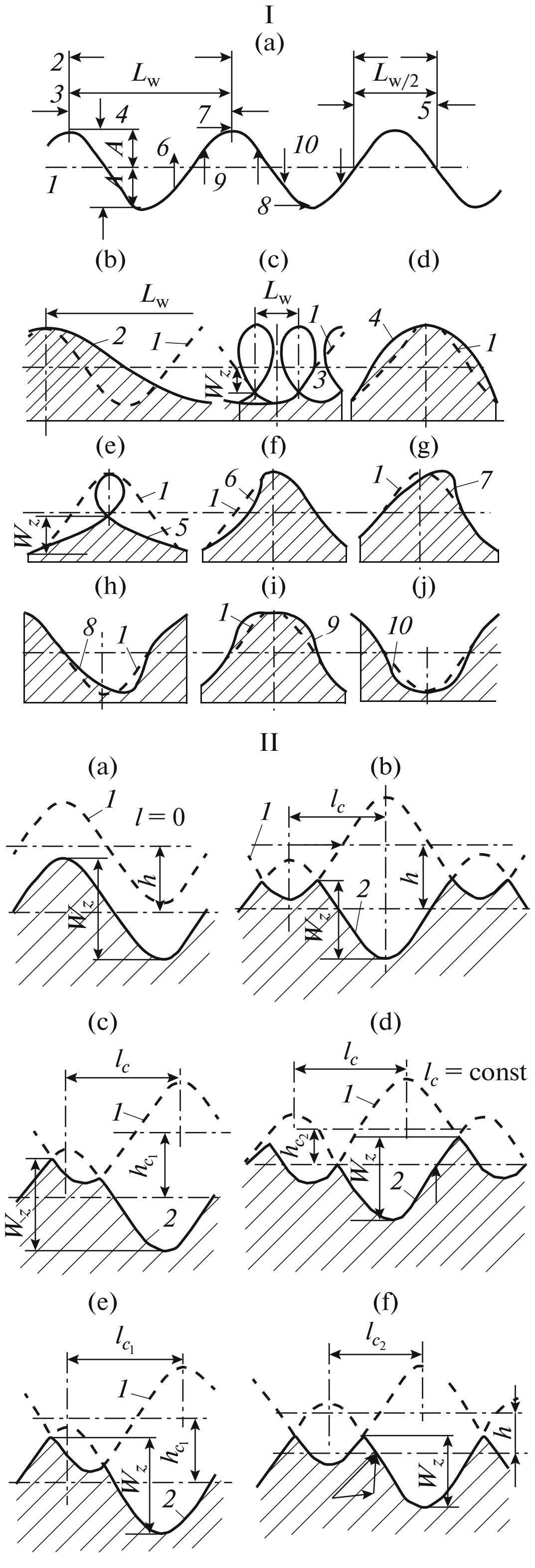

Fig. 2. Control of the mutual trajectory of the workpiece and tool and undulation profile on the basis of deformation (I) and change in position (II).

Table 1

Spectrogram	Wheel speed, rpm	Workpiece speed, rpm	Eigenfrequency, Hz	Ratio of wheel and workpiece speeds	Most intense spectral components
298	6300	156	75	40.38	40, 80
299	6300	156	320	40.38	40, 80
300	11760	156	150	75.38	75
301	11760	156	320	75.38	75
303	16000	400	280, 1200	40.42	42
304	10500	400	105	26.25	27, 28

The first two methods are appropriate for vibrational cutting. They are inapplicable to natural vibration, since they do not meet the second condition. Three approaches are of practical value: (1) $A \to \min$; (2) $V \to \min$; (3) $R_{\text{to}} \to R_{\text{ms}}$.

In grinding, the major source of forced vibrations is the imbalance of the wheel. At the workpiece surface, undulation is formed. The most intense harmonic is approximately equal to the ratio of rotational frequencies of the wheel and workpiece.

In centerless grinding, wheel imbalance of ±800.375 g cm produces the most intense harmonics (harmonics 13–14). Their magnitude is proportional to the wheel imbalance P_{im} [16]: $\Delta_{\text{pme}} = 2.24 + 0.002P_{\text{im}}$. The periodic machining errors may be associated with vibration due to rotor imbalance of the wheel's motor. Synphase rotation plays a significant role here.

The balancing of grinding wheels is a subject of intense interest [16]. This process calls for compactness, speed, high sensitivity, precision, reliability, and compatibility with automation. Such requirements may be met by devices in which the compensating mass is filtered working fluid [17, 18].

The relative velocity v of the tool and workpiece may be decreased by lowering the workpiece speed v_{wo} in the final stage (dwelling). Continuous change in workpiece speed is more effective [15]. In that case, all except the third harmonics of the periodic machining errors may be decreased (Fig. 3).

To more closely match the tool and workpiece radii, we use bars pressed against the machined surface by centrifugal forces—that is, centrifugal honing [15].

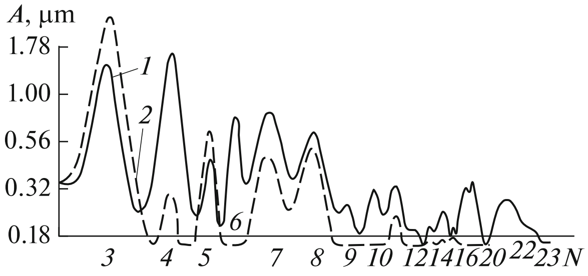

Fig. 3. Spectrograms of the surface after external grinding with constant (*1*) and variable (*2*) workpiece speed [15]: (□) UAPK algorithm; (△) VAPK algorithm.

That sharply decreases the high- and moderate-frequency spectral components.

Research on surface undulation in machining was reviewed in detail in [19, 20]. To calculate the height of the undulation, we use three parameters associated with initial surface condition of the workpiece, the tool and workpiece wobble, and the tool's geometry and kinematics. A calculation method has been proposed for the three main groups of machining methods (Table 2, item 21).

The periodic machining errors may be classified in terms of the ratio n of the wavelength L_{w} of the dominant vibrations to the length of the machined surface [21]. In other words, the ratio n corresponds to the number of waves of periodic machining errors within the machined surface. On the basis of n, the unity of all the periodic errors may be understood, and the arbitrariness of the familiar classification is apparent. The errors were divided into seven classes (in terms of n) in [21]. In each class, the size, shape, and positional errors are different. This corresponds to the surface extent.

In the first class, corresponding to several workpieces with small extent L of the machined surface, the high-speed process affects the dimensional, shape, and wave precision. Workpieces at the trough of the wave will be smaller than those at the peak of the wave.

For each part, the surface is of different shape. With a sinusoidal wave, the components at the peak of the wave are convex, while those at the trough are concave; those on the incline are nonparallel. In the third class, the surfaces of revolution are characterized by positional error: eccentricity. Those in the fourth class are characterized by shape error: oval or elliptical distortion. The fifth class is transitional. The sixth is characterized solely by undulation and the seventh by roughness. This is conditional, and the type of surfaces may be the same in the sixth and seven classes and even in the fifth class.

It is wrong to regard undulation as irregularity with a pitch greater than the base length [22]. Experience shows that the pitch in undulation may be less than the base length by an order of magnitude or more. Table 1 presents the relation between the periodic machining errors and the frequencies of the most powerful sources of vibration for internal grinding.

Table 2 presents mathematical models of the periodic machining errors.

Table 2

Item	Operation, wave sources	Formulas for wave height and profile	Year, source
1	Any	Profile: $Y(x) = Y_\beta(x) + Y_\gamma(x)$, where $Y_\beta(x)$ and $Y_\gamma(x)$ are the systematic and random components	1971 [1]
2	Tooth milling, discontinuity	Facet height: $H_B = 1.9 \times 10^{-5} m_n S_0^2 \theta_Z \dfrac{\cos a \cos^3\beta \cot^2\varphi}{\cos\varphi}$	1971 [3]
3	Slot milling, vibration	Height of undulation: $H = H_{\varphi_k} + H_{A_C} + H_\delta \cos\varphi_1 + H_{e_1} = \xi \dfrac{D}{2}(1 - \cos\varphi)$	1972 [4]
4	Plastic deformation (finishing)	Height of undulation: $H_2 = 2C_0\left\{1 + \cos\left[(n-1)\dfrac{180}{n}\right]\right\}$	1972 [23]
5	External grinding, wheel imbalance	Height of undulation: $H_B = H\{1 + \cos[(p-1)180/\eta]\}$	1972 [24]
6	Grinding, vibration	Height of undulation: $H_1 = \Delta Y_k + \Delta(Y_{\text{wo}} + Y_k)$, where $\Delta Y_k = \dfrac{\Delta P\beta}{B}\dfrac{1}{K_a^*}$; $\Delta(Y_{\text{wo}} + Y_B) = \dfrac{\Delta P_y}{j_{\text{sp}}}$	1973 [25]
7	Machining, vibration	Height of undulation: $H = C_0\{1 + \cos[(p-1)180°/m]\}$	1973 [26]
8	Machining and grinding, vibration	Fourier-series description of profile: $y(x) = \dfrac{a_0}{2} + \sum\limits_{n=1}^{\infty}\left(a_n \cos\dfrac{n \times 2\pi x}{B_1} + b_n \sin\dfrac{n \times 2\pi x}{B_1}\right)$	1973 [2]
9	Thread grinding, vibration	Height of undulation: $H = \dfrac{2}{\pi} H_{\max} \arctan\dfrac{3.64}{H_{\max}}$; $H_{\max} = \dfrac{\lambda^2 \sin\alpha/2}{8R_{\text{re}}}$	1974 [27]
10	External grinding, wheel imbalance	Height of undulation: $H_{\text{w}} = \dfrac{l^2}{8}\left(\dfrac{R_H - R_{\text{cr}}}{R_H R_{\text{cr}}}\right)$	1974 [28]
11	Grinding, oval wheel	Maximum height of undulation: $H_{\max} = \left\{\dfrac{\Delta R}{2}\left[1 + \sin\left(\arccos\dfrac{-t}{\Delta R \sin\dfrac{\xi}{2}} + \dfrac{\xi}{2}\right)\right] + t\right\}\left(1 - \dfrac{C_y}{f}\right)$	1975 [29]
12	Boring, variable rigidity	Shape error of hole: $\Delta\phi = 2A_2$, $A_2 = \dfrac{(j_{\max} - j_{\min})\, x_1 t_{\text{me}}^{\alpha}}{v j_0 \sqrt{\left[j_0 + x_1 t_{\text{me}}^{\alpha-1} - m\omega_1^2\right]^2 \mu^2\omega_1^2}}$	1975 [7]
13	Internal grinding, trimming	Height of undulation: $H_{\text{w}} = 10^{8.785} V_n^{0.165} V_p^{9.99}$	1975 [30]
14	Plane grinding, wheel imbalance	Height of undulation: $H = \dfrac{2h}{\sqrt{(\omega_c^2 - \omega^2) + 4n^2\omega^2}} K_i$	1977 [31]
15	Wheel grinding, vibration, self-intersecting waves	Height of undulation: $H_{\text{w}_n} = \dfrac{H_{\text{w}_1}}{2}\left[1 + \sin\left(\arctan\dfrac{\sin\theta_n}{1 - \cos\theta_n}\right)\right]$, $R \le \left(\dfrac{v}{2\pi\nu \times 60}\right)^2 \dfrac{1}{A}$	1978 [11]
16	Plane grinding, vibration	Height of undulation: $H = 2A\sin^2\dfrac{\pi v}{2\omega\sqrt{AR}}$	1980 [32]
17	Internal grinding, wheel discontinuity	Height of undulation: $H_{\text{w}} = R + t - \dfrac{\tau}{\sin\dfrac{\varphi}{2}} \sin\left[\dfrac{\varphi}{2} + \arcsin\left(\dfrac{R + T - r}{r}\sin\dfrac{\varphi}{2}\right)\right]$	1981 [6]
18	Deep honing, initial undulation	Height of undulation: $W_Z = 2.578 \times 10^3 \dfrac{S^{0.26\ln t + 0.16 ln}}{t^{-1.264} n_\sigma A}$;	1985 [33]

Table 2 (Contd.)

Item	Operation, wave sources	Formulas for wave height and profile	Year, source
19	Grinding by discontinuous wheels, vibration, discontinuity	Undulation profile: $x_{\text{w}} = x_{\text{dyn}} + S;\ S = S' + S'',\ y_{\text{w}} = y_{\text{dyn}} + H$; $x_{\text{dyn}} = \left(A_i + u_{Z_i}\sin\omega_{b_i}\tau\right)\cos\omega_{c_i}\tau + \nu_g\tau + \frac{R_{\text{cr}}\left(B_i + u_{y_i}\sin\omega_{b_i}\tau\right)\omega_i\cos_{c_i}\tau}{v}$ $y_{\text{dyn}} = \left(B_i + u_{y_i}\sin\omega_{b_i}\tau\right)\sin\omega_{c_i}\tau + \nu_g\tau + \frac{R_{\text{cr}}\left(u_{z_i}\omega_{b_i}\cos\tau\cos_{c_i}\tau\right) + v_g - D}{v}$	1986 [34]
20	Plane grinding, vibration	Conditions of loop appearance: $\frac{\left(x^2 + y^2\right)^{3/2}}{\dot{y}\ddot{x} - \ddot{y}\dot{x}} \geq R,\ \frac{\left(v^2 + 2a\omega v\cos\omega t + a^2\omega^2\right)^{3/2}}{a\omega^2\left(a\omega + v\cos\omega t\right)} \geq R$	1987 [35]
21	Basic machining methods	Mean undulation height: $W_Z = 1.2\sqrt{H_1^2 + H_2^2 + H_3^2}$, where H_1 is the initial state of the surface layer; H_2 is the workpiece and tool wobble; and H_3 takes account of the tool geometry and kinematics	1987 [19], 2000 [20]
	Cutting (first group)	$H_1 = \frac{C_y S^{y_{Py}} v^{Z_{Py}}\left[HB_{\max}^n t^{x_{Py}} - HB_{\min}^n\left(t - W_{Z_{\text{in}}} - R_{Z_{\text{in}}}\right)^{x_{Py}}\right]}{HB_{\text{me}}^n j_{\text{sp}}\sqrt{\left(1 - \lambda^2/\omega^2\right)^2 + Tn^2\lambda^2}}$, $H_2 = 2C_0\left\{1 + \cos\left[(n-1)\frac{180^\circ}{n}\right]\right\}\delta,\ \delta = \frac{180 l_{bn} v_D}{\pi v_{\text{cr}} D}$, $W_Z = \frac{1.2 C_y S^{y_{Py}} v^{Z_{Py}}\left[HB_{\max}^n t^{x_{Py}} - HB_{\min}^n\left(t - W_{Z_{\text{in}}} - R_{Z_{\text{in}}}\right)^{x_{Py}}\right]}{HB_{\text{me}}^n j_{\text{sp}}\sqrt{\left(1 - \lambda^2/\omega^2\right)^2 + T_n\lambda^2}}$	
	Diamond grinding (second group)	$H_1 = \Delta y_{\text{wh}} + \Delta\left(y_{\text{w}} + y_{\text{t}}\right),\ \Delta\left(y_{\text{w}} + y_{\text{t}}\right) = \frac{\Delta P_y}{J_{\text{sp}}}$, $\Delta y_{\text{wh}} = \frac{\Delta P_y\left[E_2\left(1 - \mu_1^2\right) + E_1\left(1 - \mu_2^2\right)\right]}{\pi B E_1 E_2}\ln\frac{2\pi B E_1 E_2 (D + d)}{\Delta P_y\left[E_2\left(1 - \mu_1^2\right) + E_1\left(1 - \mu_2^2\right)\right]}$, $H_2 = A_{\text{cr}}\left\{1 - \cos\left[13.2\frac{V_D}{f_n}\sqrt{\frac{1}{A_{\text{re}}}\left(\frac{1}{D} + \frac{1}{d}\right)}\right]\right\},\ H_3 = \frac{D(1 - \cos\delta)}{2\cos\delta}$, $W_Z = 1.2\left\{\left[\frac{\Delta P_y}{j_{\text{sp}}}\frac{E_1\left(1 - \mu_2^2\right)}{\pi B E_1 E_2}\ln\frac{2\pi E_1 E_2 (D + d)}{\Delta P_y E_1\left(1 - \mu_2^2\right)}\right]^2 + A_{\text{cr}}\left[1 - \cos\left(13.2\frac{v_D}{f_n}\sqrt{\frac{1}{A_{\text{wh}}}\left(\frac{1}{D} + \frac{1}{d}\right)}\right)\right]\right\}^{0.5}$	
	Finishing (third group)	$H_1 = W_{Z_{\text{in}}} - \left(\frac{PR_{p_{in}}^2}{\pi R_{\text{re}} HB}\right)^{0.25},\ H_2 = 1.4\left[\left(1 + f^2\right)\left(W_{Z_{p_{\text{in}}}}^2 + \Delta_P^2\right)\right]^{0.25} \times \left\{\frac{j_{\text{sp}}}{\pi R c' \sigma_{\text{y}}\left[\frac{180^\circ - \arccos\frac{s - a_{\text{pl}}}{a_{\text{pl}}}}{a_{\text{pl}}}\left(h_{\text{kin}} + h_{\text{de}}\right) - 2h_{\text{de}}\right]}\right\}^{0,5}$,	

Table 2 (Contd.)

Item	Operation, wave sources	Formulas for wave height and profile	Year, source
		$H_3 = h_{\text{kin}} - \left[1 - \frac{f\left(\sqrt{h_{\text{kin}}/2+1}\right)}{\left(\sqrt{h_{\text{kin}}/8r+1}\right)\left(1+f^2\right)}\right],$ $W_Z = 1.2\times$ $\left\{\left[W_{Z_{\text{in}}} - \left(\frac{9pRa^2_{p_{\text{in}}}}{\pi R_{\text{re}}HB}\right)^{1/3}\right]^2 + \left[\frac{27f_{\text{sp}}\left(W^2_{Z_p}+\Delta^2_P\right)^{0,5}R_{a_{\max}}}{\pi rc''\sigma_T\frac{180^\circ-\arccos\frac{s-a_{\text{pl}}}{a_{\text{pl}}}}{a_{\text{pl}}}\left(h_{\text{kin}}-h_{\text{de}}\right)-2h_{\text{de}}}\right]+h^2_{\text{kin}}\right\}^{0.5}$	
22	Wheel grinding, vibration, five frequency ranges	Range 1: $2\pi n \le \omega \le 4\pi n$ Oval distortion: $\Delta = y_{\max}\sin(\omega+\varphi);$ Range 2: $4\pi n \le \omega \le 30\pi n$ Facet height: $\Delta = R\left(1-\frac{V_{S_{\text{cr}}}}{\sqrt{A^2\omega^2\cos^2\omega\tau_x+V^2_{S_{\text{cr}}}}}\right)+A\left(1+\sin\omega\tau_x\right)$ Range 3: $30\pi n \le \omega \le 2\pi n\sqrt{\frac{(R+\tau)\tau}{AR}}$ Height of undulation: $\Delta = 2A\sin\frac{\pi^2 n}{60}\sqrt{\frac{(R+\tau)\tau}{AR}},$ Range 4: $\omega \le 0.02\pi V_{S_{\text{cr}}}/A.$ Height of undulation: $\Delta = R\left(1-\frac{V_{S_{\text{cr}}}}{\sqrt{A^2\omega^2\cos^2\omega\tau_x+V^2_{S_{\text{cr}}}}}\right)+A\left(1+\sin\omega\tau_x\right)$ Range 5: $\omega \ge 0.02\pi V_{S_{\text{cr}}}/A$ Height of undulation: $\Delta_n = \frac{\lambda}{50} = \frac{0.08\pi^2 n\tau}{\omega}$	1988 [36]
23	Thread grinding, vibration	Height of undulation: $H = \frac{V^2}{4\pi\rho f^2}\arctan\frac{29.2f^2 a\rho}{V^2}$	1982 [37]
24	Boring, displacement of cutter axes	Noncircularity: $\Delta_{\text{cr}} = 8.3e^{-1.428}\sqrt{R^2+e^2}-R$	1998 [38] 1999 [39]

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