

S.E.Kvashnin, E.V.Bosova

## THE APPLICATION OF ULTRASONIC VIBRATION DRILLS IN TRAUMATOLOGY

Moscow Bauman State Technical University  
5, the 2-nd Baumanskaya Street, Moscow, 107005, RUSSIA  
Tel.: (095) 263-6051; Fax: (095) 263-6773  
E-mail: sek@bmstu.ru

*The dynamics of ultrasonic vibration drills having the common source of rotational and reciprocal movement of the driven element has been examined. The method, the mathematical model and the specific software for the calculation of the dynamic characteristics of the drills have been developed, with regard to the power limitation of the source, namely the rod ultrasonic vibrating system. The load point dependences of the useful power and the number of revolutions of the driven element have been found for the two schemes of excitation of the piezoelectroacoustic transformer of ultrasonic vibrating system: in particular, from the voltage and current generators. The occurrence of the two extremes on the power curve has been demonstrated to be the criterion characterizing the upper limit of the useful power taken from the transformer for rotating the specific ultrasonic vibrating system. In this case, the additional power takeoff for ultrasonic tissue processing will be accompanied by the significant power reduction necessary for the rotational movement. The possibility of the synthesis of vibration drills both with soft and hard load characteristics due to the change in such parameters as the setting angle of pushers, the average radius of their adjustment, the length and the width of the pusher, as well as the changes in the scheme of excitation of the electro-acoustic transformer (voltage and current generators, respectively), has been shown.*

The application of high speed electric drills in bone tissue processing has some negative aspects, namely large necrosis area, uneven surface of the hole, fissuring, formation of small fractured fragments, significant axial cutter loads. The less are the number of revolutions while drilling, the less is the depth of necrosis, but the more is the drilling time.

Denisov V.P., Loschilov V.I., Rudakov S.G. [1, 2] discovered that many disadvantages of the ordinary process of bone tissue drilling can be eliminated if the ultrasonic vibrations are superposed upon the drill edge of the driven element. At the same time, the edges of the hole are even, without fissuring and small fractured fragments, the depth of necrosis decreases, the conditions of bone tissue regeneration improve, the load of bone tissue cutter decreases. It allows to fix minor bone fractured fragments and the ultrasonic vibrations contribute to anesthesia. The method of ultrasonic osteomyelitic deposit milling with simultaneous ultrasonic processing is very promising. Such is the case of the method of cast ultrasonic rotational cutting.

The method of ultrasonic drilling has not found a wide utility yet. In particular, it relates to bulky structures under application and, as a result, they are inconvenient to use; thus, it makes difficult to carry out surgical procedures of high quality.

Nowadays, about twenty kinematic schemes used in the design of drills with ultrasonic vibrations of the driven element are known. The analysis of advantages and disadvantages of such kinematic schemes is reported in sufficient detail in [3, 4]. The merits of kinematic scheme of ultrasonic drill equipped with vibration motor having the common source of rotational and ultrasonic reciprocal movement of the driven element are reported there and in [5]. The modeling of such an ultrasonic vibration motor (USVM) for the ultrasonic vibrating system (USVS) of infinitely large power has been performed in [4]. The obtained results correlate well with the experiment in those cases, when the power taken from the piezotransformer to rotate the working end is no more than 20% of the complex one.

This paper deals with the case when a significant amount of power is taken away from the transformer for the rotational movement. In other words, it is the case when the effect of pushers' impedance on the vibrational amplitude of the USVS cannot be neglected. Let us consider a surgical ultrasonic drill (USDR) for ultrasonic processing of dense and soft biological tissues (Fig. 1). It consists of the stator and the USVS being simultaneously the rotor of the USVM and rotating in bearings 5. The USVS contains an electroacoustic piezotransformer 1, a wave-guide 2 and a removable tool 4 with the working end. The stator consists of elastic pushers 8 mounted in the flange that is connected via the spring 7 to the base 6 fixed to avoid an axial turn and has the possibility to travel along the axe. Another

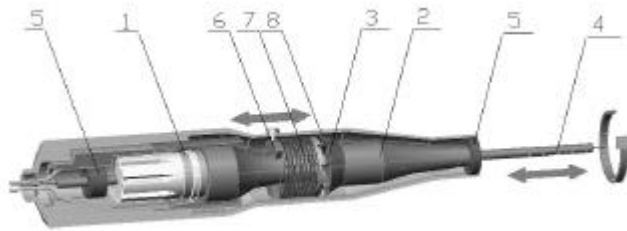


Fig. 1. Medical ultrasonic drill having the common drive for rotation and longitudinal vibrations of the working end.

side of elastic pushers has the frictional contact with the friction end 3 of the wave-guide 2 (hereinafter called the working end of the rotor of the USVM). The pushers are straightened at certain angle  $\gamma$  with respect to the friction surface.

When the USVS rotor end interacting with the pushers is set in the antinode of the longitudinal displacements, the maximum of power is taken for the rotational movement, but the minimum of power is necessary as an additional load for ultrasonic vibrations. When the rotor end is in the node

of the longitudinal displacements, the minimum of power is taken for the rotational movement, the maximum is the additional power necessary for ultrasonic vibrations.

When the excitation is in the transformer of ultrasonic vibrations, the friction end 3 of the USVM produces vibrations along the longitudinal axe and bends simultaneously the pushers 8 pressing to it. Due to the straightening of the bent pushers and changing in the friction coefficient, the latter untwist the wave-guide-shaft with the removable instrument and the transformer. The twisting moment being under formation and the number of revolutions depend on the load of pusher pressing that can be adjusted by longitudinal displacement of the opposite end of the spring.

The longitudinal forced vibrations of the USVD motor is described with the set of equations [4, 6] that can be represented in the matrix as follows:

$$\frac{d\mathbf{V}}{dz} = \mathbf{A}(z, \omega)\mathbf{V}(z) + \mathbf{F}(z) \tag{1}$$

where  $\mathbf{A}(z, \omega)$  is square matrix of the coefficients  $4 \times 4$ ,  $\mathbf{V}(z) = \{U_1(z), U_2(z), N_1(z), N_2(z)\}$  is a column-vector of phase variables,  $U_1(z)$  is the real component of longitudinal displacement amplitude,  $U_2(z)$  is the imaginary component of longitudinal displacement amplitude,  $N_1(z)$  is the real component of longitudinal force amplitude,  $N_2(z)$  is the imaginary component of longitudinal force amplitude,  $z$  is a longitudinal coordinate,  $\mathbf{F}(z)$  is a column-vector the components of which vary proportionately to the electric voltage (current) in piezoelements.

In this case, the boundary conditions for the rotor of the USVS are as follows

$$\mathbf{H}_0 \mathbf{V}(0) = \mathbf{F}_0(0) \text{ - at } z=0, \text{ and } \mathbf{H}_k \mathbf{V}(L) = \mathbf{F}_k(L) \text{ - at } z=L, \tag{2}$$

where  $\mathbf{H}_0 = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$  - for free (non-working) edge of the USVS.

$\mathbf{F}_0(0), \mathbf{F}_k(L)$  are the columns-vectors of the boundary conditions for the size 2.

$$\mathbf{H}_k = \begin{pmatrix} -w \operatorname{Im} \tilde{Z}_B & -w \operatorname{Re} \tilde{Z}_B & -1 & 0 \\ w \operatorname{Re} \tilde{Z}_B & -w \operatorname{Im} \tilde{Z}_B & 0 & -1 \end{pmatrix}, \tilde{Z}_B \text{ is the impedance from the biological tissue.}$$

In addition, at the site where the USVS rotor interacts with the pushers at  $z=z_0$ : the following condition is presented

$$\mathbf{V}^+(z_0) = \mathbf{R}(z_0)\mathbf{V}^-(z_0), \tag{3}$$

where

$$\mathbf{R}(z_0) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -w \operatorname{Im} \hat{Z} & -w \operatorname{Re} \hat{Z} & 1 & 0 \\ w \operatorname{Re} \hat{Z} & -w \operatorname{Im} \hat{Z} & 0 & 1 \end{pmatrix},$$

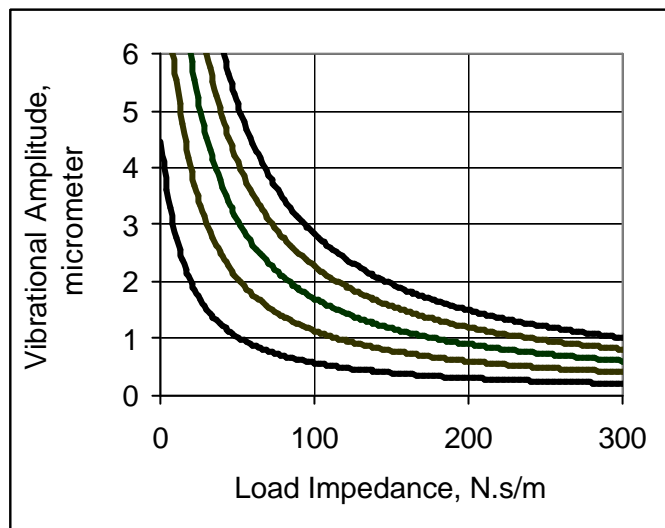
with  $\hat{Z}$  is the mechanical impedance from the pushers.

In solving the problem (1-3) on the forced vibrations of the USVS loaded with spontaneous real impedance  $Z(z_0)$  in the area  $z=z_0$ , the  $Z(z_0)$  real impedance dependence of longitudinal vibrational amplitude  $U_0(z_0, Z(z_0))$  (where  $Z(z_0)$  is a value of the real impedance being the load for the USVS, and  $U_0 = |U_1 + jU_2|$ ) of the friction surface of the rotor at the operating resonance frequency is determined.

For the two schemes of excitation of piezoelectroacoustic transformer (PEAT) of the USVS – from the voltage and current generators, respectively, the  $Z$ ) dependences of the amplitude of longitudinal vibrations of the USVS rotor’s friction surface have been made (where  $Z$ ) is the real part of the load impedance). Fig. 2 illustrates the results for the five values of voltage – 50, 100, 150, 200 and 250 V, respectively, – supplied to the piezoelements of the PEAT that is operated from a voltage generator. The use of current generator as a power source of the PEAT results in considerably faster (as compared with the use of voltage generator) reduction of the longitudinal vibration amplitude as the load impedance increases (the paper deals only with piezotransformer based on the longitudinal piezoeffect). To simplify further results, the dependences from Fig. 3 were approximated with the following function

$$\hat{Z} = Z_1 + \sqrt{(A_0/u(\hat{Z}))^2 - B} \tag{4}$$

The constant approximations  $A_0, B$  and  $Z_1$  were determined from the condition of the minimum of average quadratic error in the range of vibration amplitudes under discussion. The error for every variant being studied was not more that 1,7%.



**Fig. 2.** The load impedance dependence of the friction surface vibration amplitude in the USVS for the five values of electric voltage (V) in the piezotransformer (from 0 o 250 V, respectively, with the step of 50 V)

**The Study of the Dynamic Characteristics of USVM with the Common Drive**

The stationary working modes are studied both for USVS and USVM. While investigating the operation of the USVM with elastic pushers located on the stator, the following assumptions were accepted: the flexure of the pushers considered minor; the stationary working mode of USVM exists, moreover, it is characterized by almost constant number of revolutions of the rotor; the angle of interaction between the pusher and friction end of the USVS rotor is equal to the setting angle, there is no distance between the pusher end and friction rotor's end.

Previously in [9] it was recognized that, when the pusher is in contact with the end surface of the USVS rotor, the relevant amplitude of longitudinal vibrations remains constant with the change in the exterior moment of impedance and in the effort of pusher pressing. The USVS of finite power were studied taking into account the effect of the pushers on the amplitude of longitudinal USVS vibrations.

The peripheral velocity of the rotor's friction end  $V(t)$  at the site of its contact with the pusher is calculated via the angular speed  $\Omega(t)$  of rotation as  $V(t) = \Omega(t)R$ , where  $R$  is the average radius of pushers' setting.

The moment equation related to the longitudinal axe of the USVS rotor is as follows [7]:

$$J_R \frac{d\Omega}{dt} = \begin{cases} k \cdot N(t) \cdot R \cdot q + M_n & \mathbf{n_t}(t) > V(t) = \Omega(t)R \\ -k \cdot N(t) \cdot R \cdot q + M_n & \mathbf{n_t}(t) < V(t) = \Omega(t)R \end{cases} \quad (6)$$

where  $q$  is the number of pushers,  $J_R$  is the moment of inertia of the rotor  $k$  is the friction coefficient of sliding on the operating end surface of the rotor,  $M_n$  is the moment of resistance from the exterior load, index  $i=1$  and the upper mark conform to the acceleration of the rotor, index  $i=2$  and the bottom mark  $-$  to the braking. The solution of the equation (6) can be resulted to the solution of non-linear set of equations given in [7].

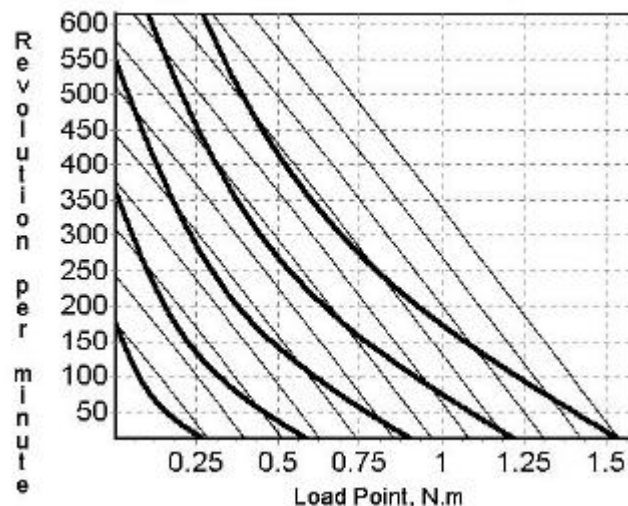
On the basis of numerical solution of the set (6), the linear velocities of the rotor at the switching points, consequently the average angular speed of rotation  $\bar{\Omega}$ , the useful power  $W = M_n \bar{\Omega}$ , as well as the real component of impedance of the pushers  $\hat{Z}_T = 2W / [wU_0(z_0)]^2$  can be calculated.

It is evident that, in the USVS of finite power at the fixed values of loading moment  $M_n$  and voltage supplied to the piezoelements of the PEAT at the site where the pushers are in contact with the friction surface of the rotor, at  $z=z_0$ , the specific amplitude of longitudinal vibrations  $U_0(z_0)$  will be established, namely the condition of impedance equality  $\hat{Z}_T(M_n, U_0(z_0)) = \hat{Z}$  will be obeyed by the system.

**Results and Discussion**

The above-mentioned techniques of solution for several USVS, various schemes of excitation of the PEAT and various parameters of the pushers used, the mathematical simulation of the dynamic characteristics of USVM was performed. Some of results are shown in the figures.

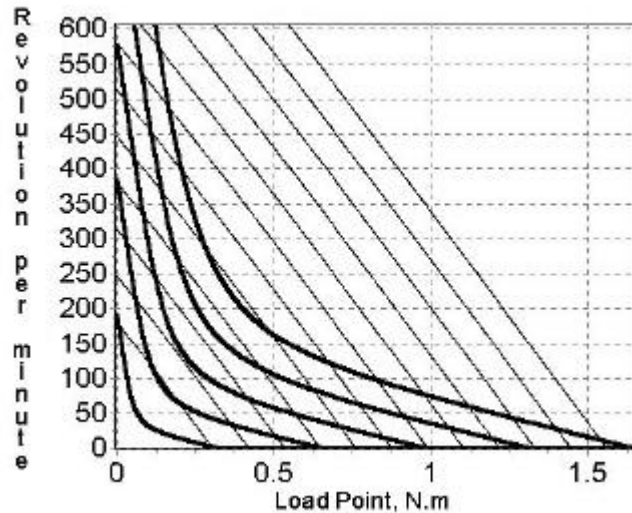
The first set of results (Fig. 3-6) (the setting angle of the pushers  $\gamma=50^\circ$ , the pusher of 2 mm long and 5 mm wide, made of titanium alloy  $W=5$ , the average radius of pushers setting  $R=20$ ) gives the possibility to compare the two applied schemes of power of PEAT, in particular from a voltage generator (Fig. 3-5) and from a current generator (Fig. 4-6). In the figures, the fine lines relate to the dependence of the USVS of infinite power at the values of amplitude on the



friction end rating from 4,3 t? 21,9 ??? , with the step of 1,4 ??? .

As reported in [8, 9], when the PEAT is supplied from the current generator, the frequency of mechanical resonance of the USVS coincides with the maximum of vibrational amplitude, nevertheless the mechanical effectiveness under these conditions appears to be higher than in the case when the PEAT is supplied from the voltage generator (the frequency of mechanical resonance of the USVS does not coincide with the maximum of vibrational amplitude).

**Fig. 3.** The load point dependence of the number of revolutions of the USVM rotor. The heavy lines relate to the USVS finite power when the voltage in the piezoelectric cell is 50, 100, 150, 200 and 250 V, respectively (voltage generator).



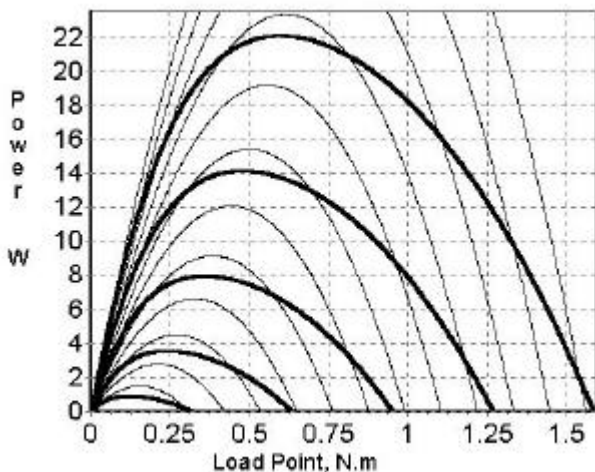
As a result, with the increase in the load point, when a current generator involved, the reduction in the number of rotor revolutions is found to be much larger than the case when a voltage generator used. The useful power taken for loading, if a voltage generator used, turns out to be 2,5 as large as that if a current generator used (Fig. 5 ? ?).

The double reduction of the radius of setting of the pushers ( $R=10$  ??), while other parameters are constant, results in decreasing in twisting moment, increasing in numbers of revolutions when the load points are soft and decreasing in numbers of revolutions when the load points are hard.

The more is the setting angle of pushers (from  $50^\circ$  to  $60^\circ$  at the radius of setting of pushers  $R=10$  ??), the more is the useful power, (so the system is ready to be saturated – double-extreme curve of the power), the more is the number of revolutions (as compared, if  $R=20$  mm and the pushers are set at the angle of  $-50^\circ$ ). The occurrence of the two extremes on the curve of power can be the criterion characterizing the upper limit of the useful power taken from the transformer to rotate the

**g. 4.** The load point dependence of the number of revolutions of the USVM rotor. The heavy lines relate to the USVS finite power when the current in the piezoelectric cells is 15, 45, 60 and 75 mA, respectively (current generator).

specific ultrasonic vibrating system. In this case, the additional power takeoff for ultrasonic tissue processing is likely to be accompanied by the significant reduction of the power taken for the rotational movement. The dependences of changes in the real part of pushers' impedance were calculated for the transition from USVS of infinite power to the USVS of finite power. From the results obtained it is evident that the maximum values of the impedance does not change, they are the same as for the USVS of infinite power. But the load moments related to those maximums decrease. The dependences facilitate to estimate the limit value of the power that can be taken for rotating the specific USVS of finite power.

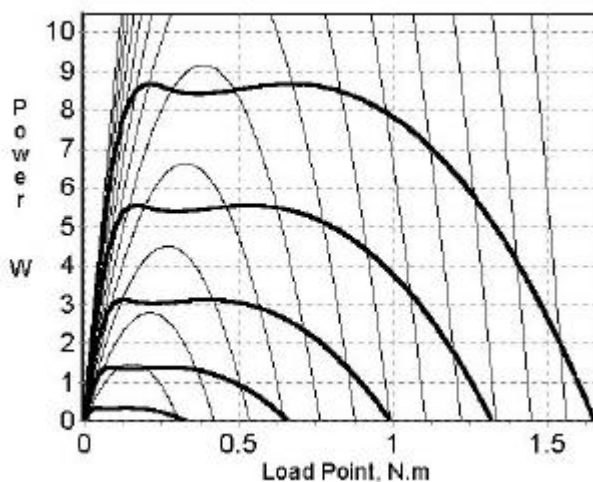


In this paper we have studied the effect of loading on the wave-guide instrument only as resistant to the rotational movement. But the

**Fig. 5.** The load point dependence of the USV useful power. The heavy lines relate to the USV finite power when the voltage in the piezoelectric cell is 50, 100, 150, 200 and 250 V, respectively (voltage generator).

tissues will be resistant to ultrasonic reciprocal movement as well; it requires another investigation and has not been discussed in the given paper.

The developed mathematical model describing the dynamics of ultrasonic vibration drills having the common source of rotational and ultrasonic reciprocal movements with regard to the limited power of electroacoustic transformer of longitudinal vibrations allows to make accurate calculations of power consumption and number of revolutions for different moments of impedance from biological tissues. The occurrence of the two extremes on the power curve has been demonstrated to be the criterion characterizing the upper limit of the useful power taken from the transformer for rotating the specific ultrasonic vibrating system. In this case, the additional power takeoff for ultrasonic tissue processing will be accompanied by the significant power reduction necessary for the rotational movement. The possibility of the synthesis of vibration drills both with soft and hard load characteristics due to the change in such parameters as the setting angle of pushers, the average radius of their adjustment, the length and the width of the pusher, as well as the changes in the scheme of excitation of the electroacoustic transformer (voltage and current generators, respectively), has been shown.



*Fig. 6.* The load point dependence of the USVM useful power. The heavy lines relate to the USVS end-point power when the current in the piezoelectric cells is 15, 30, 45, 60 and 75 mA, respectively (current generator).

## REFERENCES

1. Denisov V. P., Loschilov V. I. Ultrasonic Trepanation of Bone Tissues // The Proceedings of Moscow Bauman State Technical University.-1974.- No.201.- P.77-83 (In Russian).
2. Nikolaev G. A., Loschilov V. I. Ultrasonic Technology in Surgery.- M.: Medicine, 1980.- 272 p. (In Russian).
3. Kvashnin S.E., Bosova E.V., Lobachev A.A. Design of Ultrasonic Drills Applicable in Traumatology // Ultrasonic Processes-98: The Proceedings of Russian Scientific and Technical Conference.- M.,1998.- P.237-240 (In Russian).
4. Kvashnin S.E., Bosova E.V., Grigoriev A.V. Research and Engineering Development of Ultrasonic Vibratory Drives Applicable in Traumatology //Biomedical Radio Electronics, 2000, No.10, p. 46-54 (In Russian).
5. Patent of the RF No.2072801. Ultrasonic Surgical Instrument /S.E. Kvashnin, E.V. Bosova, V.A. Andreev // B. I.- 1996.- No. 4 (In Russian).
6. Kvashnin S.E. Ultrasonic Electroacoustic Transformers and Waveguides-Instruments Applicable in Medicine. - M.: MSTU Press, 1999. - 52 p. (In Russian).
7. Kvashnin S.E., Bosova E.V. Design of Ultrasonic Vibration Drills Applicable in Traumatology // Biomedical Radio Electronics, 2002, No.10, p. 46-54 (In Russian).
8. Kvashnin S.E., Bosova E.V. Study of Spectral Characteristics of Medical Ultrasonic Piezotransformers and Rod Concentrators of Longitudinal Vibrations // The Bulletin of Moscow Bauman State Technical University. Instrument-Making Industry.- 1993.- No.4.- P.86-93 (In Russian).
9. Kvashnin S.E., Bosova E.V. The New Generation of Ultrasonic Medical Instruments: Ultrasonic Drills Applicable in Traumatology //The Potential of Moscow Institutes of Higher Education and Its Application in the Interests of the City Community: The Proceedings of the Moscow City Scientific Conference (Theses of Reports).- M., 1999.- P.11-12 (In Russian).