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AN OVERVIEW OF WIRE ELECTRODE VIBRATIONS ON WEDM

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ABSTRACT: The paper presents the particularities of wire electric discharge machining (WEDM) technology regarding electrode-tool vibration (wire-tool vibration). It shows how the electrode-tool vibrates, as well as the shape of thevibration. The novelty of the approach is also explained, together with an overview of the factors which impact wire electrode processing and which are essential in overcoming the natural complexity of the phenomena involved. To that extent, the presented mathematical model – which uses only slight approximations to allow its study – can successfully be used in practicalimplementations to improve the accuracy of processing through wire electric discharge machining, especially with regard to positional precision and shape of surfaces machined.
KEY WORDS: WEDM, machining precision, wire electrode vibration, multi-discharge, mathematical model

1. INTRODUCTION

For a long time, manufacturers and users of wire electric discharge machining (WEDM) have been making efforts to improve the process, so as to achieve better machining stability. That is to say, within the capability of achieving the specified dimensional accuracy and surface integrity, a maximum machining rate is desired. However, owing to a large number of variables and the stochastic nature of the process, even a highly trained operator with a state-of-the-art wire cutting machine will still find it difficult to attain an optimal processing and avoid wire breakage.

In actual wire cut machining, vibrations of the wire electrode can be divided into two components: vibrations along or perpendicular to the cutting direction. As far as the latter is concerned, due to the constrains of the cutting kerf, vibration is relatively small and symmetrical.

The wire electrode is supported by two guides and is moving down or up the guides at a uniform velocity. Some external forces are exerted on the wire, which include: an axial tension, an electro-static force produced by the electric field between the workpiece and the wire electrode, an electro-dynamic and explosion force caused by spark discharge, and the damping force caused by the dielectric medium.

WEDM is a thermo-electrical process in which material is eroded from the workpiece through a series of discrete sparks occurring between the workpiece and the wire electrode (tool). The latter is separated by a thin film of dielectric fluid (deionised water) which is continuously force-fed to the area being machined in order to flush away the eroded particles. The movement of the wire is numerically controlled to achieve the desired three-dimensional shape and accuracy of the workpiece. Although the average cutting speed, relative machining costs, accuracy, and surface finish have been improved several times over since the commercial introduction of the machine, further improvement is still required by different industries to meet the increasing demand of precision and accuracy.

However, insofar as precision and accuracy are concerned, the vibrational behaviour and the static deflection of the wire (wire lag) need to be studied simultaneously. Even though a good number of research studies have been carried out to analyse the wire lag and its measurement, very few studies have focused on the vibrational behaviour of the wire, due to the numerous complexities entailed. The complexities that inevitably arise are: modelling the wire-tool vibration phenomenon, finding an approach to the solution of the vibration equation, and also conducting experiments for the purpose of measuring the amplitude of the vibration.

This makes it necessary to investigate the vibrational behaviour of the wire in detail, given that it plays a major role in setting the precision and accuracy of an electro-discharge machined part. An attempt to study the dynamic in-process mechanical behaviour of the wire has been made over a wide range of machining conditions by Kinoshita et al. [1].

The area of wire vibration in transverse plane has also been measured and the difference between a programmed path and a produced profile has been delineated during the 1980s. Some researchers [2, 3] dealt with the existence of the incurvation of the wire resulting in the wire lag behind the position of the wire guides. But the problems were analysed only from a static viewpoint; hence, the control systems were developed for the purpose of achieving an enhanced accuracy of the processing.

Mathematical modelling of the wire vibration and the development of vibration measurement systems have also been attempted throughout the decades [4, 5, 6]. However, the single discharge modelling was preferred every time. Unlike these previous attempts, we present an efficient analytical solution of a widely-used wire-tool vibration model with a slight modification, using multiple spark discharges during machining.

2. WIRE TOOL VIBRATION

The vibrational behaviour of the wire is extremely complicated in nature. This is because the magnitudes and directions of various forces acting along or upon the wire are not always constant, as the occurrence of sparks is highly stochastic in nature. The stochastic nature of the WEDM process is also attributed to a combination of factors including: fluctuations in voltage and current, decomposition and distribution of the dielectric, random ionic migration, interaction of two successive discharges, and the presence of debris particles in the machined area. Not only that, but several of the above-mentioned factors vary markedly with time and space in the discharging area [7], [9].

Moreover, while the wire is in vibrational mode, sparks continue to occur in the extreme modal positions of the wire. This renders the nature of vibrations more complicated and makes the modelling of the wire vibration a much more tedious task. To date, several researchers have opined that the main forces acting along or upon the wire are forces from the gas bubbles formed by the plasma of the erosion mechanism, hydraulic forces due to flushing, electrostatic forces and the electrodynamic force. Although it is almost impossible to determine any of these forces quantitatively, researchers have been able to determine the forces acting perpendicular to the wire during the WEDM operation for a particular experimental set-up with a certain parametric setting.

However, I contend that there is a reduced effect of the electrodynamic force on the vibrational behaviour of the wire. Instead, another force acts perpendicular to the wire, namely impact. During each individual spark discharge, the wire experiences an impact, which acts in reverse direction to the discharge occurrence. All these above-mentioned forces, along with the axial tensile force (F), applied to the wire, set the wire to vibrate when discrete sparks are generated between the electrodes. Therefore, vibration of a stretched wire supported by the two wire guides at opposite ends satisfying the standard vibration theories of vibrating strings, has been mathematically modelled by several researchers [4, 5, 6] with the following assumptions:

1. the wire mass is uniformly spread along its length;
2. the axial tension remains constant between the wire guides;
3. the wire is static (not moving);
4. the wire is perfectly flexible, and,
5. the disturbing forces acting per length unit of the wire perpendicular to the axial force, varies as a function of time and space.

Figure 1 shows the schematic representation of wire-tool vibration in WEDM processing. Therefore, the general partial differential equation of motion (Newton's second law of motion) for a stretched vibrating string of L length in a plane (along Z-axis) may be expressed [2, 3] as follows:

$$F\frac{\partial^2 y}{\partial z^2} - EI\frac{\partial^4 y}{\partial z^4} = \rho_0\frac{\partial^2 y}{\partial t^2} + \beta\frac{\partial y}{\partial t} + q(z,t) \qquad (1)$$

where: F is the wire tension (N); y the wire deflection (m); t the time (s); $\rho_0 = \rho_s$(kg/m); ρ the wire mass density (kg/m^3); s the wire cross-section (m^2); β the specific damping co-efficient (N s/m^2); E Young's modulus (N/m^2); I the area of the moment of inertia, $\pi d^4/64$; d the wire diameter (m); q(z, t) the specific external load or body force per unit of length of wire (N/m).

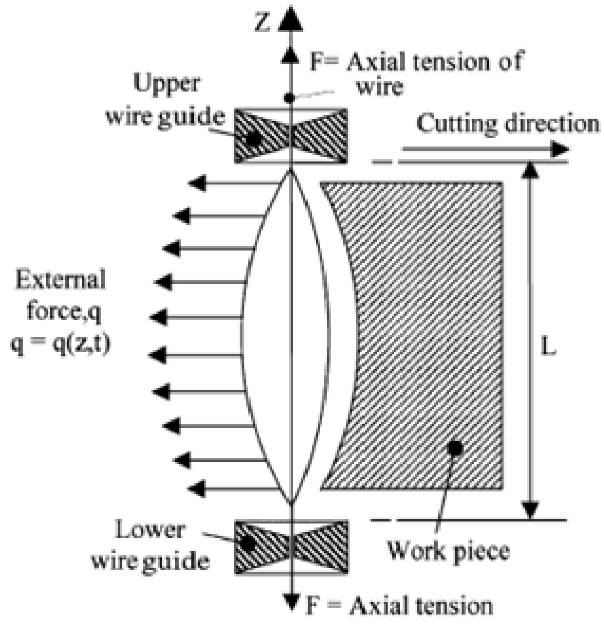

Figure 1. A schematic diagram of wire-tool vibration in WEDM processing

The term $F(\partial^2 y/\partial z^2)$ indicates the force due to bending deformation caused by the application of axial tension F. The term $EI(\partial^4 y/\partial z^4)$ represents the force required for transverse bending divided by the flexural rigidity of the string. As the wire is perfectly flexible, as has been assumed, this term is negligibly small. The terms $\rho_0(\partial^2 y/\partial t^2)$ and $\beta(\partial y/\partial t)$ represent the acceleration force (Newton's second law of motion) and damping force, respectively.

The above partial differential equation will allow the evaluation of wire deflection but, at the same time, it is extremely complicated to solve. Moreover, determination of the force q(z,t) is also a difficult task. So, the analytical solution of this equation for finding y(z,t) is very intricate and demands the particular consideration of machining operational features to develop real-time solutions. However, by making some simplified assumptions, it is possible to facilitate the arrival at a solution of the equation, sacrificing to a very small extent the accuracy and precision.

3. MODEL OF WIRE ELECTRODE VARIATIONS OF FORM AND POSITION DURING THE HIGH-SPEED WIRE-CUT EDM

During the high-speed wire-cut EDM processing, the stretching force of the wire electrode is not a stable constant, but is dependent on the degree of wire-rounding tightness and wire-driving resistance. Processing in the opposite direction as shown in Fig. 2, that is L_3, will not only enlarge the wire-span length but will also act adversely to tighten the wire; in the end, the wire flexivity will certainly be enlarged.

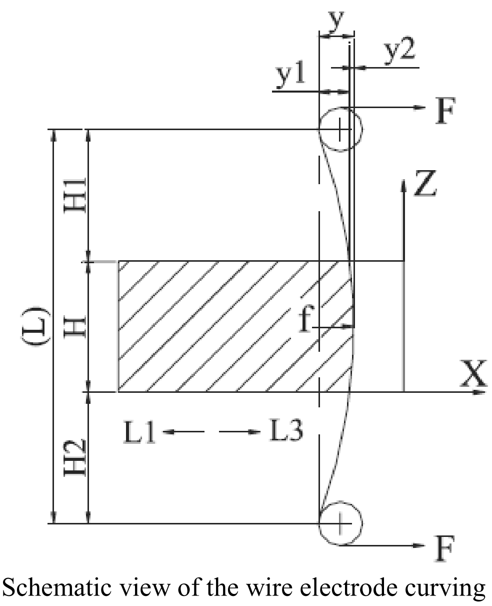

Figure 2. Schematic view of the wire electrode curving when processing along the L_1 direction

During the adjustment ready state prior to the WEDM-HS machining process, the wire electrode between the two guide wheels is a straight line linking each fulcrum (tangential point) of the wheels. While processing, provided the instantaneous interference of wire transport system (radial jumpiness and axial running of the wire-winding cylinder and guide wheels) is not taken into consideration, the form and position variations of the wire electrode mainly depend on the stretching force of the wire electrode, the static electric field force, and the discharge force of the machining process. The stretching force is an axial force, which is helpful in straightening the wire electrode and in decreasing further its form and position variations, whereas the electric field force and the discharging force are lateral forces, and work in opposite directions to one other. Before disruptive discharging, the electric field force pulls the wire electrode towards the workpiece. After disruptive discharging, the discharging force is much larger than the electric force and hence pushes the wire electrode away from the workpiece. During the entire course of processing, since the discharging force has much more influence than the electric field force, the wire electrode between the two guide wheels is generally pushed away from the discharging area, finally bending backward and generating a certain flexivity. Figure 2 shows the wire electrode flexivity generated during left-hand sideprocessing. Under the limiting flexivity condition, the dynamic WEDM-HS process is always simplified as a static variation. The bending section of the wire electrode is approximated as a pitch arc, and its flexivity may be expressed as the following equation:

$$y_1 = \frac{f(L-H)}{2F};\ y_2 = \frac{fH}{4F}$$
$$y = y_1 + y_2 = \frac{f(2L-H)}{4F} \tag{2}$$

where y representsflexivity, L is the span length of the wire electrode, H is the workpiece thickness, f is the discharge force and F is the tensile force in the wire electrode. However, during the course of actual processing, the discharge force does not concentrate on an intermediate point on the workpiece, but is distributed evenly along the whole thickness direction, whereas the dielectric emulsion will generate a damping influence.

4. MULTI-DISCHARGE MODELLING OF WIRE TOOL VIBRATION

It is assumed that the workpiece is kept at the mid-position of the wire. The length of the wire between the two wire guides is L. The wire is displaced laterally at a distance equal to the workpiece'sheight

H, upon application of the body force q(z, t), as shown in Figure 3.

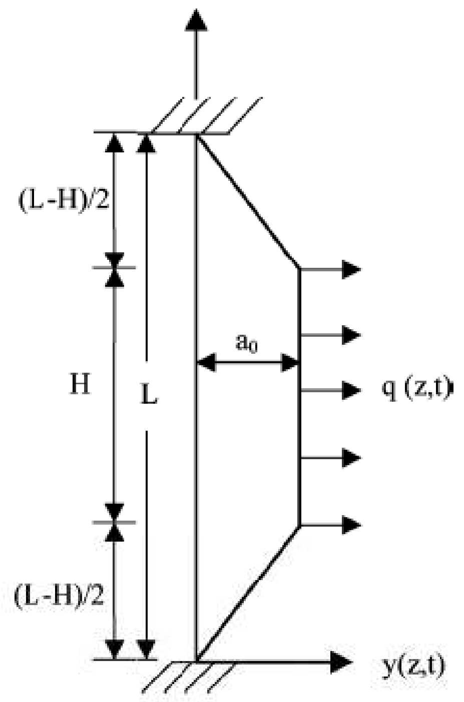

Figure 3. Action of the body force before the wire is set to vibrate.

The body force being the predominant one, pushes the wire away from the workpiece during the collapse of discharges, and the wire deviates along a distance, a_0, from its ideal initial stretched condition over the workpiece height and theoretically released at the same time, namely at t = 0. It is required to find the equation of motion, frequency and maximum amplitude of vibration of the wire under such a condition. However, Eq. (1) may also be rewritten as:

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial z^2} - K\frac{\partial y}{\partial t} - Q \tag{3}$$

where: $c^2 = F/\rho_0$, $K = \beta/\rho_0$ and $Q = q/\rho_0$, q = q(z, t).

The body force (Q) constitutes all the forces, such as forces released by gas bubbles formed by the plasma of the erosion process, the electrostatic, electrodynamic and, hydraulic force, as well as the impact on the wire. The hydraulic force may be assumed to remain constant for a particular set of machining conditions and set-up.

Thus, for an iso-energy pulse generator, the body force (Q) may be expressed as follows:

$$Q = f(E_p, \nu) \tag{4}$$

where E_p is the energy contained in a pulse or pulse energy, and ν the pulse frequency. If the pulse energy is maintained constant during a machining process, the body force, Q, is then expressed only in terms of the discharge frequency. Thus, although a universal relation is extremely difficult to establish, Q may be written as:

$$Q = K_1 \nu^A \tag{5}$$

where K_1 is a constant of proportionality in the above relation and A is a constant index for a machining system having a constant hydraulic force in the machining gap and supplying constant pulse energy during a process.

It has also been experimentally verified that external body force is directly proportional with discharge frequency (A = 1) and the value of K_1 is found to be 1.41×10^6 Ns under a pre-set machining condition [7]. It is also well understood that the amplitude of vibration will go on increasing with the increase of Q and the decrease of wire tension. However, since the wire tension remains unchanged during a machining process, the displacement function y may be expressed as:

$$Q = \alpha y \tag{6}$$

where α is the constant of proportionality. Although it may appear that Eq. (6) is overly-simplified, the complexity lies in determining α. From the above relations, the displacement function y may be expressed for a particular machining condition, and set-up in terms of only discharge frequency as follows:

$$y = K\nu,\ K = \frac{K_1}{\alpha} \tag{7}$$

The constant K may be determined through experimentation and calibration of curves, and once K is known, α may be found out if K_1 is known. Therefore, Eq. (2) is simplified through a linear homogeneous equation as stated below:

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial z^2} - K\frac{\partial y}{\partial t} - \alpha y \tag{8}$$

The above equation is solved through the method of separation of variables with the following ICs and boundary conditions (BCs):

a) IC: y(z, 0) = f(z),
b) and(∂y/∂t)(z, 0) = 0.
c) BC: y(0, t) = 0,
d) andy(L, t) = 0.

The displacement function y = y(z,t), may be determined by solving Eq. (9).

Thus:

$$y(z,t)=e^{-\beta t/2\rho_0}\sum_{n=1}^{\infty}\{A_n\cos(\varpi_n t)+B_n\sin(\varpi_n t)\}\cdot$$
$$\cdot\sin\left(\frac{n\pi}{L}z\right)$$

where

$$A_n=\frac{8a_0L}{n^2\pi^2(L-H)}\sin\left(\frac{n\pi}{2}\right)\cos\left(\frac{n\pi}{2}\frac{H}{L}\right), \quad (9)$$
$$B_n=A_n\frac{\beta}{2\rho_0}\frac{1}{\varpi_n},$$
$$\varpi_n=\frac{1}{2}\sqrt{\left(\frac{4n^2\pi^2F}{\rho_0L^2}-\frac{\beta^2}{\rho_0^2}+4\alpha\right)}$$

whereω_n is the natural angular (circular) frequency of the wire's vibration

Therefore, A_n = 0 for n = 2, 4, 6, ... , i.e. for even numbers, whereas for odd numbers, i.e. (n = 1, 3, 5, ...), A_n possesses different values. Thus, A_n may be calculated for known values of L, H and a_0. The value of a_0 may be determined experimentally for a particular machining set-up. Once A_n is known, B_n may be calculated; if β, ρ_0 and ω_n are known; ω_n may be calculated when values of F and α are known.

The values of α may be determined by the calibration curve, as stated earlier. So, finally, the exact equation of motion may be determined as given by Eq. (9). The term $e^{-\beta t/2\rho_0}$ indicates that the vibration will decay exponentially with time. However, $A_n\cos(\omega_n t)+B_n\sin(\omega_n t)$ may also be expressed as:

$$\sqrt{A_n^2+B_n^2}\sin(\varpi_n t+\theta) \quad (10)$$

where $\theta = \tan^{-1}(A_n/B_n)$. The maximum amplitude of vibration is:

$$\sqrt{A_n^2+B_n^2} \quad (11)$$

and the angular or circular frequency will be ω_n. The values ω_1, ω_2, ω_3, .. are the natural frequencies for n = 1, 2, 3, ... , respectively. The fundamental frequency of the vibration will be $(\omega_n/2\pi)$(c/s) for n = 1.

5. CONCLUSIONS

Wire electrode vibrations affect the accuracy of electric discharge machining, especially the accuracy of position and the shape of machined areas. Knowing how a wire electrode vibrates leads to the identification of methods for reduction of vibration, as shown in paper [8].

By understanding how the wire electrode vibrates, the accuracy of wire electrode discharge machining can be increased, with particular regard to positional precision and shape of processed surfaces. At the same time, the dimensional accuracy of the processing can increase through proper use of the presented mathematic model and the identification of technical solutions of reducing vibration during processing.

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