Influence of low-frequency vibration in Die Sinking EDM: a review

Laxmi Devi¹, Kamlesh Paswan¹, Somnath Chattopadhyaya¹, Alokesh Pramanik²

¹Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand 834001, India.
²School of civil and mechanical engineering, Curtin, University, Perth, Western Australia

kamlesh.gcr@rediffmail.com

Abstract. Electric discharge machining (EDM) is a thermal-based machining process where material removal in the form of melting and vaporization occurs due to repeated electrical sparks between electrode and workpiece. EDM process finds wide applications in the manufacturing, automobile, aerospace, and biomedical industries due to its remarkable feature of producing complex geometrical shapes like molds, tools, and dies. Irrespective of materials hardness. In this review, the paper author has given details about a new advancement made in the EDM process, which is low-frequency vibration-assisted Die Sinking EDM. There is also a brief introduction of vibration setups that can be used to generate low-frequency vibration. There is also some discussion about various optimization techniques (e.g., TOPSIS, MOORA, GRA) used to optimize the process parameters that are current, frequency, pulse on time, and pulse off time to get better response parameters (MRR, TWR, and SR). Besides, there is extensive discussion about the effect of current, pulse on time, pulse off time and frequency on MRR, SR, and TWR. In the end, some discussion on the effect of low-frequency vibration on surface topography is also discussed.

1. Introduction

Die-sinking electric discharge machining (EDM) is a process that utilizes the spark energy to shape the surface of molds and tools. It is highly effective in shaping materials that are complex in design irrespective of material hardness. Despite many advantages, EDM faces many technological challenges with the growing complexity of products like in aerospace, automobile, and biomedical industries [1–3]. One major disadvantage is that the machining speed is relatively slow compared to other machining methods. Also, by increasing the discharge energy to machine faster, the machined surface's quality gets deteriorated. Thus to improve the machining performance, it is essential to uniformly disperse the discharge energy and avoid debris accumulation between electrode and workpiece. To teach these disadvantages, researchers have given many new technical solutions such as PMEDM, vibration-assisted EDM and optimization of existing parameters like current, pulse on time, pulse off time, voltage, dielectric fluid pressure, electrode polarity.

In this review, the author has focused on vibration assisted EDM as this is an emerging field these days. Vibration can be integrated into EDM in two ways either in the electrode or in the workpiece. Vibration integration into electrode is quite tricky compared to that of a workpiece in the EDM process as
cited in Pandey and Singh [4]. Assisted low-frequency vibration leads to a significant increase in material removal rate (MRR), reduced surface roughness (SR), overcut, and taper angle deviation. Unune and Mali [5] used low-frequency vibration attached to Inconel 718 workpiece, and research showed that MRR increased by 27.6% when the frequency of vibration increased from (F=0-40Hz), electrode wear rate decreased by 6.16%, overcut and taper angle deviation decreased by 31.84% and 18.58% respectively. Assisted ultrasonic vibration increases the process's inefficiency by increasing the MRR and fatigue life and reducing surface roughness and recast layer [6]. A low-frequency vibration on EDM has been assigned to process SS304 stainless steel. A high MRR with reduced Total wear rate (TWR) and SR was achieved [7]. Besides, low-frequency vibration also decreases in short circuit pulses by 80% and discharge pulses by 40% [8]. This leads to an increase in the machinability stability of the process. Vibration contributes to the improvement of the flow velocity of dielectric fluid, thereby increasing the discharge frequency. This improves machining productivity and reduces electrode wear rate. Compared with the conventional EDM, the MRR increases by 187.5%, and EWR decreased by 925% when vibration was assigned to electrode [9]. Several statistical techniques have been introduced like Taguchi method combined with multiple objective optimization techniques (TOPSIS, GRA, Multiple objective optimization techniques based on ratio analysis- MOORA) has been widely used in EDM. Analytical hierarchical process (AHP) is used to determine quality indicators' weight [9,10]. The result of MOORA is better than that of TOPSIS and GRA [11]. Therefore, Taguchi, MOORA and AHP may be suitable for multiple objective optimizations of vibration-assisted EDM. The review paper is to examine the process parameters of vibration-assisted EDM of the SKD61 steel workpiece using a copper electrode. The process parameters include current (I), pulse on time (Ton), pulse off time (Toff), and frequency vibration (F). MRR, TWR, and SR are considered as quality indicators. The Taguchi-MOORA-AHP method is considered for the study. A technological solution for the EDM process shown in figure 1(a).

![Figure 1](image.png)

**Figure 1.** (a) New technological solution for the EDM process[12] and (b) Schematic diagram of vibration-assisted EDM[13]
The basic principle of EDM with vibration integration is shown in the schematic diagram. The whole setup contains a tool, tool holder, workpiece, vibration platform, dielectric, work tank, positioning table and other essential auxiliaries shown in figure 1(b).

Further, there is wide variation in necessary EDM process, e.g. EDM, Wire EDM; powder mixed EDM, dry EDM and micro EDM, which can be selected based on its applications. Every process has its merit and demerit, based on the research trends in the manufacturing industry [12]. Besides, with the growing demand for miniature products into aviation and biomedical industries, many new micro-manufacturing methods came into the picture. Of all the methods present, micro EDM is a complicated process to perform. Despite difficulties, many researchers have mixed micro EDM with other available options, e.g. wire EDM, magnetic field-assisted EDM, vibration-assisted EDM, milling and drilling [14].

Many research papers have been reviewed for deeper insights into vibration assisted EDM process. Some of these papers are listed in table 1 to provide some basic idea about the mechanism, workpiece, electrode, parameters (electrical and non-electrical), and the research outcomes.

| Name of researcher | Workpiece and tool material | Parameters | Finding and remarks |
|--------------------|-----------------------------|------------|---------------------|
| Chern and Chuang [15] | W/P: SUS 304 stainless steel and brass Tool: Tungsten steel | Voltage, capacitance, resistance, frequency, amplitude, rotational speed | a) Punching of 200µm diameter hole on a brass workpiece with an optimum clearance value with improved geometry and surface finish using a vibration-assisted micro EDM. b) SUS304 steel punching is brutal and lacking in quality compared to brass due to higher strength and low machinability. |
| Xu et al.[16] | W/P: YT15 cemented carbide Tool: Cu | Frequency, amplitude, current, voltage, pulse on time, rotational speed, flashing a pressure | a) Material removal methods of ceramic carbides are discussed. b) MRR increased because the material gets easily separated due to integrated vibrations. |
| Yu et al.[17] | W/P: Stainless steel Tool: W | Voltage, capacitance resistance, frequency, amplitude | a) The aspect ratio of micro-hole drilled by micro EDM integrated with ultrasonic vibration and planetary movement of the tool is 29. b) Aspect ratio with only planetary movement is 16.9 c) In standard micro EDM drilling, the aspect ratio is 14.7 |
| Authors               | W/P:                        | Tool:               | Parameters                             | a)                                                                 | b)                                                                 | c)                                                                 |
|----------------------|-----------------------------|---------------------|----------------------------------------|---------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Jahan, Wong, and Rahma[18] | W: WC                       | W                   | Voltage, current, frequency, amplitude | Discharge pulse rate can be increased by approximately 40% by using ultrasonic vibrations. |                                                                      |                                                                      |
| Iwai, Ninomiya, and Suzuki[19] | PCD                         | Cu                  | Current, voltage, frequency, pulse on time | Integrated axial ultrasonic vibration EDM leads to 86% decrease in TWR than standard EDM. | SR height in the range of 2.72 ~3.55 micrometre. | MRR was almost three times more than standard EDM. |
| Ichikawa and Natsu[20] | SUS 304 stainless steel     | W                   | Current, frequency, amplitude, rotational speed | With a change in amplitude from 4 to 6 µm, the average feed rate increases by 5%, resulting in an improvement of MRR. |                                                                      |                                                                      |
| Kurniawan et al.[21]  | CFRP composite              | WC- Co, Cu, Al, Brass | Voltage, frequency, pulse on time, resistance, capacitance, rotational speed, feed rate | In CFRP material, Cu is best suited as electrode material. | BRR and deburred hole quality increase considerably. |                                                                      |
| Hsue, Hab, and Lin[22] | SKD61 high-speed steel      | Cu-Cr               | Frequency, amplitude, current, pulse on time, pulse off time, voltage, rotational speed | Rotary ultrasonic-assisted EDM leads to decrement in MRR by 51% at 1500 rpm, whereas Ultrasonic assisted EDM leads to better performance. |                                                                      |                                                                      |
| Li, Tang, and Bai[23]  | Ti-6Al-4V                    | W                   | Voltage, capacitance, resistance, rotational speed | Machining with circular ultrasonic vibration-assisted on tool electrode leads to greater consistency of hole dimensions | Outlet and inlet diameters dimensions accuracy increased by 2.8% and 22% respectively. |                                                                      |
2. Experimental setup and equipment

There are various types of EDM machine that we can select based on the operations we will perform on a device like deep hole drilling, curved hole drilling, turning. In this review paper, we are concerned with modifying essential EDM into the ultrasonic EDM process. Therefore, the experiments can be performed on any primary EDM machine equipped with a vibration unit. A basic experimental setup is shown in Figure 2(a). Some of the vibration setups are discussed in this paper. High-speed cameras can also be attached to a machine to record minute details of the whole machining process [24]. There is also a proper fixture mechanism to hold the workpiece rigidly during vibration, which enhances the machine's stability and accuracy. For verification and validation of results, many trials have been performed. The vibration unit is mainly based on the ultrasonic vibration principle in this machine, but the operating frequency range is narrow (100-5000Hz). The maximum limit of vibration amplitude is fixed in the range of 2-3 mm. The MRR and TWR are measured by using a digital weighing device [25]. Surface roughness is measured by surface profilometer (MITOTOYU, Japan), and surface morphology is presented by using an electronic microscope.

[Figure 2. (a) Schematic diagram of vibration Assisted EDM [26] and (b) Three-dimensional models of a Piezo unit [27].]

2.1 Vibration Set up

There are many types of equipment that can generate vibration to a workpiece. Below are listed four types of vibration generating methods and equipment.

2.1.1 Piezo Unit

The Piezo Unit can be specifically designed for particular applications, as depicted in Figure 2(b). The unit comprises of two identical Piezo actuator, function generator, and charge amplifier. These Piezo actuators
are driven synchronously with the help of a function generator. The function of the charge amplifier is to determine the dynamics and movement characteristics of the Piezo Unit. The designed unit must be compact to restrict the machine's movement within the order and also fully insulated. It does not hinder the EDM machine working principle and avoid short circuits is presented in Figure 3. A Piezo Unit is specified by the frequency range from (0-1000Hz), the maximum deflection should be an order of 30 micrometres, and amplitude must not exceed 15 micrometres. Besides, to realize the actual load condition, the extra weight of 0.5 kg of the electrode and electrode holder should be considered per actuator. This designed unit can be verified by doing various experiments in the frequency range of (0-1000Hz) with a variation of amplitude from (2-16um), and the results can be validated by using Laser Doppler Vibrometer Sensor [27]. However, the two actuators behaved similarly at low frequency and amplitude. Whereas, there is a considerable change in the amplitude at higher frequencies (Figure 4). The best result, material removal rate also increased by 11.1%, is obtained at the frequency of (500-800Hz), and amplitude of 2um compared to EDM without vibration. The influence of vibration generated by the piezo unit has an advantage in making deep seal slots with improved MRR, decreased TWR, and better surface finish can be observed in Figure 5.

![Figure 3. Piezo unit assisted EDM set up [26]](image)

2.1.2 Ultrasonic vibration platform based on voice coil motor

Ultrasonic vibration-assisted EDM is the most preferred solution for improving machining efficiency. Despite that, ultrasonic vibration's primary challenge is the loss of vibration energy and heating effect due to fluctuation. Also, the vibration exciter operates in a very narrow range of frequency. Therefore, to avoid these drawbacks, a new method has been introduced based on voice coil motor associated with a vibration platform. The frequency range utilized in these platforms is very less than the ultrasonic range. Voice coil motor comprises a permanent magnet, coil, and coil frame, and these all assembled into a shell. This voice coil motor used in making the vibration platform, which consists of a metal flat diaphragm, Teflon diaphragm, seal ring, bottom board, and hull, is depicted in Figure 6. The metal diaphragm is an essential component and used for providing vibration. So it must have good strength, elastic modulus, hardness.
Figure 4. Vibration behaviour of two identical actuators at a different frequency and amplitude [27]

Figure 5. Influence of vibration on machining efficiency of high depth seal slots [27]

Figure 6. Design of Vibratory Platform and (b) Relation of frequency and amplitude of the vibration platform [28].

Brass is the best-suited material used in the making of flat diaphragm because it has good plasticity and higher strength. Teflon platform is provided for electrical isolation and placed above the metal
diaphragm (Figure 6). So that short circuit does not happen. Various experiments are done to check the dynamic performance with a frequency range of (100-700Hz) and excitation current from (0.1-1A) [28]. The relation between vibration amplitude and frequency is shown in Figure 12. Also, there is a remarkable improvement in the material removal rate, almost five times without vibration assisted EDM process [29].

2.1.3 Turbine vibrator

![Figure 14. Workpiece vibration with turbine vibrator and vibration behaviour [29] and (b) Time variation with drilled hole depth with and without vibration with ball-shaped electrode [29]](image)

In the turbine generator, generated vibrations are transmitted to the workpiece through an L shaped support structure combined with springs are depicted in Figure 14. It is effectively used for drilling operations, whether curved or straight. The turbine generator is used for drilling curved holes, and results are remarkable. There is no hindrance in drilling operation due to arc stop or short circuit, drilling speed is approximately twice than standard EDM drilling [29]. The time required to drill a hole gets halves with vibration than conventional EDM drilling are plotted in Figure 15. The significant advantage is that the vibration-assisted process makes it possible to dig a deep curved hole.

2.1.4 Langevin type ultrasonic vibrator

In this ultrasonic vibrator, the sine wave generated from waveform generator gets amplified with amplifier passes through a current transformer and then as input into vibrator which starts vibration with sine wave frequency, i.e. natural frequency of ultrasonic vibration shown in Figure 16. The natural frequency determined by measuring the current through the current transformer and natural frequency can be changed by changing the electrode’s length. This ultrasonic vibrator is best suited for electrode vibration. Machining results get improved considerably with frequency magnitude of up to 66.5 kHz. However, the MRR did not improve in the frequency range of (27.6-57.3)kHz, also due to high vibration frequency surface roughness increased by 1 micrometre, as shown in Figure 17.
3. Design of experiments and optimization

Current (I), frequency (F), pulse on time (Ton), and pulse off time (Toff) are taken as process parameters in the range of 3-8 A, 128-512 Hz, 12-50 us, and 5.5-12.5 us respectively. MRR, TWR, and SR are taken as quality indicators (response parameters). Using MOORA can obtain optimized results. The Taguchi method is cost-efficient and easy to implement as the Taguchi method can not optimize the parameters solely. A combination of other optimization techniques like TOPSIS, MOORA, PSI, GRA, and ANOVA is required [31]. MOORA method gives the best optimization results among available options. The hierarchical analytical process (AHP) can calculate the weightage of process parameters on quality indicators. So a combination of MOORA-AHP-Taguchi can be used for better results.

4. Results and discussion

MOORA, along with AHP and Taguchi method, used to simultaneously optimize the quality indicators that are MRR, SR, TWR. Calculation by AHP method showed that currently has the highest priority than followed by frequency (F), pulse off time (Toff), and pulse on time (Ton), respectively [9]. Various experiments have been done, and the results are plotted graphically.

4.1 Effect of current on quality indicators.

The current has the highest contribution in the given parameter and is a measure of power delivered to the workpiece. As current increases, spark energy increases, which leads to an increase in the melting and evaporation process; hence, MRR increases drastically. The current increases from 3A - 8A, the MRR increases with almost 357.81%, TWR and SR also increase by 65.5% and 55.57%, respectively, shown in Figure 18(a). However, an increase in TWR and SR harms machining efficiency, but all together increase in MRR compensate for the decrement and enhances the machining efficiency. Simultaneously, the machining tool steel by Gr electrode current increased from 5A-50A results in an increase of tool wear rate by approximately 36% [9].

Figure 16. Schematic diagram of Langevin type ultrasonic vibrator Natural frequency (kHz)[30], (b) The relation between response parameters and frequency[30]
4.2 Effect of Pulse on time (Ton) on quality indicators

As pulse on-time increase MRR, TWR and SR increase, however, the increment is small in comparison to that of current because with an increase in pulse on time spark timing increases; hence spark energy also increased. This increment of quality indicators occurs to optimal Ton after that decrement starts (Figure 18(b)). As Ton increases, Toff decreases, which leads to a reduction in time available to push the debris out of the discharge gap; hence, the Stop of arc or short circuit takes place. It is contribution ranked fourth out of given parameters. The increment of quality indicators (MRR, TWR, SR) is 22.9%, 36.25%, and 14.76%, respectively. While machining AISI D3 Die steel using copper electrode when Ton increased from 50us-100us, MRR decreased considerably [32].

4.3 Effect of Pulse off time on quality indicators.

Figure 18. The relation between (a) I and results and (b) Ton and results [9].

Figure 19. The relation between (a) Toff and outputs and (b) F and outputs [9]
It is ranked third out of the given parameters. As pulse off time (Toff) increases from (5.5-12.5us), MRR decreases drastically up to a certain point, i.e., 12.5 us because it results in a decrease in spark timing and hence spark energy also lower. Melting and evaporation of material decreases by 28.08%. With an increase in pulse off time. Debris flows from the discharge gap increase, and hence surface roughness increased by 8.85%, and TWR decreased by 16.96%. After this, there is an increment in quality indicators shown in Figure 19 (a).

4.4 Effect of Frequency on quality indicators

Frequency comes into the picture because it is a vibration-assisted EDM process. The vibration rate plays a vital role in the flow of debris and the recirculation of dielectric fluid. This increases the stability of the process and a short circuit. Due to vibration, the workpiece moves upward and downward continuously. When the workpiece moves upwards, it creates a pumping effect, making debris flow out of the discharge gap under pressure. Also, the space between workpiece and tool reduced that means tool and workpiece came into close contact, which results in an increase in spark frequency with an increase in spark energy. When the workpiece moves downward, fresh dielectric fluid came into play. These all factors cumulatively increase MRR, TWR, and SR by 64.49%, 20.30%, and 18.47%, respectively, at an optimal frequency of 512 Hz shown in Figure 19(b). The experiments were done in a frequency range of (200-600Hz). At F=200Hz, 400Hz and 600Hz MRR increased by 10.22%, 13.81%, and 34.9% respectively on the same workpiece material (i.e., SKD61 steel) with the same EDM process [8]. At the F=200Hz tool wear rate decreased by 16% compared to regular EDM. In the case of machining of seal slots in temperature resistant MAR-M247 workpiece because of vibration machining time decreases from 30.2 min to 17.4min, which means an increase in material removal rate by 42.38%, TWR decreased 21%, and surface roughness is less than 6.4um. Vibration generated by voice coil motor in the range of (100-700Hz) results in a significant decrease in perforation timing that means an increase in MRR [28]. Dimensional accuracy and machining efficiency increased by 10.5um and 18 times, respectively, while machining using a piezo actuator with vibration accuracy of 6000Hz and amplitude of 3um by using a tungsten electrode[26]. In vibration-assisted micro EDM of a brass workpiece with a frequency of 1000Hz and amplitude of 1.5 um using piezo actuator gives shortest machining time means the highest material removal rate [33].
Figure 20. Machined surface after standard EDM (a) Topography and (b) Debris particle [9]

Figure 21. Machined surface after vibration assisted EDM  (a) Topography and (b) Debris particle [9]

4.5 Surface Topography and Integrity

EDM is a thermal-based machining process in which spark generates at a very high temperature of approximately 10000 degree Celsius. Which results in high thermal stress due to the higher thermal gradient when this thermal stress increases beyond critical point micro crack formation start in material[16]. Whereas in vibration-assisted EDM there is proper circulation of dielectric fluid, resulting in low thermal gradient; hence, crack formation is reduced considerably. Also in vibration-assisted EDM process, surface topography is relatively uniform that that of normal EDM process. In standard EDM, debris particles stick to the workpiece and electrode and create non-uniformity on the surface shown in Figure 20. While in vibration-assisted EDM there is a proper flow of debris particles and recirculation of motion because of to and fro movement of workpiece or electrode. This creates stability of the process and reduces short circuit due to which there is no hindrance in tool motion. Material removal takes place continuously with approximately equal volume removed (in crater shape with the same depth) in each spark. Also, very less debris remained on the surface shown in Figure 21. The surface's topography can be seen by using a finite element scanning electron microscope [34].

5. Conclusion

There is a detailed analysis of low-frequency vibration assisted EDM on SKD61 steel, various vibration setups, process, and response parameters in the current work. Following conclusions can be drawn;

- Low-frequency vibration-assisted EDM leads to a significant increase in machining efficiency.
- Discharge current, frequency, pulse off time, and pulse on-time decrease the order of influence on response parameters.
- Vibration assisted EDM results in improved machining stability conditions.
- The number of sparks increased which results in a higher amount of available energy per unit time
In SKD61 steel, optimum results are obtained in the frequency range of 400 Hz to 512 Hz. Low-frequency vibration leads to better surface finish in comparison to normal EDM process. It is easier to assist low-frequency vibration to workpiece than to electrode. So, assisting vibration into workpiece or electrode is a new technology with great potential and enormous future experimentation scope.

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