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Design of an innovative coal screening system using nonlinear power based electromagnetic vibroexciter – a feasibility study

Shaheen Hasan Chowdhury, Abdul Md Mazid

School of Engineering and Built Environment, CQUniversity Australia, Rockhampton, Australia

ABSTRACT
Vibrating technologies are used in the different engineering fields of industries. These technologies allow to intensify the technological processes in increasing the quality of products and labour productivity. In the paper, the development of a control circuit of the electro-magnetic vibrating exciter (EMVE) has been studied. A new type of mineral screening concept design using EMVEs has been proposed. This paper represents an analysis of the nonlinear automatic oscillation system composed with a single stroke electromagnetic vibrating exciter, a velocity transducer, nonlinear amplifier and an inverter. The results were obtained for the frequency and amplitude of automatic oscillations by the describing function method depending on the parameters of the system. It was established that internal negative feedback was partly stabilized the amplitude of oscillations by the variation of frequency. The results of the paper can be used in designing and developing of Vibration setup for the wide range of frequencies.

Keywords: Coal Screening, Electromagnetic Vibroexciter, Mining, Nonlinear Power, Velocity Transducer.

1. INTRODUCTION
The electro-magnetic vibro-exciters (EMVEs) are used in various engineering fields for different purposes, such as in chemical industries for material sorting, in granular and bulk material handling in coal mining, in thermal power plants for coal/biofuel delivery to the boiler furnaces, and in many other inaccessible and dangerous for human body. Moreover robots and manipulators installed with EMVEs are used for inspection and repair works in nuclear power plants and chemical industries, operations in wreckage-sites after earthquakes or blast, or dismantling/demolition explosive devices [1, 2]. The EMVEs have been extensively used in design of bulk handling equipments applicable for various industries to ensure the smooth flow of bulk materials from storages, hoppers, and delivery chutes. The EMVEs are also used to feed the various bulk materials to mixers, grinders, crushers, packaging machinery, batching, grading, and mixing stations.

The EMVEs are coupled to a delivery trough which is vibrated by the exciter to control material flow along the chute, trough, or the pan. EMVEs are simple in design and easier to manufacture. The EMVEs are commonly fed by power with 50Hz frequency producing oscillation frequency of 100Hz [3]. Mechanical oscillations with 10Hz to 50Hz frequency ranges can be obtained integrating electronic rectifying devices. Based on the analysis of data for many vibrating arrangements, it is observed that from the view point of higher productivity it is necessary to use such schemes which have wider range of working frequencies and amplitudes. If the load changes during the operation, the vibrator falls out of resonance and the amplitude of oscillation is largely reduced; as a result, it decreases productivity and efficiency of installation. By virtue of the development of semiconductor converter technology, fabrication of more effective vibrating machines has been made possible.

The objective of the present study is to determine the frequency and amplitude of oscillations for the control mode of operation of the system integrated with an EMVE, nonlinear amplifier and velocity transducer connected to scheme of EMVE. Provided this advantage, expected it is possible to use an EMVE in the design of a more effective coal screening machine for coal mining and processing industry. Hence the second objective of this research is to make a feasibility study whether a versatile EMVE can be used as the vibration resource mechanism for a coal screening machine.

Research is being carried out for the fabrication and exploitation of vibrating technology based on Electromagnetic Vibrator, incorporating nonlinear magnetic elements and semiconductor devices for automation and control.

2. DESIGN AND WORKING PRINCIPLE OF AN INNOVATIVE ELECTRO-MAGNETIC VIBRBRATING EXCITERS
There are many advantages of EMVE over other types of vibrators, including simplicity in design and

their use, higher reliability and durability, smooth regulation of the amplitude of oscillations, and nearly noise free operation. The various types of EMVE are used in vibration technology such as Π-shaped EMVE as depicted in Fig. 1(a), E-shaped EMVE as displayed in Fig. 1(b), Π-shaped push-pull EMVE, E-shaped push-pull EMVE which are not shown in figures in this paper.

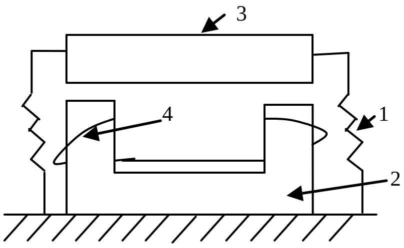

Fig 1(a). Π-shaped EMVE

An EMVE consists of two basic components: the active and reactive parts which are joined to each other by a set of plate spring 1 as in Fig. 1(a) and 1(b). Variable plate designs are used for required rigidity for the system. The ends of the springs are fastened to the base part of EMVE and the armature 3 respectively.

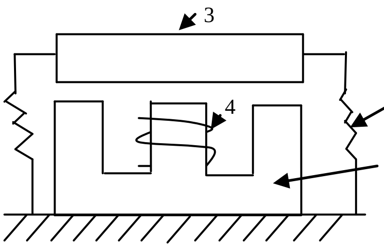

Fig 1(b). E-shaped EMVE

The reactive part of EMVE includes the E-shaped or Π-shaped core 2 including the winding 4, is mounted on a base. The armature 3 is made of electrical steel plate and the core is assembled of electrical sheet steel. It is possible to regulate the size of the air gap between the armature and the core by changing the number of pads in between them. The electrical source is connected to the winding 4 to which electrical terminals are again connected. The EMVE is assembled to the working part of desired equipment as per requirement. According to the working principle, as mentioned, EMVEs are commonly supplied from power frequency with 50 HZ provide frequency of oscillation of 100 HZ.

3. CIRCUIT DIAMRAM OF THE EMVE

The functional circuit diagram of EMVE is shown in Fig. 2. It consists of mass M, springs with spring constant K and damping mechanism with coefficient of friction B. The winding of EMVE is fed by the inverter (I) of relay transmissive character. Inverter of such characteristics permits itself to increase efficiency and decrease weight and overall dimensions [4]. The biasing source of core E_0 and the output voltage of inverter are connected in series to the winding of EMVE for simplification. Electromagnetic vibrating exciter can be represented by Π shaped electromagnet where armature is rigidly fixed with load carrying part. An Electromagnetic velocity transducer (VT) on the load carrying part is connected through integrating amplifier (A) to the input of the pulse generator.

4. POSSIBLE APPLICATION OF EMVE

The vibrating screen shown in Fig. 3 is a kind of sieving equipment for sorting minerals according to particle sizes. Coal screening equipment are widely used

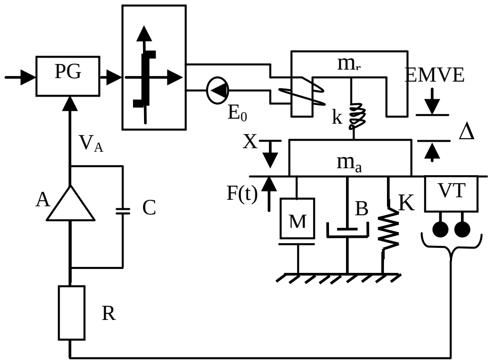

Fig. 2: Functional diagram of EMVE

for screening ore, coke, coal, minerals, quarry, building materials, water conservancy and hydropower, transportation, chemical industry, smelting, and so on. Vibratory screening machines are the optimal solutions to mass scale minerals screening. Currently there are good number mechanically operated mineral screening machines used in mining and mineral processing industry. For mechanically operated screening machines vibrations are created using mechanical mechanisms in these machines as shown as Fig. 3. The contact rolling parts of these vibratory mechanisms although are reliable, but not long lasting due to friction wear of the contacting parts. The silent eccentric gearbox (Fig. 4) possesses an

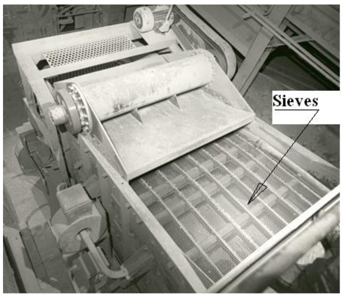

Fig 3. Mechanically operated coal screening machine

advantage that it produces lower noise in operation by virtue of revolutionary gear profiles. But manufacturing of these revolutionary profiles gear teeth is an extremely expensive business which drives the machine cost to the level of sky-rocketing untouchable for many industries. On top of that rotating eccentric masses create unnecessary radial pulsating load crashing the normal bearing life a number of times. A pair of these eccentric gear boxes is assembled to the structure of the mineral screens to produce short reciprocal linear motions of the screens by virtue of counter rotating eccentric masses.

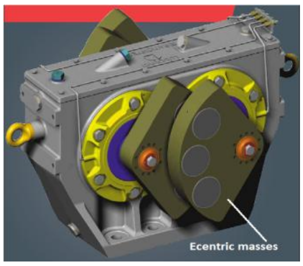

Fig 4. A vibro-exciter eccentric gear box

By virtue of the technical advantages of the described EMVE, there is an ample scope of application of EMVE for using it as a vibratory mechanism for a new type of mineral screening machines. EMVE will discard many rotating parts and mechanisms in the design of new type screening machine, thus improving the life of this essential for mineral processing equipment.

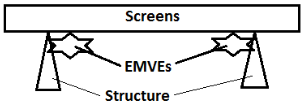

Fig 5. Concept of a new screening machine using EMVEs

In principle, at least four number of EMVEs (Fig. 5) are expected to assemble underneath the screening tray to create required oscillatory motion for screening operation.

5. MATHEMATICAL MODEL OF THE SYSTEM

The mathematical model makes it possible to determine the vibroexciters operational parameters using an electromechanical analogy. The mathematical model of Electromagnetic Vibro-exciter can be expressed by the following equations:

$$N\frac{d\varphi}{dt} + ri = V \quad (1a)$$

$$M\frac{d^2X}{dt^2} + B\frac{dx}{dt} + kX = f \quad (1b)$$

$$V_{VT} = K_{VT}\left(\frac{dx}{dt}\right) \quad (1c)$$

$$f = F_1(\varphi) \quad (1d)$$

$$V_t = F_2(V_A) \quad (1e)$$

$$V = V_I + E_0 \quad (1f)$$

In the above equations, non-linear relationships between electromagnetic force f & magnetic flux φ and output voltage of inverter V_I & input voltage of amplifier V_A have been expressed through $F_1(\varphi)$ and $F_2(V_A)$ respectively [5, 6].

The moss of the armature can be expressed by the following equation:

$$M = \frac{m_a m_r}{m_a + m_r} \quad (2)$$

The current of unsaturated core of EMVE can be calculated by $i = \frac{N\varphi}{L}$, when inductance of EMVE can be expressed as $L = \frac{L_0}{(1+\beta x/\Delta)}$ (3)

The output of inverter in harmonic linearization form may be expressed during the excitation of mechanical oscillation with frequency ω as

$$V_I = \frac{4E}{\pi}\cos\omega t \quad (4)$$

6. METHOD OF SOLUTION

The solution for the movement of armature X can be solved in the form of self-sustained oscillation with the constant X_0 and variable X_V components from equations (1) as follows:

$$X = X_0 + X_V \;; \quad X_V = X_m \sin\omega t \quad (5)$$

Similarly, for the flux φ can be expressed as:

$$\varphi = \varphi_0 + \varphi_V \;; \quad \varphi_V = \varphi_m \sin(\omega t + \theta)$$

Considering equation (3), equation (1a) can be expressed as:

$$\frac{Nd\varphi}{dt} + \frac{Nr\xi\varphi}{L_0} + \frac{Nr\beta\varphi_0}{L_0\Delta}X_V + \frac{Nr\beta}{L_0\Delta}\varphi_V X_V = V \quad (6)$$

Where, $\xi = (1+\beta x_0/\Delta)$ is the damping ratio.

The second harmonic of electromagnetic force obtained by multiplying of variable components of ω_v X_v can be ignored in fist approximation due to the filter properly of EMVE. The direct component of 0.5 φ_m x_m cos θ in second harmonic is about zero, since in almost resonance operation θ tend to π/2 [7-9]. So, fourth term of left hand side of equation (6) may be ignored in first approximation. Using Maxwell's formula the non-linear relationship of $F_1(\varphi)$ may be expressed as follows:

$$F = -\varphi^2/\mu_0 s \quad (7)$$

Using describing function method the equation (7) may be expressed as:

$$\left.\begin{aligned} F &= F_1^0(\varphi_0,\varphi_m) + F_3(\varphi_0,\varphi_m)\varphi_v\,; \\ F_1^0 &= -\frac{2\varphi_0^2+\varphi_m^2}{2\mu_0 S} \end{aligned}\right\} \quad (8)$$

; $F_3 = -\frac{2\varphi_0}{\mu_0 S}$

The non-linear function of $F_2(V_A)$ which is known as "ideal relay characteristic" may be obtained as a describing function:

$$V_I = F_4(V_{A,m})V_A \; ; \; F_4 = \frac{4E}{\pi V_{A,m}} \tag{9}$$

Where,

$V_{A,m}$ = amplitude of output voltage V_A of integrating amplifier;

The results can be chalked out by solving equations (6), (7), (8) and (9) as:

$$\varphi_0 = \frac{E_0 L_0}{M\xi r} \tag{10}$$

$$X_0 = \frac{F_1^0}{K} \tag{11}$$

$$\varphi_m = \frac{X_m}{F_1}\sqrt{(k - M\omega^2)^2 + (\beta\omega)^2} \tag{12}$$

$$X_m = \frac{4E}{\pi}\left[\frac{E_0\beta}{\Delta\xi} + \frac{BN^2 r\mu_0\xi S}{2E_0 L_0}\left(\omega^2 + \frac{r^2\xi^2}{L_0^2}\right)\right]^{-1} \tag{13}$$

where,

$$\omega = \omega_0\sqrt{1 + \frac{Br\xi}{KL_0}} \; ; \quad \omega_0 = \sqrt{K/M} \; ;$$

$$E_0 = \frac{Nr\xi}{L_0}\varphi_0$$

The obtained mathematical solution for amplitude of armature movement and amplitude of flux depend on the parameters of system of mass of armature, spring constant and damping ratio, frequency of oscillation, and easily can be obtained by changing the above mention parameters.

7. AMPLITUDE FREQUENCY CHARACTERISTIC OF EMVE

The experimental dependence of amplitude-frequency characteristic is non-linear character [10]. It is seen that the simplified results during the mechanical oscillations, the displacement of centre of oscillation taking place depends on extent of direct component. The direct component gives non-linear character of oscillation, displaying in separation of amplitude of oscillation during the change of load or increase of supply voltage V. In the presence of velocity feedback of mechanical oscillations, it excludes these separations with the continuous adjustment of frequency in resonance regime using pulse generator. The obtained analytical amplitude frequency-characteristic of self-sustained oscillations is shown in Fig.6. The experimental amplitude frequency-characteristic is shown by dashed line is obtained by constrained oscillations at the different values of frequency of force F(t) for the analogous non-linear oscillating system. The solid line which is analogous to linear oscillating system represents the amplitude-frequency characteristic for the open loop system. The obtained mathematical solution sufficiently coincided with the experimental results. It is seen that the amplitude of vibration at resonance zone is higher than the pre-resonance zone due to the effect of constant biasing of magnetic field. The curve for the natural frequency of the closed loop system almost coincided with the curve of the frequency of vibrating source, which is shown in Fig. 7 by the dashed line. The solid line shows the unstable system due to the inaccurate adjustment of parameters of the systems whereas the dashed line shows the stable system for the accurate adjustment of the systems [11].

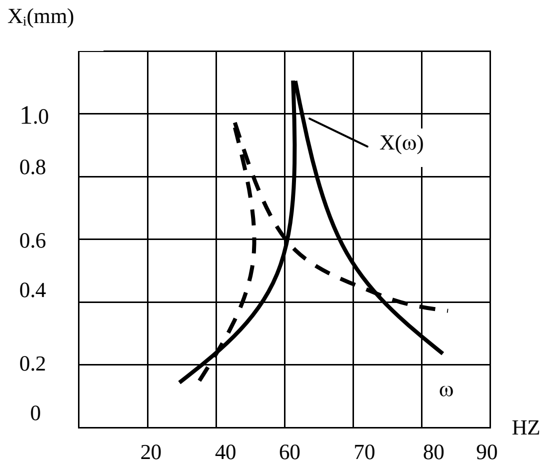

Fig 6. Amplitude-frequency of EMVE

8. ABBREVIATIONS

A = amplifier;
B = damping coefficient;
C = capacitance;
E = voltage source of inverter;
E_0 = the biasing source;
EMVE = electro-magnetic vibro-exciter;
F(t) = external force;
f = electromagnetic force;
I = inverter;
I = current in the winding of EMVE;
K = spring constant;
K_{VT} = conversion coefficient of electromagnetic VT;
L = inductance of winding;
L_0 = inductance of winding at x = 0;
M = mass of armature;
M_a = active mass;
M_r = reactive mass;
N = number of turns of EMVE winding;
R = resistance of input resistor of feedback integrating amplifier;
R_1, R_2 = feedback resistances of proportional amplifier;
r = resistance of EMVE winding;
S = cross sectional area of core ;
V = voltage in the winding of EMVE;
V_{VT} = output voltage of velocity transducer;
V_A = output voltage of proportional amplifier;

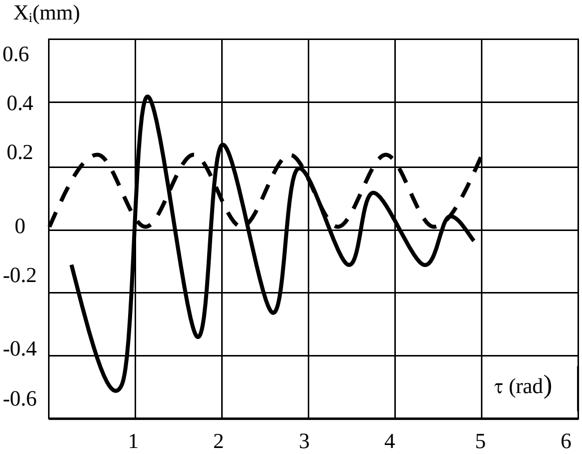

Fig 7: Curves of X_i (τ) of EMVE

$V_{A,m}$ = amplitude of output voltage V_A of integrating amplifier;
V_I = output voltage of inverter;
VT = velocity transducer;
X = linear movement of armature from gap Δ;
X_m = amplitude of armature movement;
β = coefficient of modulation of inductance;
Δ = gap between armature and electromagnetic core;
μ_0 = permeability of free space = $4\pi \times 10^{-7}$ Henry/m ;
φ = magnetic flux;
φ_m = amplitude of flux;
ω = frequency of self-sustained oscillation;
ω_0 = frequency of oscillation at X =0;
θ = phase difference of flux due to movement of armature
ξ = the damping ratio
τ = ωt - time constant

9. CONCLUSIONS

Based on the research output and investigation, the following conclusions are made:

Due to the inverter application of self-sustained oscillation, the system is stable for any parameters of the system and the value of amplitude is limited only for the unimpacted mode of operation. It is seen from the results theoretical analysis that the amplitude of EMVE of self-sustained oscillations is stabilized due to feed back system. A concept design for a new type of mineral screening machine using EMVEs has been proposed. Expected this new machine’s life will be much longer than mechanically excited machines. A prototype to build may proof the potential of the new design. The self-sustained oscillations of EMVE take place to approximate natural frequency of mechanical system considered as electrical integrator.

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11. MAILING ADDRESS

Shaheen Hasan Chowdhury
School of Engineering and Built Environment
CQUniversity Australia,
Rockhampton, Australia.
E-mail : s.chowdhury@cqu.edu.au ;
a.mazid@cqu.edu.au