Methods of Springs Failures Diagnostics in Ore Processing Vibrating Screens

Pavlo Krot¹, Radoslaw Zimroz¹

¹Department of Machine Systems, Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Na Grobli 15, 50-421 Wroclaw, Poland

pavlo.krot@pwr.edu.pl

Abstract. Large-scale vibrating screens are widely used in minerals processing industry. One of main components in any vibrating screen is a set of springs supporting the main body of machine with sieving material inside. These springs are subjected to cyclic loading and fatigue. Changing of their stiffness and subsequent failures have influence on the sieving efficiency and are difficult to predict, hence, online condition monitoring is required. Visual inspection and non-destructive diagnostic methods are not sufficient in this case. Noisy signals from vibration sensors installed on bearings supports of rotating unbalanced exciters are preferably used for diagnostics of spring failures. In this research, vibrating screen motion is represented by multi-DOF (degree-of-freedom) dynamic model, which accounts stochastic disturbances from incoming material and impacts on sieving decks. Specific features of vibration signals are analysed to identify springs deterioration modelled as the bilinear stiffness characteristics. Phase space plots (PSP) are considered as the promising method to recognise nonlinear behaviour of system under the presence of spring damage. Advantages are assessed of spring stiffness change and failures diagnostics as compared with other methods.

1. Introduction

The different types of vibrating screens (rotating vertical cylindrical, vibrating horizontal linear, etc.) are among the most commonly used facilities in minerals processing plants. These machines are applied for separation of ore and coal by the particles size. The supplied electric power, sizes and corresponding productivity of vibrating screens varies in a wide range from 10 to 1000 tons per hour. Several sieving decks can be installed inside the screens to increase overall efficiency of technological process and quality of final product. Theoretical and applied researches are conducted on their design modification and working regimes optimization [1].

Energy from source to screen and further to material can be transmitted by the rotating unbalanced masses, hydraulic or electro-magnetic actuators. Depending on motion, screens are classified as having linear, circular and elliptical trajectories of sieving decks. Some types of screens provide vibration fields with different trajectories over the deck surface.

By the oscillating regimes, screens can be categorized as resonance and above resonance machines. Resonance regime of work is preferable, but difficult to control, as the efficiency of screening is very sensitive to material volume (thickness and distribution of particles) and properties (hardness,
humidity, fractions) [2], [3], [4]. Changing (increasing) frequency of screen excitation is required for separation of more fine particles, which are prone to adhesive aggregation. Some approaches are known related to parametric excitation of vibration screens [5], [6], [7] and multi-body design to achieve non-linear or multi-frequency vibrations with wide band spectrum of excitation. However, for driving motors without speed control, excitation with the constant single frequency is the simplest case, which is mainly used in industrial plants for screens with linear motion.

Finite-elements method (FEM) and discrete elements method (DEM) are used for investigation of natural modes of screen body and particles collective motion [8], [9], [10]. These methods are applied for research and optimization of vibrating screens [11] requiring special software packages demandable to computing resources.

The components of the typical multi-deck vibrating screen are: the main box with lateral plates connected by transverse reinforcing beams, upper and lower sieving decks, under-screen deck and four supports designed as multiply springs (see Figure 1). Material is supplied to the input side by the belt conveyor and batcher. Large scale screens are always inclined by certain angle down so that to improve material particle motion from input to output with less energy consumption. Input or/and output streams of processed material are controlled by optical systems based on digital cameras or with some other types of sensors. Vibration is excited by one or two rotating shafts with unbalanced masses driven by individual motors via the belts. Mass and its eccentricity determine the amplitude of deck vibration. Vibrators are self-synchronised. Components of all vibrating machines are subjected to high cyclic fatigue. Therefore, welds are usually replaced by HUCK-BOLT joints.

![Figure 1. Typical vibrating screen with two shafts of unbalanced exciters](image)

Each support has several parallel elastic elements, which may be a helical coil steel springs, air springs or elastic rubber (see Figure 2). Although rubber elements have certain advantages, but they exhibit non-linear relations of deformation and applied load. Steel springs have linear characteristics, but up to certain level of their deformation. Lateral deformation of steel spring has also non-linear relation with its vertical stiffness [12], [13] that can cause specific dynamics features of screen. In any case, stiffness of springs is gradually reducing in time affecting vibration amplitude and frequency.
Supporting springs play one of the most important roles in a vibrating screen. Their stiffness directly affect the working performance of the machine. Trajectories of moving particles depend on several factors and deterioration of springs is among them. Some authors proposed to control the resonance regime of the vibrating screen by the use of shape memory alloy (SMA) springs to change the dynamic characteristics of the system [14].

Springs made of high grade steels are susceptible to cracks due to high-cycle fatigue (HCF). Using traditional non-destructive testing methods of diagnostics (ultra-sound, magnetic etc.) is difficult to implement due to complicated geometry of springs and continuous operation of plant.

Vibration monitoring gives a basement for diagnostics and predictive maintenance not only of the bearings on rotating shafts, but as well the elastic springs. However, bulk material is always produces stochastic component of loading. Attempts to avoid this technological noise and to record real loading signal require complicated instrumentation and strain gauges installation on the parts of machines [8], [15] or on rotating shafts [16]. Methods and instrumentation of wear measurement in the drivelines of heavy machines [17] is not applicable in this case. Methods are developed in [18], [19] of very noisy impulsive vibration signal processing from hammer mill containing stochastic components from treated material. However, a few publications are known on stochastic (random) loads accounting in vibrating screens [20].

A fruitful approach is using mathematical models for nonlinear features recognition in diagnostics of heavy machines [21]-[23] with accounting stochastic nature of applied loads [24]. Models of kinetics [25] and dynamics [26], are quite reasonable to apply to vibrating screens diagnostics including spring defects [27].

Authors in [28] considered six combinations of spring stiffness decreasing as a defects. Diagnosis rules are constructed based on dynamic model and vibration signal changes. Change of amplitudes are of small percent from normal conditions and them difficult to recognise under impulsive noise. Authors in [29] applied 3-DOF (degree-of-freedom) dynamic model to research on vibrating screen fault diagnosis.

A promising method is phase space plot (PSP), or system portrait, which is known in nonlinear systems dynamics analysis, as well sometimes used in vibration diagnostics of complicated machines[30]-[33]. Building orbits by the two orthogonal signals of shaft lateral motion from either eddy-current proximity sensors or obtained after double integration of acceleration signals is a similar kind of motion representation. However, in general case, PSP is represented in coordinates \((x; dx/dt)\), where \(x\) – one of motion coordinates (angular or linear). This method is more sensitive to parameters changes, especially, near the bifurcation points of the dynamic system and noise immune as the whole picture (portrait) of the system is observed for the analysis.

This paper represents an implementation of PSP method to the analysis of vibrating screen based on non-linear dynamic model in case of spring deterioration (crack or stiffness reduction).
distinction from other models, stochastic components are accounted in the modelled signals from the sieving material.

2. Dynamic model of vibrating screen

If we need to see response of vibrating screen as a whole body with included material mass, FEM or DEM models are not essential. Hence, dynamic model of vibrating screen is composed by assumption of six degrees-of-freedom (DOF), namely, three axes of linear displacements \((X, Y, Z)\) and three rotational angles \((\gamma, \varphi, \theta)\) correspondingly (see Figure 3).

Deterministic component of applied load consists of periodic inertial forces from two vibrating unbalanced exciters (see Figure 4a):

\[
F_0(t) = m \omega^2 \sin (\omega t + \Delta \alpha)
\]

where \(m\) – unbalanced mass of vibration exciter; \(\varepsilon\) – rotation radius; \(\omega\) - rotation frequency (rad); \(\Delta \alpha\) - phase difference between two exciters accounting imperfect geometry and detuning of rotations.

System of differential equations governing the dynamic model of vibrating screen is as following:

\[
\begin{align*}
M \dddot{x} + x \dddot{c}_x + xK_x &= A F_0(t) - k_1 F_{2x}(t) \cos \beta \\
M \dddot{y} + y \dddot{c}_y + yK_y &= B F_0(t) - F_{2y}(t) \\
M \dddot{z} + z \dddot{c}_z + zK_z &= C F_{2z}(t) \\
J_x \dddot{\varphi} + \varphi \dddot{c}_{\varphi} + \varphi K_{\varphi} &= F_{2\varphi}(t) \cos \beta L_z(t) \\
J_y \dddot{\gamma} + \gamma \dddot{c}_{\gamma} + \gamma K_{\gamma} &= F_{2\gamma}(t) \\
J_x \dddot{\beta} + \beta \dddot{c}_{\beta} + \beta K_{\beta} &= D F_0(t) + F_{2\beta}(t) L_x(t)
\end{align*}
\]

where \(K_x = (K_{X1} + K_{X2} + K_{X3} + K_{X4})\) – total stiffness of four supports in horizontal directions \(x, z(K_z = K_X)\); \(K_Y = (K_{Y1} + K_{Y2} + K_{Y3} + K_{Y4})\) – total stiffness of four supports in vertical direction \(y\); \(K_{\varphi}, K_{\gamma}, K_{\beta}\) – torsional stiffness for angular motion; \(C_X, C_Y, C_z\) – damping coefficients for linear motions; \(C_{\gamma}, C_{\varphi}, C_{\beta}\) – damping coefficients for rotational motions; \(k_1\) – coefficient of contact on the upper deck; \(\beta\) – angle of screen inclination; \(F_{2x}(t), F_{2y}(t), F_{2z}(t)\) – normally distributed \(N(\mu, \sigma)\) stochastic components of equivalent forces from material impacts, \(L_X, L_Z\) – normally distributed \(N(\mu; \sigma)\) deviation of equivalent force \(F_{2\gamma}(t)\) from nominal point, where \(\mu\) – mean value; \(\sigma\) – standard deviation; \(A, B, C, D\) – trigonometric functions of angles \(\beta, \theta\) and \(\alpha_{1,2}\) – rotation angles of two
exciters; \( a_i, b_i, c_i, d_i \) – coordinates of centre of mass (c.m.) and point of equivalent force application depending on process parameters.

2.1. Stochastic impacts from material
Stochastic component in the equivalent load \( F_{\Sigma Y}(t) \) applied on vibrating screen consist of two parts:

1) Impacts from material falling on the upper deck \( F_{\Sigma Y1}(t) \). Point of application has relative displacements \( L_X(t), L_Z(t) \) from nominal position on the central line and amplitude of force has normal distribution \( N(\mu, \sigma) \). Parameters of distributions depend on conveyor speed, bulk material profile, average density and size of particles, distance from conveyor. Mean values of these parameters are assumed to calculate particles motion from conveyor belt to upper deck of screen (see Figure 4b).

2) Impacts from material inside the screen \( F_{\Sigma Y2}(t) \). The mass balance of the whole system consists of input flow \( +M_{\text{in}}(t) \) and output flow \( -M_{\text{out}}(t) \) of material (see Figure 3). For stable process of screening, mean values of flow rates should be approximately equal in time. Hence, we can assume the constant mass of material on decks at least during several periods of screen oscillations. Influence of this volume of material on dynamics is accounted by equivalent force and its position on lower deck.

2.2. Simulation of spring defects
Maintenance staff of vibrating screens need to diagnose two types of defects:

- Reduced stiffness of springs.
- Cracks in springs.

Visual inspection of springs even on a stopped and emptied from material machine is not effective. Disassembling of support units to measure static deformations of every spring is time consuming and not feasible in practice.

Crack in spring causes transformation of its initially linear stress-strain function into bilinear characteristic. When spring is compressed, its stiffness is greater than it is stretched. Changes in lateral stiffness of spring when they bend from vertical axis depends on crack position. If it is near the vertical plane of screen motion (exciters rotations plane), then vibration signal measured on bearings of rotating exciters may contain patterns corresponding to this damage. Otherwise, this defect invisible for vibration diagnostic system.

Bilinear characteristics of springs produce harmonics of the main vibration mode, which can be detected in signals recorded in measurement points (on the bearings of rotating shafts). Another method is to detect deviation of natural frequency from nominal value when all springs are new. The problem is that during the long maintenance period, screen springs are replaced not simultaneously and have different service time. Each of four supporting units has 2-3 or more springs. Therefore, reduced stiffness of a single spring is difficult to diagnose by natural frequency deviation.

Detection of cracked spring position among four supports could be realized by comparing signals from 4 sensors on bearings, or better using sensors on the corners of screen to increase displacement...
difference between them. However, installation additional sensors and adding input signals into existing vibration monitoring systems is not encouraged by industrial customers.

To investigate possible methods of spring defects diagnostics, simulations are carried out on developed dynamic model. Parameters of dynamic model are as following: $a_1 = 1400$ mm; $a_2 = 800$ mm; $b_1 = 900$ mm; $b_2 = 300$ mm; $c_1 = 2600$ mm; $c_2 = 1300$ mm; $d_1 = 2200$ mm; $d_2 = 1200$ mm; $e = 1000$ mm; $L_X = 200$ mm; $L_Z = 1600$ mm; $\beta = 20^\circ$; $K_X=K_Z = 2.12\times 10^6$ N/m; $K_Y = 4.80\times 10^6$ N/m; $M = 32630$ kg; $J_X = 2.08\times 10^5$ kgm$^2$; $J_Y = 4.25\times 10^5$ kgm$^2$; $J_Z = 6.13\times 10^5$ kgm$^2$; $K_{XR} = 3.25\times 10^6$ N m/rad; $K_{YR} = 2.60\times 10^6$ Nm/rad; $K_{ZR} = 5.35\times 10^6$ N m/rad; $m = 80$ kg; $\omega = 96$ rad/s; and $\epsilon = 0.21$ m. Results of simulations are represented in Figure 5 – Figure 7.

![Bilinear stiffness of springs](image1)

**Figure 5.** Bilinear stiffness of springs (a); stochastic force (b); c.m. orbit (c)

![Time series](image2)

**Figure 6.** Time series (a) and spectrums for: healthy spring (b) and crack (c)

![Phase space plots](image3)

**Figure 7.** Phase space plots of vibrating screen with:
(a) health condition; (b) reduced by 20% stiffness $K_Y$; (c) crack in spring (nonlinear $K_Y$)

3. Discussion

Appearing asymmetrical spring cracks can cause damages of structural elements of screen body, such as reinforcing beams or lateral plates because of vibration modes unforeseen in design. On the other hand, decreasing spring stiffness can reduce material separation efficiency due to deviation of amplitude and direction of decks motion from nominal values.
Every of four supports usually contains 2-4 springs and diagnostics of a single failed element by the static deformation under load is impossible without disassembling of supporting unit. Using non-destructive testing techniques for their diagnostics is not feasible because of complicated configuration. Detection of a single spring defects is as well problematic due to about 10% scattering of steel properties (elastic modulus, endurance limit etc.).

The frequency of screen forced vibration from unbalanced exciters ($\approx 16$ Hz) is far above of its natural frequencies of either rotational or linear motion (<3 Hz). Therefore, methods of health monitoring by the deviation of natural frequencies and harmonics analysis are not appropriate here because detection of small relative changes at very low frequencies requires long times of sampling (10-20 s), that is not feasible under non-stationary stochastic loads affecting natural frequencies.

A distinctive feature of the developed dynamic model of vibrating screen is accounting stochastic components of loads from sieving material, which change amplitude and point of equivalent force application. Changing stiffness of springs and assuming bilinear characteristics as the result of crack are definitely visible in results of simulations with real level of noise from material impacts.

Proposed approach to vibrating screens monitoring and diagnostics based on PSP method of signals representation and analysis has some advantages as compared with frequency domain methods. There is no need long sampling times. Using coordinates of generalized variables of screen motion and their derivatives ($x; dx/dt$)allows representing and interpreting the whole portrait of the dynamic system. The scope of this paper does not cover special cases of non-linear system bifurcations near the special points, where PSP method is especially sensitive to small changes of parameters (progress of damage). Implementation of PSP method in maintenance practice requires development of qualitative metrics of trajectories in phase space topology. This is a subject of further research in vibrating screens diagnostics.

4. Conclusion
The main idea highlighted in this work is the application of dynamic model for analysis of vibration signals from industrial vibrating screens for diagnostic purposes. Proposed approach to monitoring and diagnostics of the vibrating screens allows to detect damages of supporting springs by the trajectories on the phase space plots, which are affected by stiffness reduction and nonlinear characteristics of the dynamic system. Phase space representation and analysis of signals is more immune to noise. Linear model response on a phase space plot is considered as a healthy condition of springs without defects. The main task is only once to compose dynamic model of the screen and then to use it for interpretation of measured signals. Proposed method helps to plan maintenance actions and to ensure reliability of equipment and sustainable technological process. Further research is directed on development of qualitative metrics for PSP results analysis.

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