# Diagnostics of Bolted Joints in Vibrating Screens

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Contributor: Pavlo Krot , Hamid Shiri , Przemysław Dąbek , Radosław Zimroz

The condition-based maintenance of vibrating screens requires new methods of their elements' diagnostics due to severe disturbances in measured signals from vibrators and falling pieces of material. The bolted joints of the sieving deck, when failed, require a lot of time and workforce for repair. Dynamical effects are investigated, which can occur due to bolted joints' degradation. Based on a reduced order dynamical model, important potential issues in screen design are discovered and new methods of diagnostics are developed.

vibrating screen | bolted joints | clearances | diagnostics | multi-body model | natural frequency | damping

## 1. Problems in Vibrating Sieving Screen Operation and Diagnostics

Sieving material is fed to the top of the screen by the belt conveyor with a specific linear speed. Some systems are under development [1] to prevent damage to equipment and improve process monitoring, but the conventional way is to design the upper deck of the screen as massive grizzly bars for providing scalping of the intake stream from the oversized components. The upper deck and lower levels of sieves are subjected to blinding, which induces screen overloading and technological process interruption. Also, large falling fragments of material generate force impacts with significant amplitude; thus, those disturbances which are stochastic by nature should be considered to prevent false alarms in fault diagnostic procedures [2][3][4][5][6]. The impulsive noise cancellation method for copper ore crusher vibration signal enhancement is proposed in [7]. The selection of the informative frequency band in a bearing fault diagnosis in the presence of non-Gaussian noise with a comparison of recently developed methods is fulfilled in [8]. Battery-powered wireless sensors are designed in [9], which are able to withstand vibratory loading and are embedded in the rubber screens for condition monitoring. Nevertheless, diagnostics of vibrating machines, in particular sieving screens, still is a challenge in theory and practice.

At the design stage, by using the discrete and finite element approach [10][11][12][13][14][15][16][17], the natural modes of the screen are examined to confirm minimal structural stresses and required trajectories of bulk material motion. Nonetheless, these approaches need significant computing resources in optimization and research. Also, statistical fraction distribution in the input flow, particle configuration, and a 3D screen model with details are required [18]. Hence, the reduced degree-of-freedom spring–mass models can be appropriate to accomplish a dynamical analysis of a vibrating screen as a set of rigid bodies connected by links with a certain stiffness and mass [19][20][21]

[22][23]. To account for the non-linear features of such systems, a piecewise model and estimates of damping and natural frequency are implemented [24], including adaptive diagnosis of the bilinear mechanical systems based on the free oscillation method with the decrement as a recognition feature [25].

Supporting springs are well-known as vital components of sieving screens, and they substantially affect particles' trajectory and overall process efficiency due to a significant influence on their dynamics [26]. Although there are a few advantages of using elastomeric or air-filled springs, they could create nonlinear behavior of the mechanical system [27][28]. In contrast, steel springs have linear stiffness within a wide range of deformation. However, specific dynamical effects can appear due to the nonlinear relation between the side bending displacement of steel springs and vertical stiffness [29][30]. Coupled mode parametric resonance in a vibrating screen is investigated on the two-mass models in [31]. The additional disturbances in the measured signals and dynamical effects can be produced by the inertial vibrators' bearings [32], damage and wear from which can result in a complex vibration spectra structure.

The most desirable by energy consumption are resonance vibrating screens [33] but they are not widely used in the industry due to working mode instability and complexity of control when material mass is changing. Issues of multiple vibrators' synchronization are considered in [34] and many other works. A chaotic vibrating screen is proposed in [35] to improve its sieving performance.

In the standard far beyond resonance vibrating screens, a serious dynamical problem causing excessive energy consumption constitutes the Sommerfeld effect when the machine structure passes its main resonance at startup. About 30% of the additional power of electric drives is needed for reliable transition through the resonance, which results in excessive energy consumption at the working rotation speed. When the rotation speed of vibrators goes down, the screen structure passes resonance very slowly and its elements are subjected to excessive loading cycles of high amplitude. Some solutions are proposed in this regard based on magneto-rheological dampers (MRDs) [36][37] and electric drive control [38], which are not yet widely implemented in the industry.

The additional dynamical loading is caused by the gaps opening, which can appear due to contact wear in joints and deformation of bolts. This effect has a potential threat to appear in non-stationary vibrating machines with reverse loading. Thus, due to the significant influence on the lifetime and reliability of different parts of the vibrating screen, clearances may be thought of as the most critical but hidden for measurement operational parameters. The bolted joints are one of the most vital factors determining the correct operation of vibrating screens. The strength capability of bolted joints supposes that the designers of machines should forecast their peak loads and prevent the contacted surfaces from opening at any joint under any forces because in this case, the additional stresses (torsional, bending, shear) appear in the bolt shank [39]. The greater preloading (limited by yield stress) can reduce the chance of bolt failure. Although preloading of bolted joints is the crucial factor, the specific tightening torque is not usually available during the repairing process, especially for large-size industrial systems where bolts' diameter can reach 100 mm. Based on the ASTM F568M, the metric bolts used for heavy-duty applications should have property classes 8.8, 10.9, or 12.9 and be made of alloy steels. However, in practice, the strength capacity of bolts can significantly deviate from the standard values due to different factors.

## 2. Diagnostics of Bolted Joints Loosening in Structures

The diagnosis of bolts loosening is a complex scientific and engineering problem considering the potentially massive number of bolted joints and the dramatic outcomes of their loosening, leading to the unexpected redistribution of inner loads between other bolts in joints, not only in rotating systems but in building, bridge, and other infrastructure that use a lot of bolts. Health monitoring of bolts can be divided into two general approaches. The first is based on smart bolts and dense sensors in the local area, and the second approach uses analysis of bolts based on modal analysis of whole structures and systems. A dense sensor approach can be performed by measuring tensile stress with ultrasonic waves [40][41], utilizing acoustic emission on rotating systems [42], electrical conductivity [43], vibroacoustic modulation (VM), and wave energy dissipation (WED) [44][45][46], as well as using spectral sidebands and high-order harmonics [47]. For measuring, such instrumentation can be used as piezoelectric active sensing [48][49][50][51], smart washer manufactured by lead zirconate titanate (PZT) [52][53][54][55]. Also, these methods can be combined with wireless technology for critical civil infrastructure and industrial facility monitoring. In the sieving screens, strong continuous excitation from unbalanced vibrators may have an influence on the reliability of electronic components.

In recent years, due to technological improvement of cameras and related algorithms, the approach based on image processing to diagnose bolts has accumulated some favor [56][57][58]. This method is usually combined with deep learning technology [59][60][61], support vector machines [62], and nonlinear decomposition such as empirical mode decomposition [63]. Selecting the reference points to detect changes in the nuts' position has a substantial effect on the reliability of these methods. Nevertheless, these methods cannot detect phenomena such as bolt creep and axial deformation in some states.

Another category of bolt diagnostic approaches is based on identified modal parameters of the system. Detecting changes in a natural frequency and phases can detect the weak bolt tightening caused by changing the system's stiffness and contact friction [64]. For instance, the vibration transmissibility function is a more reliable parameter to determine the joint state, while natural frequency and modal damping in modes with low frequency seemed less reliable. In other studies [65][66], experimental and theoretical methods have been accomplished to assess system modal properties and frequency response functions to detect bolted joint degradation [67][68][69]. In [70], the authors demonstrated that the first-order phase difference parameter is susceptible to the looseness of the bolts on the plate joint of the wind turbine tower. In [71], a finite element simulation is used to analyze rod flange-bolt structure unit (FBSU). Authors in [72] developed a simple method to assist bolt tightness by measuring natural frequency and damping ratio during the hammer test. In [73], non-linearity and damping ratio in bolt frequency response were studied. In [74], the authors modelled the bolt as a plane beam with two linear end springs (transverse and rotational).

For higher performance of vibrating screens, it is desirable to have a wider spectrum of excitation and vibrators' frequency control for better adaptation to changing properties of sieved materials. The energy-saving inertial drive for dual-frequency excitation of vibrating machines is proposed [75] and its dynamic analysis is conducted [76]. The coaxial unbalanced rotors and only one motor allow for saving energy and obtaining the required vibration trajectories (orbits).

In this research, the authors are focused on the dynamical analysis of a vibrating screen with an emphasis on the causes of frequent failures on the heavy upper deck and methods of bolted joint diagnostics. All further calculations are regarding only those bolts that fasten the upper deck to the screen structure to restrain its vertical displacement but not the other bolts in side panels, which loosening is planned for analysis in the future research. Researchers consider the most difficult case when nuts are fixed and other methods, e.g., visual inspection, are not sufficient in the bolted joint maintenance on the screens.

Both practical and theoretical goals motivated this research. The practical goal was to understand the reasons for frequent failures of bolted joints in the vibrating screen and to develop remedies against such failures. The theoretical goal was to develop methods of bolted joint loosening based on a dynamical model and implement the appropriate signal processing techniques. In fact, the developed method and diagnostic parameters are applicable to any horizontal screens and other vibrating machines (feeders, transportation tables) where two main parts are joined by the bolts and susceptible to frequent failures.

The scope of the conducted research covers industrial research and measurements on the fully functional laboratory screen. The novelty of the developed approach is in considering the vibrating screen as a system with a changeable structure when an additional degree of freedom appears due to bolted joint degradation. For certain combinations of design parameters of vibrating screens, the additional excitation can be generated by the higher harmonics of the inertial vibrators' frequency when their bearings are damaged. In this case, the second mode natural frequency change and the first mode damping values are used as the diagnostic parameters of bolted joint loosening. In addition, anti-resonances are identified in the 2DOF dynamical system and their possible effect on screen working efficiency and diagnostics is explained.  Also, for bolts' looseness detection, the phase space plots (PSPs) are applied, which are constructed by the vibration signals in coordinates of displacement and velocity. Their explicitly observable changes are caused by the non-linear characteristics of the bolted joints’ stiffness when clearance appears. The developed methods are not sensitive to the non-Gaussian noise created by the sieved bulk material because external impacts cannot change the modal parameters of the mechanical system.

The loosened bolted joints will significantly disturb the designed trajectory (orbit) of the sieving screen motion and reduce its technological efficiency. The out-of-phase vibrations of the upper deck will cause the gradually increasing plastic deformations of bolts and finally lead to their breaking. The critical value of clearance is determined, above which the bolt failure is unavoidable. In practice, with two accelerometers installed on the screen body and on the sieving deck, tensile forces (stress) can be easily calculated with relative displacements (deformation), which are then applied to the proposed diagram. Such interpretation and visualization of the bolts' degradation process help the maintenance staff to undertake repair actions in time to prevent an abrupt failure and unplanned machine downtime.

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