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AN EXPERIMENTAL STUDY OF VIBRATION OF A MECHANICAL SYSTEM CONTAINING A MEMBER WITH VARIABLE MASS

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ABSTRACT
This paper describes an experimental investigation of vibration of a mechanical system containing a member with variable mass, on the example of a ball mill which is used for grinding the limestone and similar minerals in industry for production of construction materials. This mechanical system consists of the driving motor, couplings, gear box and of the shell of ball mill which in this case is a member with variable mass. The mass of material inside the ball mill varies during operation in accordance with technological demands and so do the vibration of the complete system. Using acceleration sensors the vibration signals are recorded and processed for different values of the mass inside the ball mill. Prior to the measurement of vibration the main forcing frequencies of rotating parts of the ball mill have been determined. The time waveforms, frequency and acceleration envelopes spectra as well as cepstrums have been analyzed and discussed. The results show that the variation of the mass of one member of this mechanical system has a certain influence on vibration of the system as a whole.
Keywords: ball mill, mass variation, vibration, frequency and envelope spectra, cepstrum.

1. INTRODUCTION
Mechanical systems that gain and/or lose the mass during the motion are referred as mechanical systems with variable mass. These systems can be with continuous and with discrete mass variation. A drum on which the paper or metal sheet strip is wound up belongs to the class of mechanical systems with the continuous variation of mass. Into this class falls also the impeller of an industrial fan on which the build-up of firm particles from the gasses is created increasing by that way the mass and inertia of the impeller. As examples of mechanical systems with the discrete mass variation one can consider the mechanism for unloading of wagons, crane while unloading material, etc. Into this class belongs also the above mentioned impeller of the fan in a case of a sudden brake-off of a piece of the settled build-up. That would be a case of the discrete loss of mass of the impeller i.e. discrete variation of its mass. The ball mill investigated in this paper is a mechanical system with the continuous mass variation since its shell is a member with variable mass in which the mass varies continuously. The aim of this study is to quantify the responses of the system by analyzing the vibration signals acquired on the bearing housings of all members of the mechanical system and to correlate them to the variation of the mass inside the shell of the ball mill in order to identify the vibration parameters of this system that are sensitive to the mass variation. If such a correlation exists it would help us to detect many vibration problems just by adaptation of the mass flow to the desired vibration measurement.

2. MASS VARIATION IN THE BALL MILL
A ball mill investigated in this study is the main component of the lime stone grinding plant in a cement factory of which the material flow sheet is given in Fig. 1. As it is seen from the flow sheet the mass of material entering into the ball mill consists of the fresh raw materials that are fed from the bins and of the ground material which is rejected from the air classifier and is conveyed back into the ball mill to be ground once again. From the air classifier particles of material are transported by an air stream to the cyclones and further to the fabric bag filter where they are extracted as a final product.

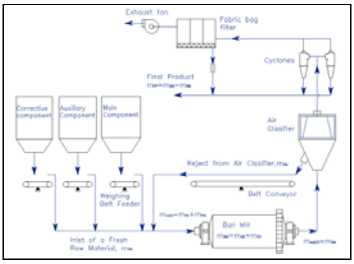

Figure 1. Flow sheet of a grinding plant

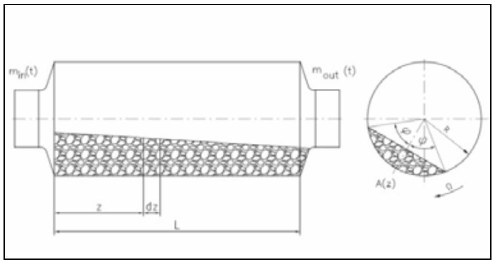

Figure 2. Distribution of the mass inside the ball mill

The total mass inside the ball mill in operation consists of the mass of a fresh raw material m_{FM}, which is fed into the ball mill shell, mass of material which is rejected from the air classifier m_{RM}, and of the mass of grinding bodies, m_{GB}, which in this case are the steel balls of various sizes. Grinding bodies together with the raw material are called the charge. The mass of the ball mill shell which is a member with variable mass includes also the mass of the shell itself, m_{SH}. Thus total mass of that member is:

$$M = m_{FM} + m_{RM} + m_{GB} + m_{SH} \qquad ..... (1)$$

Mass of raw material varies during operation in accordance with technological requirements. The mass of each material inside the ball mill can be changed by changing capacity of feeding of that material and the mass of a primary ground material rejected from the air classifier can be changed by changing the speed of rotation of its impeller. Distribution of the mass of charge along the ball mill shell is in general case not even. It means that the cross section area varies with the distance $z \in (0, L)$, of the observed cross section from the inlet into the mill, i.e $A = A(z)$, where L is the length of the ball mill. Thus, the mass of charge in an arbitrary volume of the length dz ,is a function of the coordinate z, and of the time, t. Equation of conservation of mass in that arbitrary volume, has the next form, [1]:

$$\frac{dM}{dt} = m(z,t) - \left[m(z,t) + \frac{\partial m(z,t)}{\partial z} dz \right] \qquad .....(2)$$

Taking into account that $m = A(z) \cdot \rho(z) \cdot w$, and $dM = A(z) \cdot \rho(z) \cdot dz$, where w is the absolute velocity of motion of mass of arbitrary volume along the ball mill shell, Eq. (2) takes the next form:

$$\frac{\partial m(z,t)}{\partial t} + w \frac{\partial m(z,t)}{\partial z} = 0 \qquad .... (3)$$

The density of the charge in the above equation also changes with coordinate z, due to the change of granulometric properties of the charge along the ball mill shell. Thus $\rho = \rho(z)$. If we neglect the variation of the cross section area of the charge as well as the variation of the density along the shell, i.e if we assume these entities as constant for a given capacity, the above hyperbolic partial differential equation becomes a common first order differential equation which represents the rate of change of mass of the charge inside the shell when it is considered as a control volume. Then Eq. (3) becomes:

$$\frac{dM}{dt} = m_{in} - m_{out} \qquad .... (4)$$

Where:

$$m_{in} = m_{FM}(t) + m_{RM}(t), \text{ and } m_{out} = m_{GM}(t) \qquad .... (5)$$

Here one should notice that even in a steady state operation $m_{in} \neq m_{out}$, but it only applies the next relation: $m_{FM} = m_{FP} = m_{out} - m_{RM}$, where m_{FP} is the mass of final product of grinding.

3. EQUATION OF MOTION

Mechanical system of the ball mill together with its drive train is here considered as a multi degree of freedom mass-spring system whereas one of its member has a variable mass. Since the mass of the material streams in- and out of the ball mill at the same time this mechanical system gains and looses the mass instantly. The mass of charge inside the ball mill shell $M(t)$, moves through the ball mill shell with absolute velocity $\vec{w}$. Mass $m_{in}(t)$ is the mass which is added into the ball mill with absolute velocity $\vec{u}_1$, and the mass $m_{out}(t)$ which streams out of the ball mill with velocity $\vec{u}_2$, is the separated mass and $\vec{u}_2$ is the absolute velocity of that separation. The equations of motion for this mechanical system can be written by using a law of conservation of momentum in the next form, [2]:

$$M(t)\frac{d\vec{w}}{dt} = \vec{F} + (\vec{u}_1 - \vec{w})\frac{dm_{in}}{dt} - (\vec{u}_2 - \vec{w})\frac{dm_{out}}{dt} = \vec{F} + \vec{F}_{R1} + \vec{F}_{R2} \quad .....(6)$$

Although velocities $\vec{u}_1$ and $\vec{u}_2$ are much greater then velocity $\vec{w}$ both reactive forces $\vec{F}_{R1}$ and $\vec{F}_{R2}$, due to the small rate of change of the mass, are small comparing to the other forces and they can be neglected in this case. But the total change of the mass inside the ball mill after a certain time interval cannot be neglected. Results of vibration measurement that has been performed for two different values of the mass of charge inside the ball mill shell show that clearly. Thus Eq. 6 takes the form:

$$M(t)\frac{d\vec{w}}{dt} = \vec{F} \quad .... (7)$$

4. A BALL MILL VIBRATION MEASUREMENT

Measurement of vibration has been done by using a piezo electric accelerometer SA620 with sensitivity of 100 mV/g (Metrix,USA), and an amplifier of type Spider 8, with software for signal acquisition and analysis, Catman, Co. HBM, Germany. Measurement has been done for two different values of the mass inside of the ball mill corresponding to the capacities, Q_1=72t/h and Q_2=30t/h. Speed of rotation of the ball mill has been held constant. Prior to measurement the specific forcing frequencies of all rotating parts of the ball mill were determined in a manner described in [3] and [4].

5. RESULTS AND DISCUSSION

Time waveforms of the vibration measured with capacity of ball mill Q_2=30 t/h show higher overall readings. Peaks in frequency spectrum, spectrum of envelope of acceleration as well as the peaks in the cepstrum for capacity Q_2 are higher than the same peaks in the spectra of vibration signals obtained at capacity Q_1. They indicate the problems with gears and rolling bearings in the gearbox. The prominent peak at the gear mesh frequency of the gear pair Z_1/Z_2, F_{GM}=413.25 Hz, and its harmonics are present in all obtained spectra. The 2nd harmonic of this frequency at 826.5 Hz which is dominant in the spectra in Fig. 4 and 5, indicates the misalignment of the gear pair Z_1/Z_2. The sidebands spaced around this peak at running speed frequency of gear Z_1, F_{PN}=16.53 Hz, indicate that the main problem is with gear Z_1, which, the most probably is wear.

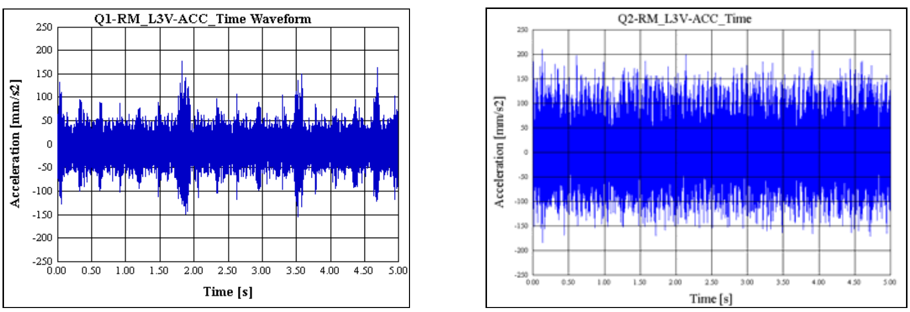

Figure 3. Time waveform of vibration signal from MP L3V: left for Q_1=72t/h, right for Q_2=30t/h

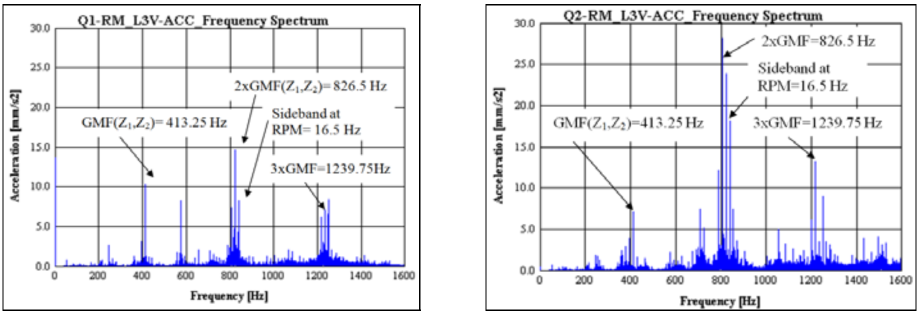

Figure 4. Spectra of acc. of vibration from MP L3V: left for Q_1=72t/h, right for Q_2=30t/h

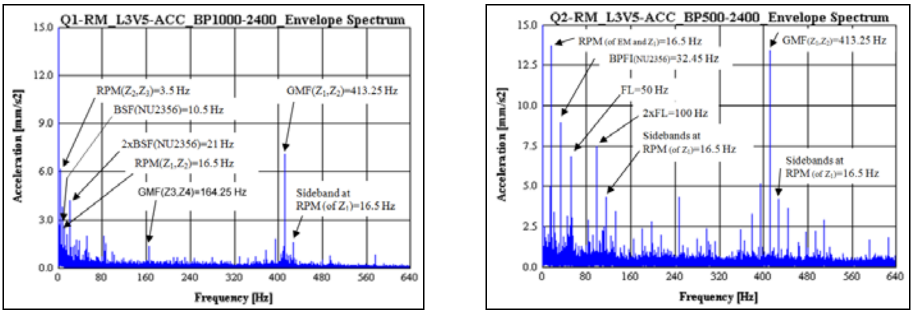

Figure 5. Spectra of envelope of acc. of vibration from MP L3V: for Q_1=72t/h, and for Q_2=30t/h

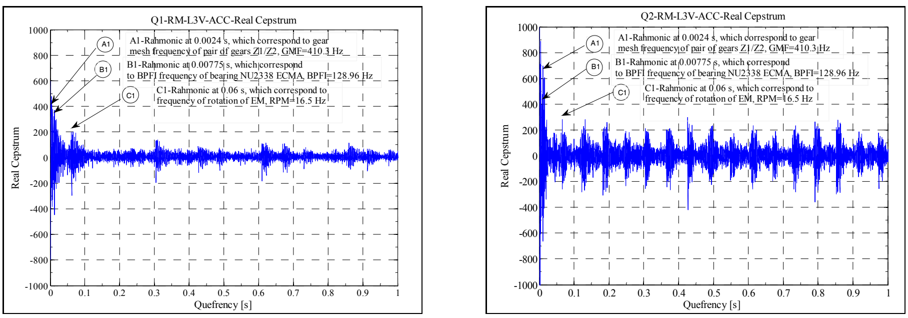

Figure 6. Cepstra of acc. of vibration from MP L3V: left for Q_1=72t/h, right for Q_2=30t/h

6. CONCLUSION

This experimental study has shown that the variation of mass inside the shell of the ball mill has a significant influence on all analyzed vibration parameters. Amplitudes of vibration increase with decrease of the mass inside the ball mill showing that there exists a distinct correlation between the mass variation and the intensity of vibration of the ball mill components. Peaks at the gear mesh frequencies and at the specific forcing frequencies of rolling element bearings caused by faults such as wear, cracks, spalls, misalignment, imbalance, looseness and other defects were clearly higher in the spectra of vibration measured when the ball mill was operating with lesser mass inside of its shell.

7. REFERENCES

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