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MODELLING OF GRINDING FACILITIES

by

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ABSTRACT

The development of numerical methods to model grinding mill systems is presented. These methods can be used during design of grinding facilities in mineral processing and other plants to reduce the risk of adverse behaviour. The results obtained using these methods have been compared with physical data gathered from mineral processing plants. The accuracy of the results is sufficient for design purposes. The methods presented represent a significant improvement over traditional methods used to analyse mill systems components such as mill foundations and gearless drives. Direct estimates of deflection and vibration levels for the entire grinding system can be obtained. In general, traditional methods provide information on stiffness and natural frequencies from which it is difficult to extract quantitative estimates for stiffness and vibration.

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INTRODUCTION

The mechanical design of grinding facilities in mineral processing plants is based on designing the individual components and then fitting these components together. The mill vendor designs the mills; one or more vendors (depending on the drive arrangement) design the drives for the mill and the main contractor responsible for the project designs the concrete foundations for these components. The main contractor has the responsibility for making these components work as a system. To this end, the contractor may require the mill vendor to undertake a torsional vibration analysis of the mill system if the mills are driven through gears or a “system stiffness analysis” when the mills are driven by gearless drives (wrap-around motors). However, this approach neglects the dynamics of the foundations. Furthermore, the “system stiffness analysis” does not model the nonlinear interaction between gearless drives, the mill and the foundations correctly.

The consequences of failing to consider system interactions and dynamics can be dramatic. Mill foundations can vibrate excessively resulting in severe discomfort to personnel working near the mill and in some cases, in buildings far removed from the mill foundations. In some cases, vibrations have been severe enough to cause complete failure of component supporting piers, the repair of which was costly due to lost production. Drive failures can also occur. Torsional vibrations can lead to premature gear failure, as can differential stiffness and thermal ratcheting [1]. Gearless drive stators can deflect excessively under load resulting in contact between the stator windings and the rotor poles. Large amplitude vibrations can also occur in the stators and can lead to the loss of availability of the mill [2].

The flexibility of the mill, drive and foundations increase as the size of mills become larger. Second order effects then become more important in the design of these components and can sometimes dominate. Therefore, the trend towards purchasing larger mills will lead to greater risk of adverse behaviour occurring in new mineral processing plants. Methods used to design and analyse new, larger grinding system components and the grinding systems as a whole will need to be more sophisticated so that the risk of adverse behaviour can be minimised.

This paper presents modelling techniques developed to assess the likelihood of adverse behaviour in grinding systems. The development of these methods commenced during the design of the mill foundations for the Cadia Project in NSW, Australia. A brief review of the Cadia mill foundation dynamic analysis will be presented highlighting the need for further development of the numerical methods. A short summary of the mill drive problems at Cadia is also presented, illustrating the need for modelling of these components during the design phase of the plant. The current modelling methods for the mill systems will then be presented and the application of the methods to a new plant built in South America will be discussed.

METHOD HISTORICAL DEVELOPMENT

The methods developed to model mill systems presented herein were initially developed for the Cadia Project in New South Wales, Australia. The Cadia concentrator is the largest concentrator in the southern hemisphere. It employs the world's largest SAG mill, 40 ft diameter and two 22 ft ball mills in the grinding circuit. In that project, the owners considered it necessary to assess the dynamic response of the foundations for the SAG and ball mills due to vibration problems experienced in other installations. Numerical models of the foundations were developed using the Finite Element Method (FEM). However, the analysis faced two major problems. Firstly, the dynamic loads generated by the mills were not known. Secondly, the radiation damping provided by of the sub-surface soil could not be modelled using *finite* elements, as this required modelling an *infinite* volume of soil below the foundations. The approximation chosen was to model the soil as a finite volume under the concrete foundations. The models resulted in excessive deflection amplitudes due to the reflection of stress waves back to the foundation from the artificial soil boundaries. This inability to model the radiation damping necessitated the use of the following comparative method for assessment for the foundations:

a) Models for the foundations were developed and analysed using nominal dynamic loads and a large volume of soil beneath the foundations.

b) The results from these models were then compared with the results from similar models of existing foundations for which the actual vibration levels were already known and considered acceptable.

c) The foundation designs were considered adequate if the calculated vibration amplitudes from the models of the new foundations were less than or equal to the calculated levels from the models of existing foundations which were known to have low vibration levels.

Whilst this comparative assessment approach proved successful, it had the following inherent disadvantages:

a) The method required an extensive database of results from other foundations to perform the assessment.

b) The comparison was valid only between models of foundations built on soil with similar properties and stratification.

c) The global calculated vibration amplitudes were fictitious and were dependent on the nominal loads supplied by the equipment vendors and the volume of soil modelled under the foundation.

It was clear that a more quantifiable approach based on the physics of the foundation systems to assess mill foundation dynamics was desirable.

Drive commissioning at Cadia

During commissioning of the Cadia mills and shortly after, problems developed in the mill drives. The SAG mill gearless drive stator deflected excessively during inching and it “resonated” at normal operating speeds. Furthermore, the ball mill gears were severely scored after four months of operation. EAnD were commissioned by Cadia to determine the causes of the drive problems and to develop remedial measures [1,2]. The causes of both the SAG and ball mill drive faults were related to the stiffness of the drive components.

During this work, the characteristics of the SAG mill system were measured. The resonant frequency of the foundation was determined using an amplitude decay technique. Vibrations in the SAG mill stator were of sufficient magnitude to cause vibrations in the foundations of up to 0.1 mm. Using seismic accelerometers, the decay of these vibrations after shutdown was recorded from which the damping and natural frequency of the foundations were determined. Mill forces were also measured. The SAG mill force frequency spectra showed distinct peaks at the mill shell and head liners passing frequencies and at some higher harmonics. Tests on the ball mills also showed the presence of all of these frequencies as clear peaks on the frequency spectra. Finally, the stator vibration mode shapes, natural frequencies and static deflections were determined using accelerometers, instrumented sledgehammers and dial gauges respectively. This work showed that the actual stiffness of the electrical core was significantly less than the design value and this was the cause of the excessive vibrations and deflections in the stator.

The data obtained at Cadia were then compared with data available from other SAG and ball mill installations. It was found that the forces generated in mills by the charge were similar for all the mills considered when normalised against diameter and speed of rotation. In particular, the forces generate by the shell and head liners were consistent between SAG and ball mills with widely varying diameters.

QUANTITATIVE NUMERICAL MODELS BASED ON MILL SYSTEM PHYSICS

The Cadia measurements provided physical insight into the interaction between mills, drives and their foundations. Numerical models of these components were developed and the results obtained were compared with the measurements to determine the accuracy of the models. It was found that once radiation damping from the soil and the forces form the mills were incorporated into the models, sufficiently accurate estimates of the complete mill system behaviour for design purposes were obtained. A description of these modelling methods is presented in the following sections.

Mill foundation analysis

Dynamics of flexible mill foundations are difficult to analyse using standard analytical or numerical methods. Classical empirical methods such as the Barkan model [3] assume that the foundation acts as a rigid body. This results in an overestimation of the foundation global natural frequencies, as the coupling of the flexural and global modes is not considered. Furthermore, no information on the flexural vibration of the foundation piers and raft can be obtained using these standard methods. Numerical methods such as the finite element method are also difficult to apply, as the direct simulation of radiation damping is not possible. Radiation damping is the dominant energy dissipation mechanism in most dynamically loaded foundation systems. Typically, *radiation* damping ranges from 30 to 70% of critical for mill foundations whereas the other sources of damping, mainly *material* damping, provided by the concrete or the soil, range between 3 to 6%. Radiation damping cannot be included in models developed with standard finite element packages. The often used approximation of modelling the base of the foundation as being fully fixed in space, i.e., neglecting the contribution of the soil, results in poor estimates of the individual pier amplitudes and frequencies.

A hybrid numerical method was developed to incorporate radiation damping into the analysis. The method combines the finite element method to model the concrete foundation and includes radiation-damping effects by using a boundary element approach to model the soil. This technique was validated against measured data from Cadia and results

were found to be within 20% of measured vibration levels. This level of accuracy is sufficient for use in design of foundation systems. The importance of including radiation damping in foundations analysis is shown in Figure 1. For the particular foundation modelled, the amplitude of vibration is significantly reduced at normalised frequencies between 0.5 and 0.8. These frequencies correspond to the global translational and rotational natural frequencies of the foundation and hence are reduced when far field effects are included. When the normalised frequency equals 0.15, the effect of radiation damping is not significant as this frequency corresponds to a flexural mode of the foundation.

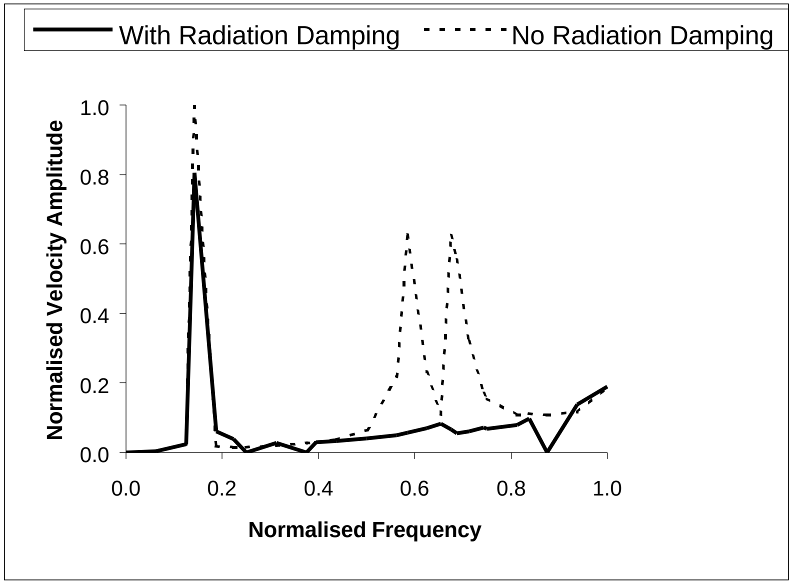

Fig. 1: Effect of radiation damping on vibration amplitude.

Gearless drive stators – dynamic analysis

The electromagnetic forces in the air-gap caused the excessive vibrations encountered in the Cadia stator. A method has been developed to assess if such vibrations will occur in other stator designs. It is based on the following process:

a) A detailed finite element model of the stator is developed to determine natural frequencies and mode shapes.

b) The modal information is then used to develop a system of equations that describe the forced vibration response of the stator.

c) The forced-vibration analysis is run for the entire range of mill running speeds to determine if unstable vibrations will occur.

d) The natural frequencies are also compared with the forcing frequencies in a forced vibration analysis to determine if resonance can occur.

This method was applied to the Cadia stator. The dominant mode of vibration was the second mode as shown in Figure 2. The air-gap forces were then applied to the model to determine the response. It was found that sub-harmonics of the forcing frequency developed at approximately 60% of the mill critical speed. The amplitudes of the sub-harmonics increased gradually with speed until they became dominant at about 75% of the mill critical speed. These results matched observation of the mill behaviour and indicated that the method could be used to assess other gearless drive stators.

Fig. 2: Dominant mode of stator vibration (SAG Mill).

Stator static deflection analysis – minimum air-gap

One of the critical features of a gearless drive is the air-gap between the stator and the rotor. This air-gap must be kept within certain tolerances to ensure proper and efficient operation of the drive.

The electromagnetic forces in the air-gap attract the stator to the rotor. Hence the total mill system must be sufficiently stiff to ensure that the air-gap does not collapse.

A method of determining the minimum air-gap has been developed. A model of the mill, the stator, their foundations and the foundation sub-surface soil is created as shown in Figure 3. Forces are then applied to the core of the stator and to the rotor poles to determine the deflections. When the eccentricity between the rotor and stator is known, these models produce estimates of minimum air-gap that are within 5% of the actual result. This level of agreement is sufficient for design purposes. The standard “system stiffness” analysis may be in error by as much as 200%.

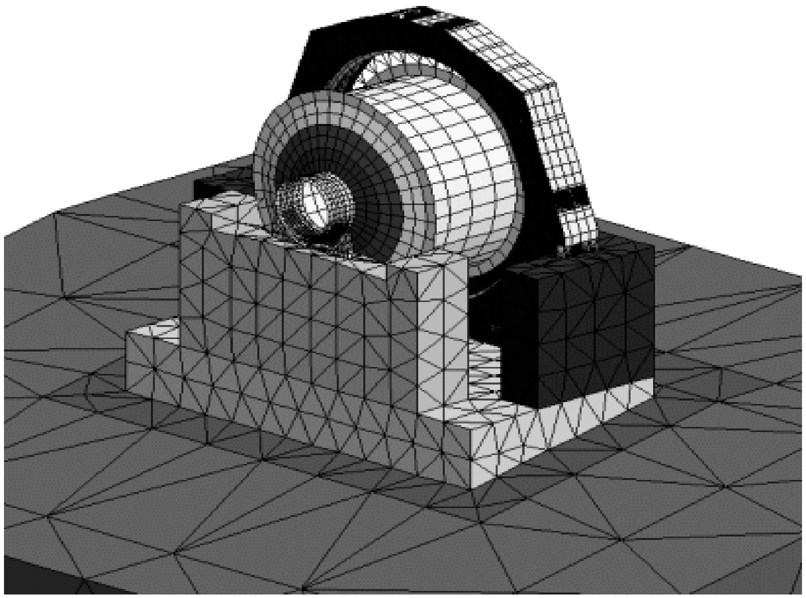

Fig. 3: Part model of the SAG mill system.

APPLICATION OF MODELLING METHODS TO A NEW GRINDING FACILITY

At about the time that the Cadia stator was being repaired, a concentrator for a new mine development in South America was being designed. The new concentrator was larger than the Cadia concentrator. The grinding circuit consisted of a 38 ft SAG mill and three 24 ft ball mills, each driven by gearless drives. The client recognised the risk involved in the development of the mill systems given the difficulties encountered at Cadia. Therefore, EAnD were commissioned as an independent auditor to assess the behaviour of these systems.

A broad scope for the audit of the grinding plant was developed. The mill foundations and the gearless drive stator designs were assessed to determine the potential for excessive deflection and vibration. Cross-excitation of mill foundations from charge forces developed in mills on adjacent foundations were estimated. The concentrator building and the office block were assessed to determine the likelihood of excessive vibration levels. The audit was to be based on the modelling methods presented above.

Mill foundation analysis

The new grinding facility is required to process two distinctly different types of ore. Therefore, each mill is required to operate at a range of speeds; the maximum nominal speed is approximately twice the minimum nominal speed. This meant that the frequency content of the forces generated by the motion of the charge in the mill has a wider range than other mill installations. The aim of the foundation dynamic analysis was to ensure that the design of the mill foundations would not result in excessive vibrations at any of the operating speeds.

The results of the mill foundation analysis showed that the natural frequencies of the fixed bearing piers matched the charge forcing frequencies when the mills were operating at their lowest nominal speeds. The forces generated by the charge in the mills would be sufficient to cause excessive vibrations at these frequencies. This was the case for both the SAG and ball mill foundations. The information was passed onto the foundation designer who then modified the foundation piers. It is important to note that the designers of the foundations, followed accepted engineering practice, yet a problem with natural frequency was still likely. The mass of the foundations was greater than two times the rotating mill mass plus charge and a rigid body dynamic analysis was also performed. This shows that methods commonly used to design foundations for mills do not provide sufficient information regarding the flexural behaviour of the foundation piers. The flexibility of the foundations needs to be considered in design. This cannot be achieved using classical methods.

SAG and ball mill gearless drive stators

The SAG mill gearless drive for this project is the largest designed by the drive vendor. The aim of the audit was to assess if excessive vibrations and deflections would be likely to occur.

The results of the minimum air-gap analysis showed that the deflections in each stator should be acceptable if the initial eccentricity between the stator and rotor in each drive could be kept to less than 2 mm, the nominal eccentricity guaranteed by the mill vendor. Greater eccentricities would result in greater deflections. Increasing the initial eccentricity to 5 mm would effectively reduce the air-gap by half; this would be unacceptable.

A dynamic analysis of the stator was performed as described above. The analysis showed that the stator was not likely to vibrate excessively due to the development of sub-harmonics. However, it was found that the first in-plane mode of vibration, Figure 4, could equal the stator forcing frequency depending on the modulus of elasticity of the electrical core. A core stiffness of 100 GPa would result in sufficient separation of the natural and forcing frequencies. This information was relayed to the drive vendor for their consideration.

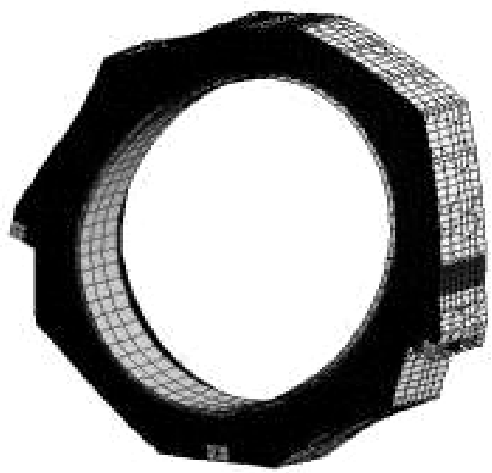

Fig. 4: Dominant mode of stator vibration (SAG Mill).

Other analyses

Cross-excitation analyses of the foundations were performed as part of the audit. The models of the individual mill systems were coupled and dynamic loads were applied to each mill to determine the influence of one mill on another. It was found that the levels of cross-excitation were negligible due to the large mass of the foundations.

Analyses of the grinding building were also performed to assess the likelihood of excessive vibrations, particularly on the work platforms and in the office block. A model of the building was developed from the column bases up. Sinusoidally varying displacements were applied to the bases on each column to simulate the vibration levels in the soil caused by the mills. The amplitudes of these displacements were determined from an amplitude decay analysis. In general, the work areas in the building were found to be less than the maximum allowable limits. The analysis of the office block region of the building predicted levels of vibration that would be noticeable to personnel but less than the "reduced comfort boundary" after 8 hours of exposure (AS2670). Using this information, changes were made to the design of the office block by the building design contractor.

CONCLUSION

The development of methods to model the structural response of the major components of a grinding system has been presented. The methods are based on the physical behaviour of the individual components. Models based on these methods have been calibrated against field measurements and proven to provide results that are sufficiently accurate for design purposes.

A complete grinding facility was modelled using the methods described in this paper during the design phase in order to assess the likelihood of adverse behaviour. Estimates of deflection levels and vibration amplitudes for the system components were provided to design engineers who were then able to assess the need for modifications. This is a significant improvement over standard analytical methods that provide only qualitative information to the designer such as (a) the proximity of forcing frequencies to natural frequencies or (b) the "stiffness" of the system rather than a direct estimates of the minimum air-gap.

Methods commonly used to design mill foundations are based on mill total mass to foundation mass ratios and rigid body analysis of vibration using classical techniques such as the Barkan method. The analysis of the mill foundations using the numerical methods presented in this paper shows that these methods do not provide information regarding the flexural behaviour of the foundation piers. The flexibility of the foundation rafts and piers needs to be considered in design to ensure that excessive vibrations do not occur.

FURTHER RESEARCH

The analysis of the grinding facility presented in this paper employed three sub-analyses to determine the overall system behaviour. These analyses were based on a combined model of the mill, foundation and

gearless drive stator, simplified models of the four mill foundations to determine cross-excitation response and a model of the concentrator building structural steelwork. An investigation has been undertaken to assess if an advantage could be gained by combining these models into a single model of the grinding facility prior to performing the analyses. An example of such a model is shown in Figure 5. Results indicate that the additional accuracy obtained from this approach does not warrant the cost associated with the extra solution time required to solve the larger model.

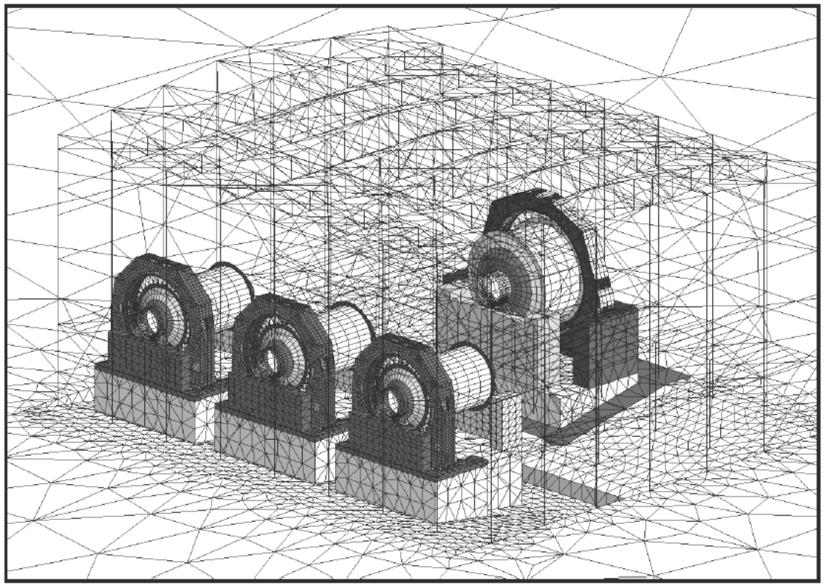

Fig. 5: Model of a complete grinding facility.

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