

EAnD's Engineers Solve Vibration Problems in the World's Largest Mill Drive.

Focus for this issue:

- SAG Mill Gearless Drives
- Vibration Testing and Analysis
- Modal Testing and Analysis
- Calibrated FEA Models
- Root Cause Analysis



The grinding circuit at a new gold mine in Australia, includes the world's largest mill, a 40 ft SAG mill. Drive problems were encountered during commissioning of the mill and later during operation. EAnD have recently completed the third stage of a major project aimed at finding the root cause of these problems and providing solutions to ensure the mill runs optimally for the full design life. Use of the latest vibration measurement methods and computer modelling techniques have been applied with excellent results. Addition of extra stiffening at strategic locations has provided a fully functional drive.

Inside this issue:

Stator Vibration Analysis	2
Root Cause of Vibration Problem	3
Root Cause of Inching Difficulties	3
Remedial Design Options	4
Results of Repairs	4
Insight Supplement	5

Introduction

The stator of the SAG mill gearless drive at one of Australia's newest mines exhibited excessive vibration during commissioning. EAnD engineers were called in by the mine owners to assist in solving the problem. Initial measurements taken by EAnD showed that the vibration levels exceeded 300 mm/s at the top of the stator. Initially, operators had to limit the speed of the mill (and reduce throughput) to avoid the vibration. The drive also would trip intermittently during inching thus hampering mill relines. The drive vendor installed temporary chocks to relieve the vibration problem. Mine staff were eventually able to control both the vibration and inching problems by careful adjustment of the chocks. Full availability was eventually achieved. However,

the longevity of the stator remained a major concern to the mine management and a more permanent solution was required.

EAnD were commissioned to undertake a detailed study of the stator and to develop a range of possible remedial solutions. The articles presented in this edition of Insight cover the following major aspects of the study:

- vibration measurement and modelling,
- vibration root cause analysis
- low speed inching root cause analysis
- remedial design options
- results of repairs.



SAG Mill Stator - Vibration Study

The stator was designed by the drive vendor using their established methodology. Several 38 ft stators had been built and commissioned without incident. The 40 ft stator was the first to exhibit any vibrations. The vendor suspected that the foundations were too flexible and that they reduced the overall stiffness of the stator. They also stated that the foundation resonated on the subsurface rock, thus causing the stator to vibrate as observed. The foundation, like the mill and the stator, was also the largest of its type ever built. Although EAnD were skeptical that the vibrations were related to the foundation, it was not obvious that this was the case. EAnD's first task was to measure and analyze the vibrations to determine if the stator or the foundations were resonating.

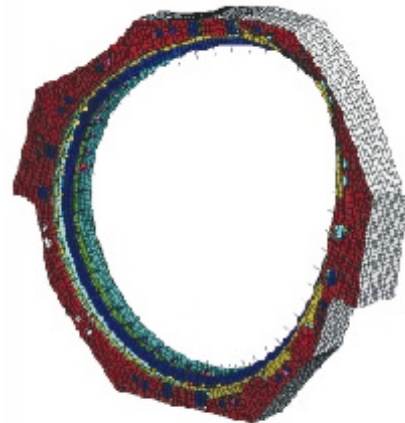
The initial step in the study was to determine the nature of the vibrations in the stator. The vibrations occurred suddenly and reached full amplitude in a matter of 1 or 2 seconds. The speed at which the vibrations occurred varied from 70 to 78 % of the critical mill speed depending on various operating and environmental conditions. The amplitude of vibration was so high that the vendor, quite rightly, would stop the mill immediately upon noticing the vibration. However, this made measuring the vibrations more difficult.

EAnD engineers decided that the best way to tackle the problem was to measure the mode shapes of both the stator and the foundation, that way a "picture" of how the stator and foundations were moving could be obtained. They decided to do this during the short time period between when the large vibration started to occur and when the emergency stop was hit. They suspected that the stator vibrated in its second mode. To capture this mode and the vibration of the foundation simultaneously would require over 30 low frequency accelerometers – a tall order for any testing operation. So EAnD used a technique in which the vibration could be measured in three separate tests and then the total mode shape could then be pieced together using purpose made software.

The result of the tests confirmed that the stator vibrated in its second mode. This explained why the temporary chocks at the bottom of the stator were effective in reducing the vibration – they effectively stiffened the stator thereby reducing the amplitude of the vibration. However, the vendor indicated that their design calculations had estimated the second mode frequency of the stator was almost twice the resonant frequency. This meant that more needed to be done to prove to everyone's satisfaction which component of the system was resonating, the foundation or the stator.

A two-stage analysis was performed to answer this question. First, the finite element models of the stator and foundation were analyzed to determine the relative amplitudes of vibration that could be expected in the stator and foundation. The analysis showed that the measured vibrations correlated closely with the case when the stator was resonating and the foundation was "following" the vibration of the stator; the vibration levels in the foundation were an order of magnitude lower than the vibrations in the stator. Second, the vibration phase data between the stator and the foundations was analyzed. The phase relationship between the stator and foundation vibrations indicated that the stator was resonating rather than the foundation. At this stage, the mine project team were satisfied that the analysis and testing had proven conclusively that the stator was not behaving as intended in the design and that the foundation was not resonating.

The next stage of the project was to determine the reason why the stator vibrated at a lower frequency than expected. See the following story on page 3.



Second mode of vibration of the stator. The deflected shape (exaggerated) is identical to the mode measured on site.
Model developed by EAnD.



Root Cause Analysis 1: Vibration

The next step in the analysis was to determine what caused the stator to vibrate at a frequency that was much lower than the design natural frequency, ie, what was the root cause of the problem. The frequency of vibration was also of concern; the vendor indicated that there was no forcing frequency generated in the motor equal to the vibration frequency.

EAnD developed a number of very detailed finite element models of the stator. These models considered the effects of the winding shields, the connection to the foundations and the stiffness of the electrical core. Other effects initially thought to be of secondary significance such as the offset between the rotor and stator and the thermal expansion of the stator were also investigated.

The finite element study showed that the core stiffness was most likely to be the source of the problems. The vendor was skeptical. To overcome the impasse, and to quantify the core stiffness, EAnD recommended to the mine that the stator natural frequencies should be *measured*. The tests would allow EAnD to calibrate the finite element models they had developed so that they could be used as predictive tools. Hopefully, the results of the tests would also be sufficient to convince the vendor that the core was not as stiff as had been assumed in the design.

Natural frequencies can be measured in a number of ways, but the method chosen in this case was an impact test. EAnD's 5 kg instrumented sledge hammer was used to excite (hit) the stator at a critical location. The frequency of the resulting vibrations would give the natural frequency. An instrumented hammer was

required as the natural frequencies were required when the mill was stationary and when it was running. In the latter case, the instrumented hammer allowed the background vibrations from the motor and mill to be filtered out.

The tests carried out by EAnD engineers showed that the natural frequency of the stator when the mill was stationary was 30% less than design estimates. The natural frequency reduced by a further 10% when the mill was running. This meant that the magnetic forces in the stator were sufficient to influence the dynamics of the mill and supported EAnD's argument that the stator core stiffness was less than the design stiffness. The data obtained allowed EAnD to estimate the stiffness of the core and thus develop a predictive finite element model of the stator.

With the root cause of the vibration problems determined as an unexpectedly low core stiffness, it was then necessary to determine the cause of the inching problems prior to the mine committing to the down-time required for any repairs. See Part 2 below.



Instrumented sledge hammer used in modal testing of the stator.



Root Cause Analysis 2: Inching

During operation, the most difficult problem to control was the intermittent tripping of the motor during inching of the mill. The trips were a headache for the mine's maintenance team as they caused delays during mill relines. Their persistence with the adjustment of the temporary chocks finally proved fruitful and the relines proceeded more-or-less as if there were no problems with the stator. However, even with the chocks installed and adjusted properly, the stator deflected visibly and this was a major concern to the mine.

EAnD developed a nonlinear finite element model of the stator that simulated the conditions during inching. The analysis accounted for the initial offset between the rotor and stator and the core stiffness determined from the vibration study. The nature of the magnetic forces generated in the stator were also considered. These forces are a complex function of the "air-gap", the distance between the stator and the

rotor active elements, thus the governing equations for the stator are nonlinear. The analysis was run and results were compared with very accurate measurements of the stator static deflections. An excellent correlation between the measured and calculated results was obtained.

The model was then run using the design stiffness for the core material. Calculated displacements were less than 20% of the measured displacements. The model was also able to predict the reduction in observed displacements caused by the chocks.

The vibration and inching studies showed that the low core stiffness was the root cause of the stator troubles. EAnD's finite element models developed during the stator study that included the reduced core stiffness could then be used with confidence as predictive tools to assess potential remedial measures. These remedies are discussed in the article on page 4.

Remedial Design

The aim of this work was to come up with a remedial design of the stator that would engender a high level of confidence in all parties. To the mine owners in particular, the driving force behind the work has been to ensure that the probability of success of any remedial measure should be high enough to justify the downtime required for the repair. Furthermore, the mine owners preferred a permanent solution that would not rely on their staff's continual intervention and would ensure the longevity of the machine.

Right from the start in the project, there was a concern that the temporary chocks were inducing stresses in the stator that were not considered in the original design. Of particular concern were the stresses caused by the restriction of the thermal expansion of the stator by the chocks. The remedial design would have to account for this.

Several ideas were proposed to solve the problem. EAnD preferred a passive solution, the application of a stiffener or *strongback* to the upper half of the stator. EAnD developed a preliminary design of a strongback. Modelling showed that a strongback was a feasible solution but its implementation would require the consent of the vendor who eventually would be required to complete the detailed design due to warranty considerations. EAnD also developed preliminary designs for active solutions including a vibration absorber and thermally compensated pedestals to replace the temporary chocks.

The vendor took another path. They believed that the cause of the low core stiffness was due to a high pre-stress in the structure. They argued that the four main bolted joints in structure were not shimmed during erection as required and hence the deformation in the structure caused by the gap in the joints generated a high pre-stress in the structure. They believed that this pre-stress caused the core to buckle.

The mine allowed the vendor to shim the joints in December 1998. This was unsuccessful; the vibration problem actually increased. The vendor advised that the gap in the joints was larger than they had planned and that they were confident that a further re-shimming would solve both the vibration and inching problems. Whilst the vendor was certain that the shims were the cause of the problem, they also adopted EAnD's strongback idea as "belt and braces" to ensure success. They designed a "light weight" strongback that could be fitted to the stator with minimal shut-down time. However the vendor's modelling showed that the strongback provided almost the same increase in natural frequency as the temporary chocks. This strongback was initially unacceptable to the mine as more margin in the design was preferred.

The mine owners asked EAnD if it was likely that the vendor's proposed solutions would successfully eliminate both the vibration and inching problems. Our engineers created a model of the stator that coupled the magnetic forces with the structural dynamics of the stator. The model was able to correctly predict the observed original stator behaviour with and without the chocks and showed that the shimming would have no effect. The model was then applied to the stator with the strongback. It showed that whilst the predicted increase in the natural frequency of the stator caused by the strongback was similar to the increase from the chocks, the strongback would result in lower overall deflections. This is because additional stiffening is applied directly to where the vibrations are greatest, whereas the chocks are remote from this location. EAnD then designed a modification to the strongback that would provide an additional 30% increase in stator natural frequency for very little extra weight. EAnD advised the mine that the strongback should be installed *if modified as per EAnD specification* and that the shimming should not proceed as it was unlikely to have any effect on the stator behaviour.

Results & Conclusion

The vendor insisted that the shimming of the stator was necessary and they recommended that both the shimming *and* the strongback should be undertaken. Given the potential contractual implications, the mine had little option but to agree to this request. During a shut-down this month, the stator was unbolted at all four main joints and re-shimmed. The *modified* strongback was also installed.

Upon completion of the re-shimming and with the strongback only partially installed, the mill was inched for relining. Excessive deflections were again observed in the stator; the re-shimming was not effective. These deflections were eliminated only after the modified strongback installation was completed. EAnD then

measured the stator natural frequency and found that it agreed exactly with predictions from their model.

The stator now behaves correctly. There are no more inching or vibration problems as the strongback has provided the additional stiffness required.

This project shows the benefits of combining measurement and modelling over the use of modelling alone in predicting the response of complex structures. It is imperative that designers should obtain as much information from existing equipment before designing new, larger machines. See the "Insight Supplement" for further information for designers

The Insight Supplement

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Specifications for Gearless Drives: Stator Design

From time to time, EAnD include this supplement with Insight Magazine to provide specific design information for our readers. The information is related to one or more of the main stories in Insight Magazine. Back-copies of Insight Magazine and Supplements can be obtained from EAnD upon request. For contact details, see the back page of Insight or below.

A stator is required to provide sufficient stiffness to ensure that the rotating magnetic field forces do not significantly alter the air-gap between the active elements of the rotor and stator. In general, this is not a difficult task to achieve. However, rotor diameters for SAG mills can exceed 13 m, yet the air-gap is of the order of 15 mm. Making a stator stiff enough to ensure that the air-gap remains constant around the circumference of a rotor of this size is not feasible. The air-gap in mill gearless drives varies significantly around the rotor circumference. The object of the structural design of the stator is to ensure that the air-gap does not collapse to zero under the magnetic field forces and thus cause mechanical damage to the windings and rotor poles.

Many factors influence the stiffness of the stator. Some of these have been discussed in the current issue of Insight Magazine. The stator housing is the major stiffening element with some additional stiffness provided by the core. However, mill stators are not generally intrinsically stiff; they rely on the foundation to provide fully fixed lateral restraint at both supports. Most stators would collapse under the magnetic field forces if the standard combination of fixed and roller supports were used. The connection between the stator and foundation is also critical.

A question now arises: how can the drive air-gap be controlled if different contractors design the stator, the mill and the foundations? The practice currently employed is based on the calculation of an overall system stiffness. Once this parameter has been determined, each component is assigned a target design stiffness so that the overall stiffness of the system is met.

The stiffness approach relies on the principal of superposition for linear systems. However, the behaviour of stators is far from linear. The magnetic field forces in the stator are a function of the air-gap, that is, they increase as the air-gap decreases. This is further complicated by the complex relationship between the magnetic field and the speed of the stator. In a stator recently

analysed by EAnD, the stiffness at 11.2 rpm was 30% higher than the stiffness at 9.2 rpm. However, the stator deflection at 11.2 rpm was twice that obtained at 9.2 rpm. Clearly, the use of a single stiffness parameter to assess air-gap behaviour is at best ambiguous and at worst erroneous.

EAnD recommend that specifications for the purchase of gearless drives should include a detailed scope of work for the analysis of stators. The use of the "stiffness method" for assessing stators should be considered only as a preliminary means of assessing the overall system design. The specification should stipulate that a more direct method of estimation of the motor air-gap should be used to assess the final design. The specification should also stipulate acceptable methods of analysis (analytical, numerical, etc) and a minimum set of parameters that should be considered in the assessment of the overall system. Furthermore, the dynamics of the stators should also be assessed. The scope and complexity of the analysis required would be contingent on the size of the stator being built, the power rating of the drive and whether the proposed design is new or a slight variation of an existing design. If a new stator design is being proposed, either due to an increase in diameter or an increase in power draw, a full analysis should be requested. This would include:

- a nonlinear static analysis;
- a modal and forced vibration analysis which includes the mill, foundation and sub-surface soil;
- a coupled magnetic field – structural dynamics analysis;
- a complete system analysis to determine the air-gap.

A thorough knowledge of the interaction of the structure and magnetic field forces is required to assess potential designs. The need for experienced independent auditing as is common practice for mills is clearly warranted. The cost of repairs and down-time far outweigh the initial investment.