Mill Vibration Phenomena during Cold Rolling
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All machines vibrate during operation and only a few of these vibrations cause problems to the product or the machine itself. Typically, the most damaging vibrations involve a natural resonance of the machine which significantly increases the motion of critical components. The vibrations within a rolling mill are no different and the most damaging modes of vibration involve some very specific natural resonances of the mill stand. If no structural resonances are excited then the vibration amplitude is simply a consequence of the way the mill responds to a cyclic exciting force acting at a particular location within the mill.

The simplest type of mill vibration is found in all mills and is a forced vibration due to roll eccentricity and so is experienced at roll rotation frequencies. These frequencies are usually lower than any of the resonant frequencies of the mill stand and so gauge variation is a result of the stiffness response of the mill and the material being rolled. In some cases, at higher speeds, it is possible for this vibration to be worsened by excitation of torsional resonances of the main, unwind or rewind drives. These torsional resonances usually occur at frequencies up to around 30Hz and if the mode involves a fluctuation of work roll speed then there may also be interaction with lubricant instabilities in the roll bite. This phenomenon is sometimes referred to as torsional chatter.

Natural resonances of the rolling mill involve translational motion of the rolls and typically occur at frequencies greater than 50Hz. Of the large number of these resonant modes that could become excited during rolling, only a few will cause damage to the metal being rolled or the surfaces of the rolls. Excitation of these specific, damaging modes are the typical cause of the phenomena of third octave gauge chatter and fifth octave roll and strip chatter marking. Because of its self-exciting nature, third octave gauge chatter still poses a difficult problem for the industry, in some instances causing significant financial loss due to a reduction in cold rolling speeds. Fifth octave chatter is more prevalent on mills and can cause significant surface quality issues. This article will now focus on these two key mill vibration phenomena.

Third Octave Gauge Chatter
A third octave gauge chatter problem can produce significant gauge variation from a few percent of nominal gauge up to higher percentages and can even cause strip breaks. This is due to excitation of one of the natural resonances of the mill stand. Commonly these natural resonances have frequencies between 100 and 150Hz but sometimes as high as 300Hz. These frequencies are much higher than the bandwidth of most gauge control systems, so the gauge variation is averaged over several vibration cycles and not seen by the system.
The onset of gauge chatter vibration occurs at high rolling speed and usually can only be stopped by reducing speed. It is rarely possible to stop the vibration by increasing speed if the mill is truly unstable. Typically the amplitude of vibration will rise very rapidly (in less than a second) and the vibration will become audible at the vibration frequency. Without vibration monitoring equipment this audible noise is often the only indication to the mill operator that the mill is vibrating. Some lower frequency modes may also be felt in the ground supporting the mill housing.

During gauge chatter the gauge variation will be fairly uniform and in-phase across the strip width. It is often only detected by careful off-line thickness measurements of the final product. Figure 1 shows a simulated gauge variation produced by vibration with several vibration cycles per metre length of strip.

![Figure 1: Simulated 3-dimensional gauge trace for a 0.5m section of sheet product showing +/-5% gauge variation due to third octave gauge chatter](image)

Figure 2 shows the typical rolling mill resonances that can become excited to produce gauge chatter. The most common mode for a 4-high mill is shown in Figure 2 (a) and involves the top two rolls moving vertically in anti-phase against the bottom two rolls. The mill stand housing is also involved in the vibration mode. There is very little deflection of the work roll barrels which helps to understand why the gauge variation is similar at all positions across the strip width.
There is a special class of vibration called self-excited vibration. Self-excited systems begin to vibrate of their own accord spontaneously, the amplitude increasing until some non-linear effect limits any further increase. The alternating force that sustains the motion is created by the motion itself and stops when the motion stops. A natural resonance is often involved in the self-exciting behaviour, providing the structural flexibility. Common examples include machine tool chatter, the sounds from some musical instruments, aeroplane wing tip flutter, chimney sway and bridge vibration. A good example of a self-excited bridge vibration is the famous Tacoma Narrows bridge that collapsed in 1940 due to high wind speed.

Third octave gauge chatter also falls into the category of self-excited vibration and like the Tacoma Narrows bridge, the cold mill will vibrate without an independent external cyclic force to excite it. This means that during gauge chatter there is a feedback mechanism that provides a sustaining force to increase the mill vibration amplitude which is a consequence of the vibration motion itself. This mechanism has its origins in the roll bite and is a consequence of the continuity of mass flow through the stand. Figure 3 illustrates this mechanical feedback loop that exists in every mill stand.
On the basis of continuity of mass flow through the mill stand during rolling it can be shown that a change of exit gauge, \( H_o \), will produce a change in strip speed, \( V_o \), entering the mill, assuming the entry gauge, \( H_i \), and exit speed, \( V_o \), remain constant. The change in strip speed at one end of the entry strip compared to the other will produce a change in entry strip tension. A change in entry tension will produce a change in exit gauge, \( H_o \), thus completing the loop. Analogous to electrical control system instabilities, there is a 180 degree phase change around the loop and so the loop will go unstable as the gain is increased above a certain threshold value. From the equations given in Figure 3, coupling each term in the loop, it can be seen that gain is proportional to the exit speed of the strip. This explains why rolling mills prone to gauge chatter vibration exhibit the problem suddenly as the speed is increased above a threshold value. Normally this threshold speed cannot be exceeded and to do so would cause strip break and/or damage to the mill.

Other factors such as the material being rolled, the rolling conditions and the natural damping of the mill stand resonance will all affect the threshold rolling speed for vibration. However, these are difficult to change and none vary as significantly as the speed during a particular rolling pass.

Third octave gauge chatter can be seen in single stand cold mills and cold tandem mills, the latter being a little more complex due to interaction between the stands via the interstand strip.

The rolling speeds on cold mills suffering from this type of gauge chatter vibration are often constrained for certain products. For these products the rolling speeds are kept below the threshold speed at which mill vibration occurs, sometimes with the use of on-line vibration monitoring equipment. This can represent a significant loss of productivity if the mill is a bottleneck machine.

There are various solutions that can be applied to this problem to increase the threshold rolling speed of cold mills and Innoval Technology Ltd is active in this area.
Fifth Octave Chatter (Roll and Strip Chatter Marks)

Fifth octave chatter marks usually develop on the backup roll barrel and print via the work roll onto the strip surface with a spacing between 10 and 40mm. Figure 4 shows an example of severe chatter marks around the barrel of a backup roll before grinding. The markings are parallel to the roll axis and often have uniform intensity across the backup roll barrel. With very sensitive surface proximity measurements it is possible to measure surface features with amplitude of a few microns that relate to the markings.

![Figure 4](image-url)

Figure 4: Example of severe fifth octave chatter marks on the barrel of a backup roll that would produce similar surface markings on the strip.

The chatter mark problem requires a source of forced vibration within the mill. Typical sources on the mill may be forced vibrations from defective gear teeth, roll bearings and drive couplings. If the forced vibration excites a fifth octave resonance of the mill stand then the vibration amplitude will be increased by the flexibility of the mill and the marking problem will be more severe. The vibration frequency associated with fifth octave chatter is usually in the range 600 to 1200Hz. Another source of forced vibration in the mill is due to periodic sub-micron features on the roll surface produced during roll grinding. These are created by forced vibrations within the roll grinder that usually also excite a natural resonance of the grinding machine. Very careful vibration measurements are required to identify the source of the marking before this problem can be solved.

It can be helpful to understand the fifth octave resonant frequencies of the mill stand and this can be approached through computer simulation or experimental modal analysis. If the grinder is involved then a full modal analysis of the grinder is also useful.
Figure 5 shows a typical fifth octave chatter mode that can be responsible for producing chatter marks if excited in a 4-high mill. The mode involves the two work rolls moving in-phase and vibrating between the two backup rolls. The backup rolls move in anti-phase to the work rolls but their amplitude is significantly less than the work roll amplitude. The relative motion between the work roll and the backup roll damages the backup roll surface during the period that the backup roll is in the mill. The predicted mode involves significant bending of the work roll necks. It should be noted that this type of mode belongs to a family of fifth octave modes, all capable of damaging the backup roll through relative motion between the work roll and backup roll.

Some solutions to this problem may require an on-line monitoring strategy on the grinder and/or the mill to identify the source and then minimise its impact. This is an effective operational strategy to maximise productivity while maintaining high quality of the strip surface.
Summary

The two common forms of mill vibration that are most difficult to solve are third octave gauge chatter and fifth octave chatter. Both can cause significant strip quality issues if they occur on a mill. There is always a source of vibration responsible for fifth octave chatter so a solution can usually be found to this type of problem.

Third octave gauge chatter vibration, however, is particularly difficult to solve because it is self-exciting so can occur with no source of forced vibration. The problem usually represents a speed limit on cold mills and can cause significant loss of productivity. For this reason, the gauge chatter is still the subject of significant ongoing research and development. In principle, there should be a threshold rolling speed on all cold mills where gauge chatter vibration will become self-exciting. For most mills this threshold speed is greater than the current maximum rolling speed so vibration is not experienced. As cold mill speeds increase this problem is likely to become more of an issue unless a good solution can be found.

Please contact the author for further information on how best to resolve mill vibration issues and all other rolling and finishing problems associated with aluminium production.